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Annotation

The conference is going to open a comprehensive discussion of the fundamental problems of sustainable energy development in the world and regions. This forum is expected to gather leading world scientists and specialists in the field of energy.

The main topics are:

- Sustainable energy development
- International energy cooperation
- Interstate energy systems, global energy interconnection
- Energy security
- Energy markets and energy policy
- Energy systems development and operation
- Smart control and management, cybersecurity
- Integrated energy supply systems
- Reliability and quality of power supply
- Environmental energy issues
- Innovative energy technologies, renewable energy sources, hydrogen energy
- Systems analysis, mathematical modeling, computational methods and information technology in the energy.

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Contents

Definition of Key Indicators to Identify Optimal Distribution Grid Restoration Strategies

Christoph Strunck and *Christian* Rehtanz
TU Dortmund, Institute for Energy Systems, Energy Efficiency and Energy Economics, 44227 Dortmund, Germany

Abstract. Due to significant changes in the power energy system and extreme weather conditions as a result of the increasing impact of climate change, large scale blackouts become more likely. With the rising penetration of renewable energy sources in distribution grids and the shutdown of large conventional power plants, the system inertia and therefore the resilience is decreasing. This will have a significant influence on the provision of ancillary services in the future. Especially for grid restoration processes, new concepts are necessary to assure an optimal integration of the distributed energy resources to resupply a grid after a blackout. However, to identify and assess the capability of distribution grids to restore the grid operation to resupply their grid independently of the transmission system key indicators are necessary for an analysis. Hence, this paper introduces a key indicator system, which has the goal to address several challenges of a distribution grid restoration.

1 Motivation

To reach the global goals of carbon reduction, to minimize the negative effects of climate change, especially the energy systems has begun to change in the last years. In the electrical power system, these changes are mainly on the generation side. Huge nuclear and coal power plants are going to be shut down and replaced by smaller decentralized energy resources (DER) units like wind power turbines and solar power plants. This poses several challenges for the grid operation in the future. On the one hand, these power plants are fluctuating generation units and therefore less reliable. Moreover, they are not necessarily near load centres, but rather distributed and connected to the geographically optimal place in the distribution system. On the other hand, DERs are mostly connected via converter. Hence, the inherent inertial reaction of the synchronous generators that provide additional stability and resilience to the grid is no longer available. [1] In the future, more system splits and blackouts can be expected, as it can already be observed today due to e.g. extreme weather situations [2,3]. However, DERs offer new opportunities for new innovative strategies like a grid restoration of distribution grids and the stable and reliable island grid operation of such grids.

Already today, many distribution grids, especially in Europe, theoretically have the potential to perform a grid restoration with DERs. [4] However, sophisticated strategies and investigations are necessary to identify the best grid restoration strategy as well as to assess the critical steps during the process. Obviously, additional communication and digitalization as well as the enhancement of control schemes of larger DERs will improve the capability to be able to blackstart the grid. A considerable amount of research is focusing on the possibility of the restoration process based on quasi-dynamic analyzations that are considering the net balance of demand and generation with DER and battery energy storage systems (BESS) under different weather and load conditions [4-6]. However, in future research it will be important to evaluate grid restoration processes in a distribution grid with dynamic studies, which poses several challenges. [7]

Hence, to validate not only the dynamic ability for a distribution grid operator to restore its grid, but also the best restoration strategy, key indicators are necessary. In this paper, different indicators are presented and discussed with regard to the restoration process and the subsequent island grid operation. The factors are classified and further analysed in respect to possible strategies or recommendations for such. To build up the restoration process indicators, available data of distribution grid operators will be considered. This includes but is not limited to the annual peak load $P_{load,max}$, the number of grid areas $n_{gridarea}$, the number of remote controllable circuit breakers, and the installed PV P_{PV} or DER P_{DER} power, respectively. This data should be available as part of the published grid structure data which are published by every European distribution system operator (DSO) yearly [8]. However, more detailed information like the share of remote-controlled circuit breakers and grid areas are not publicly available. The better the database, the better the grid operator can be given an indication of the blackstart capability of the grid and which additional measures the operator may have to consider.

This paper is structured as follows. In section 2, the challenges of a blackstart of a distribution grid is addressed. Based on these challenges, the developed key indicators are presented in chapter 3. In chapter 4, the indicator system will be applied on a real German distribution system before chapter 5 concludes the paper and gives an outlook.

2 Challenges of a distribution grid restoration process

In case of a grid restoration process in a distribution grid with a high share of renewable energy sources (RES), there are different challenges compared to a conventional grid restoration process. For once, blackstart units (BSUs) with suitable control schemes are needed.

Moreover, a significant part of the available RES power comes from distributed PV plants, which cannot be controlled or even reparametrized in practice. Therefore, the protection devices are shutting off the PV plants for frequency drops below 47.5 Hz or gradually reducing the power for frequencies above 50.2 Hz before shutting off at 51.5 Hz. This poses one of the greatest challenges for the grid restoration process of a distribution grid. Frequencies below 48 Hz are usual due to a low share of rotating masses. With the aforementioned protective shut-downs of PV plants the effective load step is even larger and can lead to instabilities or a new blackout. [9-11]

Moreover, most circuit breakers in distribution grids are not remotely controllable. In order to be able to switch the circuit breakers, personnel is required who have to drive long distances to reach the substations. Additionally, a stable and reliable communication needs to be assured between the control center and the personnel in the field.

In this case, voltage instability is of no concern during the grid restoration process of a distribution grid, frequency stability is the primary criterion [12]. Therefore, sophisticated control schemes are necessary to assure a participation of DERs in order to maintain the frequency and avoid critical drops. However, these should be designed without the need of communication between the DERs. [12]

Moreover, reliable load forecasts for switchable feeders are not possible due to several uncertainty factors. Therefore, worst-case scenarios with, among others, cold load pick-up (CLPU) and the magnetization currents of transformers need to be considered. However, it is also important to consider how even the load and RES are distributed in the feeders. [13]

While transmission system operator have a high observability of their grid and measurements of every line and substation, DSOs have not the necessary technology installed in their grid. Moreover, to assess the blackstart capability, indications are needed to be made based on data, which is easily accessible.

Moreover, in Europe a grid restoration process for distribution grids is mainly for rural distribution grids with high shares of RES. However, these grids are also having long feeders and often imbalanced load and PV power in these feeders. This can pose a significant challenge if e.g. feeders with high loads are reconnected in a later stage of the restoration process.

3 Key indicators to classify distribution grids

To address the aforementioned challenges in a distribution grid restoration, key indicators to classify a distribution grid regarding the capability of a restoration process are introduced in this chapter. An overview of the key indicators is given in table 1.

First, the main question is if to build up the grid centralized from one blackstart unit or decentralized with more BSUs. Therefore, the commanding DER with $P_{BSU,high}$, which is often a CHP plant or a hydro power plant with the benefit of rotating masses and blackstart capability, is of great importance. This key indicator is telling two things regarding the grid restoration:

- Depending on the types of the Commanding DERs the maximal permissible load step and with this
- if the Commanding DER is capable to restart the grid from its connection point or if a decentralized grid restoration should be approached

$$ComDer = \frac{P_{\text{BSU,high}}}{P_{\text{load,max}}}. \quad (1)$$

Another important indication is the homogeneity of the distributed load and PV systems in the individual, with circuit breaker separated, feeders. To calculate the load balance

$$LoadBal = 1/\frac{Span}{IQ} * g. \quad (2)$$

a analysis of the connected loads in the grid areas is necessary. Therefore, the range of the load values is divided by the interquartile distance IQ. The reciprocal of this is then multiplied by the skewness g of the load data set. This gives an indication regarding the expected homogeneity of the grid areas depending the load and is important to perform further investigations. These could identify critical grid areas where sophisticated strategies should be applied, or on the other hand, small grid areas which could be reconnected simultaneously.

As it is described in section 2, PV plants can become a challenge during a distribution grid restoration process. Therefore, the PV balance in the grid areas is another important factor in defining the best switching sequence. The PV balance is calculated analogous to the load balance with

$$PvBal = 1/\frac{Span}{IQ} * g. \quad (3)$$

Another substantial factor in a grid restoration process is the speed of the grid restoration. Since distribution grids are not as remotely controllable as transmission systems, it is important to consider the remote controllable circuit breakers

$$ReCBc = \frac{n_{\text{cb,ctrl}}}{n_{\text{cb}}} * n_{\text{gridarea}}. \quad (4)$$

Table 1. Definition of the developed key indicators

Commanding DER (**ComDer**)	Nominal power of the largest DER for an indication of permissible load steps
Load Balance (**LoadBal**)	Homogeneity of the grid areas regarding the maximal active power of connected loads
PV Balance (**PvBal**)	Homogeneity of the grid areas regarding the installed PV power
Propotion of PV plants (**ProPV**)	The share of the installed PV power in relation to the total installed DER power
Remote circuit breaker controllability (**ReCBc**)	The share of switchable grid areas via remotely controllable circuit breakers
Restoration process controlled poweravailabillity (**ResPow**)	Available controllable DER power for the grid restoration process (e.g. CHP plants, hydro power plants or large wind turbines)
Storage Ratio (**StoRat**)	The ratio of installed energy storage power with regard to the maximal load
Non-fluctuating DER share (**NonFlu**)	The ratio of non-fluctuating installed power

Especially in distribution grids with large supply areas it is important to increase remote controlled circuit breakers since the alternative is that personnel needs to drive to the circuit breakers which can take up to 30 minutes for each switch.

As described, it is not practical to control every small DER. Hence, the ResPow

$$ResPow = \frac{P_{DER,ctrlable}}{P_{load,max}} \qquad (5)$$

indicates the controllable DER power. Depending on the grid, this can be extended to non-fluctuating controllable DER power.

It is not only important to be able to restore the grid but also to operate the grid in an island grid mode following a grid restoration. Therefore, it is evenly important to have some form of energy storage. This could be a BESS, which is able to help during the restoration process with providing power faster than e.g. CHP plants. Moreover, BESS can provide important balance power for the volatility of PV plants or wind turbines. This is necessary during the blackstart as well as the island grid operation. Therefore, the ratio of the available storage power is defined by

$$\text{StoRat} = \frac{P_{stor}}{P_{load,max}}. \qquad (6)$$

Lastly, it is important to assess the share of non-fluctuating DERs like CHP plants, hydro power plants or BESS with

$$\text{NonFlu} = \frac{P_{stor}+P_{CHP}+P_{hydro}}{P_{load,max}}. \qquad (7)$$

Obviously, a distribution grid restoration is highly dependent on fluctuating energy resources. Therefore, with this indicator the possibility to restore a grid with changing weather conditions is given. However, further considerations and distinctions between solar and wind power should be made.

4 Study case of a German distribution grid

In this chapter, an approach for a restoration process in a distribution grid is evaluated. First, the main challenges of a distribution grid restoration process are explained. Next, the methodology for the proposed restoration process will be introduced.

4.1 Specifics of the present distribution grid

In this case study, a German distribution grid has been investigated. It supplies 18,000 customers with a cable length of 170 km in the medium voltage and 260 km in the low voltage grid. Moreover, it is divided in eleven feeders. In 2018, the annual peak load was 13.34 MW.

In general, the grid is meshed. However, due to the high protection requirements of a meshed network, it is not operated as such, but rather as an open ring system. It is possible to control larger generation plants remotely. This allows the system operator to control the active power of larger DERs to assure a reliable and stable island grid operation and restoration.

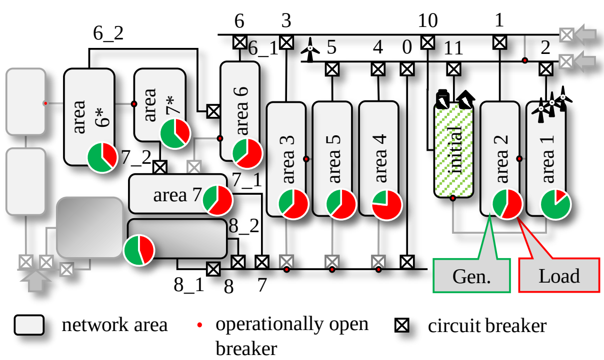

Fig. 1. Schematic plan of the considered medium voltage grid

The distribution grid in this case study has a high penetration of RES. A significant part of the installed generation capacity is located in the city centre (area 3-5) and the urban areas of 1-2 and 7 (cf. Fig. 1). Notably, this includes a 13.5 MW CHP plant and an 8 MVA BESS displayed with *initial*. Additionally, a 1.2 MW black start capable CHP plant is connected to the same common point of coupling.

Moreover, four wind power plants with an installed capacity of approximately 10 MWp are located at different connection points in feeder two. Throughout the grid, about 700 PV systems with a maximum peak power of 11 MWp are connected to the low voltage (~95%) and the medium voltage level (~5%). Moreover, almost 93% of the installed PV systems are household systems with less than 50 kWp. Especially these PV plants are not evenly distributed in the grid and are not controllable from an economic point of view. Therefore, these PV plants are primarily responsible for the challenges that are described in section 2.

4.2 Key indicators of the case study

In the present case study, the developed indicator system is shown in figure 2. The corresponding input data and values of the key indicators are shown in table 2.

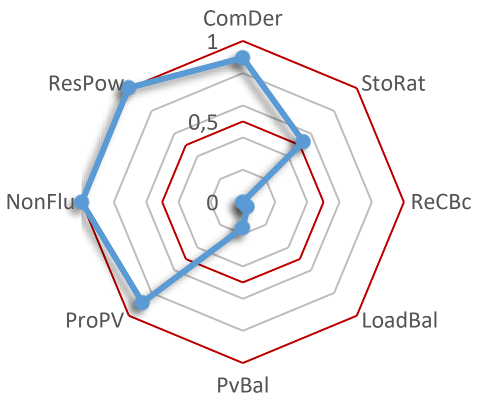

Fig. 2. Key indicators systems for the considered use case

As it can be seen, the chosen example grid has a strong characteristic towards the left part of the radar chart. Hence, the value for ComDer is with 0.9 exceptional high. This shows, that the commanding DER can supply almost 90% of the maximal load. Obviously, the large CHP plant for an industrial application is of great use for restoring this grid. Not only that, but also a StoRat of 0.53 is an indication for the capability to be able to restore the grid. Another positive indicator is the ResPow which shows that the power of controllable power plants is above the maximal load P_{max}.

However, the weak manifestation of the lower left part of the spider chart shows on the one hand highly imbalanced feeders regarding both, the installed PV power and the load. This shows that the installed PV power is not evenly distributed through the feeder. The same applies to the distribution of the loads. Hence, a stable grid restoration even with the large commanding DER cannot be assured.

What's more, the ReCBc shows with 0 that the circuit breakers are not remotely controllable. This results in potentially long waiting periods between the switching actions. However, the distance between the switches should be taken into account here.

The ratio of PV plants (ProPV) together with the imbalanced distribution in the feeders show a significant influence of the PV plants. Hence, a grid restoration by night could be difficult while a strategy for minimizing their negative impact on the grid during a blackstart needs to be considered.

Concluding, the non-fluctuating DERs are with a share of over 100%, especially due to the non-fluctuating commanding DER, well equipped to restore the grid independently of the weather situation.

Table 2. Key indicators for the considered case study

Commanding DER (**ComDer**)	**0.90**
Load Balance (**LoadBal**)	**0.03**
PV Balance (**PvBal**)	**0.16**
Proportion of PV plants (**ProPV**)	**0.88**
Remote circuit breaker controllability (**ReCBc**)	**0.0**
Restoration process controlled poweravailabillity (**ResPow**)	**1.01**
Storage Ratio (**StoRat**)	**0.53**
Non-fluctuating DER share (**NonFlu**)	**< 1**

4.3 Concluding grid restoration strategies

With the key indicators of the use case from section 4.2, various restoration strategies for the considered grid can be developed and derived.

Here, four conclusions can be made straight away. First, the remote controllability of the circuit breaker is a significant feature of a stable and reliable grid restoration. Therefore, a meaningful investment for the distribution system operator for a stable and reliable grid restoration is exposed.

Moreover, the ComDer and StoRat values are showing that coordinated control schemes between the commanding DER and the storage systems could be beneficial. Hence, innovative control strategies for grid restoration processes with CHP plants and BESS should be applied here. Moreover, a centralized grid restoration process should be considered in this case.

The most critical feature of this grid is the imbalance in installed PV power and the load distribution. Therefore, even with the large commanding DER, critical load steps are possible. However, feeders with low load share can be connected faster or simultaneously. To minimize the load step of the critical feeders, demand side management or the coordination with commercial/industrial customers in the corresponding feeder are necessary.

As explained in section 2, PV plants can complicate the grid restoration during the application of the load. Here, the share of PV plants is considerable high. Since the change of the control scheme of every small PV plant is not practical, strategies like a 52 Hz Strategy should be taken into account. Especially in the considered use case, the non-fluctuating installed power is sufficient to provide the necessary power during a grid restoration. Therefore, the commanding DER could operate the grid at a frequency of 52 Hz where the PV plants would not be reconnecting to the grid. This would also lead to higher frequency NADIRs. After successful grid restoration, the frequency could be decreased to the nominal value f_{nom}.

5 Conclusion and outlook

In this paper, a key indicator system, especially focusing on the grid restoration of distribution grids, has been developed. These indicators, like the ratio of the commanding DER in regards to the maximal annual load (ComDer) or the homogeneity of loads and installed PV power in the feeder of a distribution grid (PvBal, LoadBal), are aimed to lucidly displaying the key information to evaluate a distribution grid regarding a grid restoration and narrow down possible restoration strategies. Therefore, the main challenges of a distribution gird restoration after a large scale blackout are defined and analyzed. The developed key indicators are addressing these challenges with the use of accessible data from distribution grid operators. However, not all data are publicly available. Especially the number of grid areas and the load and PV distribution in the feeders.

The main focuses in this work are the significant impact of PV plants, investment recommendations for DSOs and the applicability into the practice. Investment recommendations are given in particular for the digitalization of the distribution grid and the investment in BESS. The applicability into the practice aims primarily at the feasibility of the control schemes and the suggested restoration strategies. However, the indicator system just gives a broad overview of the capability to blackstart the grid.

In future works, a pre-analysis based on a grid model in a power system analyzation software should be developed to specify the restoration strategy in more detail. Therefore, load and RES balances in the feeder can be monitored and valued. However, while a pre-analysis can be load flow based, dynamic investigations need to be performed to assess the real behavior during a distribution grid blackstart.

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Research and Outlook on Global Energy Interconnection

Jun Li[1], *Zhengxi* Chen[1], *Chen* Chen[1], *Yangzi* Wang[1], *Fulong* Song[1] and *Xiaoxiao* Yu[1]

[1]Global Energy Interconnection Development and Cooperation Organization, Economic and Technology Research Institute, No.8 Xuanwumen Street Xicheng District Beijing, China

Abstract. Currently, the world is confronted with a series of challenges including resource shortage, climate change, environment pollution and energy poverty, which are rooted in the humanity's deep dependence on and large-scale consumption of fossil energy. To tackle with those challenges is an urgent task for realizing sustainable development. The Global Energy Interconnection (GEI) is a clean energy-dominant, electricity-centered, interconnected and shared modern energy system. It is an important platform for large-scale development, transmission and utilization of clean energy resources at a global level, promoting the global energy transition characterized by cleaning, decarbonization, electrification and networking. The GEI has provided a scientific, novel and systematic solution to implement *Agenda* 2030 as well as the *Paris Agreement*. Focusing on the scope of clean transition and sustainable development, this paper has implemented qualitative and quantitative methods based on historic data. The global power demand and supply has been forecasted. Based on global clean energy resources endowments and distribution, a global main clean energy bases layout and generation planning optimization has been proposed. Later in this paper, the global power flow under the GEI scenario and corresponding GEI backbone grid has been explored and proposed. Finally, based on a preliminary investment estimation, the comprehensive benefits of building the GEI have been analyzed.

1 Introduction

In 2020, the COVID 19 virus has caused huge disasters to people all over the world, and it has sounded the alarm: mankind and the planet have entered an era of *'crisis-ridden'*. More urgently, climate change is accelerating its evolution into a global ecological environment crisis.

Climate change is a comprehensive reflection of the interactive effects of the earth system. After the climate system is affected by human activities, it will cause changes in the various layers of the earth system, resulting in complex, interconnected, and global effects, and it is very likely to cause irreversible changes in other layers. From 1980 to 2018, the number of global natural disasters showed a steady upward trend. In 2018, there were more than 800 major natural disasters globally, which quadrupled compared with 1980. In the past 20 years, global natural disasters have caused an average of more than 68,000 lives and 220 million people affected each year. The human social system is becoming more and more complex, and the connection with the natural system is getting closer. A single crisis, social crisis and natural crisis conduct among each other, which can rapidly deteriorate into multiple crises, with more serious consequences. Therefore, the climate and environmental crisis will not only accelerate various natural crises and ecological crises, but also cause social crises such as food shortages and conflicts and wars. It is the biggest potential risk faced by all countries.

Research by Global Energy Interconnection Development and Cooperation Organization (GEIDCO) shows that the development of the climate crisis mainly presents four phases. The first is the risk-controllable stage: climate change reaches or exceeds the 1.5°C safety threshold, but the overall risk is still controllable; the second is the threshold breakthrough stage, when climate change exceeds the 2°C safety threshold, the ecosystem rapidly deteriorates and the impact is irreversible; the third is temperature rise acceleration phase, climate change has accelerated the emission of greenhouse gases stored in ice caps, frozen soil and oceans into the atmosphere, and the temperature rise suddenly accelerated; fourth is the overall crisis phase, when climate change exceeds the critical threshold of 5°C, the earth system and human society are facing a full crisis . Once the safety thresholds of 1.5°C and 2°C are exceeded, the climate system will irreversibly accelerate its temperature rise and enter the *'full crisis'* stage.

At present, we are on the fast track of *'full crisis'*. Continuing the existing development path is likely to lead to a temperature rise of 3.2℃–5.4℃, which will cause the earth system to deviate from the normal and stable natural cycle, and its consequences will bring four major disasters. First, the melting of ice sheets triggers the collapse of key climate systems and chain reactions, leading to climate disasters; second, climate and environmental disasters comprehensively trigger polar, terrestrial, freshwater, and marine ecological disasters; third, climate disasters cause sea levels to rise sharply, leading to survival disasters; fourth, climate and environmental disasters lead to economic collapse, social unrest, and social disasters. Obviously, the fate of mankind in the future depends to a large extent on our actions to deal with the climate and environmental crisis.

The root of the climate crisis comes from dependence on fossil energy, and the international community already has a broad consensus on this. Mankind's misconceptions and development thoughts are deeply rooted, and the inertia of high-carbon economic development is huge. Global, systematic and implementable solutions are needed to form ideological consensus and joint actions to deal with crises, and accelerate the implementation of clean energy transition and sustainable development. Only by getting rid of the dependence on fossil energy can the risk of crises be reduced fundamentally. In essence, the core of sustainable development is clean development. The key is to promote clean replacement on the energy production side, replacing fossil energy with clean energy such as solar, wind, and hydropower; on the energy consumption side, replacing coal, oil, gas and firewood with clean electricity.

The GEI is a modern energy system which is clean, electricity-centered, interconnected, co-constructible and sharable. It will establish a platform for world-wide large-scale exploitation, transmission and utilization of clean energy, promote the global energy transition featured with clean, de-carbonization, electrification and networking. Building the GEI can fully implement the United Nations *2030 Agenda* and the *Paris Agreement* to address climate change, ensure that everyone enjoys clean, reliable, and affordable modern energy, and achieve comprehensive and coordinated economic, social and ecological development. In order to accelerate the development of the GEI, since 2016, GEIDCO has carried out systematic and in-depth research on energy interconnections of the world, continents, key regions and countries. Through extensive research, comprehensive analysis of global economic and social, energy, power, climate and environmental data, GEIDCO has fully studied relevant development strategy plans and policies of government departments of various countries, widely absorbed research results of relevant international organizations, institutions and enterprises, and applied research methods, models and tools to conduct in-depth research on the development vision, path and major issues of the GEI.

Based on the development concept of the GEI and related research results, from a global perspective, this paper deeply analyzes the development trend of the energy interconnections on various continents, and conducts research and prospects on the overall development of the GEI, and proposes systematic and overall innovative solutions under the framework of the GEI, which are of great significance for accelerating the green energy transition, coping with climate change, and achieving sustainable development. The follow-up discussion structure of this article is as follows. Section 2 will introduce the development concept and connotation of the global energy Internet; Section 3 discusses the outlook of the future development trend of energy and power; Section 4 proposes the distribution of large-scale clean energy bases based on the global clean energy resource distribution.; Section 5 proposes the global power flow pattern, the GEI backbone grid and the development direction of continental energy interconnections; Section 6 estimates the comprehensive benefits of building the GEI; finally, in Section 7 provides a comprehensive summary.

2 Development Concept of the GEI

Energy is the material basis of economic and social development, and the sustainable supply of energy is the fundamental guarantee of the human sustainable development. Therefore, to address the challenges in achieving sustainable development, the key is to promote clean development and rigorously implement *'Two Replacements, One Increase, One Restore and One Conversion'* which aims to build the GEI and accelerate the formation of a modern energy system that is clean, electricity-centered, interconnected, co-constructible and sharable, ensuring clean, safe, affordable and efficient energy can be accessed by all individuals. In this way, we can find a scientific solution to promote global sustainable development through clean energy development.

Two Replacements are to use clean alternatives in energy production, replacing fossil fuels with hydro, solar, and wind energy known as *Clean Replacement*, and to promote *Electricity Replacement* in energy consumption, replacing coal, oil, natural gas and firewood with electricity. *One Increase* in the level of electrification and energy efficiency, increase in the proportion of electric energy in final energy consumption, and reduction in energy consumption on the premise of ensuring energy consumption needs. *One Restore* to the restoration of fossil energy to its basic attribute as industrial raw material to create greater value for economic and social development. *One Conversion* means that CO_2, water and other substances will be converted to fuels and raw materials such as hydrogen, methane, and methanol and minerals by virtue of electricity to resolve the resource constraints and pave the way for future energy development and sustainable development of mankind.

The essence of building the GEI is the holistic construction of *'Smart Grid + UHV grid + Clean Energy'*, where smart grid is the foundation, UHV grid is the key and clean energy is the source. By integrating modern intelligent technologies such as advanced transmission, intelligent control, new energy integration and advanced energy storage, a smart grid can adapt to grid connection and accommodation all kinds of clean energy, meet the needs to integrate various intelligent power equipment and provide interactive services, realizing the coordinated development of power source, network, load and storage, multi-energy complementarity and efficient utilization. UHV power grid is composed of 1000 kV AC and ±800 and ±1100 kV DC systems, with significant advantages including long transmission distance, large capacity, high efficiency, low loss, reduced land occupation and good security. It can realize thousands-of-km and tens-of-GW power transmission and interconnection of transnational and transcontinental power grids. With the advancement of conversion technologies and cost reduction of hydro, wind and solar energy, the competitiveness of clean energy will surpass fossil energy in an all-rounded way, accelerating the replacement process of fossil energy and becoming the main source of energy in the future energy system.

The GEI is the fundamental strategy to cope with climate change and achieve the goal of temperature control. The GEI provides a technically feasible, economically sound, operational, statistical and transparent system solution for the world to tackle climate change and implementing the *Paris Agreement*. During the course of the GEI construction, replacement of carbon-based energy with clean electricity can be promoted to accelerate the process of realizing global carbon emission reduction goals, decouple the economic development with carbon emissions, and comprehensively implement the core targets of the Paris Agreement, such as mitigation, adaptation, capability-building of financial and technical, and transparency. The CO_2 emissions that come from global energy consumption can peak around 2025 and fall to about 10 billion tons by 2050 which is less than half of the 1990 level. By achieving zero net emissions by 2065, the goal of controlling global temperature rise within 2°C by the end of the century could be achieved. By accelerating the construction of the GEI, global clean energy and power interconnection will develop rapidly, which will promote energy system carbon emissions to decline earlier and achieve zero net emissions as early as possible with low negative emissions, and therefore, the temperature control target of 1.5°C could be achieved.

3 Energy and Power Development Trends

Analysis and forecast on the trends of global energy and power has been carried out for promoting the comprehensive, coordinated and sustainable development of the global economy, society, environment and achieving the 2°C temperature control target of the *Paris Agreement*.

3.1 Energy Demand

Global primary energy demand continues to grow. By the partial substitution method, the global primary energy demand in 2035 and 2050 will reach 24.5 and 26.2 billion tons of coal equivalent (tce), respectively. The average annual growth rate is 0.7% from 2016 to 2050, of which the rate is about 1% from 2016 to 2035 and about 0.4% from 2036 to 2050.

The main direction to optimize the global energy structure is to develop clean energy as the dominant source of energy. Around 2025, the total demand of global fossil energy will reach its peak before declining year by year. The global coal demand will peak around 2025, reaching about 5.4 billion tce, before declining to 1.79 billion tce in 2050, accounting for 6.3% of the total global primary energy demand. The share of clean energy in primary energy will increase from 24% in 2016 to 70% in 2050. Before 2040, the share of clean energy will exceed the share of fossil energy and become the main primary energy source.

The increase of global primary energy demand is mainly contributed by Asia. From 2016 to 2050, Asia's primary energy demand is expected to rise by 57%, from 9.5 to 14.9 billion tce, with an average annual growth rate of 1.3%. Asia's share in global primary energy demand continues to increase, from 46% to 57%. The primary energy demand in Africa and Central and South America will increase by 1.4 and 0.62 billion tce, with an average annual growth rate of 2.3% and 1.3%, respectively.

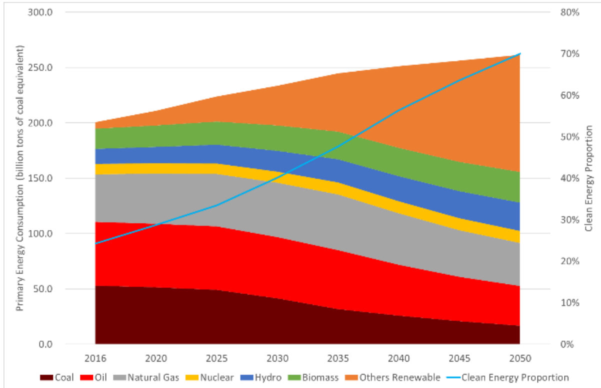

Fig. 1. Primary energy demand forecast under the 2°C-scenario.

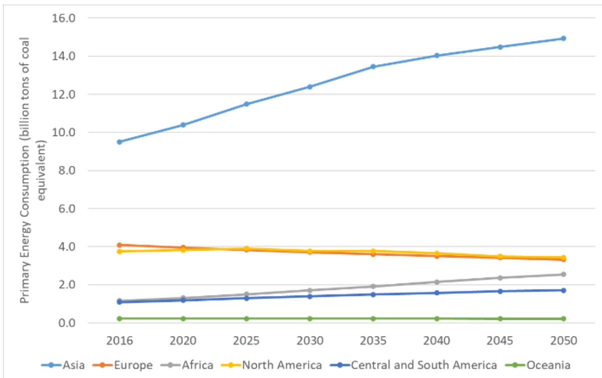

Fig. 2. Continental primary energy demand forecast under the 2°C-scenario.

Global final energy consumption will peak around 2040. From 2016 to 2040, the global final energy consumption will grow steadily from 13.7 to 16.2 billion tce with an average annual growth rate of about 0.7%. Due to the slowdown of the world economy and the improvement in energy efficiency, the final energy consumption is expected to decline. In 2050, the global final energy consumption will fall to 15.7 billion tce with an average annual decline of 0.3% from 2040 to 2050. From 2016 to 2050, the average annual growth rate of final energy will be about 0.5%. The final consumption of fossil energy will drop significantly. From 2016 to 2050, the share of fossil energy in final energy consumption will fall from 63% to 24%. The final coal consumption will peak at about 1.7 billion tce around 2025, before falling by 63% to 550 million tce in 2050. The final oil consumption will remain stable from 2020 to 2035 at around 5.8 billion tce. Thereafter, the consumption will fall rapidly to 3.0 billion tce in 2050 accounting for a decrease of 47% compared to the consumption in 2016. After the natural gas consumption reaches its peak in 2040, it will drop to about 1.4 billion tce in 2050, accounting for a decrease of about 34% from the level in 2016. The basic trend of the global final energy structure will be electricity-centered and the share of electricity will increase significantly. The share of electricity in the total final energy consumption is expected to increase from 22% in 2016 to 54% in 2050, and in around 2035, electricity will surpass oil and become the dominant source of energy in the final energy structure.

The share of electricity in final energy consumption will significantly increase in all continents and there will also be an acceleration in the implementation of Electricity Replacement. With the accelerated development of Electricity Replacement technologies such as electric vehicles, electric heating and electricity-produced hydrogen, the energy transition in developed regions such as Europe and North America will accelerate and move towards becoming more electricity-centered in the final energy structure. In 2050, the share of electricity will be 59% of the final energy in both regions, significantly higher than the global average. Africa will also gradually reduce its dependence on primary bioenergy such as fuelwood, agricultural and forestry wastes, and establish a modern energy system by replacing low-quality energy with electricity.

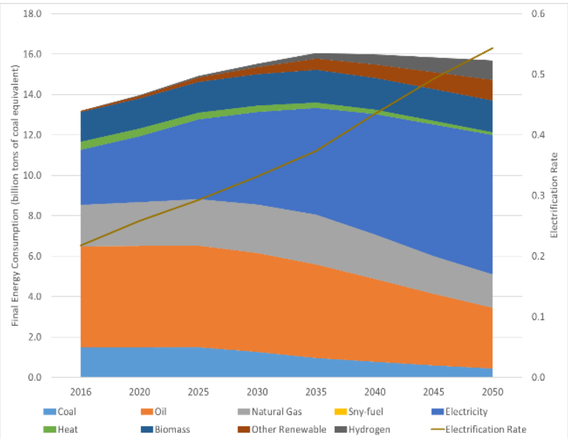

Fig. 3. Final energy demand forecast under the 2°C-scenario.

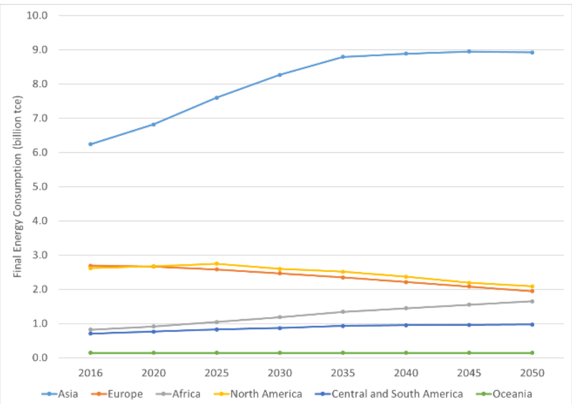

Fig. 4. Continental final energy demand forecast under the 2°C-scenario.

3.2 Power Demand

With the global economic recovery, steady population growth, continuous technological advancement and rapid implementation of *'Two Replacements'*, the global power demand will generally grow steadily at a high pace in the future.

It is estimated that in 2035, the global electricity consumption will reach 44.1 PWh, and the average annual growth rate will be 3.66% from 2016 to 2035. In 2050, the global electricity consumption will reach 61.6 PWh with an average annual growth rate of 2.25%. The global electricity consumption per capita will increase from 2985 kWh in 2016 to 6300 kWh in 2050.

Asia's position as a global power load center will become increasingly prominent. It is estimated that the average annual growth rate of electricity consumption in Asia will be 4.42% from 2016 to 2035, and the demand will reach 24.9 PWh which accounts for 58.9% of the total global power demand. From 2036 to 2050, the increase rate in electricity consumption will be reduced to 2.53%, and the electricity consumption will reach 36.3 PWh, accounting for 58.9% of the global total.

Power demand is growing rapidly in Africa, Central and South America, and their electricity consumptions increasing fastest in the world. There are still a large number of people with no access to electricity in Africa, and the electricity consumption per capita is low at present. Considering the growth of power demand and the *Electricity Replacement* from industrialization and urbanization, the growth rate of power demand in Africa and Central and South America will reach 6.92% and 4.92% from 2016 to 2035, respectively, and the electricity consumption will increase to 2.27 PWh and 2.65 PWh. From 2036 to 2050, Africa's electricity consumption will continue to grow rapidly with an average annual growth rate of 3.79%, and the electricity consumption in 2050 will reach 3.97 PWh. The annual average growth rate of electricity consumption in Central and South America will fall to 2.49%, and in 2050, the consumption will reach 3.83 PWh.

In Europe, North America and Oceania, the electricity consumption per capita will be high and the Electricity Replacement in sectors such as railways, electric vehicles, and clean heating will result in high power demand. The growth rate of mid and long-term power demand is expected to remain 1%–3%.

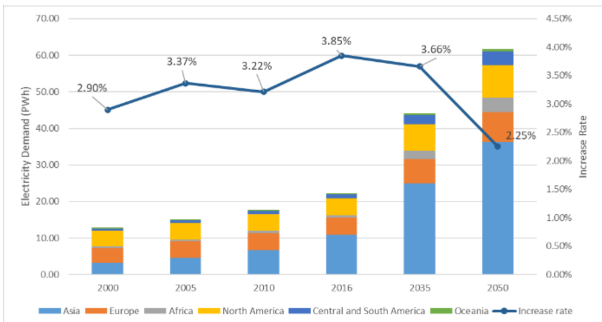

Fig. 5. Electricity demand forecast under the 2°C-scenario.

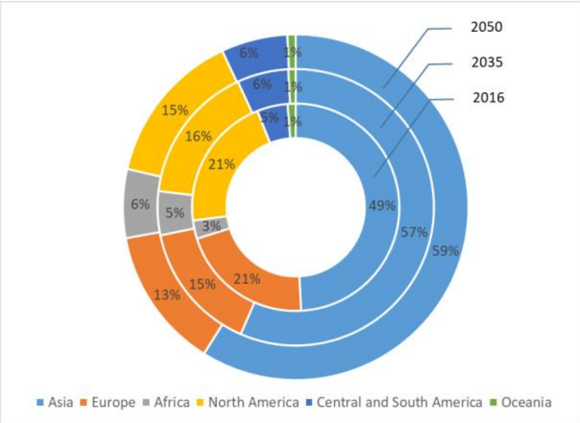

Fig. 6. Continental electricity demand proportion under the 2°C-scenario.

3.3 Power Supply

In order to achieve clean transformation and sustainable development in an optimal way, it is necessary to coordinate the factors such as the consideration of global resource endowments, energy and power demand, energy development costs, land value and environmental carrying capacity and power system operation.

It is estimated that by 2050, the global installed capacity will be 26 TW with clean energy installed accounting for 84%, among which wind power is 26%, solar power is 42%, hydropower is 11%, nuclear power is 2%, and bioenergy, geothermal and others is 3%. Meanwhile, the installed per capita will have reached 2.7 kW. The global clean energy generation will be 51 PWh, accounting for 81% of the total amount, of which 23% is wind power, 32% is solar power, 15% is hydropower, 6% is nuclear power, and 5% is bioenergy, geothermal and others.

Global coal-fired power installed capacity will peak around 2030. In 2016, the global installed capacity of coal-fired power was 2.08 TW, and by 2030, the net increase will have been 310 GW, which will basically be at its peak (new coal-fired generating units are mainly in Asia). Subsequently, coal power will gradually decrease to 1.8 TW in 2035 and within 1.3 TW in 2050.

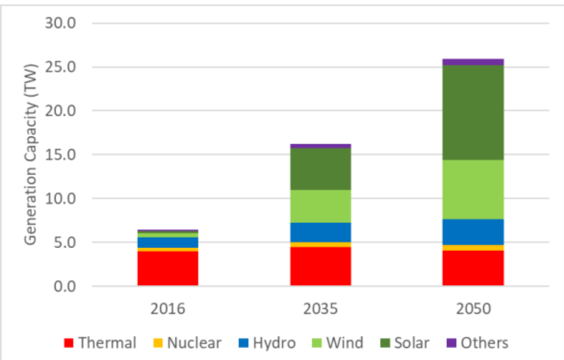

Fig. 7. Generation capacity forecast under the 2°C-scenario.

In terms of continents, in 2050, the installed capacity of Asia, Europe, Africa, North America, Central and South America, and Oceania will be accounting for 61%, 15%, 5%, 14%, 5%, and 1% respectively. The proportion of thermal power installed in Asia will drop from 67% in 2016 to 16%, from 48% to 7% in Europe, from 78% to 23% in Africa, from 65% to 19% in North America, from 42% to 16% in Central and South America, and from 66% to 32% in Oceania. The overall installed capacity of hydro, wind and solar clean energy will develop simultaneously. The installed capacity per capita in Asia, Europe, Africa, North America, Central and South America, and Oceania will be 3.05 kW, 4.71 kW, 0.52 kW, 6.06 kW, 2.14 kW, and 3.2 kW, respectively.

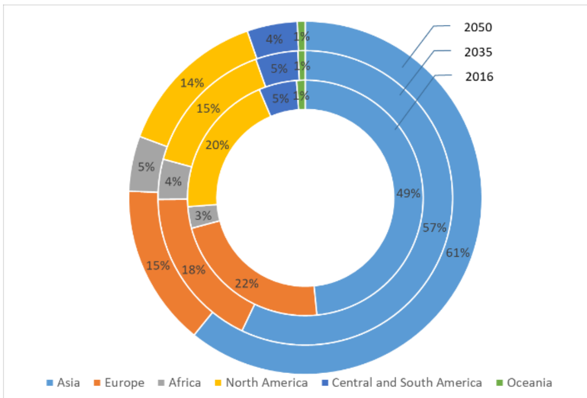

Fig. 8. Continental generation capacity proportion under the 2°C-scenario.

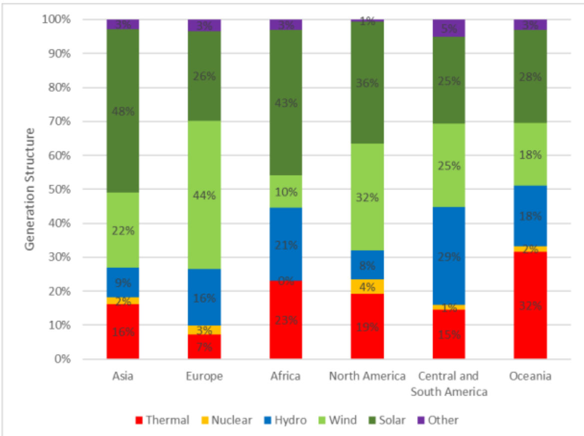

Fig. 9. Continental generation structure under the 2°C-scenario.

4 Clean Energy Bases Distribution

The global clean energy resources, such as hydro, wind and solar energy, are abundant. The theoretical potential of clean energy is higher than 150000 PWh/year. With breakthroughs in clean energy technologies, the economic feasibility of implementing the technologies has been greatly improved, and replacing fossil energy with clean energy is becoming an important trend in the global energy development. Large-scale development and efficient use of global clean energy resources can be achieved through coordinating the distribution and demand of clean energy in either centralized or distributed methods.

4.1 Overall Clean Energy Resources

4.1.1 Hydro

The theoretical potential of global hydropower resources is about 39 PWh/year, of which, Asia, Africa, Europe, North America, Central and South America, and Oceania account for 47%, 11%, 6%, 14%, 20% and 2%, respectively.

Table 1. Global hydropower resources.

Region	Theoretical potential (PWh/year)	Global share (%)
Asia	18.31	47
Africa	4.4	11
Europe	2.41	6
North America	5.51	14
Central and South America	7.77	20
Oceania	0.65	2
World	39.06	\

4.1.2 Wind

The global wind energy resources are abundant, and the annual average wind speed ranges from 2 to 14 m/s at the height of 100 meters above the ground. Many regions have an annual wind speed higher than 7 m/s, and the best wind speed is mainly distributed in Greenland, Denmark, eastern of North America, southern of South America, northern Europe, northern Africa and southern Oceania.

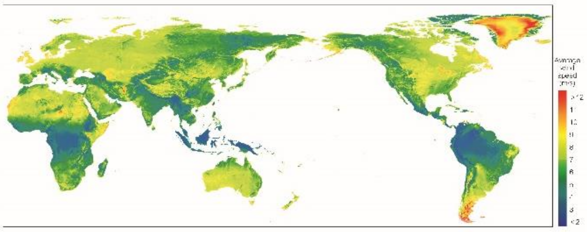

Fig. 10. Distribution of global annual average wind speed.

The theoretical potential of global wind energy resources is about 2050 PWh/year, of which Asia, Africa, Europe, North America, Central and South America, and Oceania account for 24%, 32%, 7%, 21%, 11% and 5%, respectively.

Table 2. Global wind energy resources.

Region	Theoretical potential (PWh/year)	Global share (%)
Asia	500	24
Africa	650	32
Europe	150	7
North America	430	21
Central and South America	220	11
Oceania	100	5
World	2050	\

4.1.3 Solar

Solar energy is remarkably rich around the world. The annual global horizontal irradiance (GHI) ranges from 700 to 2700 kWh/m^2. The areas with the GHI higher than 2000 kWh/m^2 include the sub-Saharan Africa region, the southwestern Africa, Asia and the Middle East, the southern North America, the southwestern South America and the northern Oceania.

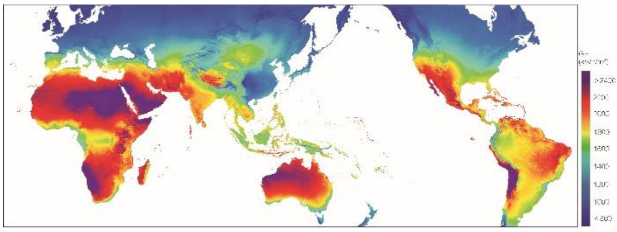

Fig. 11. Distribution of Global Horizontal Irradiance (GHI).

The theoretical potential of global solar energy resources is about 150000 PWh/year, of which, Asia, Africa, Europe, North America, Central and South America, and Oceania account for 25%, 40%, 2%, 10%, 8% and 15%, respectively.

Table 3. Global solar energy resources.

Region	Theoretical potential (PWh/year)	Global share (%)
Asia	37500	25
Africa	60000	40
Europe	3000	2
North America	15000	10
Central and South America	12000	8
Oceania	22500	15
World	150000	\

4.2 Distribution of Global Large-scale Clean Energy Bases

4.2.1 Large-scale Hydropower Bases

According to the distribution of global hydropower resources, hydropower bases with large-scale development conditions are mainly distributed in the Jinsha River and the Yarlung Zangbo River in southwestern China, the Mekong River, the Irrawaddy River Basin in Southeast Asia, the Congo River and the Nile River in Africa, the Amazon Basin in South America, Norway, Sweden, etc. There are fifteen large-scale hydropower bases to be developed globally, with the total installed capacity of 880 GW by 2035 and 1.3 TW by 2050.

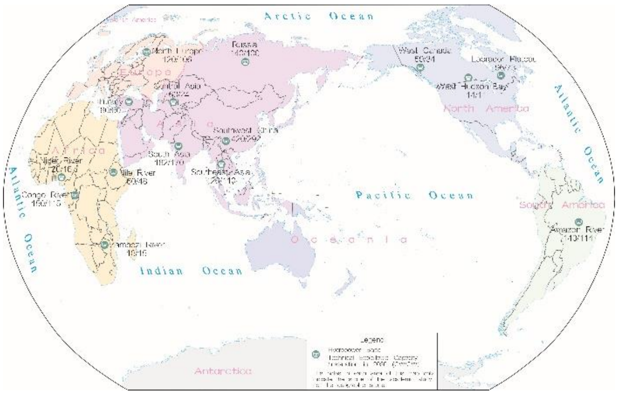

Fig. 12. Distribution and installed capacity of the global large hydropower bases.

4.2.2 Large-scale Wind Power Bases

The wind power bases with large-scale development conditions are mainly distributed in Artic regions including Greenland, Sakhalin Island, Okhotsk Sea, etc., as well as in the northwest of China, the North Sea of Europe, the central United States and southern Argentina. There are sixteen large-scale wind power bases to be developed globally, with the total installed capacity of 900 GW by 2035 and 1.49 TW by 2050.

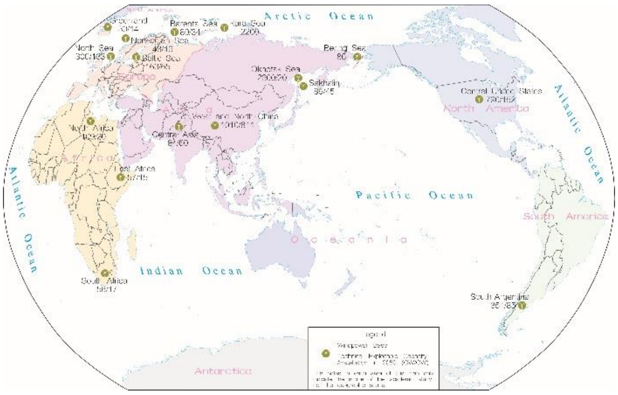

Fig. 13. Distribution and installed capacity of the global large wind power bases.

4.2.3 Large-scale Solar Power Bases

According to the distribution of solar energy resources, solar power generation bases with large-scale development conditions are mainly distributed in areas including the northern Africa, the southern Africa, the western Asia, the Central Asia, the western China, the western United States, Mexico, Chile and the northern Australia. There are nine large-scale solar power bases to be developed globally, with the total installed capacity of 1.71 TW by 2035 and 3.82 TW by 2050.

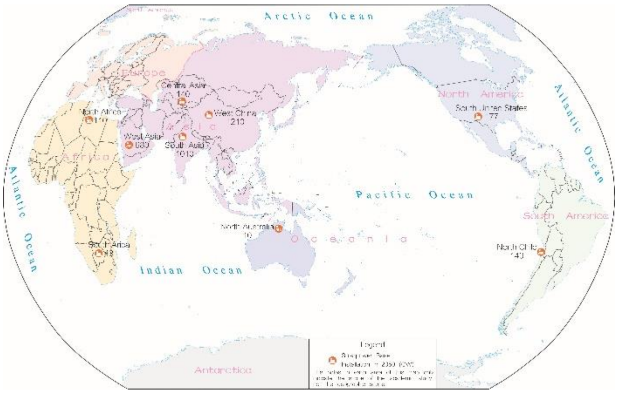

Fig. 14. Distribution and installed capacity of the global large solar power bases.

4.3 Global Trend of Generation LCOE

With the rapid development of clean energy power generation technology and the significant reduction in power generation costs, clean energy power generation will gradually replace fossil energy power generation as the dominant power source. As the development and utilization cost of fossil energy and the demand for low-carbon, clean and safe energy increases, the cost of internal and external input of traditional fossil energy utilization will increase. The scaling effect of clean energy is becoming more and more prominent, where its cost will continue to decrease. As shown in Fig. 15., the LCOE of hydropower will be largely be maintained at 4 US cents/kWh, while in some areas with abundant hydro resources such as the Congo River Basin, it will be kept as low as 3 US cents/kWh. The LCOE of offshore wind power, onshore wind power, photovoltaics and concentrating solar power all show a downward trend, which will have fallen to 5.5, 2.6, 1.5, and 5.3 US cents/kWh by 2050. It is expected that the competitiveness of photovoltaic and onshore wind power will have surpassed coal- and gas-fired power by 2025.

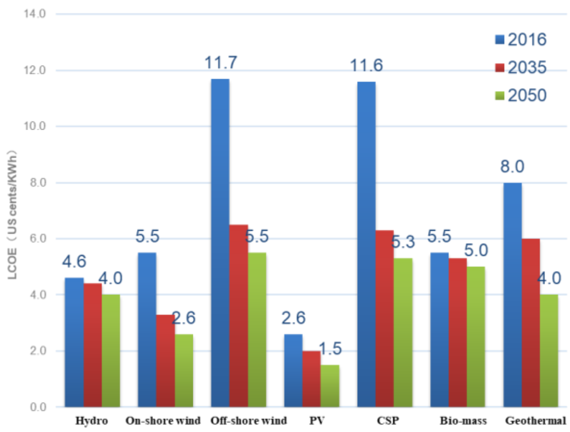

Fig. 15. Global trends in the LCOE of clean energy.

5 Development Outlook of Global Energy Interconnection

5.1 Global Power Flow Pattern

According to the principles of green, low-carbon, economic, efficiency, and technical feasibility, and considering the resource endowment and demand distribution, the multi-energy complementarity and large-scale mutual support, the local development and long-distance power transmission, the multi-region power optimization model is used to calculate power balance. The balance results of various continents form a power flow pattern with optimal allocation of global resources.

Before 2035, the global power flow will be dominated by cross-border power exchange across continents, and inter-continental power exchange will begin. By 2035, the global inter-continental and inter-regional power flow will reach a total of 330 GW, of which, 46 GW will be inter-continental. The inter-regional power flow will mainly run from transmitting hydropower and wind power of Russian Far East and clean energy bases of Central Asia to China, South Korea, Japan and other countries; from the solar bases in West Asia to South Asia India; transmitting hydropower of Central Africa and Eastern Africa to western and southern regions; transmitting hydropower and wind power of Northern Europe to the Continental Europe; transmitting wind power in the mid-western United States and solar power in the southwestern to its eastern regions; transmitting wind power in southern Argentina, solar energy of northern Chile and hydropower of Bolivia to Brazil. Meanwhile, the inter-continental power flow mainly run from the North Africa solar energy bases, the Central Asian clean energy bases and the West Asia solar power bases to Europe; and from the West Asia solar power bases to North Africa Egypt.

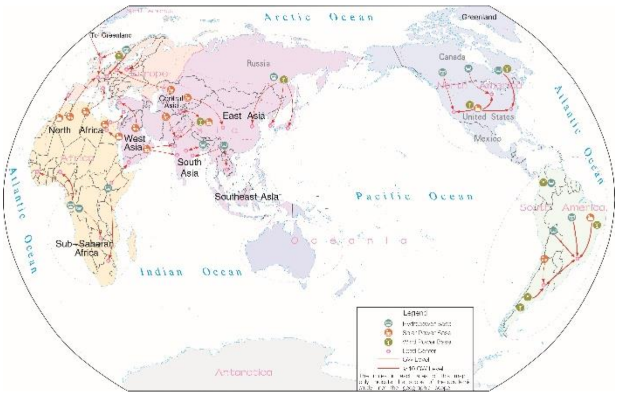

Fig. 16. Illustration of global power flow in 2035.

By 2050, clean energy bases will have entered a large-scale development stage, forming a globally optimal allocation of clean energy, multi-energy complementation, and cross-time-zone mutual support. In 2050, the total inter-continental and inter-regional power flow in the world will reach 660 GW, of which, the inter-continental power will be 110 GW. The inter-regional power flow will run from Russian hydropower and wind power and Central Asia's clean energy bases to China, South Korea, Japan and other countries with further increase in scale. At the same time, West Asia will send solar power to South Asia; the Arctic wind power bases will send power to China, South Korea and Japan; Central and East Africa will send more power to other African regions; and hydropower in Peru and Bolivia will be sent to Brazil. The inter-continental power flow will mainly run from North Africa solar power bases, Central Asian clean energy bases and West Asia's solar power bases to Europe. With the increasing understanding of the Arctic and breakthroughs in polar transmission technologies, the Arctic region will become an important clean energy base for clean energy worldwide. Power demand of regions such as Asia, Europe and North America will be met through large-scale exploitation of the Arctic wind and Equatorial solar resources.

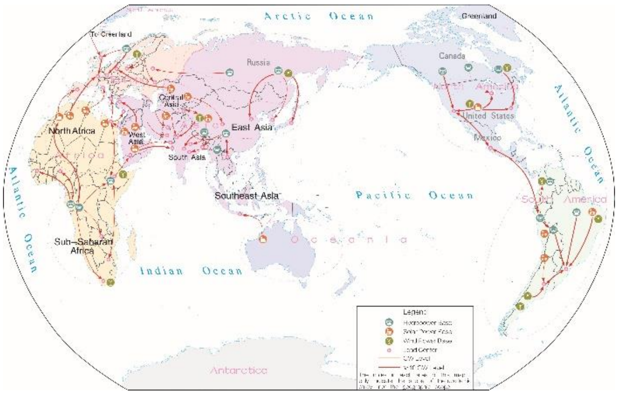

Fig. 17. Illustration of global power flow in 2050.

5.2 GEI Backbone Grid

With considerations on the resource endowment, energy & power demand, and climate & environmental requirements, the *'Nine Horizontal and Nine Vertical'* GEI backbone grid will be constructed based on the national backbone and cross-border interconnection. Large-scale clean energy bases and load centers will be interconnected to achieve clean energy resource allocation globally across different time zones and seasons, providing mutual power support and backup.

The *'Nine Horizontal and Nine Vertical'* backbone grid as shown in Fig. 18. includes Asia–Europe–Africa's *'Four Horizontal and Six Vertical'* interconnection channels, America's *'Four Horizontal and Three Vertical'* channels and the Arctic energy interconnection channel.

5.2.1 Nine Horizontal Channels

(1) *Arctic Energy Interconnection Channel* begins in Norway in Northern Europe, crosses Russia and Bering Strait and stretches all the way to Alaska. The channel crosses 19 time zones and connects 80% power grids of north hemisphere with a length of 12000 km. The channel achieves mutual power support and backup between continents in an intensive manner.

(2) *Asia–Europe North Horizontal Channel* inter-connects countries such as China, Kazakhstan, Germany,

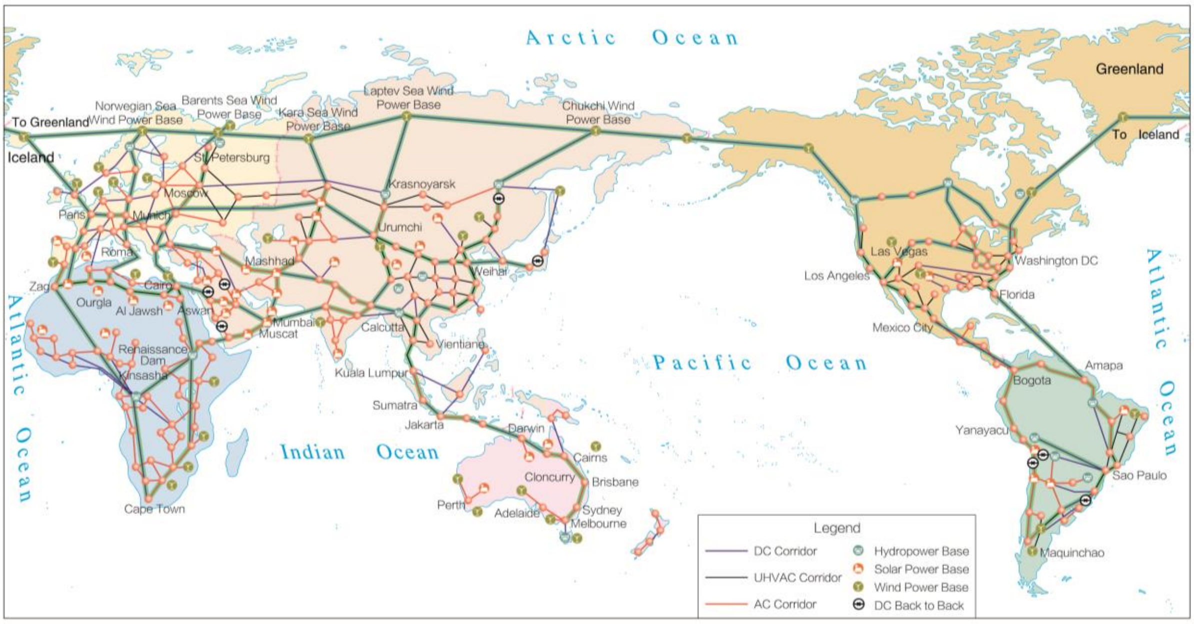

Fig. 18. Illustration of the overall pattern of the GEI backbone grid.

France, and delivers clean energy from Central Asia to Europe and China. Together with the UHV backbone grid of China, clean energy is further delivered to Northeast Asia to provide inter-continental power support. The channel length is 10000 km.

(3) *Asia–Europe South Horizontal Channel* interconnects Southeast Asia, South Asia, West Asia and Southern Europe, and delivers solar power from the West Asia to load centers in Southeast Europe and South Asia through the UHV DC. The channel also delivers hydropower from Southeast Asia and China to South Asia. The channel length is 9000 km.

(4) *Asia–Africa North Horizontal Channel* interconnects clean energy bases in Southeast Asia, South Asia and West Asia and North Africa. The channel delivers solar power from the West Asia to Egypt and further delivers to Morocco by the 1000 kV UHV AC. The channel length is 9500 km.

(5) *Asia–Africa South Horizontal Channel* interconnects hydropower bases of the Congo River, the Nile, and solar power bases of West Asia to provide mutual power support between the African hydropower and the West Asia's solar power. The channel length is 6000 km.

(6) *North America North Horizontal Channel* interconnects the grids in eastern and western Canada to improve power exchange capabilities, receives the Arctic wind power and delivers to the load centers in eastern Canada. The channel length is 4500 km.

(7) *North America South Horizontal Channel* gathers the western American solar power, Central American wind power and the Mississippi River hydropower, and delivers to load centers in New York, Washington and western America. The channel length is 5000 km.

(8) *South America North Horizontal Channel* interconnects the northern countries such as Columbia, Venezuela, Guyana, French Guyana, and Surinam to strengthen the interconnection and power exchange capabilities. The channel length is 3500 km.

(9) *South America South Horizontal Channel* gathers Peru and Bolivia's hydropower along the Amazon River, along with Chile's solar power, and delivers to load centers in southeastern Brazil. The channel length is 3000 km.

5.2.2 Nine Vertical Channels

(1) *Europe–Africa West Vertical Channel* crosses Iceland, Great Britain, France, Spain, Morocco, West Africa and South Africa, and delivers the Greenland and North Sea's wind power to Continental Europe; and the Congo River's hydropower to the North and South Africa. The North African solar power and Central African hydropower are jointly delivered to the load centers in Europe. The channel length is 15000 km.

(2) *Europe–Africa Central Vertical Channel* interconnects the Arctic wind power bases, the Northern European hydropower bases and the North African solar power bases, crosses countries including Germany, Austria, Italy, and extends southward to Tunisia. The channel length is 4500 km.

(3) *Europe–Africa East Vertical Channel* begins from the Barents Sea shore, crosses Russia, Baltic, Ukraine, Balkan Peninsula, Cyprus, Egypt and East Africa to South Africa, and delivers the Arctic and Baltic wind power to Europe, and the Nile's hydropower to the North and South Africa. The Nile hydropower and Egypt solar and wind power are jointly delivered to the Europe. The channel length is 14000 km.

(4) *Asia West Vertical Channel* interconnects the solar power bases of Central Asia and West Asia and Siberia hydropower bases, gathers multiple forms of energy via the Central Asia synchronous grid, and extends to the Arctic Kara Sea's wind power bases. The channel length is 5500 km.

(5) *Asia Central Channel* interconnects the Russian hydropower bases, solar and wind power bases of northwestern China, and hydropower bases of southwestern China, and delivers to the load centers in South Asia through the UHV DC. The channel length is 6500 km.

(6) *Asia East Vertical Channel* interconnects Russia, China, Northeast Asia, Southeast Asia via China and the UHV grids in Southeast Asia, and delivers the clean energy power of Russian Far East, China and Southeast Asia to the load centers, in order to provide power support during the seasons, connect the Arctic wind power bases and extend the channel to Australia in the future. The channel length is 15000 km.

(7) *America West Vertical Channel* connects the Arctic wind power bases, and constructs a synchronous UHV AC grid around Vancouver, located in the west coast of the U.S., and Mexico. The channel enables efficient utilization of the Canadian hydropower, the U.S. and Mexico's solar and wind power, and interconnects the northern South America's grids through Central America by the UHV DC. This channel extends southward to Chile and enables mutual power support between the North American solar power and South American hydropower. The channel length is 15000 km.

(8) *America Central Vertical Channel* begins from Manitoba in Canada, crosses the North Dakota and Texas in the U.S., and further extends to Mexico City to form the main UHV vertical channel. The channel collects northern Canada's hydropower and the central U.S.'s wind power to provide mutual power support with multiple forms of energy and cover a wide area of clean energy allocation between the northern and the southern regions. The channel length is 4000 km.

(9) *America East Vertical Channel* starts from Quebec in Canada, crosses the eastern coast of the U.S. to Florida, forming a main UHV AC vertical channel. This channel connects the northern Canada's hydropower, western U.S.'s solar power and central U.S.'s wind power, traverses across the Caribbean grids, and connects the northern South America grids. This channel further extends to Argentina to provide mutual power support with multiple forms of energy and covers a wide area of clean energy allocation between the northern and the southern regions, as well as connects the Greenland wind power and hydropower. The channel length is 16000 km.

5.3 Continental Energy Interconnection

5.3.1 Asian Energy Interconnection

The development focus of the Asia power grid will be to accelerate the exploitation and power transmission of large-scale clean energy bases such as South Asia West Asia's solar power, Central Asia's wind power and Southeast Asia's hydropower, transforming these resource advantages into economic advantages, as well as speeding up the construction of power grids in Southeast Asia and South Asia so as to increase electricity accessibility, the interconnection of East Asia for broadening the supply channels of energy and power and maximizing the advantages of the UHV technology, and promoting the inter-continental and inter-regional interconnection, facilitating the direct supply of clean energy from power bases to load centers.

Power flow in Asia is generally featured by power transmission from West to East, North to South. Inter-continentally. Asia will transmit power to Europe, complement with Africa and receive power from Oceania. The power flow will reach 200 GW with 51 GW inter-continental power flow.

In the future, Asia will form an interconnected pattern consisting of five regions: East Asia, Southeast Asia, Central Asia, South Asia and West Asia. In 2050, the Asian energy interconnection will be fully established with *'Four Horizontal and Three Vertical'* interconnection channels.

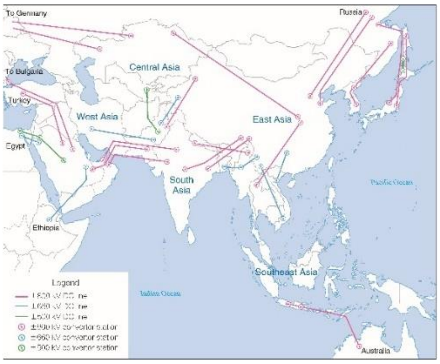

Fig. 19. Illustration of the overall pattern of grid interconnection in Asia.

5.3.2 European Energy Interconnection

The development goals of Europe power grid will be to strengthen the construction of domestic transmission channels, thereby improving the access and allocation capacity of renewable energy sources, to improve the level of smart grids, in order to ensure the operational reliability of high-proportion clean energy systems, to strengthen the construction of cross-border transmission channels, to expand the grid interconnection for delivering power from the Baltic and Arctic wind power bases, to take advantage of the *'European Regulatory Power Pool'* of the Northern Europe hydropower to realize the mutual power support, to expand inter-continental interconnection, forming interconnection between Asia, Europe and Africa, and to inter-continentally receive clean energy power.

The power flow will render such a pattern as *'intracontinental power transmission from North to South and inter-continental power import from Africa and Asia'*. In 2050, inter-continental and inter-regional power flow will reach 133 GW, including an inter-continental power flow of 75 GW.

In the future, with the upgrade of the power grid and the interconnection scale, Europe will build the European VSC HVDC power grids, connecting the wind power bases of the North Sea, the Baltic Sea, the Norwegian Sea and the Barents Sea, the Northern European hydropower base, and interconnect to North Africa, West Asia and Central Asia inter-continentally. In 2050, a flexible and controllable DC grid covering Europe will be formed. The Northern Europe DC grid will be further extended to the Norwegian Sea and the Barents Sea; the DC looped grid will be strengthened in the central Continental Europe, expanding to the Eastern Europe, and forming a DC grid covering Europe; the scale of Asia – Europe – Africa interconnection will be further expanded, and there will be as many as 11 inter-continental DC projects.

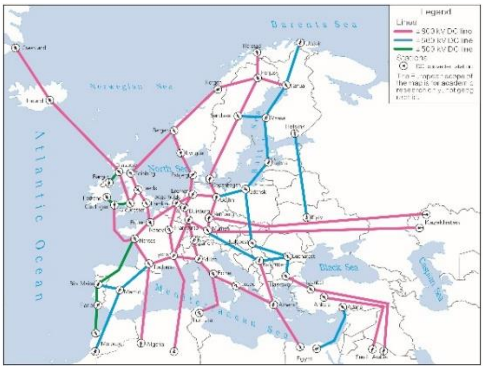

Fig. 20. Illustration of the overall pattern of grid interconnection in Europe.

5.3.3 African Energy Interconnection

The development goals of the power grids in Africa will be to strengthen the construction of power grid infrastructure in various countries within the continent, to expand the grid coverage, to improve power supply efficiency and reliability through reinforcement, upgrading and constructing new transmission and distribution grids, to build power transmission channels for large clean energy bases such as hydropower, wind power and solar energy for a coordinated development of clean energy and power grids to meet the power demand from load centers, to accelerate the intra-continental and inter-continental interconnection through exporting clean energy electricity by transforming resource advantages to economic advantages and achieve a wide range and optimal allocation of clean energy.

Form a pattern of *'Central Africa exports power to North and Southern Africa, realizing mutual complementation with Asia and Europe'*. In 2050, the total scale of power flow will reach 141 GW, of which 54 GW will be inter-continental.

In the future, Africa will have three synchronous grids in the North Africa, Central-West Africa and South-East Africa. In 2050, Africa will build a basic yet strong energy interconnection, forming the *'Two Horizontal and Two Vertical'* backbone grid, and expanding the scale of Asia, Europe and Africa interconnection.

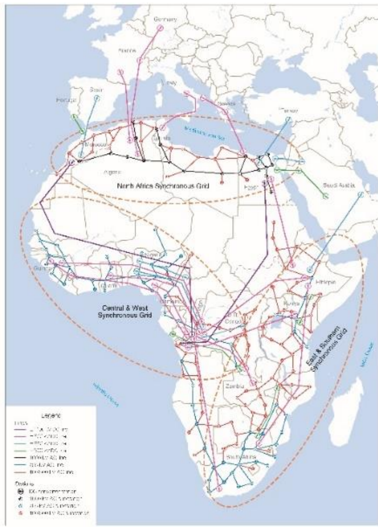

Fig. 21. Illustration of the overall pattern of grid interconnection in Africa.

GEIDCO evaluates the theoretical hydropower potential of the Congo River on its Digital Hydropower Planning Platform. The theoretical hydropower potential in the Congo River are about 2500 TWh per year, accounting for 54% of the African total amount. According to the comprehensive and coordinative research on river-section hydropower planning, through three-level cascade exploitation, the total installation capacity could reach above 100 GW with an annual generation of about 690 TWh.

Hydropower from the upstream and the tributaries of the Congo River will be sent to D. R. Congo, R. Congo, Central African Republic, Cameroon, etc., along the Congo River basin via EHV AC transmission corridors.

Hydropower from the downstream of Congo River, will be sent to the demand centers of more than 2000 km away via UHV transmission technology. UHV transmission has the advantages of long transmission distance, large capacity, low loss, etc., which enables larger scale hydropower development, transmission and consumption of the downstream Congo River.

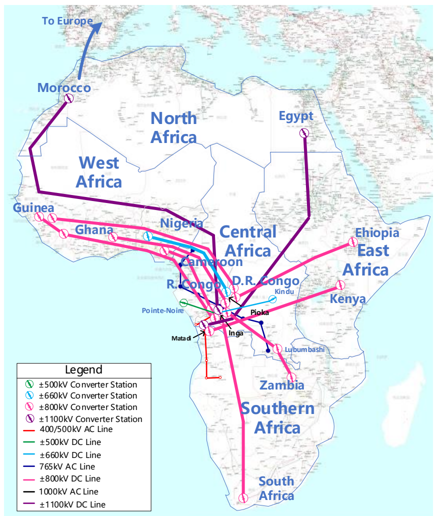

Fig. 22. Overall transmission pattern of the hydropower in the downstream of the Congo River.

5.3.4 North American Energy Interconnection

The development goals of North American power grid will be to accelerate the development and delivery of clean energy bases, and build large-scale clean energy bases such as Canada's hydropower, the Midwest U.S.'s wind power and solar energy, and Mexico's solar energy, in order to achieve coordinated development of clean energy and power grids, as well as building strong North American energy interconnection backbone grids by fully upgrading the existing power grids, so as to strengthen the inter-continental and cross-border interconnection with an interconnected network platform covering large clean energy bases and load centers for an optimal allocation of clean energy.

The overall pattern of power flow in North America will be power transmission from *'north to south, central to coasts, and complementary with Central & South America through inter-continental power interconnections'*. In 2050, The power flow will reach 200 GW, including an inter-continental power flow of 10 GW.

In the future, North America will build three synchronous grids in the North America eastern synchronous grid, the North American western synchronous grid and the Quebec grid. In 2050, the North America Energy Interconnection will be fully established, and the UHV AC/DC vertical channel on the east and west coasts and the central clean energy horizontal transmission channel will be built.

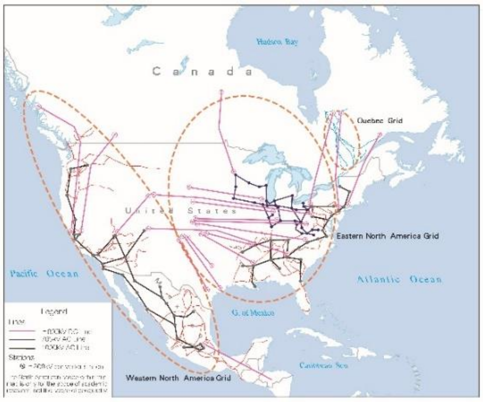

Fig. 23. Illustration of the overall pattern of grid interconnection in North America.

5.3.5 Central and South American Energy Interconnection

The development goals of the Central and South America power grid will be to rigorously develop inter-regional and cross-border interconnection, to support the exploitation of hydropower, to actively develop non-hydro clean energy, to achieve large-scale development of clean energy and complementarity, and to meet the economic needs of sustainable economic and social development.

The power flow features *'hydropower transmission from North to South, wind power transmission from South to North, solar power transmission from West to East, and inter-continental power mutual support with North America'*. By 2050, the total amount of inter-continental and inter-regional power flow will exceed 73 GW, of which 10 GW are inter-continental and inter-regional.

In the future, in addition to the Caribbean region, Central and South America will form an overall pattern of three synchronous grids in eastern South America, southern South America, western South America, and Central America. The Caribbean will achieve power exchange or DC cross-island networking. In 2050, the Central and South American Energy Interconnection will maintain the overall pattern of having three synchronous grids, thereby achieving the interconnection to the North America grid.

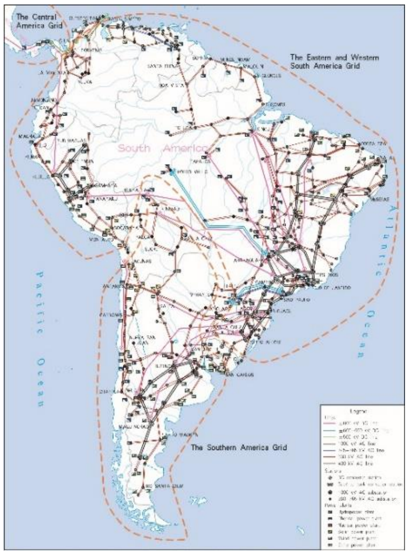

Fig. 24. Illustration of the overall pattern of grid interconnection in Central and South America.

5.3.6 Oceania Energy Interconnection

The development goals of Oceania's power grid will be to support the large-scale exploitation, complementation and utilization of solar, wind and hydro power through inter-continental, cross-border and domestic interconnection, in order to realize the transition of clean energy and promote the sustainable development of economy and society. Fiji and other island countries will focus on the construction of domestic transmission and distribution grids, and microgrids to support the exploitation of distributed clean energy generation.

The hydropower of Papua New Guinea shall complement with the solar energy of Australia, and the solar energy of Australia will complement with the seasonal hydropower of Southeast Asia. In 2050, The power flow will reach 10 GW, including an inter-continental power flow of 8 GW.

In the future, Oceania will construct five synchronous grids in the eastern Australia, western Australia, northern New Zealand, southern New Zealand, and Papua New Guinea, and the power reliability and supply capacity will be further enhanced. In 2050, Oceania will continue to maintain the pattern of five major synchronous grids in the eastern and western Australia, New Zealand's South and North Island, and Papua New Guinea. The power exchange between Papua New Guinea and Australia will further be enhanced.

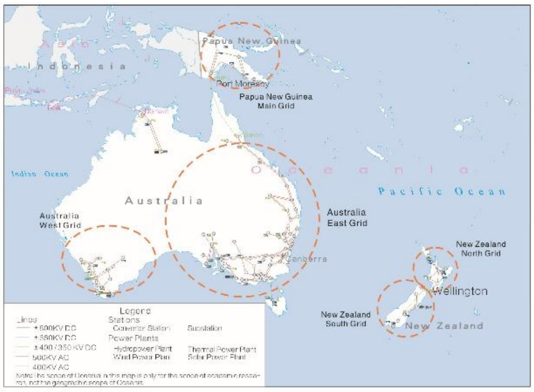

Fig. 25. Illustration of the overall pattern of grid interconnection in Oceania.

6 Comprehensive Benefits

6.1 Investment Estimation

The investments for GEI power source and grids will be estimated based on the trends in power supply, grid technology development and cost levels. By 2050, the GEI backbone grid will have an increased channel length of 202000 km and transmission capacity of 660 GW, including 11000 km of submarine cables and 120 GW of submarine transmission capacity, with an estimated total investment of 509.8 billion USD.

With considerations in the different cost levels of power supply and grid investment of the various continents, the amount of investment needed for the various power sources and voltage grade grids in various continents is estimated. From 2019 to 2050, the total investment in GEI is estimated to about 34 trillion USD, of which, the power investment is about 24 trillion USD, and the power grid investment is about 10 trillion USD.

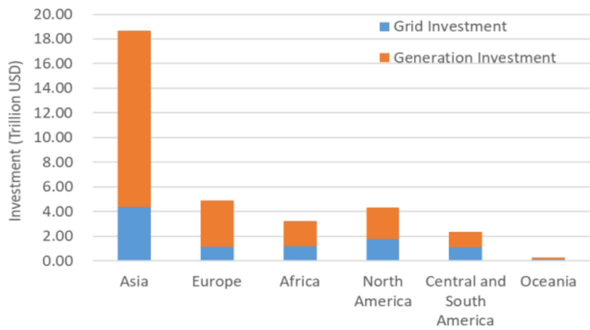

Fig. 26. Total investment estimation of GEI.

6.2 Benefits Estimation

It is of great importance to accelerate the development and utilization of clean energy, meet the global power demand, stimulate the world economic growth, reduce the price of electricity, cope with climate change, protect and improve the ecological environment, create a better life for the society and support the building of a community of common destiny for all mankind by building the GEI and the national energy interconnections. Considering the 2°C-scenario, the following benefits have been estimated.

(1) The power demand can be met by using clean energy. Clean energy will account for more than 70% of primary energy, and clean energy will account for 81% of total global power generation in 2050.

(2) With clean energy, the world economic growth will be further promoted. The total investment on GEI will reach about 34 trillion USD, with the average contribution rate of 2% to the global economic growth.

(3) Cost of energy supply can be reduced. Clean energy resources will be developed in a large scale and allocated optimally, which will effectively reduce the cost of energy supply. In 2050, the average LCOE of global clean energy will be around 40% lower than that of 2016.

(4) The issue of climate change will be effectively addressed with the help of clean energy. Energy system emissions will further drop to about 10.9 billion tons of CO_2/year in 2050, and the temperature control target of 2°C of the *Paris Agreement* will be achieved. Around 2065, zero net emissions of CO_2 from energy use will be achieved.

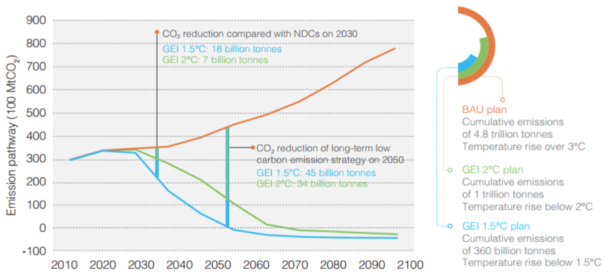

Fig. 27. GEI carbon-emission roadmap.

(5) Clean energy can also protect and improve the ecological environment. By 2050, annual SO_2 emissions will be reduced by 50.7 million tons, annual NO_x emissions by 78.1 million tons, and annual fine particulate matter emissions by 11.43 million tons. The scale of fossil energy development and utilization will be greatly reduced, in terms of mining, processing, transport, storage, combustion, etc. Groundwater pollution, geological damage, terrestrial and marine ecological damage that are brought about by the process will be increasingly reduced, and the ecological environment will be protected and restored.

(6) Clean energy can create a better life in the society. With the sharp decline in electricity prices, green and clean electricity will be made affordable, and the problem of human populations living without electricity will be solved effectively. The number of diseases and death cases caused by pollution will be reduced significantly with reduction of 8 to 10 million related disease cases every year. In 2050, more than 300 million jobs will be created globally. Areas that are rich in resources such as Africa will be able to make use of this advantage and turn it into economic advantages, which will effectively promote economic development and solve poverty issue.

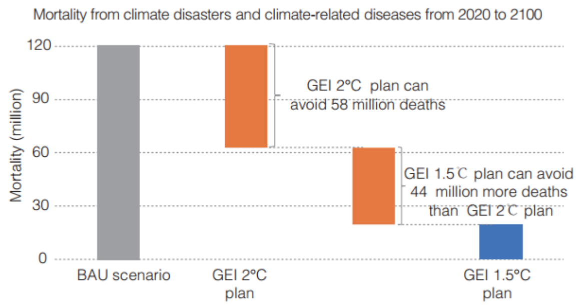

Fig. 28. Diseases reduced under GEI.

7 Conclusion

The GEI is a systematic plan of accelerating global energy transition and realizing economic, social, environmental development in a coordinative and sustainable way. To realize the UN *2030 Agenda* and *Paris Agreement*, under the 2°C-scenario, by 2025 the global fossil energy in primary energy consumption will reach its peak; by 2040 the clean energy will surpass fossil energy and become dominated in primary energy consumption; around 2040, the total final energy consumption will peak and by 2050, 54% of the total final energy consumption will be electricity. The potential from electrification will be stimulated and released, by 2050 the global electricity consumption will reach beyond 62 PWh with its annual growth rate of about 3%, which is more than 3 times that of energy demand. To provide green and sustainable power supply, the global clean energy installed capacity will surpass fossil energy around 2030; by 2050, 84% of the total capacity will be clean energy generation. Through constructing the *'Nine Horizontal and Nine Vertical'* GEI backbone grid, clean energy bases and load centers will be closely connected to achieve global allocation and share of clean energy in a wide range, to ensure clean, safe, economic and efficient supply of energy and power, effective address climate change and protect ecological environment. The total investment of building the GEI is estimated to about 34 trillion USD, through which comprehensive climate, environmental, economic and social benefits can be achieved.

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Comparative analysis of Azerbaijan's energy sector efficiency trend at the current development stage

Nurali Yusifbayli[1,*], *Valeh Nasibov*[2]

[1] Azerbaijan State University of Oil and Industry, 16/21 Azadliq, Baku, Azerbaijan
[2]Azerbaijan Scientific – Research and Design–Prospecting Institute of Energetics, 94, Zardabi, Baku, Azerbaijan

Abstract. Methodological and practical aspects of the energy sector efficiency trend in various countries of the world and Azerbaijan for 2013-2017, based on the methodology presented by the World Economic Forum (WEF), are analyzed and considered in the paper. The basis of the methodology for evaluating the effective energy sector performance is the use of an energy triangle, where the vertices are Economic growth and development, Environmental sustainability and Energy access and security, where a set of indicators with their own weighting coefficients is used to evaluate each of subsystems. Naturally, the number of indicators and the weighting coefficients are adjusted in time in order to fully take into account all the features of the energy sector. The Azerbaijan's energy sector efficiency values for the period under review, taking into account all available indicators, are re-calculated, due to this fact the Azerbaijan's place in the world's ranking of countries has moved several positions higher.

1 Introduction

The basis of the methodology for evaluating the effective energy sector performance is the use of an energy triangle, where the vertices are Economic growth and development, Environmental sustainability and Energy access and security, where a set of indicators with their own weighting coefficients is used to evaluate each of subsystems. Naturally, the number of indicators and the weighting coefficients are adjusted in time in order to fully take into account all the features of the energy sector [1-6].

2 Energy Architecture Performance Index of World

For comparative analysis of changes in the Energy Architecture Performance Index for 2013-2017, the countries of the world were grouped into seven regions, for which the corresponding relationships were constructed [2]. The relationships of the Energy Architecture Performance Index subsystems of the European Union countries are shown below.

As is obvious from Figure 1, during the period under review, all 3 components of the energy sector efficiency in European countries have a positive growth trend, where the greatest growth is observed in the Environmental sustainability subsystem-17%, Energy access and security subsystem-11%, Economic growth and development subsystem - 6%. At the same time, the subsystem values themselves as of 2017 are as follows: for Environmental sustainability - 0.7, Energy access and security - 0.82, Economic growth and development - 0.61.

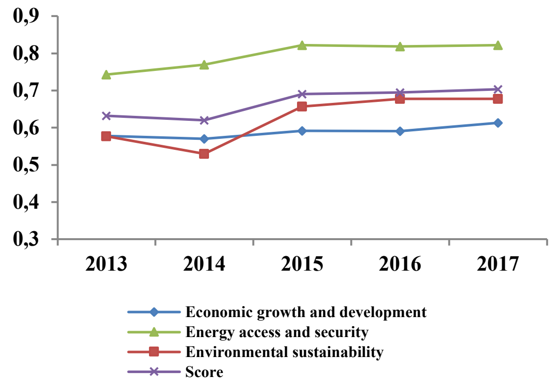

Fig. 1. Energy Architecture Performance Index of EU

In general, the energy sector efficiency in European countries increased by 11%.

The curves for subsystems of efficient energy sector performance for the North America countries are shown in Figure 2. As is obvious from the figure, the Environmental sustainability subsystem has increased by 20% compared to 2013, Energy access and security by 10%, and Economic growth and development by 4%. The subsystem values themselves as of 2017 are as follows: for Environmental sustainability subsystem - 0.63, Energy access and security subsystem - 0.66, Economic growth and development subsystem - 0.53.

* Corresponding author: author@e-mail.org

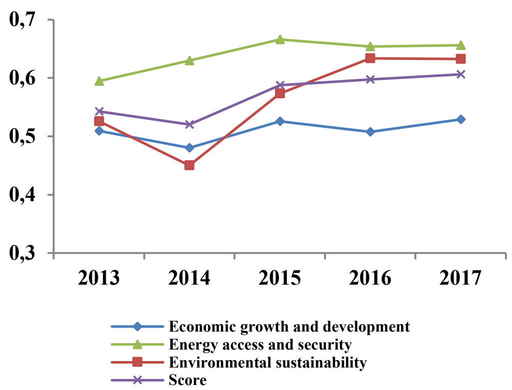

Fig. 2. Energy Architecture Performance Index of North America

On the whole, the energy sector efficiency for the North America countries increased by 12%.

The energy sector performance efficiency subsystems curve for Middle East & North Africa is presented in Figure 3.

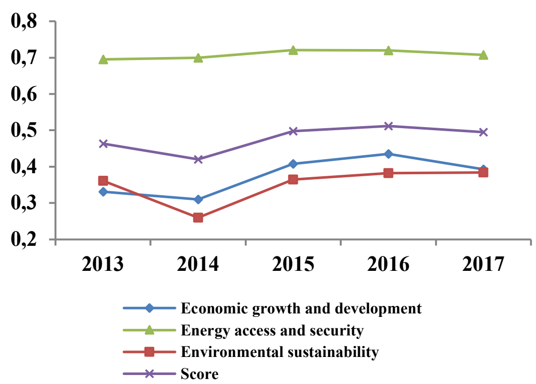

Fig. 3. Energy Architecture Performance Index of Middle East & North Africa

Unlike the EU and North America countries, , the largest growth in the Middle East & North Africa countries is observed in the Economic growth and development subsystem, which is 18%. Low growth is observed in Environmental sustainability and Energy access and security subsystems, 7% and 2% respectively. These subsystem values as of 2017 are as follows: Economic growth and development - 0.39, Environmental sustainability - 0.38, Energy access and security-0.71.

On the whole, the energy sector efficiency for the Middle East & North Africa countries increased by 7%.

A different picture is observed in the BRICS countries. Although some drop of the Environmental sustainability subsystem value occurred in 2014, as shown in Figure 4, in 2015 it recovered up to 0.54 and remained practically constant during the last several years. Slight growth is also observed in the other two subsystems.

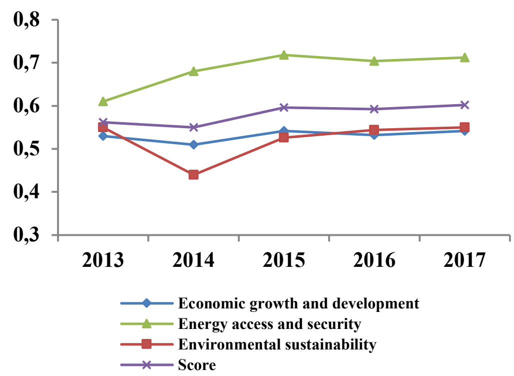

Fig. 4. Energy Architecture Performance Index of BRICS

In general, the energy sector performance efficiency of the BRICS countries also has a low growth compared to 2013-7%.

In the ASEAN countries, slight growth is observed in the Economic growth and development subsystem by 16% and in the Environmental sustainability subsystem by 15%, as is obvious from Figure 5. At the same time, the subsystem values themselves as of 2017 are as follows: Sustainability environmental sustainability - 0.57, Energy access and security - 0.70, Economic growth and development - 0.52.

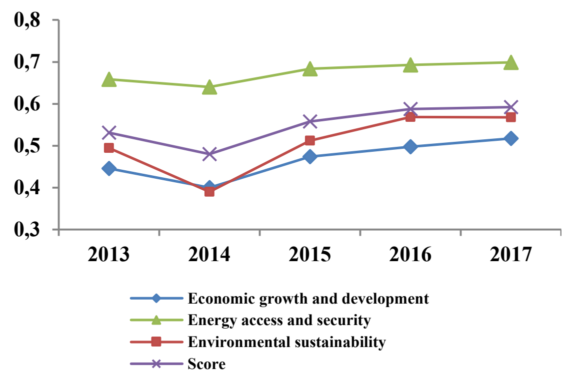

Fig. 5. Energy Architecture Performance Index of ASEAN

In general, the energy sector performance efficiency for the ASEAN countries increased by 11% compared to 2013.

Among the 7 regions considered, the most significant growth in the Economic growth and development and Energy access and security subsystems of effective energy sector performance is observed in the Sub-Saharan Africa countries, 24% and 33% respectively. At the same time, the subsystem values themselves in the Sub-Saharan Africa countries are still low compared to other regions, 0.47 and 0.39 respectively (Fig. 6).

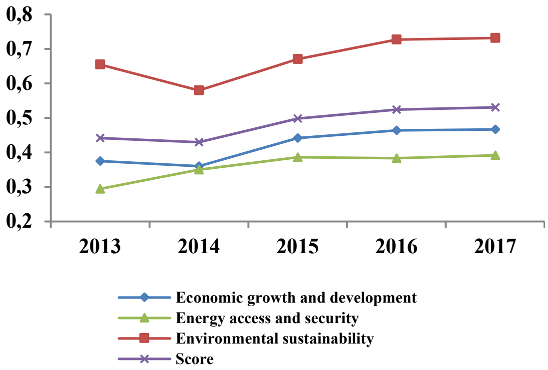

Fig. 6. Energy Architecture Performance Index of Sub-Saharan Africa

On the whole, the energy sector performance efficiency in the Sub-Saharan Africa countries also has the highest indicator among 7 regions, which has increased by 20% compared to 2013.

In CIS countries, as is obvious from Figure 7, there is relatively small but steady growth in all subsystems. In 2014 a significant decline of the value to 0.48 happened in the Environmental sustainability subsystem, and some decline also has occurred in the Economic growth and development subsystem to 0.36, which led to the decrease in the score to 0.51.

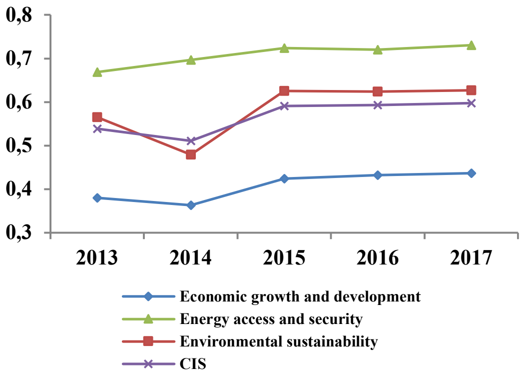

Fig. 7. Energy Architecture Performance Index of CIS

The values as of 2017 for the energy sector performance efficiency subsystems of CIS countries are as follows: for Economic growth and development - 0.44, Environmental sustainability - 0.63, and Energy access and security - 0.73.

On the whole, the energy sector performance efficiency in CIS countries increased by 7%.

Analyzing all regions, one can reach a conclusion that small but steady growth is observed in all subsystems of the energy sector performance efficiency. As is obvious from all the above curves and as shown in Figure 8, in 2014 the value of the Environmental sustainability subsystem dropped significantly in all regions, and in 2015 it recovered and remained almost unchanged over the past few years.

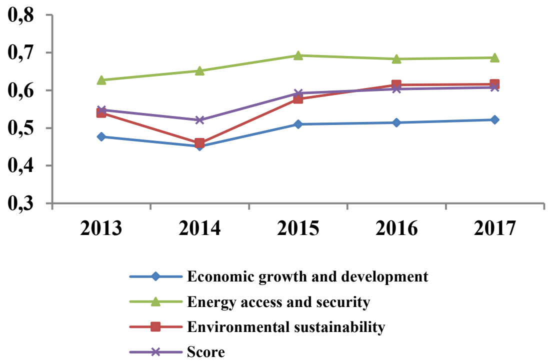

Fig. 8. Energy Architecture Performance Index of World

Values of world energy sector performance efficiency subsystems as of 2017 are as follows: Economic growth and development-0.52, Environmental sustainability-0.62, Energy access and security-0.69.

In general, the world energy sector performance efficiency for 2013-2017 increased by 11%. The location of the curves of all 3 subsystems of energy efficiency around the world repeats the location of the corresponding curves for the EU, North America, ASEAN and CIS countries. As is obvious from the Figure 7, Economic growth and development (0.52) and Environmental sustainability (0.62) subsystems have significant potentials for the improvement. Due to the fact that the Energy access and security subsystem is at very high level in most countries of the world (0.7-0.82), the potentials for improving the state of this subsystem for the whole world are small (0.69).

3 Energy Architecture Performance Index of Azerbaijan

Similar studies have been conducted to determine the efficiency of Azerbaijan's energy sector performance [7-9].

As is obvious from Figure 9, during the period under review in 2013-2017, the efficiency of Azerbaijan's energy sector performance according to calculations of the World Economic Forum on the whole showed an increase of 14%, while the "Economic growth and development" subsystem grew by 38%, the "Environmental sustainability" subsystem by 12%, and "Energy Availability and security" by 1%.

It should be noted that according to the same calculations, the numerical values of the Energy Architecture Performance Index of Azerbaijan on the whole as of 2017 are 0.67, and for the subsystems are 0.65, 0.57 and 0.79 respectively.

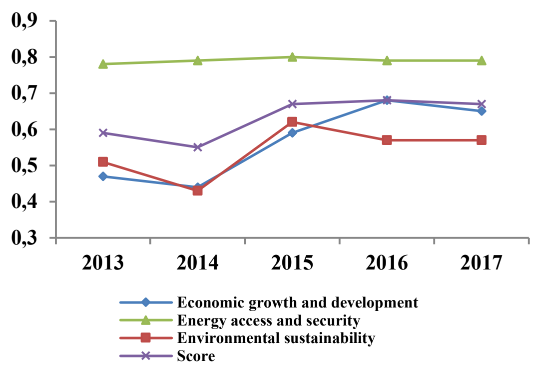

Fig. 9. Energy Architecture Performance Index of Azerbaijan

During the period under review, the efficiency of Azerbaijan's energy sector performance has significantly increased in the rating of countries. If in 2013 Azerbaijan was ranked 42nd among 105 countries, then in 2017 it was ranked 36th among 127 countries.

During the analysis it was found that the research of the World Economic Forum was incomplete, since the values of some indicators for evaluating the values of individual subsystems are not available, which led to inaccuracies in the assessment of both individual subsystems and the resulting value of the efficiency of the energy sector performance of Azerbaijan.

Below are curves of some indicators included in the subsystems of energy performance efficiency in Azerbaijan.

The chart of Energy intensity indicator, which is part of the Economic growth and development subsystem, is presented in Figure 10. As is obvious from the chart, the Energy intensity indicator value in 2018 increased almost by 25% compared to 2010. It should be noted that this occurred mainly due to diversification of economy and sustainable development of non-oil sector [10-14].

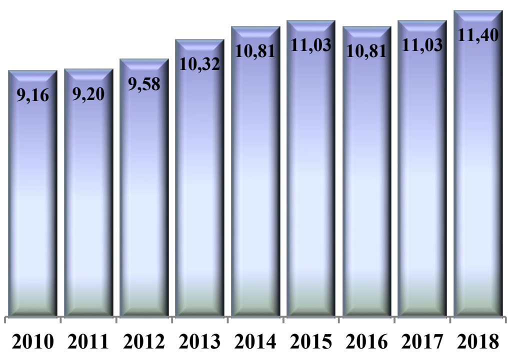

Fig. 10. Energy intensity (GDP per unit of energy use)

Another indicator from the Economic growth and development subsystem is Electricity prices for industry (US$ per kilowatt-hour), which is not taken into account in the WEF report.

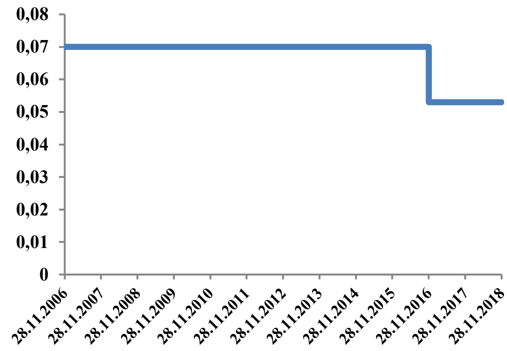

Fig. 11. Electricity tariff in Azerbaijan

The "Electricity prices for industry' for Azerbaijan is presented in the Figure 11. As is obvious from the figure, since 2016 the price of electricity for industry has dropped by almost 25% from $ 0.07 per kWh to $ 0.053 per kWh, indicating a high level of this indicator.

Another indicator of this subsystem is cost of Energy imports (% GDP). As a result of the formal approach, the value of this indicator in the WEF report is shown as 0.28, which worsens the resulting value of the subsystem under consideration. Analysis of the Energy imports indicates that the import of energy resources in Azerbaijan has increased in recent years (2016-2018) due to the increase in natural gas import. The energy balance of natural gas of Azerbaijan is shown in Table 1.

Table 1. Natural gas, mln.cubic meters

	2016	2017	2018
Production	18717.6	18186	19207.1
Import	298.4	2109.9	1798.2
Export	8049.1	8556.9	9911.8

As is obvious from the Table 1, natural gas is imported not for domestic consumption of Azerbaijan, but to fulfill international obligations for its export, actually the imported natural gas is transit. It should be noted that because of this also the state of the Value of energy exports indicator (%GDP) worsens, which in the WEF report for 2017 is indicated as 24.97%, but actually it should be less.

Charts for some indicators included in the Environmental sustainability subsystem are given below. The chart for "Nitrous oxide emissions in energy sector" indicator, included in the Enviromental sustainability subsystem, is presented in Figure 12. As is obvious from the chart, the value of this indicator has significantly decreased in recent years, although there is some growth in 2017-2018.

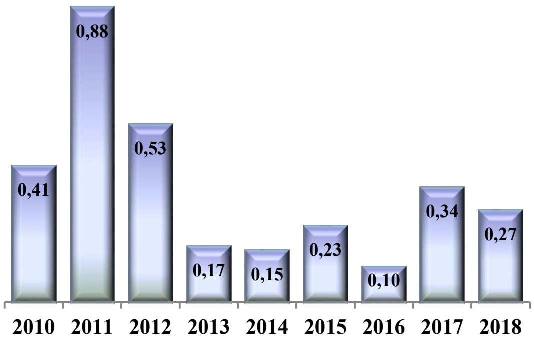

Fig. 12. Nitrous oxide emissions in energy sector, ton/population

Another indicator from the Enviromental sustainability subsystem is Methane Emissions in energy sector (metric tons of CO_2 equivalent)/Total Population).

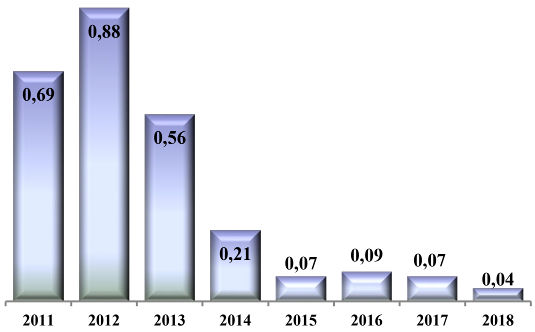

Fig. 13. Methane Emissions in energy sector, ton/population

As is obvious from Figure 13, Methane Emissions in the energy sector have decreased significantly in recent years.

The value of the "CO2 emissions from electricity" indicator in Figure 14 tends to decrease slightly, which is mainly due to the greater use of more efficient power plants for power generation.

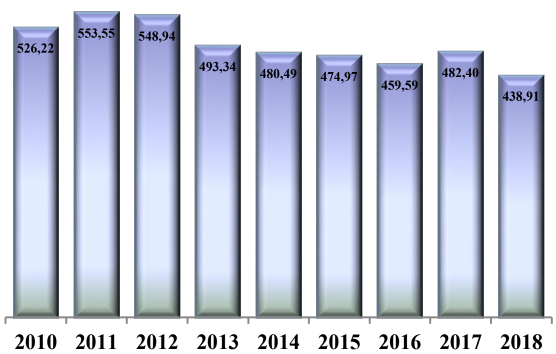

Fig. 14. CO2 emissions from electricity, gr/kWh

In the WEF report the Energy access and security subsystem is evaluated using 6 indicators. The most important for Azerbaijan are indicators Quality of electricity supply, Percentage of population using solid fuels for cooking and Diversity of total primary energy supply (Herfindahl Index). As shown above, energy resources imports mainly reflect the natural gas import, which is exported and actually is transit. Therefore, the values of the Import dependency and related Diversification of Import Counterparts indicators are calculated formally, and are not particularly important for evaluating the Energy access and security subsystem in Azerbaijan.

Percentage of population using solid fuels for cooking in Azerbaijan is presented in Figure 15. As is obvious from the figure, this indicator is in a very high level, conforming to gasification level in the country, although the value of this indicator in the WEF report is significantly worse.

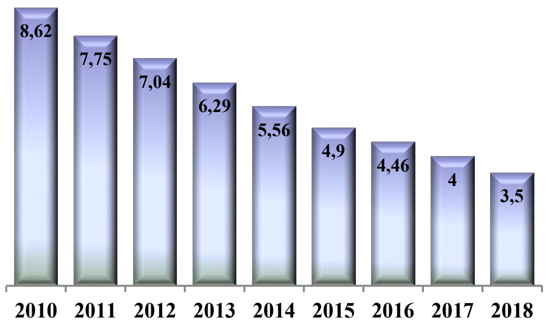

Fig. 15. Percentage of population using solid fuels for cooking, %

Taking into account all available indicators included in the system of indicators for evaluating individual subsystems of energy performance efficiency in Azerbaijan, the values of energy sector performance subsystems were recalculated and their updated values were determined: for 2017 for the Economic growth and development subsystem-0.68, for the Environmental sustainability subsystem-0.62, for the Energy access and security subsystem-0.8, while the Overall score was 0.7

The energy triangle "Energy Architecture Performance Index of Azerbaijan" for 2017 with updated values of subsystems is presented below in Figure 16 [15].

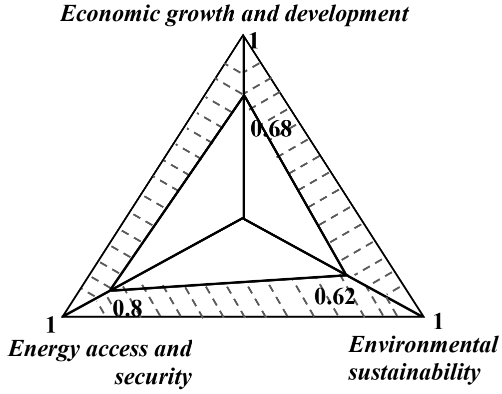

Fig. 16. Energy Architecture Performance Index of Azerbaijan

As is obvious from the energy triangle, there are significant potentials for improvement of the state in the

Environmental sustainability subsystem, quite large potentials are in the Economic growth and development subsystem and small potentials for improvement are in the Energy access and security subsystem.

Conclusions

1. The most characteristic features of energy sector performance in the selected regions are identified: in relatively developed countries (regions) the "Energy access and security" subsystem shows high values and "Economic growth and development" subsystem shows relatively low values, and resulting value of the energy sector performance efficiency of countries of the mentioned regions have a relatively middle position. This state of the energy sector performance efficiency is observed in the countries of the European Union (EU), North America, South Africa (BRICS), the Association of Southeast Asian countries (ASEAN) and CIS countries.
2. In less developed countries (South of Sahara (Sub-Saharan Africa)) a characteristic feature of energy sector performance efficiency is the relatively high value of the "Environmental sustainability" subsystem and the low values of the "Energy Access and safety" subsystem. At the same time, in the Middle East and North Africa (MENA) countries, high values for "Energy access and security" subsystem and low values for the "Environmental sustainability" subsystem are observed.
3. Recalculations of values of Azerbaijan's energy sector performance efficiency for the period under review have been performed, taking into account all available indicators included in the system of indicators for evaluating individual subsystems, due to this fact the Azerbaijan's place in the world rating could move several positions higher.

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ENERGY OF VIRTUAL AND REAL REALITY IN POST-CRISIS "FUTURE" PROJECTS

Yuri Plakitkin *[1]

[1] Energy Research Institute of the Russian Academy of Sciences (ERI RAS), Moscow, Russia

Abstract. The questions of the search for fundamental laws of development of the world energy and economy during the period of growth in the volume of virtual reality are considered. The results of calculations are presented, indicating the probable implementation of two large technological "leaps" in the post-crisis period.

Keywords. Virtual reality, energy, technological development, energy density, time, forecasts, energy cycles

Introduction

The future development of the world energy sector is characterized by very great uncertainty. Even on the eve of the onset of the 2020 crisis associated with the spread of the COVID-19 virus, many well-known foreign and domestic agencies demonstrated such a wide range of forecasts for the future development of the world energy sector that any analyst had legitimate doubts about the existence of a scientific basis for forecasting, taking into account the impact of modern global processes of various "Nature".

A legitimate question arises: "What awaits the global energy industry: energy transition, peak consumption of oil and other traditional energy sources?" Perhaps the world expects the use of a more powerful source of energy? Dont clear. To answer these and other questions, of course, it is necessary to conduct fundamental research on the topic: "Where is our world heading."

Hybrid reality and its components

The 2020 crisis has shown that global development is moving towards the expansion of virtual reality and is increasingly becoming hybrid. During the research, several options for the development of hybrid, virtual and real reality were considered. As a result of the analysis of these options, it was found that the hybrid reality has an expanding dynamic that has a limit to expansion. With this variant of the development of hybrid reality, its constituent components will be characterized by an expansion of virtual reality (logistic dependence) and a shrinking reality (cyclical dependence) (Fig. 1).

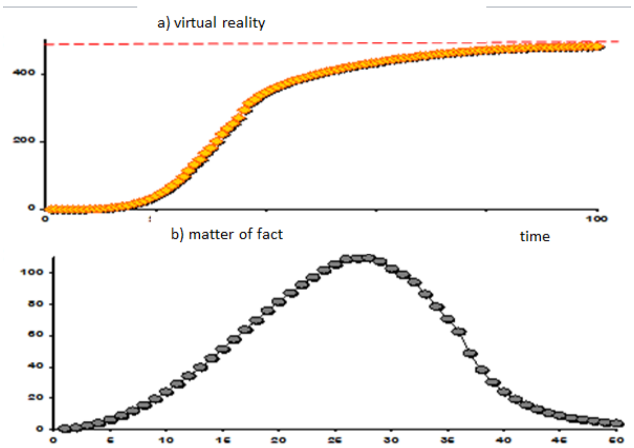

Fig. 1. Components of an "expanding" hybrid reality

The development of reality is provided by physical energy. On the basis of physical energy, work is carried out, as a result of which material results of labor appear. In general, physical energy can be calculated using the formula:

$$E_f = q_f * m \qquad (1)$$

where: m – the mass of the energy source used;

q_f – physical energy density, i.e. the amount of physical energy per unit mass of the source.

In power engineering, the above given energy density is called the caloric equivalent of the fuel used. In general, the energy density of energy sources has a growth limit determined by the formula of A. Einstein:

$$E = m * c^2 \qquad (2)$$

where: c – speed of light.

In this regard, the energy density of energy sources cannot be greater than c^2. Thus, the change in the energy density over time will be characterized by a logistic dependence, "abutting" the limit equal to c^2. Then, in

* Corresponding author: uplak@mail.ru

accordance with the cyclical nature of reality, the mass of the energy sources used should also change in a cyclical relationship. The development of virtual reality can be characterized by the dynamics of physical energy.

The question arises: "What characterizes the development of virtual reality?" Virtual reality is not a material space, it is a collection of knowledge, technological skills, information, etc. Given the informational nature of virtual reality, its development can be characterized by the level of entropy achieved.

However, it is known that entropy can be measured by energy:

$$S = K * LN(E_v) \quad (3)$$

where: К – constant coefficient;

E_v – energy of virtual reality.

The above expression indicates the possibility of evaluating virtual reality by the amount of energy used. Since virtual reality reflects the level of accumulated knowledge of technology and information, it characterizes scientific and technological development.

In this regard, the energy of virtual reality is a special type of energy - the energy of scientific and technological development.

In accordance with the universal nature of the calculated energy formulas, the energy of virtual reality can be represented as:

$$E_v = q_v * m \quad (4)$$

where: q_v – energy density of virtual reality;

m – the mass in virtual reality.

The above indicates that both virtual and real reality have a single energetic "nature". At the same time, it is very important to establish the relationship between physical energy and the energy of virtual reality. In the course of the research, it was revealed that the fulfillment of such fundamental laws as the law of conservation of energy and the law of conservation of mass requires the fulfillment of the condition of equality of the density of physical energy and the energy density of virtual reality:

$$q_f = q_v \quad (5)$$

Equality (5) is of fundamental importance. It testifies that the development of virtual reality and, accordingly, the level of scientific and technological development can be measured by the density of physical energy of the energy sources used. It turns out that the caloric equivalent (energy density) of energy sources used in the economy determines the level of technological development. If in equality (5) the current energy density is related to its limiting density (c2), then we can obtain a logistic dependence of the change in the relative energy density over time. In this case, the limiting value of the relative energy density will be equal to unity (Fig. 2).

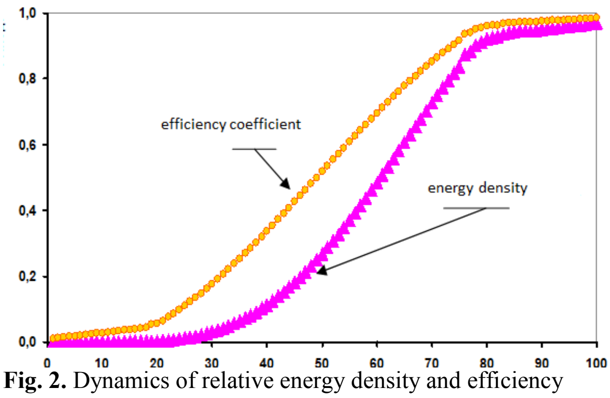

Fig. 2. Dynamics of relative energy density and efficiency

Specific energy density (see Fig. 2) has a fairly strong relationship with the efficiency of machines and mechanisms used in the economy. The change in efficiency reflects the level of technological development of the economy. This circumstance strengthens the argument that the energy density of the used energy sources can characterize the level of technological development of the economy.

The Energy of the waves of technological development and time

Analyzing the relationship between such fundamental categories as “time” and “energy”, we will conduct a thought experiment: “look” into the past from the standpoint of the current present and try to find what was in common that characterized the implementation of all the processes and phenomena in the global technological development. All phenomena and processes are characterized by the same form of realization ций cyclical development, in which the stages are sequentially carried out: growth, achievement of maximum values, decline. As you get closer to the present, the cycle frequency increases. There is a more rapid change in technologies and applied technical solutions. This frequency determines the speed of the technological process in the global economy. Based on an expert assessment of the frequency of cycles of technological development, the forecast dynamics of the average frequency of cycles of world technological development has been established (Fig. 3).

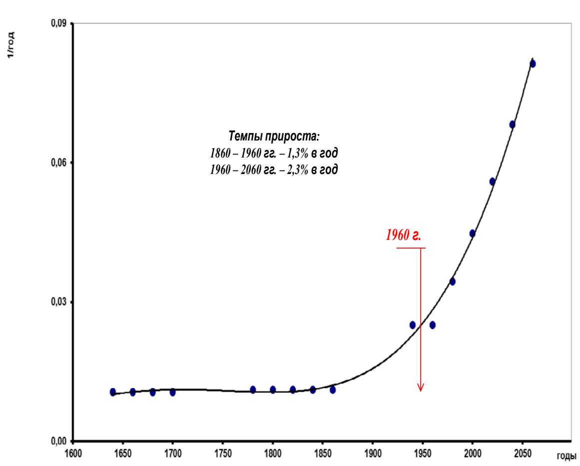

Fig. 3. Base frequencies adopted for assessing the cycles of global technological development

Since the 60s of the XX century, there has been a significant increase in the average annual rate of increase in the frequency of cycles. The cycle frequency began to change exponentially. In accordance with this frequency, in the process of research, a model of the wave (average) of world technological development was built, which can be described by an equation of the form:

$$Y_t = A * Sin(6{,}28 * \upsilon_t * t) \qquad (6)$$

where: A – wave amplitude;

V_t – wave frequency at time;

t – time.

The wave of world technological development has energy, the density of which can be determined by the expression:

$$W_t = \frac{\rho * A_t^2 * (6{,}28 * \upsilon_t)^2}{2} \qquad (7)$$

where: p – density of the medium in which the wave propagates.

Note that the energy density of a wave depends on the square of its frequency. Taking into account the exponential increase in the frequency of the wave in the future period, one can state an unprecedentedly high increase in the energy density during the period of significant immersion of world development in virtual reality (Fig. 4).

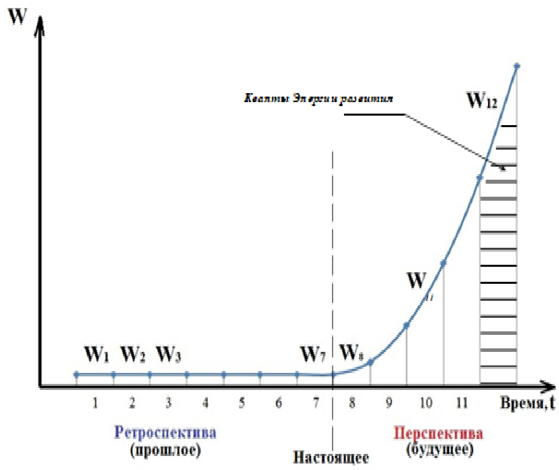

Fig. 4. Forecast corridor of dynamics of energy density (caloric equivalent) in the global energy sector of the XXI century

In fig. 4 shows that each current year is characterized by the "input" of a new quantum of energy. Moreover, the value of the "introduced" quanta significantly increases in the future period of time. In fact, physical time, which is used in world practice, is nothing more than just the ordinal number of "introduced" quanta of energy of technological development. So, what comes out all forecast calculations in the economy, energy, etc. Researchers carry out not by "the phenomenon itself", but by its ordinal number? In general, such forecasting is rather paradoxical. Yes, this was acceptable in the past period (see Fig. 4), since the introduced energy quanta were not very large, but in the promising period of high rates of energy growth in technological development, such forecasting becomes untenable.

We need approaches to forecasting based on taking into account the growth of energy of technological development. The energy of technological development is primary in relation to the emergence of new technologies. During the entire civilization process, there was a change in energy sources in the direction of a higher energy density provided by them. This was accompanied by a change in global energy development cycles. Wood, coal, oil, gas, energy cycles, replacing each other, increase the energy density (caloric equivalent) used in the world economy. Due to such an upward increase in energy density, it should be expected that the 21st century is the period of the beginning of the use of sources with high and very high caloric equivalents. In accordance with the change of energy sources, new technologies used in the world economy appear. For example, the use of such an energy source as coal led to the creation of a steam engine, a steam locomotive, the construction of railways and stations. The beginning of this process was a new energy source, and not the other way around. It was not train stations, railways and a steam locomotive that determined the appearance of an energy source.

Big technological leaps in the coming period

Taking into account the caloric equivalents of energy sources achieved in the global energy industry, as well as the logistic nature of their change over time, in the process of research, a predicted corridor of energy density values was obtained that can be achieved in the 21st century (fig. 5).

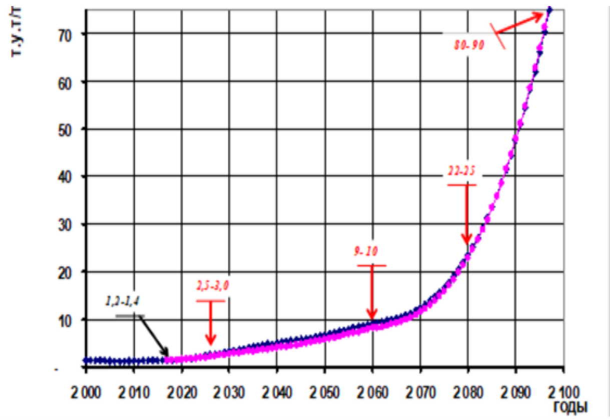

Fig. 5. Forecast corridor of dynamics of energy density (caloric equivalent) in the global energy sector of the XXI century

The resulting predictive dynamics of energy density indicates that in the next ten-year period (2020-2030), it should be doubled. By the middle of the 21st century, the energy density, in relation to the period 2020-2030, should double for the second time, and by the end of the century its values should reach values exceeding 100 tons of fuel equivalent per ton (t / t). A twofold increase in energy density in the next 10-year period, in all likelihood, means widespread use of hydrogen in the world economy.

What is the energy of the fuel used? It can be stated with all certainty that this energy is converted into the kinetic energy of the movement of machines and mechanisms that perform certain work, as a result of which new goods and services are received in society.

In the course of the study, it was found that in the nearest forecast period the average speed of movement of people and goods in the economy (implementation of kinetic energy) will be proportional to the square of the energy density of the energy sources used.

By doubling the energy density, for example, by switching from the use of methane to the use of hydrogen, it can lead to a 4-fold increase in the average speed of movement in the economy. It is clear that in the limiting case (when the speed of movement is equal to c^2, the speed of movement will be determined not by the square of the energy density, but by the power factor at it equal to 0.5.

In accordance with the predicted dynamics of the energy density values reached in the XXI century, possible levels of the speed of movement of people and goods in the world economy have been established (fig. 6).

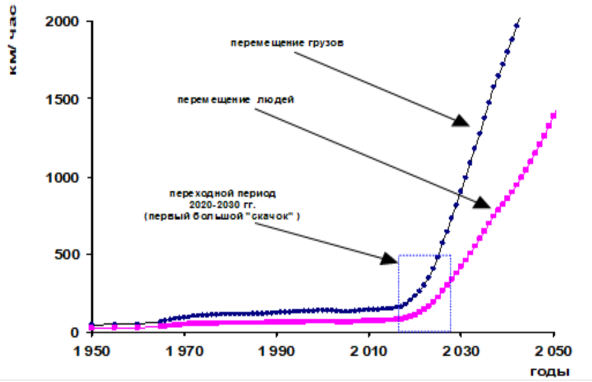

Fig. 6. Forecast dynamics of the average speed of movement of goods and people for the period up to 2050

Calculations show that already in the period 2020-2030. there will be a "break" in the predicted trajectory of the speed of movement in the economy during this period. This speed will receive an impulse for its further growth. It is obvious that this impulse is associated with the powerful "impact" of new technologies used in the economy.

Most likely 2020-2030 - these are the years of transition, in which the first big technological "leap" will take place. Calculations show that the second technological "leap", which, respectively, determines the second impulse to increase the average speed of movement in the economy, will be implemented approximately in 2060-2070. (fig. 7).

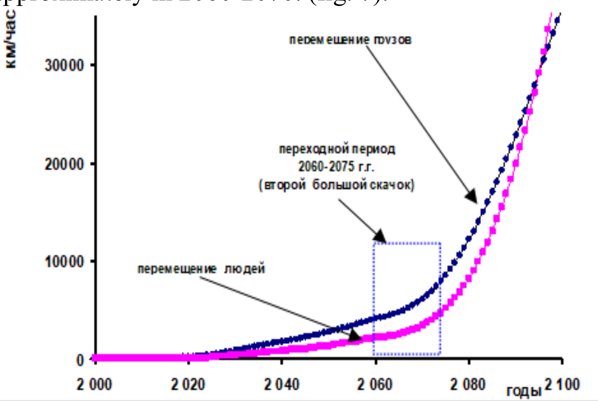

Fig. 7. Forecast assessment of the dynamics of the average speed of movement of goods and people for the period up to 2100.

Apparently, the first big "leap" will be associated with the implementation of the world project "Industry 4.0", and the second, respectively, with the project "Society 5.0".

It is significant that the leader in the implementation of the Industry 4.0 project, Germany, probably “realizing” that a technological “leap” cannot be made on the basis of the energy density of the energy sources used, in June 2020 adopted the national program “Hydrogen Energy” and started to its implementation. For this purpose, two program committees (government and scientific-public) were created to finance and promote technologies for the production and transportation of hydrogen.

The higher the speed of movement in the economy, the more work is done per unit of time and, therefore, the higher the labor productivity achieved in the economy. Calculations show that by the middle of the twenty-first century, one can expect that labor productivity in the economy may increase by 8-10 times. Such an increase in labor productivity can be achieved through the use of intelligent cyber-physical systems provided for by the world project "Industry-4.0". The growth in labor productivity will lead to a decrease in the supply prices of goods and services in the world economy. In accordance with the carried out model calculations, estimates of a possible price reduction were obtained for three options for the impact of labor productivity on production costs (very weak, weak and strong impact). In all cases, a decrease in prices was obtained in the prospective period. Even if the impact is weak, supply prices are likely to be reduced by at least 15% (by 2050). The maximum price reduction can be approximately 40-50%.

Forecast cycles and parameters of global energy development

In addition to the average speed, in the economy, in the process of research, the predicted values of the maximum travel speeds were obtained. These speeds are calculated on the basis of retrospective dynamics of maximum speeds, some of which are associated with the implemented space projects. The retrospective dynamics of the above mentioned speeds, as well as their "convergence" with an average speed in a deep perspective period, made it possible to form predictive estimates of the maximum speeds.

Note that the maximum speed in the previous period of time was first associated with the achievement of the first cosmic speed, intended for the movement of the spacecraft in the Earth's orbit. Then the second cosmic speed, allowing you to leave the Earth's orbit. And, finally, the third, achieved in 2013, and allowing the spacecraft to leave the solar system.

In accordance with the calculations, it was found that approximately, in the period 2055-2060. the 4th space speed must be reached, allowing the spacecraft to leave the Galaxy.

Most likely, the main mission of Mankind at the present stage of development is the expansion of outer space. First of the near, then the middle and, finally, the far space. The implementation of such a mission provides for the implementation of large-scale space projects that "pull" projects carried out in the economy.

Predictive estimates of the maximum speeds of movement made it possible to determine the future dynamics of changes in the maximum values of the energy density of the energy sources used.

In accordance with the carried out model calculations, it was found that, approximately, in 2042-2047. the massive use of energy sources based on nuclear fission should begin. Most likely, these will be small-sized sources (fuel cells) that directly convert nuclear energy into energy energy.

Approximately in 2055-2060. perhaps the beginning of industrial use of the energy of thermonuclear fusion. Such an event, of course, will have a very significant impact on all spheres of human activity. Note that in the same period it is planned to reach the fourth cosmic speed. In addition, in the above-mentioned period of time, the level of artificial intelligence will significantly increase - from the category of "strong", achieved by 2040, it will become "very" strong. "Artificial intelligence with such a level will have abstract thinking that allows them to engage in creative and managerial work.

The period of the 60s of the XXI century, which provides for the implementation of the second big technological "leap", will be characterized by three significant events:

- the beginning of the use of energy sources based on thermo-nuclear fusion;
- the development of a very strong artificial intelligence;
- reaching the fourth cosmic speed, allowing the expansion of deep space.

The obtained predicted values of the average and maximum energy density (caloric equivalents) made it possible to carry out model calculations to identify future cycles of global energy development (Fig. 8).

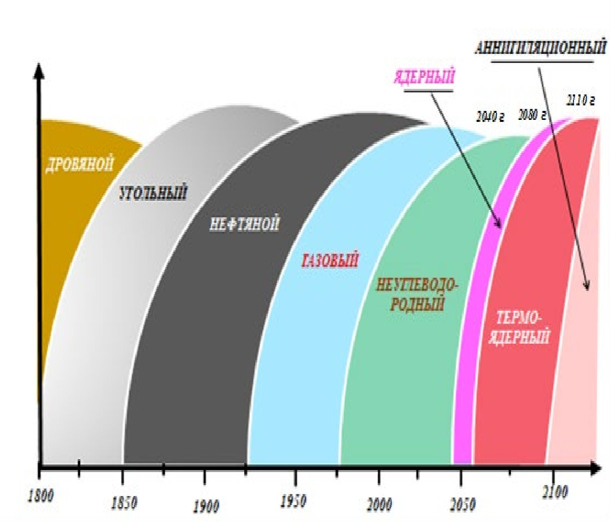

Fig. 8. Forecast cycles of global energy development

Calculations show that after the oil cycle, which in turn replaced the coal cycle, the dominance of the gas source will emerge in the near future. It will manifest itself approximately in 2035-2040, and then non-carbon-hydrogen energy resources, including all the variety of solar, wind, geothermal, hydro and nuclear sources, will become the dominant energy source.

Note that the period 2020-2040. will be characterized by a wide variety of traditional and non-hydrocarbon energy sources used. The dominance of nuclear sources of direct energy conversion will come approximately in the period 2080-2100.

Outside of this period, thermonuclear energy sources will dominate, the industrial development of which will probably begin in 2055-2060.

The established cycles of global energy development made it possible to assess the forecast dynamics of global consumption of traditional and renewable energy sources (Fig. 9).

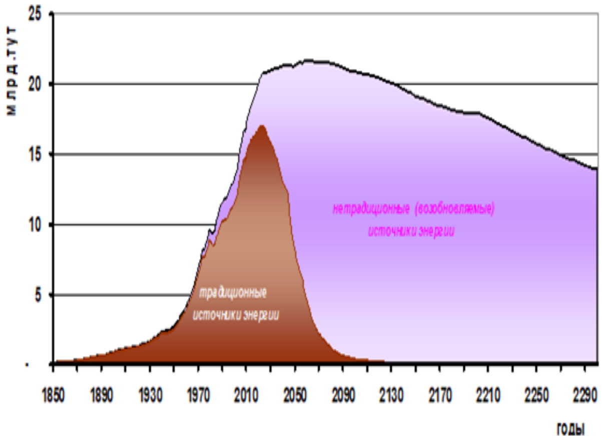

Fig. 9. Forecast dynamics of global consumption of traditional and renewable energy sources

The calculations made it possible to establish the dynamics of reducing the consumption of traditional energy sources in the coming period.

For a long time, many experts argued that energy consumption will increase in the forecast period. However, the calculations carried out not only do not confirm the presence of future "upward" trends in energy consumption, but on the contrary, they indicate a decrease in both the total world energy consumption and its per capita consumption. At the same time, the coming period of time will be characterized by a slight increase in energy consumption, turning into stabilization, approximately until the 90s of the current century.

Outside this period, there is a high probability that global energy consumption will decline. The decrease in consumption of traditional energy sources will occur against the background of a decrease in the main modern energy carriers - oil and gas. So, in accordance with the calculations, a twofold reduction in oil consumption is likely to be realized approximately in 2045-2048.

The subsequent, another twofold decrease in oil consumption, will begin approximately in the 60s, during the period when thermonuclear energy sources began to be used.

Gas energy sources, having reached their maximum level of consumption, are most likely to keep it until about the 40s of this century. A twofold decrease in gas consumption is likely to occur in the period 2050-2055.

The subsequent twofold decrease is likely to occur in the period 2065-2070, that is, during the period of growth in the use of thermonuclear energy sources. Such a "downward" dynamics of the use of traditional energy resources will lead to a decrease in prices for the world's main energy carrier - oil. Calculations have established that the world oil price will continue its systemic decline and by 2040, most likely, will drop to $ 20-25. US / bar. (average annual oil price). Despite the existing opinion of some experts and representatives of the state regulator that the oil price will "win back" its positions, the calculations carried out indicate its further decline.

Conclusion

The presented forecast tendencies form a multi-profile “image of the future” realized in the context of expanding virtual reality. An assessment of its parameters based on fundamental research by the author of the publication can be used to make investment and organizational decisions developed by representatives of Russian business and government bodies.

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Flexibility and Operating Reserves in Electric Power Systems

Elena Aksaeva, *Anna* Glazunova

Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

Abstract. Maintaining the efficiency of electric power systems (EPSs) requires some flexibility margin, which decreases in the case of adopting a variety of renewable energy sources (RESs). For this reason, the determination of the EPS flexibility several hours ahead becomes especially urgent. In this study, the flexibility of a 5-node EPS with a four-minute load change during a 6-hour time horizon is calculated. To this end, a probabilistic method based on the analysis of the cumulative probability of the available flexibility is used.

1 Introduction

One of the main characteristics of the flexibility of an electric power system (EPS) is the ability to maintain the efficiency of EPS under changing internal and external factors.

Depending on the purpose of flexibility application, all studies of flexibility can be divided into two groups: long-term planning and real-time. Flexibility metrics can be probabilistic [1] and deterministic [2].

The scientific articles describe different metrics of flexibility, including:

1. Determination of a range of maximum uncertainties within which the system remains flexible for a specified time and a cost threshold [2].
2. Calculation of the insufficient ramping resource expectation (IRRE). Formation of the probability distribution of available flexibility resources for each direction and time horizon [1].
3. Calculation of a flexibility residual, i.e. the difference between the available flexibility and the expected load ramps for each observation and horizon. Then, the determination of the probability that the residual flexibility will be less than zero, which means the probability of insufficient resources in the system [3].
4. Calculation of the ramping rate (ΔR), power (ΔP), and energy (ΔE). These values are used to determine flexibility in EPS [4].
5. Calculation of flexibility sets, which determine the allowed deviations from the current state of the EPS. The method is based on computational geometry using polytopic projections, which requires a limited amount of information exchange between two EPSs, and it can do without central coordination [5].

EPS flexibility is achieved by increasing and properly utilizing power reserves. The calculation of the EPS flexibility requires accurate information about the available power reserves in the EPS and the rules for using these capacities.

This paper presents a quality characteristic of the EPS flexibility, which is calculated by a probabilistic method [1]. The structure of the article is as follows. Section 2 presents an overview of the EPS reserves. Section 3 focuses on advanced energy storage technologies. Section 4 describes the modeling of EPS facilities' flexibility. Section 5 presents the research results. Section 6 gives the conclusion.

2 Reserves of electric power system

Reserves are provided either on-line or in a standby mode. They are used in the case of load increases or generation decreases due to unpredictability or variability of the conditions. In EPS having a large number of variable generation sources (wind, solar), which can unexpectedly increase or decrease power output, it is crucial to have both upward and downward reserves [6].

The operating reserve is the capacity used to maintain active power, which comes in different shapes and sizes. The need for operating reserves arises for many reasons, including the variability and uncertainty of the state variables. The variability is the expected changes in the state variables. The uncertainty is the unexpected changes in the state variables.

Scientific articles provide an overview of the operating reserves used in the USA and Europe [6], [7].

The procedures for the use of operating reserves are set by different entities depending on the operating reserves required, who can provide them, when they should be unfolded and how they are used. The standards are usually based on specific reliability criteria and criteria for acceptable risk but often differ from region to region. Due to the high penetration of renewable energy sources, which have new characteristics for EPS, it is necessary to adjust standard rules and policies to account for the increased variability and uncertainty caused by them. The presented methodologies emphasize how reserve requirements can change with significant penetration of the variable generation in EPS [6].

Ref. [8] presents a methodology for determining the minimum required volumes of active power reserves of the EPS of Russia. According to the given methodology, the system operator determines and places the normative amounts of reserves, which are divided into three kinds according to the degree of maneuverability: spinning reserve, including the reserves of primary, secondary, and tertiary control; hot reserve; and cold reserve.

In an energy system having renewable energy sources, a decrease in the power output from solar and wind farms (due to changes in weather conditions: illumination, strength, and direction of the wind) is determined based on actual (statistical) information within 10 minutes. If a decrease in the power output leads to an emergency imbalance of the active power, then it is considered as a normative disturbance of the second group [9].

3 Advanced energy storage technologies

In [10], the authors describe in detail the EPS flexibility measures and advanced technologies for energy storage. An electricity-to-heat technology enables the excess energy from wind and solar farms to be converted into heat. Power-to-gas technologies produce synthetic methane, which can be used in gas distribution systems. Power -to -hydrogen technology allows hydrogen to be produced and stored for some time. The hydrogen can then be converted back to electricity. Due to vehicle-to-grid technology, energy storage services are provided in a distributed form, which implies the use of electric vehicles.

Siemens Gamesa has launched an ETES (Electric Thermal Energy Storage) pilot facility in Hamburg, Germany. The pilot facility converts electrical energy into hot air using a resistance heater and blower. The hot air heats about 1000 tons of volcanic rock to 750 ° C. The facility can store up to 130 MWh for a week due to effective insulation, according to a company spokesman. During the periods of high electricity demand, the stored thermal energy is to be converted back to electricity by using a steam turbine. This electricity will be sold by a local utility company [11].

The energy company ENERTRAG has launched a thermal energy storage device that allows the utilization of surplus electricity generated by the wind farm and provides heat to the central heating system. The thermal energy storage device is a water tank with a capacity of about one million liters, which is used in the local district heating system. This volume heats up in just a few hours to 93° C. Heating turns on automatically when the wind farm is disconnected from the network. The thermal energy storage device can supply heat to the village for up to two weeks [12].

Sonnen, the largest European manufacturer of home energy storage systems, has commissioned a virtual power plant (VPP) in northeastern Germany. The virtual power plant combines storage batteries into a uniform virtual network, a distributed large-scale storage system. Free volumes of these storage batteries are sold through a digital exchange. For example, according to the weather forecast, the future surplus of wind energy is known. In order not to waste wind energy, the system operator informs about the need for appropriate energy storage. The software logs this request and automatically matches it with the available storage capacity at the Sonnen virtual power plant and calculates how long the surplus wind power will be stored [13].

Scottish startup Gravitricity has announced the start of a pilot gravitational energy storage project at Scotland's largest closed deep-water port. The storage devices work according to the principle used in the pumped-storage power plant, but instead of water, they use solid materials (concrete blocks or environmentally sustainable raw materials, namely waste that would otherwise be sent to landfills). To accumulate energy, the weights are raised, and to release the energy, they are lowered (potential and kinetic energy is converted into electrical energy). The 250 kW prototype will use two 25-tonne weights suspended from a 16-meter tower on steel cables. The industrial Gravitricity system is installed above a shaft 150-1500 m deep [14].

ThyssenKrupp is launching electrolysis plants in the energy market. They will act as a buffer to stabilize the power system: if there is a surplus power output from wind and solar power farms, then hydrogen production will increase. On the contrary, when the electricity demand is high, the plant stops producing hydrogen. Based on the results of the tests, the company claims its water electrolysis technology for the production of green hydrogen meets the criteria for participation in the primary control. A condition is the ability to gain full power for a maximum of 30 seconds and maintain it for at least 15 minutes [15].

The project for energy storage technology developed in [16] involves a 4.5 MW solar power farm, a 4.5 MW/4.5 MWh Li-ion energy storage system, and a 2 MW and 17 MWh hydrogen energy storage system. Excess solar power output will be converted to H_2, which will be stored in a solid material called sodium borohydride ($NaBH_4$). It can absorb hydrogen like a sponge and then release it back. The hydrogen released back is sent to the fuel cell to generate electricity.

The Dutch energy company GreenChoice is going to install ten mobile storage containers with a capacity of 336 kW each next to a small 12 MW Hellegatsplein wind farm. The batteries will be charged directly from wind turbines and will provide ancillary services to the Dutch electricity grid, increasing its flexibility. A specific feature of the project is the mobility of the batteries, the ability to move them to provide various types of services to different clients. The system charging time is 43 minutes [17].

Energy storage systems are essential tools for increasing the flexibility of the power system because they can shave peaks in electricity generation and consumption. Energy storage devices can be classified according to their location. Table 1 shows the classification of energy storage systems.

Table 1 Classification of energy storage systems

Location	Brief characteristic
Near wind and solar farms	Energy storage systems are installed near the wind or solar farms. They are charged directly from wind turbines or solar cells. Thanks to this feature, the generation of electricity is stable around the clock.
Near the consumer	A storage device stores energy over a user-specified period and then returns it when needed. Currently, the technologies are being implemented that allow all home storage devices to be combined into one virtual power plant with a large storage capacity. This technology will enable the system operator to use these batteries. Lithium-ion (Li-Ion) batteries, nickel-cadmium (NiCd) batteries, supercapacitors, electric vehicles are used as storage devices.
Significant nodes of the power system	Energy storage systems that evenly store electricity by converting it into heat, into hydrogen, or use energy to lift loads to a height. These energy storage devices store energy at the moment of its surplus, and give it out at the moment of shortage, by reverse conversion; they are installed near consumers and are capable of supplying heat and electricity to individual settlements.

4 Modeling the flexibility of EPS elements

Model of generator flexibility of a conventional plant

The flexibility of each generator is determined by the power generated over the considered time horizon and is calculated by the formula [1]

$$F_g = V_{i+} * (t - (1-b) * S_i), \tag{1}$$

where V_{i+} is load ramp time (MW/min), *t* is the considered time horizon, S_i is the startup time (hour), *b* is the binary on-line variable when a generator is on $b=1$.

Model of battery flexibility

The flexibility of the battery is determined by its state of charge (SOC). If the battery is charged within the specified limits

$$SOC_{\min} < SOC(t) < SOC_{\max}, \tag{2}$$

then the power output is calculated by the formula:

$$F_B = P_{\max} \quad , \tag{3}$$

otherwise:

$$F_B = 0 \quad . \tag{4}$$

Model of system flexibility

The system flexibility is determined as a sum of flexibilities of all facilities in the system

$$F_S = \sum_1^m F_g + \sum_1^n F_B \ , \tag{5}$$

where m is the number of generators at conventional plants, n is the number of batteries.

5 The case studies

In this study, the flexibility of a 5-node EPS (Fig.1) is calculated using the IRRE method. In the proposed network bus 1 is a wind turbine, bus 2 is a generation unit, bus 3 and 4 are loads, bus 5 is the BESS. Bus 2 is a slack bus.

The means of flexibility are the balancing plant and the battery. It is assumed that it takes 4 minutes for the entire available reserve at the balancing plant to be switched on and that it takes 0.01 minutes for the battery to produce maximum power.

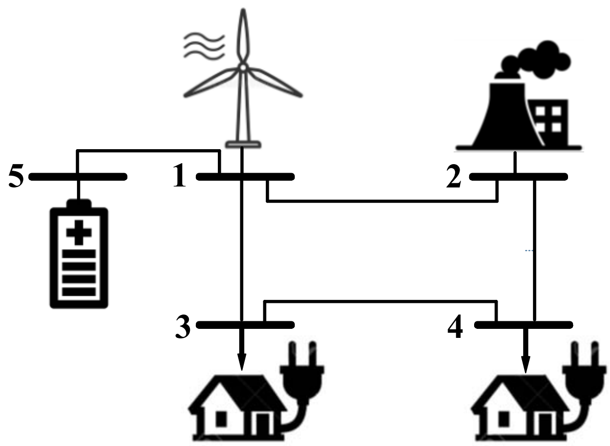


Fig1. Test schema

The work is aimed at determining the EPS flexibility for 6 hours for the case of a four-minute change in the load curves.

Information about flexible resources

The description of the flexible resources requires the following information:

1. Retrospective or simulated data of a flexible resource power output. In this study, simulated data are used.
2. Availability of data for each resource (on, off, how long it will turn on).
3. The upper limit of generation.
4. The lower limit of generation.
5. Startup time of a flexible resource.
6. Power ramp rate (increase).
7. Power ramp rate (decrease).
8. The probability of equipment failure.

.

Table 1 shows the characteristics of flexible resources.

Table 1. Characteristics of flexible resources.

№	Characteristic of flexible resources	Means of flexibility	
		generator	battery
1	Data on flexible resources	simulated data, 90 snapshots, 4 minutes	
2	Availability of data for each resource	1	1
3	The upper limit of generation (MW)	22	7
4	Startup time	4min	0.01 min
5	Ramp rate	22MW/4 min	7MW/0.01 min
6	The probability of equipment failure	0	0

Creation of a measurement archive

In this study

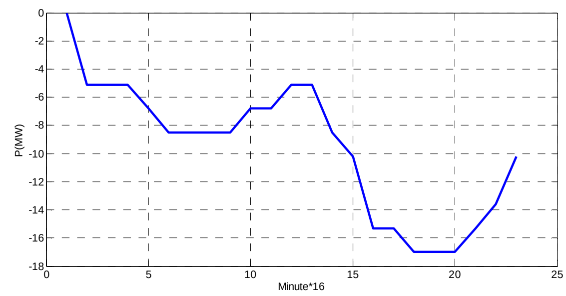
- 60 intervals are considered (5 days a week, 4 weeks a month, 3 months) with a duration of 6 hours.
- 90 snapshots are simulated every 4 minutes (360 minutes).
- Reserves are calculated every 4 minutes.

An algorithm for creating an archive of measurement snapshots is as follows:

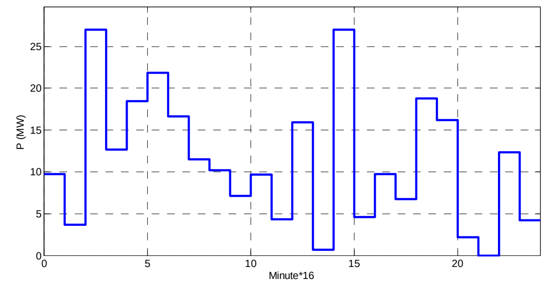
1. Simulate the loads at nodes 3, 4. Figure 2a shows a based load profile at node 3. Simulate power output at the wind farm. Wind turbine characteristics are known, and the wind speed is determined according to the Weibull distribution. Figure 2b shows the power output profile at node 1.
2. Calculate steady state for each point of the given load and generation curves. An obtained set of state variables is taken as true values (y_{true}).
3. Simulate the set of measurements $\bar{y}$ based on the set of y_{true} and information about the location of measurement devices:

$$\bar{y} = y_{true} + a\sigma, \tag{6}$$

where σ is measurement standard deviation, a is the value obtained by a random number generator, $a \in N(0,1)$. Each set y_{true} is used to simulate four snapshots, which means that four snapshots consist of measurements that differ from each other in the magnitude of the random error.



a) Load profile at node 3



b) Power output profile at node 1

Fig. 2. Load and power output profiles at nodes.

Figure 3 shows a curve of wind speed.

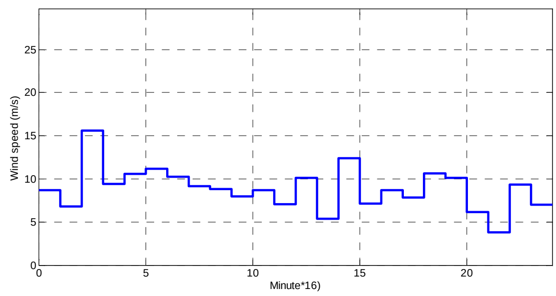


Fig. 3. Wind speed.

Figure 4 shows the SOC value of the battery over six hours at node 5 in the base case.

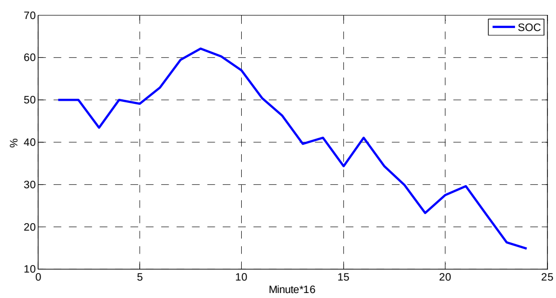


Fig. 4. SOC of the battery at node 5 in the base case.

Figure 5 shows the power output profile and the upper limit of generation at node 2. Figure 6 shows the SOC value of the battery at node 5.

Calculation of the cumulative probability of reserves distribution

The probability of the insufficiency of power system flexibility at each time horizon is the cumulative probability of the system's ability to provide power in the case of changes in the load.

Figure7 shows a distribution of the available flexible resources for a 6-hour time horizon. This distribution is used to calculate IRRE.

An algorithm for calculating the cumulative probability of the available flexibility is as follows:

1. Calculate reserves at each considered moment (90*60=5400 points). It is assumed that it takes 4 minutes for all available reserves in the power system to be switched on. Power system flexibility is calculated by the formula:

$$F_g = P_2^{max} - P_2 \quad , \qquad (7)$$

where $P_2^{max} = 22MW$, P_2 is power output at the balancing plant at a considered moment. Nominal energy that can be stored by the battery is $W_{CAP} = 7MWh$.

2. Classify the obtained values into several groups. Each group integrates the same reserves.
3. Sort the groups in ascending order of the reserve magnitude.
4. Calculate the probability that the given reserve will be available for each group (the larger the group, the higher the probability).
5. Determine the cumulative probability of the available flexibility.

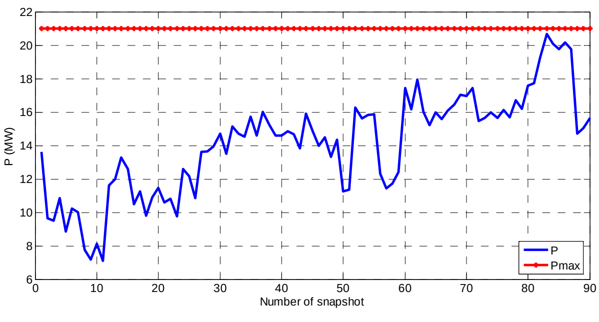


Fig.5. Power output profile and the upper limit of generation at node 2

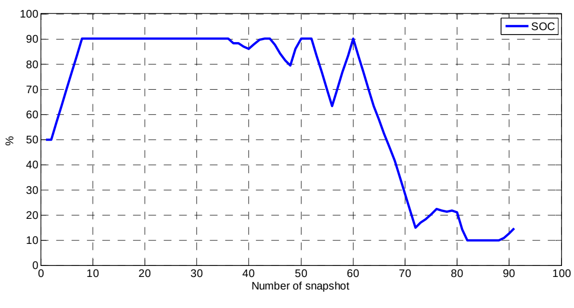


Fig.6. SOC of the battery at node 5

Figure 5 shows that a reserve is available at the balancing plant (node 2) within six hours (90 snapshots). Figure 6 shows that the battery is in a discharging mode at 6 snapshots (82–88) and, therefore, it cannot supply power. Figure 7 shows the distribution, which indicates the probability that x MW or less, of flexible resources, will be available four minutes ahead within the 6-hour time horizon. For example, there is a 26.6% probability that 6 MW or less of flexible resources (56.6% probability that 13 MW or less) will be available any 4 minutes ahead (4 min upward rumps) during a 6-hour time horizon.

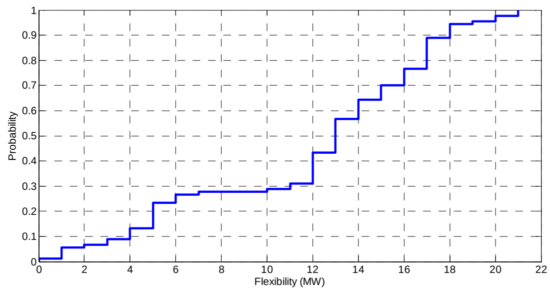


Fig.7. The cumulative probability of the available flexibility

Application of the cumulative function of reserve distribution

Two scenarios were developed for calculating power system flexibility (4-minute upward ramps) using the cumulative probability of the available flexibility (Figure 5).

Scenario 1. Load ramps are 16 MW/4min.

Scenario 2. Load ramps vary from 10 MW/4min to 18 MW/4min.

Scenario 1. Analysis of the graph presented in Figure 5 shows that there is a high probability (70%) that there will not be enough resources to meet the 16 MW load for 6 hours any 4 minutes ahead. It means that in this case, the system will face a shortage of flexibility.

Scenario 2. The probability that there will be insufficient resources to meet the changes in load in a range from 10 MW/4 min to 18 MW/4 min is calculated by the formula:

$$P_{IRRE} = P(18) - P(10), \qquad (8)$$

$$P_{IRRE} = 0.95 - 0.29 = 0.63. \qquad (9)$$

There is a 63% probability that there will be insufficient reserve to meet the load ramps in the range from 10 MW /4 min to 18 MW /4 min for 6 hours any 4 minutes ahead.

Conclusion

In the context of variability and uncertainty of state variables, operating reserves are required to maintain a power balance in an EPS. When determining the size of operating reserves to calculate the flexibility of EPS, one should take into account the fact that there is no uniform standard for applying the operating reserves in the world.

The article overviews the flexibility measures and advanced energy storage technologies. The analysis of the location of advanced energy storage devices indicates that they are located near wind and solar farms, consumers, and significant EPS nodes.

The cumulative function of the probability distribution of the 5-node EPS flexibility at a 6-hour interval with a four-minute load change was built.

Acknowledgment

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Application of Digital Technologies for Expansion Planning of Integrated Energy Systems

Valery Stennikov[1], *Nikolai* Voropai[1], *Evgeny* Barakhtenko[1,*], *Dmitry* Sokolov[1], *Oleg* Voitov[1], *Bin* Zhou[2]

[1]Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia
[2]Hunan University, Changsha, China

Abstract. Active promotion of digital technologies in the energy sector requires a change in the principles of building energy systems, as well as the concept of their expansion planning. The functioning of infrastructural energy systems that are transforming as a result of the innovative development is fundamentally impossible without advanced information and communication technologies and intelligent digital tools. Energy systems are becoming sophisticated cyber-physical systems. At the same time, the problems of cybersecurity are exacerbating. The joint functioning of several types of energy systems in the form of a single integrated energy system provides new functional capabilities. The use of digital technologies in integrated energy systems provides the collection, processing, transmission and representing of information on all components of the system regarding all aspects of integration. Digitalization of integrated energy systems is carried out in the following two directions: application of digital technologies for individual subsystems for the purpose of their control; the use of digital technologies for technical and technological integration solutions in order to ensure coordination of subsystems and the implementation of system-wide goals. The adoption of digital technologies in integrated energy systems contributes to the organization of flexible, coordinated control of the expansion planning of such systems.

1 Introduction

Modern cities and industrial centers have a developed energy infrastructure, including fuel, electricity, heat and cool supply systems. These systems have a certain functional independence and can interact with each other in normal and emergency conditions, as well as at the level of interchangeability of primary energy resources and the use of energy carriers. All this shows their natural integration, which is even more intensified as the formation and development of intellectual, information, telecommunication systems. Jointly they present a new structure that is integrated energy systems. This structure combines a certain independence of the systems with their coordinated participation in solving the main problem related to ensuring of social and economic activity. The quality of its solution is ensured by the use of digital technologies. Control of digital integrated energy systems is an urgent and complex problem.

2 Characteristics of studies on the integrated energy systems

Energy systems, primarily electricity, heat supply, gas supply and oil supply systems, perform an important infrastructural function. This function is to ensure energy supply to consumers with the required quality of energy carriers and reliability. Traditionally, these systems are integrated in the production of electricity and heat at CHP plants using gas as a fuel. The potential for the integration of electricity, heat and gas supply systems at the level of energy consumption has emerged as a result of the development of technologies and mechanisms. Alternative possibilities for consumers are an active choice of possibilities for obtaining and using energy, for example, centralized heat supply from a CHP or electric heating, electric or gas stoves for household consumers, etc. As a result, the integration of energy supply systems at the levels of energy production and consumption leads to the need to jointly consider these systems as integrated when the tasks of expansion planning and operation control are solved [1-4, etc.]. The integration of energy systems served as an impetus for the formation and development of the concept of an energy hub [5-7, etc.].

Considering a set of tasks of control of integrated energy systems, it is advisable to divide these tasks into two groups: expansion planning of intelligent integrated energy systems and their operation control.

As the analysis of the literature carried out in [4, 8] shows, the main attention of the authors is concentrated on the tasks of operation control, while the calculation of the flow distribution and its optimization in the integrated energy system is considered as the basic task. On this basis, other tasks of operation control of the integrated energy system are formulated and solved, in particular, at the optimization of daily operating

* Corresponding author: barakhtenko@isem.irk.ru

conditions at their dispatching, the analysis of the reliability of energy supply, etc. The group of tasks under consideration is solved taking into account the various components of the integrated energy system: electricity and heat supply systems; electricity, water, and gas supply systems; electricity and gas supply systems; electricity, heat and cool supply systems; etc.

Research has been carried out to analyze integrated energy systems taking into account the activity of consumers in control of their energy consumption, the use of energy storage devices, modern information and communication technologies, etc. [9, 10]. Mainly, network models of flow distribution are used, including with the integration of models of interconnected energy systems into a common model [8]. A fractal approach to modeling large integrated electric-thermal networks is considered in [11]. A simulation model of an integrated energy system based on the concept of an energy hub is proposed in [12]. To optimize operation, both classical methods of mathematical programming and evolutionary algorithms are used.

With regard to the methodology and tasks of expansion planning of integrated energy systems, it is advisable to pay attention primarily to the review [13]. This review examines the problem of sustainable urban development based on the integration of energy supply systems. In general, this work reflects the interpretation of the traditional methodology for expansion planning of energy systems, taking into account the multicriteria nature of tasks under various scenarios of external conditions with the optimization of target indicators of the efficiency of expansion planning of integrated energy supply systems, reducing harmful emissions and encouraging the use of renewable energy resources. In [14], the task of joint expansion planning of electric and gas transmission networks with endogenously given market gas prices, taking into account their volatility due to network restrictions, is considered. In [15], an innovative architecture of an intelligent integrated energy system and its control system is proposed based on the principles of a cellular structure, symmetric (multidirectional) energy flows, automatic reconfiguration of the network in emergency conditions, network-centric concept of control and self-regulation, etc.

Summing up, it should be noted that the methodology and tasks of expansion planning of integrated energy systems have been worked out significantly less compared to the methodology and tasks of their operation control.

3 Background and benefits of energy digitalization

First of all, it is necessary to define the concept of "digital energy". This concept is revealed in the Decree of the President of the Russian Federation “On the national goals and strategic objectives of the development of the Russian Federation until 2024” No. 204 dated May 7, 2018. This document sets the goal: “... to transform the priority sectors of the economy and social sphere, including ... energy infrastructure through the adoption of digital technologies and platform solutions ... " by " ... implementing intelligent control systems for electric power grid based on digital technologies". It is worthwhile to add here that the said applies not only to the electric power system, but also to energy systems in general. These are first of all heat/cool, gas and oil supply systems.

Thus, the digitalization of infrastructural energy systems means a transition to a digital base of technical tools for measuring, collecting, transmitting, processing, presenting information, as well as transferring and implementing control actions, and using intelligent information technologies at all stages from measuring state variables of energy facilities and systems to implementation of control actions. The need for digitalization of infrastructural energy systems is determined by significantly increasing consumer requirements for the reliability of energy supply and the quality of energy resources, due to the digitalization and computerization of consumer production technologies.

The operation control of infrastructural energy systems, which are transformed as a result of innovative development, is fundamentally impossible without effective control systems. These systems are implemented using advanced information and communication technologies and intelligent tools on a digital basis. The physical and control subsystems of energy systems are comparable in complexity and responsibility. Energy systems are becoming complex cyber-physical systems. Objective tendencies of changes in the structure and properties of future energy systems complicate the conditions for their controllability, which is shown in [16] by the example of electric power systems.

The digitalization of infrastructure energy systems is actively developing. There are numerous examples of the successful implementation of intelligent digital technologies in electric, heat and gas supply systems. The advantages of energy digitalization are determined by the following statements:

- significant improvement in the reliability of energy supply and the energy quality and energy services,
- a radical change in the paradigm of relationships between stakeholders in the field of energy supply based on the principles of the Internet of energy,
- implementation of large-scale economic effects for all stakeholders,
- increasing the efficiency of decisions and the work of company personnel.

4 Special aspects of digitalization of integrated energy systems

The introduction of digital technologies into integrated energy systems makes it possible to organize flexible coordinated control of expansion planning of such systems. Conceptually, integration is carried out in the following three aspects [8]:

• a system aspect representing the integration of systems of various types, includes systems of electricity, heat/cool and gas supply, in each case, they can be integrated all or individual types;

• a spatial-scale aspect reflecting the size of systems with differentiation into super-, mini-, microsystems;

• a functional aspect determining the type of activity of the system (its purpose), including: energy (technological); communications and control; making decisions.

Consider the digitalization of integrated energy systems in accordance with the noted aspects. The use of digital technologies ensures the collection, transmission, processing and receiving of information in real time on all constituent components of an integrated energy system in relation to all aspects of integration. Integrated energy systems consist of different types of energy supply systems that are subsystems in the integrated systems. Each of the subsystems contains its own set of elements. These elements can be grouped according to the following performed energy functions: generation, transport, distribution and consumption. In turn, each element has its own set of equipment in accordance with the performed energy functions and belonging to the type of energy supply system. Digitalization is ensured by the introduction of digital technologies for all subsystems, their set of elements and equipment. This corresponds to the digitalization of individual energy systems. At the same time, there are special features of digitalization in the joint consideration of systems of various types within the framework of integrated energy systems. These features are associated with technical and technological solutions for integration, therefore, the digitalization of integrated energy systems can be considered in the following two directions:

• application of digital technologies for individual subsystems for the purpose of their control;

• the use of digital technologies for technical and technological solutions for integration in order to ensure the coordination of subsystems and the implementation of system-wide goals.

The use of digital technologies also enables the integration of systems of various sizes. This corresponds to the spatial-scale aspect of integration (Fig. 1) and is done by aggregating information for individual systems of a smaller scale and presenting it to coordinate larger systems, or vice versa, disaggregating it to coordinate the work of large systems with smaller systems.

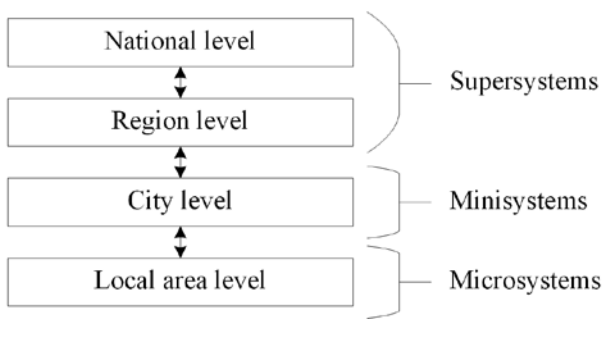

Fig. 1. Energy supply system levels.

The implementation of integration in the functional aspect depends on the completeness, quality and relevance of the information. Such information can only be obtained through the implementation of modern digital technologies. At the same time, cybersecurity problems are aggravated [17, 18].

The complex for digitalization of the IES includes the following components:

• Digital devices.
• Digital models.
• Methodological support of digital modeling.
• Communication technologies.
• Information and intelligent technologies.

Digital devices will provide adaptive control and protection, full monitoring of all elements of the energy supply system, distributed state estimation. Receiving, processing and representing information is carried out on the basis of digital technologies.

Digital modeling involves the development of digital models and the solution of a set of control tasks based on these models using the appropriate methodological support. The IES model is a set of data structures that describe the configuration of the system, the composition of its equipment and its characteristics, the state of the elements and their properties. Energy supply systems of various types, which are part of the IES, have common structural and topological properties and physical laws of energy transport, which allows us to formulate the following general statements for the development of IES models:

• Modeling the IES in the form of a graph, the vertices of which correspond to nodes (sources, connection nodes, consumers), and arcs correspond to branches (pipelines, power lines, etc.).

• Representation of the IES computer model as a set of graph describing the configuration of this system, and a set of graphical and mathematical models describing the properties of its elements.

• The hierarchical construction of the IES model is provided by the formation of individual element and subsystem schemes nested at several levels of the hierarchy.

Methodological support for digital modeling of IES has a commonality of its conceptual and mathematical statements, and the methods, algorithms and specialized software are used to solve tasks can be universal. At the same time, various types of energy supply systems have their own individual characteristics, which must be taken into account in their digital modeling as part of an IES. For example, unlike other large energy systems and large pipeline systems, the operation of the heat supply systems is characterized by two parameters that are different in their physical essence: dynamic changes in flow and temperature are very different from each other. The flow rate in the network substantially changes without inertia. The process of propagation of a temperature wave through a heating network, which is determined by the flow velocity of the heat carrier, can last for hours.

Modeling IESs as new objects of research with corresponding new properties and features, causes, first of all, the problems in:

• Aligning a common goal with multiple systems goals.

• Intersystem distribution and many decision-making centers.
• Development and implementation of an optimal strategy in general and for systems in particular.
• Resolution of intersystem conflicts.
• Coordination of interests of suppliers and consumers.
• Coordination of multiple decision-making centers.
• Conjugation of hierarchical levels in each system and horizontal links between individual systems.

Communication technology. The digital communication networks and data exchange interfaces are provided to ensure information exchange in the IES and its control. One of the most important goals is to ensure a continuous controlled balance between demand and supply of energy resources. For this, the network elements must constantly exchange information with each other about the parameters, the amount of consumed energy and planned energy consumption, and various commercial information.

Information and intelligent technologies. The large size of the IESs and the computational complexity of the models, methods and algorithms do not allow the study of these systems without the use of specialized software. Information and intelligent technologies should ensure the solution of all tasks of expansion planning and operation control of IESs within a unified information space. Fig. 2 shows the architecture of the information and communication platform for IESs research [19], developed at the ESI SB RAS to create a unified information space.

The creation of digital integrated energy systems requires not only the introduction of digital technologies into existing energy supply systems, but also the transition from their rigid existing hierarchical structure "generation - networks - consumers" to a more flexible one, in which each node of the system can be an active element. The new system design should combine a certain independence of many decision-making centers and their coordination to ensure sustainable energy supply to consumers.

5 Conclusion

Creation on the basis of several separately functioning mono-systems (electricity, heat/cool, gas supply and others) of a new energy technology structure in the form of an integrated energy system significantly expands their functional capabilities, ensures the interchangeability of energy carriers and implements a synergistic effect to ensure reliable, safe, economical and environmentally friendly energy supply. The technological transformation of energy systems becomes possible due to the active development of modern digital technologies, telecommunications and information systems and their interpenetration, which allows the formation of flexible intelligent expansion planning and operation control of IESs, the coordination of individual subsystems and the implementation of system-wide

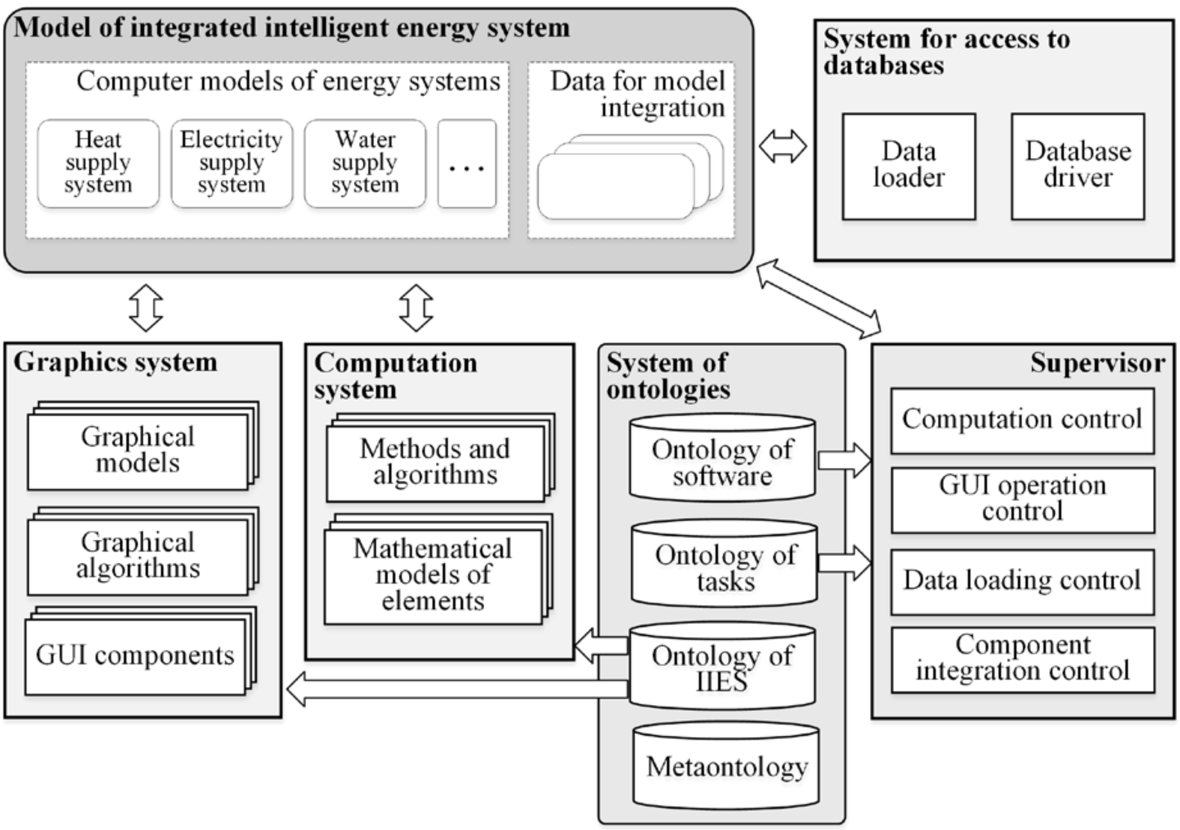

Fig. 2. Architecture of an information and communication platform for integrated energy systems research.

targets. This leads to the emergence of new tasks of control of such systems and the need to develop methods for their solution, to study of properties, trends and features of development.

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Prospects and problems of intellectualization of electric power systems in Mongolia

Bat-Erdene B.[2], *Batmunh* S.[1], *Nikolai* Voropai[3*], *Bat-Undral* B.[1] and *Enhtur* E.[2]

[1]Mongol State University of Sciences and Technologies, Ulan-Bator, Mongolia
[2]Moscow Energy Institute "Research University", Moscow, Russia
[3]Melentiev Energy Systems Institute, Siberian Branch of Russian Academy of Sciences, Irkutsk, Russia

Abstract. Status and prospects of electric power systems (EPSs) development in Mongolia are presented. Directions and peculiarities of EPS intellectualization activity in centralized and local RPSs are suggested.

1 Introduction

Principles and directions for development of the energy sector and electric power systems (EPS) in Mongolia are in the focus of many studies both within the fuel and energy complex of the country (including large-scale development of renewable energy sources), and within the concept of interconnection of stand-alone EPS and construction of Single EPS in the country, as well as considering participation of Mongolia in the inter-state cooperation of Northeast Asia countries on formation of Interstate Power Grid (IPG) [1-5].

Technological infrastructure of present-day EPS in Mongolia is characterized by complexity and includes a large number of stand-alone but interrelated on-line technical elements within the infrastructure systems that produce, transmit and distribute electric power to ensure its reliable supply of required quality to consumers. Requirements of consumers to power supply reliability and to power quality are currently much higher due to digitalization and intellectualization of their production processes.

The paper gives brief characteristic of the state-of-the-art and prospects for development of the energy sector and EPS in Mongolia, analyzes directions and peculiarities of EPS intellectualization with account of their specific features, and discusses problems of large-scale use of intellectual technologies for controlling the operation of future EPS of Mongolia.

2 Status and prospects of EPS development in Mongolia

Energy sector and EPS in Mongolia are currently presented and in the perspective will be presented by two directions:

- Centralized EPS in the zones of centralized power supply;
- Microgrids for power supply of islanded power consumers.

In the group of centralized EPS there are five independent energy systems in operation (Fig. 1) with the corresponding installed capacity, namely [1-5]:

1. Central EPS (CEPS) - 1250 MW;
2. Western EPS (WEPS) - 12 MW;
3. Sothern EES (SEPS) - 77 MW;
4. Altay- Uliastai EPS (AUEPS) - 11 MW;
5. Eastern EPS (EEPS) - 36 MW.

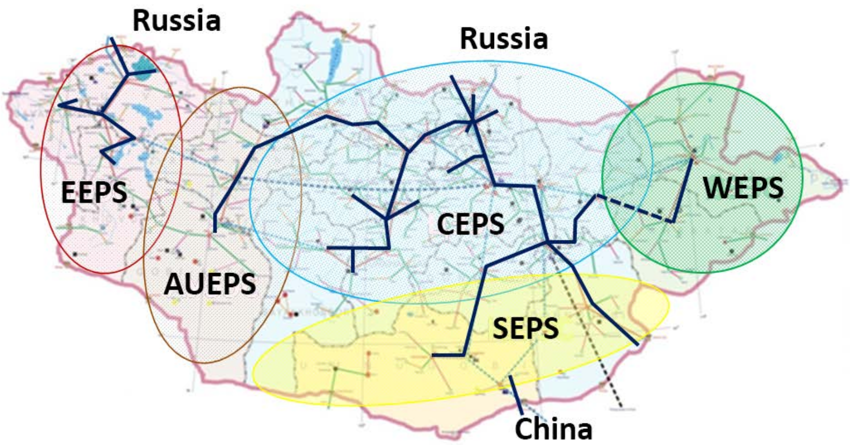

Fig. 1. Geographical position of centralized EPS of Mongolia

*Corresponding author e-mail voropai@isem.irk.ru

Currently, 80% of power consumed in the country is produced by thermal power plants (TPP), and 20% is imported from Russia and China. On the average, 14.4% of power produced is consumed for auxiliary needs; power losses in the electric networks average 13.7%. These indicators are 1.3-1.7 times higher than those for countries with developed networks. The main causes are as follows [1-5]:

- Large extension of transmission lines versus relatively low voltage (e.g., one-circuit 700 km Muren-Telmen 110 kV transmission line);
- Irregularity of daily power consumption (e.g., average annual factor of daily load curve irregularity makes 0.7);
- Obsolete equipment and technologies used by power suppliers and consumers (for example, average period of boilers and turbine generators operation at TPP-4, the largest power plant within CEPS, is 150-200 thousand hrs);
- Irrational allocation (concentration) of generating capacities (68% of capacities are located in Ulan-Bator and in its vicinity).

Centralized power sector in Mongolia in the future should be developed aiming at two interrelated objectives: interconnection of five stand-alone EPS into a Single EPS of the country; integration of Single EPS of Mongolia into the interstate energy grid of Northeast Asia (Fig. 2). Depending on the high or low scenario, development of coal-based generation is proposed at the North-East of the country, construction of large farms of solar and photo-electric power plants is expected in the Gobi desert, and powerful wind mill farms are planned to be constructed predominantly at the East of Mongolia [1-5].

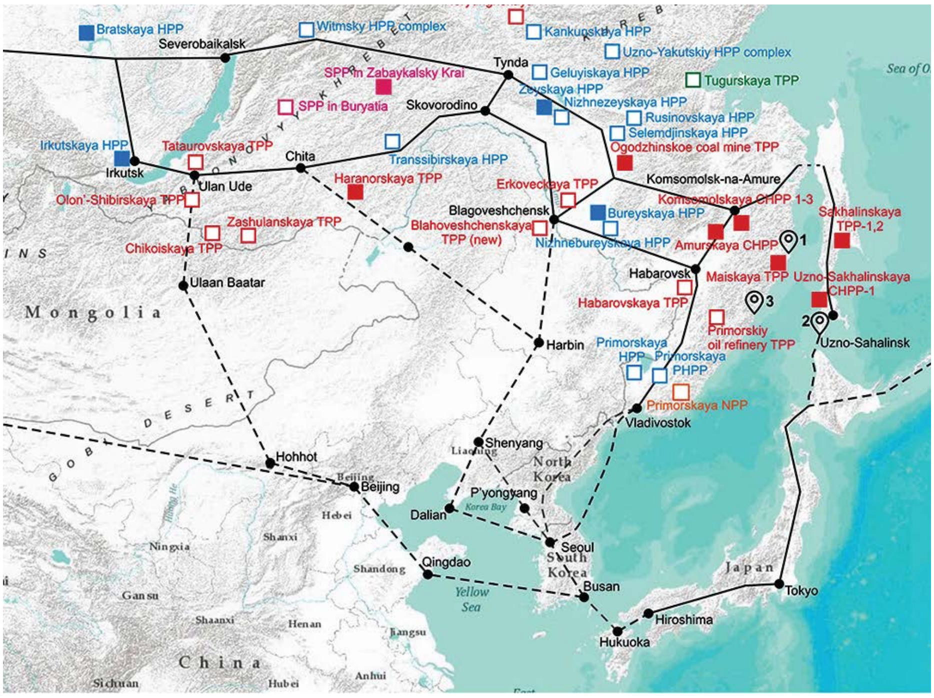

Fig. 2. A chart of and interstate power grid of the Northeast Asia

Small-scale power production has been rapidly developing in Mongolia in recent years. There are in operation 13 mini and micro HPP with the total installed capacity of 28.1MW, 17 mini and micro solar power plants (51.6 MW), three (3) mini wind mills (155 MW), seven (7) hybrid microgrids (photo panels and wind mills with or without power storage, 1.275 MW) [8].

Of special interest is a unique Roadmap “100 000 solar photo panels” for creation of DC microgrids for power supply of islanded consumers, whose implementation was financed by the World Bank and governments of Japan and China. The Roadmap realization was started in 2000 and accomplished 12 years after. Owing to implementation of the Roadmap, power was supplied to 70% of livestock farmers or to about 500 000 rural people busy with seasonal grassland farming. Total capacity of photo panels makes 3-4 kW per yurt (a nomads tent). There are also backup photo panels and power storage devices.

Standard mix of electric devices of a yurt of an islanded power consumer at present includes the following: lighting, an electric stove, a refrigerator, an electric heater and a digital TV. Some other electric appliances may surely appear in the nearest future, such as computers, micro ovens, automatic washing machines, and others. Judging from the experience of other countries, a total number of electric appliances in a yurt in the future may exceed 10 names [10, 11].

Considerable transformation of structure and functionality of the considered microgrids will take place in the conditions of large-scale use of electro mobiles. In addition, detailed study of benefits and drawbacks of joint use of microgrids (a system of microgrids) by several yurts on the relational or contractual base may be of interest.

It is obvious that independent operation of the considered microgrids for islanded consumers distant from centralized power supply will be continued in the future.

3 Directions and peculiarities of EPS intellectualization in Mongolia

Taking into account present-day international tendencies, Energy Ministry of Mongolia declared the year 2019 to be a “Year of Intelligent Energy Sector” and proposed a developed state-financed Roadmap of “Intelligent Energy System” whose introduction would improve stability and raise efficiency of Mongolian EPS, and energy security of the country.

Implementation of this Roadmap requires performance of works in three directions:

1) Ensurance of reliable and sustainable operation of EPS in different conditions;
2) Higher economic efficiency of energy sector of the country;
3) Introduction of intelligent systems in the distribution networks and at the level of power consumers.

Analysis of works proposed in the Roadmap within three directions allows the following comments to be given:

a) Creation of Intelligent Energy System (IES) is the systems transformation of energy industry that, judging from experience of other countries [12–14], requires development of conceptual provisions and identification of priorities of IES creation. Meanwhile, according to the Roadmap, development of documentation for construction of IES infrastructure (standards, regulatory documents, etc.) is considered to be a base for EPS intellectualization in Mongolia. Despite the value of standardization documentation, it should be stressed that it shall be developed with view of IES creation concept [7].

b) Large-scale use of wind and solar units in the future would dramatically change the performances of EPS of Mongolia. Those changes would worsen the system controllability in normal conditions since, first, 80% of power is generated by coal-fired thermal power plants (TPP) operating as per the heating cycle; second, due to random fluctuations in power production by wind mills that are caused by variable wind velocity); it will also raise the problems of EPS stability in emergencies [15].

c) The Roadmap proposed does not give due considerations to peculiarities and problems of intellectualization of microgrids for islanded consumers. Despite relatively small scale of this direction, it is of high social value. Moreover, as it was mentioned above, the implemented national Roadmap “100 000 solar photo panels” did not solve all the problems of power supply for islanded consumers.

d) Implementation of the EPS intellectualization program in Mongolia requires training the specialists of new generation, as is noted, for example, in Ref. [16]. This important problem was not given consideration in the Roadmap.

Therefore, it is necessary to develop the concept of forming the intellectual EPS of Mongolia that shall be based on the systems consideration of the existing problems of power industry of the country and directions of its innovative development using intelligent technologies of power production, transmission, distribution and consumption within the fuel and energy complex and with view of integration of EPS of Mongolia into the interstate grid of the Northeast Asia.

Transition to IES is a complex engineering, economic, scientific and organizational problem that implies updating of all the fleet of power (generating, network and consumption) equipment on the innovative base and change over to a new generation of process control and market control systems at all the levels of management and control. With view of the changes in the methods and tools for EPS operation and control, the studies should include three main stages:

- Perfection of automatic control that would ensure faster response of automatic devices and control systems both in emergencies and in normal, transition and operating conditions by using a large specter of emergency control devices, such as stability control schemes, frequency and voltage control devices, etc.
- Better availability of information that would ensure a new level of the EPS conditions observability and monitoring, controllability of operating modes of separate elements and of the system as a whole owing to wider use of digital vector measurements of state variables.
- Introduction of intelligent technologies at all the levels of EPS operation control systems that would ensure both the ‘on-line response’ and ‘forecast response’ based on the assessment of probable variations in the parameters of modes of individual devices, systems, and consumers.

Thus, transition to energy of new type shall harmonize all the directions of EPS modernization by expanding the boundaries of an ordinary production process beyond conventional extensive scenario of energy sector development that is characterized by simple quantitative increase of production potential and its saturation with new innovative technologies. It is obvious that intellectualization of microgrids of islanded consumers is of higher availability for implementation than centralized EPS owing to availability of new equipment and lesser complexity and scales of microgrids themselves.

Transition to IES actually implies implementation of an intensive scenario of the energy sector development to be accompanied by functionality change, i.e., transformation of the existing and emergence of new properties in the separate structural segments and in EPS as a whole.

4 Conclusions

The problem of IES creation requires preliminary systems studies of the existing structures and characteristics of EPS of the country that would form a methodological base for development of scientifically grounded concept of transition to a self-actualizing, self correcting system with complex control functions at all the hierarchical levels both for EPS of Mongolia and for power grids for islanded consumers.

To make the future IES of the country meet those requirements, a set of problems need to be solved to rationalize the system structure and update the control systems on the base of digital devices using intellectual technologies. An intellectual Single EPS of Mongolia for its integration into an interstate super grid, i.e., trans-national IEPG of the Northeast Asia, shall be ready to meet additional requirements.

Intellectualization of microgrids of islanded consumers, despite their incomparability with the Centralized EPS of Mongolia in terms of capacity, is of high social importance as microgrids play more and more important role in the total power supply in the specific conditions of the country, and it shall achieve a worthy position in that innovative process.

Creation of IES on the whole shall become a key mechanism in achieving the objectives of the Energy Strategy of Mongolia on transformation of fuel and energy sectors. An intellectual Single EPS of the country shall be converted into high-tech and efficient infrastructure ensuring both quantitative and qualitative economic growth of the country.

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DEVELOPMENT OF ENERGY SYSTEMS PLANNING METHODS

Nikolay Belyaev[1,*], *Andrey* Egorov[1], *Nikolay* Korovkin[2] and *Vladimir* Chudny[2]

[1] JSC «Technical Inspection UES», Russia
[2] Peter the Great St.Petersburg Polytechnic University, Russia

Abstract. The article is devoted to improving the methods of planning the development of an electric power system (hereinafter - EPS) for the long term. The list of tasks to be solved when planning the development of EPS, the formulation of the task of substantiating the development of EPS, and the features of its solution are considered. Within the framework of the study of the multicriteria formulation of the problem of substantiating the development of EPS, possible criteria for planning an EPS are proposed. Calculations were performed for two and four criteria. Based on the results obtained, conclusions were drawn about the prospects of a multicriteria approach to planning the development of EPS.

Introduction

Current conditions of electric power development in the world feature increasingly stringent requirements for EPS safety and quality of power supply to consumers, which is due, on the one hand, to economically reasonable trends dealing with deepening electrification of the economy and households (including the introduction of modern production technologies and digitalization of technological processes), on the other hand, to the growth of social and economic importance of reliable electric power supply, especially in big and metropolitan cities. In this case, strong restrictions are imposed on the development of energy engineering in respect of price and tariff consequences of adopted investment decisions that are also due to socio-economic factors expressed in restraining the increase of electricity and demand capacity prices.

Along with these trends, the development of the electric power industry is characterized by the active introduction of new technologies, such as flexible AC transmission systems (FACTS), high-capacity energy storage, and demand Response management, allow for enhancing significantly the EPS efficiency, while reducing capital and operating costs.

Under such conditions arises the problem of increasing the efficiency of power system planning for the purposes of cost minimization so as to ensure the growing energy demand while meeting eligible technical, environmental and economic requirements with account made for the implementation of mentioned advanced technologies. Given the fact that modern EPS are large power units that may include tens of thousands of units of generating equipment, power transmission lines and substations, the task of EPS planning is generally reduced to a multi-criteria optimization problem to be solved on a discrete set of higher dimensions. The solution of such problems is only possible with modern capabilities of computer technology, but still requires the development of special methods.

1 The modern practice of energy system planning

To date, the main methodological provisions for planning the development of EPS have been thoroughly worked out and set out in both domestic and foreign publications. In general, these methodological provisions were developed and generalized during the period of the centralized development of EPS [1,2] and received additional development in connection with the reform and decentralization of management in the electric power industry in recent decades [3,4]. The indicated methodological provisions were used in the development of normative and technical documents governing the planning and design of EPS development, as well as specialized software and computer systems. The structure of tasks to be solved in planning the development of EPS can be summarized in the form of several stages:

1. Forecasting the development of technologies for the production, transmission, accumulation, and distribution of electrical energy.
2. Forecasting the demand for electricity and capacity.
3. Substantiation of the rational structure of generating capacities.
4. Justification of the location and composition of generating capacities.
5. Justification for the development of the main (backbone) electrical network.
6. Assessment of the economic and environmental consequences of the development of the electric power industry.

* Corresponding author: Belyaev.NA@yandex.ru

Stages 1 and 2 relate to forecasting the external conditions of EPS functioning for the future. Stages 3 - 6 relate directly to the justification of the development of EPS and are carried out sequentially, while at each stage of planning, the decisions obtained in the previous stages are refined.

The standard problem statement of the growth substantiation EPS reduces to a cost-minimizing procedure in relation to total reduced costs 3 connected with the electric power supply to consumers [2]:

$$C(\mathbf{x}) = \sum_t (C_t^{\mathrm{K}}(\mathbf{x}) + C_t^{\mathrm{O}}(\mathbf{x})) \cdot (1+d)^{-t} \xrightarrow[\mathbf{x}]{} \min, \quad \mathbf{x} \in R, \tag{1}$$

where C_t^{K}, C_t^{O} – capital and operational costs per year t respectively, d – discount rate.

Variables $\mathbf{x}$ in problem (1) are the actions taken for the development of systems for the production, transmission, and distribution of electrical energy, which determine the amount and structure of costs. These activities include:

- modernization of existing generating capacities, including actions to extend their resource;
- construction of new generating units (power units) at existing or new power plants of various types;
- buildup of electric energy storage units, including pumped storage power plants;
- buildup of new power lines;
- increasing the transformer capacity of substations;
- actions to increase the transmission capacity of the electrical network, including the use of reactive power compensation means or FACTS devices, and others.

Each action is characterized by technical and economic indicators, including the amount of capital and operating costs.

The area of limitations R is determined by the requirements for the reliability and safety of EPS that affect the choice of individual technical solutions or their combinations. These requirements include both technological restrictions on the operation modes of the EPS equipment and restrictions on the operation of the EPS as a whole. The first group of restrictions includes restrictions on a load of generating equipment - these are available capacity, technological minimum, integral restrictions on electricity generation, as well as power grid equipment - these are permissible current loading and voltage levels, maximum power fluxes under stability conditions. The second group includes the required level of EPS reliability, the permissible impact of electric power facilities on the environment, the available investment, and others.

Statement (1) contains the principle of minimizing the costs of power supply to the economy and households while observing the mandatory requirements for the operation of EPS. Taking into account the discreteness of measures for the development of EPS, for modern large EPSs, the solution of problem (1) is very laborious and comes down to finding the global optimum on a representative discrete set. In this regard, in practice, when solving (1), a number of assumptions are used, including the decomposition of the problem (1) into the above stages and the use of a simplified (aggregated) representation of the EPS structure at the initial stages of the solution. This makes it possible to reduce the dimension of the problems solved at each stage and to use standard optimization methods, including linear programming methods, to solve them. This, however, requires refinement of the obtained solution at subsequent stages, including compliance with the specified constraints and, in general, reduces the accuracy of the solution (1).

In addition to the computational complexity, the problem of substantiating the development of EPS in the formulation (1) is accompanied by two methodological problems. The first problem concerns the tasks of planning the development of EPS and lies in the uncertainty of a number of initial data, including external conditions for the functioning of EPS. These are the demand for electricity and capacity, fuel prices, etc. Also, the technical and economic indicators of certain measures for the development of EPS are poorly defined. These are cost indicators, reliability indicators, etc. Uncertainty of the initial data, especially in the long-term planning of EPS, led to the introduction of probabilistic methods for planning the development of EPS, widely presented in [5].

The second problem, for the statement (1), is the complexity of describing the region of limitations R. The limitations of the first group, associated with the operating modes of the EPS equipment, are determined, as a rule, unambiguously. However, the restrictions of the second group, imposed on the functioning of the EPS as a whole, in some cases are difficult to set with fixed values of the corresponding indicators. Such limitations, for example, include the required level of EPS reliability. Theoretically, the required level of EPS reliability is determined by a separate feasibility study, taking into account the costs of ensuring reliability (redundancy) and compensation for damage from unreliability (interruptions in power supply and shortage of electricity). In practice, such an approach is unrealizable due to the variety of EPS consumers and the lack of unambiguous estimates of the specified damage. Similarly, it is difficult to unambiguously determine the restrictions on the impact of EPS on the environment, since such restrictions are set for the industry as a whole, and not only for electric power facilities. In this regard, some of the constraints that form the domain R in problem (1), it is advisable to transfer into additional functionals. Thus, problem (1) is transformed into a multicriteria problem. The main approaches to solving multicriteria problems of substantiating the development of EPS are considered in [4].

2 Development of energy system planning methods

Taking into account the increasing requirements for the functioning of power systems and the complexity of the unambiguous definition of a number of restrictions, which as noted above, it seems promising for the development of the theory of planning EPS is the transition to multi-criteria formulations of the problem of substantiating the development of EPS. The following can be taken as possible criteria for justifying the development of EPS:

- criteria for the reliability of the EPS functioning, including the functions of the expected shortage of electrical energy and power;
- criteria for the economic efficiency of EPS, including criteria for the social efficiency of the development of the electric power industry and the commercial efficiency of individual projects in it;
- criteria for the reliability and quality of power supply to consumers, including the functions of the expected frequency and duration of power supply interruptions;
- criteria for the impact of EPS facilities on the environment, including emissions of pollutants by power plants operating on fossil fuel;
- criteria for energy security, including criteria reflecting the diversification of the fuel and energy balance and redundancy of critical EPS facilities;

other criteria reflecting the efficiency of EPS.

Modern methods of multicriteria optimization, including those applied to solving problems in the electric power industry, are known [6]. From a formal point of view, in multicriteria optimization, it is of interest to rank the set of Pareto optimal solutions obtained from the optimization results and to select specific solutions for their subsequent implementation. Currently, the approaches used for this [4] are, in one way or another, based on expert assessments, with the use of which, for example, ranking criteria by significance or assigning weight coefficients to them is performed.

The second promising direction in the theory of EPS planning is the use of modern evolutionary optimization algorithms, for example, the genetic algorithm, ABC, or BAT algorithms, which are widely used to solve discrete global optimization problems, including in related industries [7,8]. These algorithms use directed enumeration and thus are well combined with probabilistic methods for planning the development of EPS, which currently use random enumeration (methods of the Monte Carlo type). It is expected that the use of these algorithms will significantly increase the efficiency of justifying the development of an EPS, including allowing one to abandon the assumptions made in solving (1).

Next, we will consider the results of solving several multicriteria optimization problems obtained using a genetic algorithm when planning the development of an EPS.

For EPS with a maximum electrical load of 13 GW, the structure of generating capacities was optimized according to two criteria:

$$C(\mathbf{x}) \xrightarrow[\mathbf{x}]{} \min,$$
$$J_D(\mathbf{x}) \xrightarrow[\mathbf{x}]{} \min, \qquad (2)$$
$$\mathbf{x} \in R.$$

where C is the total reduced costs for the construction and operation of generating capacities, J_D is the probability of a power shortage in the EPS [9], R is the area of limitations reflecting the permissible operating modes of the generating equipment.

When optimizing, various types of generating equipment were considered, including nuclear and hydroelectric power plants, units of thermal power plants of various types and unit capacity. Technical and economic indicators and indicators of the reliability of generating equipment are taken according to reference data. The results of the solution (2) are presented in Fig. 1.

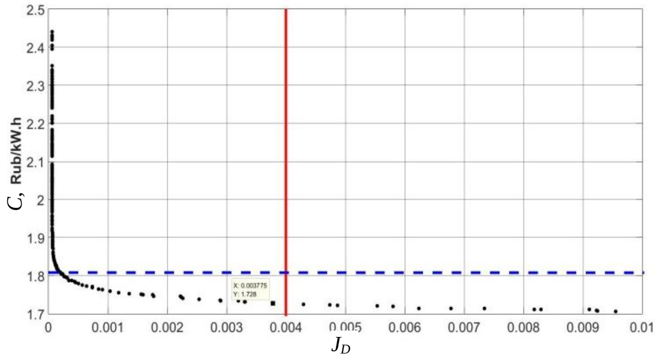

Fig. 1. Results of optimization of the structure of generating capacities according to two criteria.

On Fig. 1 the values of target functions (2) are plotted on axes: on horizontal line – probability of capacity shortage, on vertical line – working cost of electric energy compatible with accumulated total costs. Points mark the results. The total number of obtained solutions is equal to 375 [10].

During Soviet time the regulated value of CAI has been justified and until now it is applied at the level of 0,996, that is in line with J_D = 0,004. Thus, when using this rate one should choose the solution marked on Fig. 1, in this case the electricity cost will make 1,73 Rub./kWh. However this option does not seem to be optimal if other solutions are examined. For example, an insignificant price increase within 1 cop./kWh allows reducing J_D to the level of 0,00226. Moreover, it should be noted that from cause-and-effect view under circumstances when the operating conditions of EPS through the long run are uncertain, the parameter setting error for technologies applied in problem as source data, cost parameters, first of all, may reach up to 5 per cent and more that significantly affects the accuracy of cost assessment. In this case the price increase by 5 per cent as compared to the solution marked on Fig. 1 (up to 1,81 Rub./kWh, shown by horizontal dot lines) allows reducing J_D up to 0,00016, i.e. more than by an order of magnitude.

Further reduction of J_D may appear to be cost-ineffective as costs progress at a far quicker rate and an insignificant reduction of J_D results in price hikes. At a price of 1,97 Rub./kW·h the limit value of $J_D \sim 6,3\cdot10^{-5}$, is reached, in practice it is insensitive to price increase.

The range of installed capacity variation upon got solutions was within 14,95 GW – 22,15 GW that is in line with the margin capacity value from 16,2% to 72,1% of EPS maximum load. For the solution marked on Fig. 1 which is in conformity with regulated CAI, the capacity margin was 19,7%. For the solution with the price of 1,81 Rub./kW and J_D = 0,00016 the capacity margin is equal to 29,8%.

In Fig. 2 shows the results of optimization of the structure of generating capacities of EPS with the same initial conditions according to four criteria:

$$\begin{aligned} & C(\mathbf{x}) \xrightarrow[\mathbf{x}]{} \min, \\ & J_D(\mathbf{x}) \xrightarrow[\mathbf{x}]{} \min, \\ & W_F(\mathbf{x}) \xrightarrow[\mathbf{x}]{} \min, \\ & P_{MAX}(\mathbf{x}) \xrightarrow[\mathbf{x}]{} \min, \\ & \mathbf{x} \in R. \end{aligned} \quad (3)$$

where W_F is the share of electricity generated at thermal power plants, P_{MAX} is the maximum share of the type of generating capacity in the structure of installed capacity.

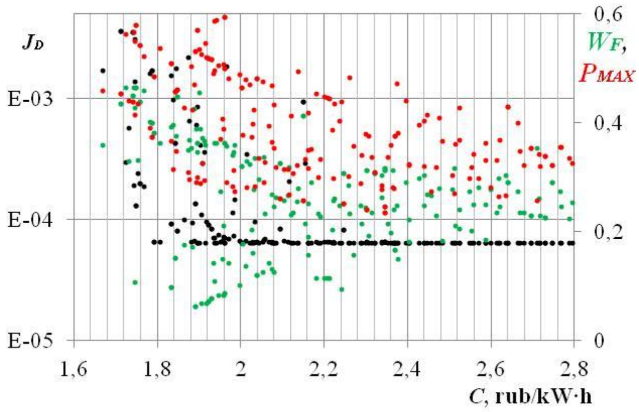

Fig. 2. Results of optimization of the structure of generating capacities according to four criteria.

On Fig. 2, along the abscissa axis is shown the cost value, the ordinate axis is shown the probability of a power shortage (black marker), and the additional ordinate axis are shown the W_F and P_{MAX} values (green and red markers, respectively).

From the presented results, it can be seen that the minimum level of the probability of a power shortage is achieved at a cost of 2 Rubles / kWh. This corresponds to the obtained solution (2). At the same time, decisions with a cost level within 2 Rubles / kWh are characterized by a conflict of two other criteria. The so-called “green” solutions (with a W_F value of less than 0.2) have high P_{MAX} values, namely, a high share of nuclear power plants in the structure of generating capacities. On the contrary, solutions with relatively low P_{MAX} values are characterized by high W_F values (at the level of 0.3 - 0.5). To obtain a more favorable combination of the values of these criteria, it is necessary to consider solutions with a higher level of costs, which provide for the construction of hydroelectric and power plants on renewable sources. This means that if the last two criteria are set in problem (3) as constraints, depending on the choice of their values, solutions in the low-cost area can be cut off and excluded from consideration.

Conclusion

The growing requirements for the technological and economic efficiency of EPS, the technological development of the electric power industry requires an increase in the accuracy and efficiency of planning and justification of EPS development. Taking into account the general formulation of the problem of justifying the development of EPS, a promising method for its solution is the use of multicriteria optimization using modern evolutionary algorithms.

As the calculations show, the translation of a number of restrictions into criteria expands the search area for solutions for development EPS. This makes it possible not only to take into account the regulatory requirements for the values of certain criteria but also to choose the optimal combination of the considered criteria, taking into account the structure of a specific EPS and possible measures for its development.

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Development of Mechanisms for Active-Adaptive Control of Reactive Power Based on Intelligent Electrical Networks

Roman Belyaevsky[1,*], *Alexey* Gerasimenko[2]

[1]T.F. Gorbachev Kuzbass State Technical University, 650000, 28 Vesennyaya St., Kemerovo, Russia
[2]Siberian Federal University, 660041, 79 Svobodny Av., Krasnoyarsk, Russia

Abstract. Improving the energy efficiency of the power grid complex is an urgent problem. The need to solve this problem is due to various technical and economic reasons. First of all, this is due to high power losses in distribution electrical networks, caused by a significant load of its elements by reactive power flows. In this regard, the development of mechanisms for active-adaptive control of reactive power is becoming increasingly important. Currently, the Smart Grid concept has become widespread in the global electric power industry. The use of these technologies allows not only to optimize power losses in distribution networks, but also to improve the efficiency of the electric grid complex. The article proposes an algorithm for optimizing the placement of compensating devices in the distribution network on the example of one of the territorial network organizations of the Kuzbass. This algorithm is based on the theory of multilevel systems using the method of indefinite Lagrange multipliers. The results of applying this algorithm based on the developed simulation model are presented.

1 Introduction

Currently, there are over 3,000 power grid companies operating in the power grid complex of the Russia. At the same time, a significant part of these companies is characterized by relatively low energy efficiency indicators. This is due to significant power losses in distribution networks, as well as high depreciation of power grid equipment.

In the general case, technological power losses s consist of: technical losses due to physical processes occurring during transmission of power through the network elements, power consumption for the auxiliary needs of substations, as well as losses due to permissible errors of the power metering system.

Analysis of the structure of technological power losses shows that they are largely determined by the excess reactive power transmitted through the network [1]. It follows from the diagram (Fig. 1) that the share of losses due to the transfer of reactive power accounts for 47%. These include no-load losses of transformers and load losses from the flow of reactive power through the network elements. Technological power losses due to active power transmission account for 31% and include other conditionally constant losses, as well as load losses from active power flow. Another 22% falls on the share of losses caused by permissible errors of the accounting system.

The presence of excessive reactive loads in networks leads not only to an increase in losses, but also causes a decrease in the throughput of distribution networks, and also negatively affects the voltage mode.

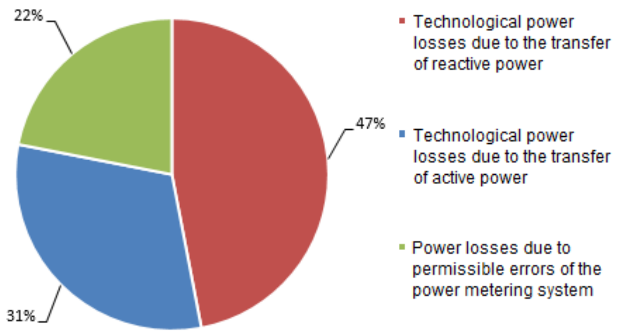

Fig. 1. Generalized structure of technological power losses in distribution networks of power grid companies

In Fig. 2 shows the dynamics of power losses changes in the distribution networks of power grid companies [2]. It shows that for the period 2015–2019, losses increased from 104.9 to 107 billion kWh. At the same time, there is a tendency for a further increase in power losses.

The depreciation of power grid equipment also has a significant impact on the energy efficiency of distribution networks. To date, the share of distribution networks that have reached their standard term is 50%. At the same time, 8% of power grids have worked out two standard terms. The total wear of distribution networks is 70% [3]. In addition, there is an irrational configuration of distribution networks.

Thus, an urgent problem is to reduce the reactive power transmitted through the distribution networks of power grid companies. The need to solve this problem is due to various technical and economic reasons.

* Corresponding author: brv.egpp@kuzstu.ru

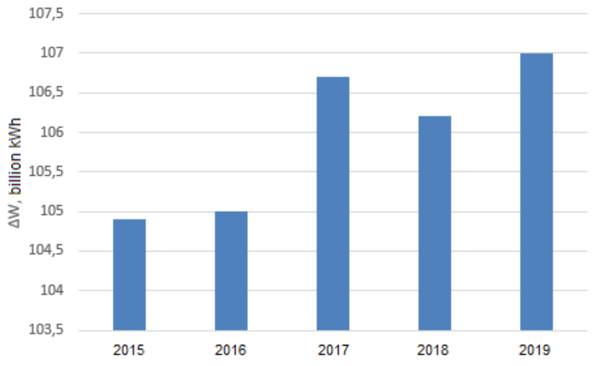

Fig. 2. Dynamics of power losses changes in the distribution networks of power grid companies

2 Study Objects and Methods

There are different approaches to improving the power efficiency of distribution networks. The most algorithmically developed and software-tested approach is the reduced gradient apparatus [4, 5] with stochastic consideration of the variety of modes [6].

At the present stage of development, an important role is assigned to the active-adaptive control of the of technological processes parameters.

The development of mechanisms for active-adaptive control of reactive power is becoming increasingly important. These mechanisms should be based on the regulation of reactive power when changing voltage, load, structure and other parameters of the network.

This is also in line with the general policy of the Russian Federation's transition to the digital economy. The essence of digital energy as a part of the digital economy, in addition to technological equipment, is the formation of new mechanisms of economic interaction. This gives its subjects an increased potential for efficiency gains. The greatest effect of digitalization can be achieved when the scale and nature of such interaction changes qualitatively.

An active-adaptive network assumes the development of elements aimed at improving the efficiency of control over the generation, transmission and distribution of electricity and interaction with consumers.

At present, the concept (technology) of intelligent electrical networks (Smart Grid) has become widespread in the world power industry [7]. In the Energy Strategy of the Russian Federation for the period up to 2035, intelligent electrical networks are defined as “key areas and technologies that should ensure the effective economic and social development of Russia” [8].

Despite the fact that research in the field of smart electrical grids has been conducted since the 1970s, in world practice, a unified approach to their definition and principles of construction has not yet been formulated. The most complete definition of this approach is formulated by the IEEE as the concept of a “fully integrated, self-regulating and self-healing electric power system, having a network topology and including all generating sources, transmission and distribution networks and all types of power consumers controlled by a single network of information control devices and systems in real time " [9].

An active-adaptive network is built using advanced intelligent systems for monitoring and controlling the main parameters in real time, as well as using the multi-agent principle of organizing the control system. These solutions are based on next-generation ICT and power electronics.

The Russian power grid complex is characterized by high moral and physical depreciation of equipment. Therefore, the introduction of smart power grid technologies, obviously, should be carried out in parallel with the comprehensive technical re-equipment of the power grid complex.

At the same time, today there are the following scientific and technical prerequisites for the development and implementation of this concept in Russia: the use of emergency control systems; the presence of automated control of the operation modes of the united power systems; the use of intelligent technologies elements in power grids (devices for regulating reactive power, voltage), etc. [9].

The following main factors stimulating the introduction of smart grid technologies can be identified:

− demand response and reduction of power losses;

− monitoring and regulation of power consumption and power distribution modes;

− increasing the capacity of power grid facilities;

− adaptive control of the power system and its elements;

− reduction of the land allocated for power grid facilities [10].

Distribution networks built using Smart Grid technologies are a multi-level system. It includes measuring systems, automation equipment, and voltage and load control devices. Based on the measurement results, both short-term and long-term power consumption forecasts can be built. Also, active-adaptive control of modes can be realized by regulating the voltage and load in the network nodes, carrying out switching operations, introducing additional sources of reactive power, etc.

Each distribution network is characterized by its own optimization efficiency in accordance with predetermined criteria, which is the difference between their values at the optimal reactive power compensation mode and the initial state of the network. Therefore, the choice of compensating devices for controlling reactive power is an optimization problem. Its purpose is to determine the best location, capacity and load of compensating devices and the organization of such control of their mode of operation, which provides the maximum economic effect, subject to all technical conditions for the normal operation of power grids [11].

The choice of levels (models) with which the system is described depends on the objectives of the study. The hierarchical approach consists in a certain set of subtasks that should be solved iteratively. The solution to each of them determines some parameters in the subsequent problem, making it more definite. The concept of organizational hierarchy implies that the system consists of a set of strictly defined interacting subsystems, which are decision-making elements. In this case, the subsystems are arranged hierarchically, that is, some of them are under the control of other subsystems.

The existing methods for optimizing the placement of compensating devices differ in the initial formulation of the problem and its subsequent implementation, but they are united by the fact that they refer to direct methods of solution based on iterative processes of calculating and comparing the values of the optimized functions. In this case, the original problem is, as a rule, an unconstrained optimization problem.

At the same time, this optimization problem should be considered as a conditional optimization problem, formed in the form of a classical mathematical programming problem [5, 12, 13]. They define the relative extremum of the objective function, that is, the extremum of the objective function in the presence of connecting constraints on its variables, which allows obtaining solutions that best meet the conditions of the real problem.

It is obvious that solving problems of conditional optimization is much more difficult than solving problems of unconstrained optimization. Therefore, it is natural to strive to reduce the problem of conditional optimization (search for a relative extremum) to a simpler problem of unconditional optimization (search for an absolute extremum) [14]. One of the most general approaches in which this procedure is implemented is the method of indefinite Lagrange multipliers. This method belongs to indirect methods of solution and is widely used to solve nonlinear optimization problems [15]. The method of indefinite Lagrange multipliers is used to solve problems of the same complexity class as when using direct methods of solving, but with restrictions on independent variables. In addition to the requirement of the possibility of obtaining analytical expressions for derivatives of the optimization criterion, a similar requirement is added regarding the analytical form of the equations of constraints [16].

The analysis shows [1] that among the considered optimization methods, the method of indefinite Lagrange multipliers most closely meets the requirements of accuracy, completeness and ease of implementation for solving the problem. A certain complication in this case arises only from the introduction of additional variables, as a result of which the order of the system of equations solved to find the extrema of the optimization criterion increases by the number of restrictions. Otherwise, the procedure for finding solutions and testing them for optimality fully corresponds to the procedure for solving problems without restrictions.

In this case, a multilevel hierarchical decision-making system will include:

− determination of Lagrange multipliers according to the main optimization criteria and search for an optimal solution;

− taking into account factors that are difficult to formalize (determining the optimal dimension of the system);

− taking into account the uncertainty of the initial data (interval estimates);

− multivariate development of distribution networks (planning methods).

3 Results and Discussion

As a result of the research, an algorithm was developed to optimize the placement of compensating devices in the distribution network on the example of one of the territorial grid organizations of Kuzbass, based on the theory of multilevel systems using the method of indefinite Lagrange multipliers [1].

In this algorithm, the process of reactive power flow control is implemented on the basis of a set of complex and mutually influencing subsystems. The presented algorithm allows to achieve the optimal value of reactive power in distribution networks and provides a significant reduction in power losses. In addition, using this algorithm, it is possible to implement reactive power control based on compensating devices, taking into account the load of installed transformers. This allows to optimize the operating mode of distribution networks of power grid companies.

The algorithm assumes an input assessment of the actual reactive power factor tgφ in the distribution network in relation to the economically justified normalized value equal to 0.4.

If tgφ $\leq$ 0.4, then the distribution of reactive power in the electrical network is optimal, or close to optimal. If tgφ $>$ 0.4, then this indicates an increased consumption of reactive power. And, hence, about increased losses of electricity. Then it is necessary to take measures to reduce the reactive power in the electrical network.

First of all, it is necessary to assess the load factor of power transformers β installed in the distribution network of the territorial grid organization, and determine the feasibility of replacing them. If $\beta \leq 0.2$, then low-loaded power transformers should be replaced and other organizational measures to compensate for reactive power with the obligatory determination of the economic effect from their implementation. After carrying out these measures, a re-assessment of the load factor of transformers in the electrical network should be performed.

If, after normalization of β, the reactive power factor tgφ exceeds the normalized value, then it is necessary to proceed to technical measures to compensate for reactive power with the optimization of the placement of compensating devices in the distribution network based on the method of indefinite Lagrange multipliers. The characteristic modes of operation of the electrical network should be selected, the objective function should be formulated, the optimization criteria and the corresponding restrictions should be determined. For these conditions, the Lagrange function must be compiled, and then its partial derivatives are determined and equated to zero. The solution of the obtained system of equations gives the optimal solution for the placement of compensating devices in the distribution network based on the criterion of minimum active power losses:

$$\Delta P = \sum_{i=1}^{n} \left(Q_i - Q_{\kappa i}\right)^2 R_i \Big/ U^2 \to \min, \qquad (1)$$

where Q_i – reactive load of the *i*-consumer, kvar; n – the number of consumers; $Q_{\kappa i}$ - power of the *i*-compensating device, kvar; R_i – active resistance of the *i*-element of the network, Ohm; U – mains voltage, kV.

If the obtained value deviates from the optimal one, the objective function and task constraints must be refined, then the optimization process is repeated until condition (1) is satisfied.

When this condition is met, a control comparison of the actual tgφ value with the normalized value must be made. If tgφ ≤ 0.4, then the reactive powers are optimally distributed, and the results of optimizing the placement of compensating devices and controlling reactive power in the distribution network are achieved. If tgφ exceeds the normalized value, the algorithm must be repeated until the reactive power factor is within the range of tgφ ≤ 0.4.

The constant development of electrical networks makes the decision-making process for the selection and placement of compensating devices multi-stage, continuous in conditions of constant updating of information, which is characteristic of open systems. At each stage one should not limit oneself to a single inflexible solution, but one should focus on a certain set of solutions that are close to optimal according to the adopted criteria. It should be such a decision-making system that would adapt the selection and placement of compensating devices in relation to the changing conditions of the development of the electrical network with minimal costs..

In this respect, adaptive reactive power control is important. It is a process of changing the value of reactive power flowing through the network, with a change in its load, composition and configuration.

The solution of the considered optimization problem should begin at the design stage of electrical networks. It is a solution to the dynamic problem of short-term and medium-term development planning, when calculations of flow distribution in perspective development schemes are made. In this case, the choice of places and capacity of compensating devices is performed without restrictions on their total capacity. At this stage, the problem of optimization criteria for each specific network should be resolved. It depends primarily on the voltage levels in the network nodes in normal operating modes. The next stage of the problem of optimal compensation of reactive loads is the operational stage as a solution to the static problem of optimal network functioning.

The choice of capacity and location of compensating devices is made taking into account the restrictions, based on the given total reactive power available from these networks. The solution of both problems can be carried out in parallel and does not exclude one another. This assumes the application of the principles of the adaptive approach (sliding planning) [17] and the direct implementation of adaptive control mechanisms [18]. Thus, the definition of the rules for regulating reactive power is assumed taking into account the entire set of modes [5, 6] according to the adopted optimization criteria in accordance with the needs of the power grid complex.

According to the principles of adaptive reactive power control in distribution networks of power grid companies, smart grid technologies are of considerable interest. In this case, the proposed algorithm can be represented as a hardware and software complex, which includes several basic subsystems, such as: intelligent information and measuring systems (Smart Metering), Dynamic Grid Management and Load Regulation (Demand Response). Intelligent information and measurement systems allow technical metering of power consumption in real time and with high accuracy. Based on information about the actual operating mode of the network, it is possible to predict the active and reactive load, as well as to carry out operational control of the electrical network modes by automatic load regulation, control of compensating devices, etc. To reduce power losses, an increase in operating voltages, optimization of the distribution of power flows, and the use of transformers with low ohmic losses are used.

Thus, the use of the developed algorithm makes it possible to optimize the placement of compensating devices in distribution networks, helping to reduce power losses and increase their energy efficiency.

In order to evaluate the efficiency of the proposed algorithm, a simulation model of a real grid of a territorial network organization was developed using the MATLAB Simulink package [1].

For this model, based on the method of indefinite Lagrange multipliers, the power of compensating devices was optimized according to the criterion of minimum active power losses (1), taking into account the corresponding restrictions. The normalized value of the reactive power factor in the distribution network was taken equal to tgφ = 0.4.

For this purpose, a model was built from MATLAB Simulink blocks to optimize the objective function. Next, using Simulink Design Optimization, variables were defined that will change during the optimization process. The initial average load factor of transformers in the distribution network was β = 0.15.

As a result of the iterative optimization process, the optimal values of the capacities of the compensating devices installed in the network nodes were determined.

Further, the load factors of transformers in the distribution network of the territorial grid organization were changed. As a result, their average load factor increased to β = 0.502. At the same time, the optimal values of the powers of the compensating devices were recalculated using the developed model.

As a result of optimization, the reactive power factor decreased to tgφ = 0.4 and began to be within the economically justified standardized value. At the same time, losses in the distribution network with an average load factor of transformers β = 0.15 and optimal placement of compensating devices decreased by 15.7%, with β = 0.502 - by 3.3% (Table 1).

Table 1. Parameters of distribution network 6 kV before and after optimization of the placement of compensating devices

Parameter	Network without compensating devices		Network with compensating devices
	β = 0,15	β = 0,502	
Reactive power factor tgφ	0,697	0,479	0,4
Active power losses Δ*P*, kW	386,8	336,9	325,7
Power losses Δ*W*, thousand kWh	1547,2	1347,5	1302,8

Due to the fact that it is recommended to install compensating devices in a low voltage network, the placement of compensating devices in a 0.38 kV distribution network was similarly optimized using the resulting model, all other initial conditions being equal.

As a result of optimization, the reactive power factor decreased to tgφ = 0.4 and is within the economically justified standardized value. At the same time, зщцук losses in the distribution network with an average load factor of transformers β = 0.15 and optimal placement of compensating devices decreased by 16.7%, with β = 0.502 - by 4.3% (Table 2).

Table 2. Parameters of distribution network 0.38 kV before and after optimization of the placement of compensating devices

Parameter	Network without compensating devices		Network with compensating devices
	β = 0,15	β = 0,502	
Reactive power factor tgφ	0,697	0,479	0,4
Active power losses Δ*P*, kW	386,8	336,9	322,3
Active power losses Δ*P*, kW	1547,2	1347,5	1289,2

The economic effect from the implementation of these measures amounted to about 2 million rubles with a payback period of less than 1.5 years.

Thus, the developed simulation model of the distribution network showed a sufficiently high efficiency of optimization of the placement of compensating devices, ensuring the optimal distribution of reactive power and a significant reduction in electricity losses in the electrical network. In addition, with the help of this model, it is possible to control reactive power in the network depending on the load factors of power transformers, which allows you to obtain the most optimal operating mode of the network.

4 Conclusion

The widest and most promising group of methods and tools for improving energy efficiency is currently the use of Smart Grid technologies. The relevance of the innovative development of the Russian power grid complex based on this concept is due to the low potential for increasing the efficiency of the use of power grid assets (the possibilities for increasing the productivity of equipment are practically exhausted) and the limited investment resources.

The need to implement solutions based on Smart Grids is due to the following factors:

– changes in the conditions for the functioning of the electricity and capacity markets;

– decrease in the reliability of power supply;

– the emergence of new technologies that have not found their application in the power grid complex;

– a pronounced trend of constant growth of tariffs for power;

– the presence of an objective need to increase both the energy and environmental efficiency of the power grid complex;

– implementation of a systematic approach in terms of building a digital economy.

In this regard, the use of intelligent electrical networks technologies pursues the main goal of ensuring the reliability and improving the energy efficiency of the power grid complex.

The implementation of the proposed algorithm for optimizing the placement of compensating devices based on the method of indefinite Lagrange multipliers using the developed simulation model of the distribution network has shown its efficiency. As a result of optimization, power losses have significantly decreased, and the technical and economic indicators of the network have increased.

Thus, the use of Smart Grid technologies allows not only to reduce power losses in distribution networks. Using active-adaptive elements, the main directions of modernization of power grid assets can be determined, studies of the efficiency of implemented innovations can be carried out to make decisions about the possibility of their further distribution, etc., which ultimately should ensure an increase in the efficiency of the power grid complex as a whole.

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Hybrid Power Systems for Buildings and Factories

Chung-Jen Tseng[1,2,*], *Cheng-I Chen*[2,3], Cheng-You Yao[1] and *Kan-Rong Lee*[1,4]

[1]Department of Mechanical Engineering, National Central University, Taoyuan City, Taiwan.
[2]Center for Energy Research, National Central University, Taoyuan City, Taiwan.
[3]Department of Electrical Engineering, National Central University, Taoyuan City, Taiwan.
[4]Institute of Materials Science and Engineering, National Central University, Taoyuan City, Taiwan.

Abstract. Integrated hybrid power systems have become more and more important in recent years. The functioning of medium-temperature proton-conducting solid oxide fuel cell (pSOFC) hybrid system is proposed in this work. The combined system consists of a pSOFC stack, steam methane reformer, compressors, burners, heat exchangers and methanol synthesizing reactor. The excess waste heat of the burner is recovered using heat exchangers. Also, the unutilized hydrogen from SOFC is used for carbon reduction by methanol production. The functioning of configured system is explored by using Matlab/Simulink/Thermolib software. In pSOFC operation, stoichiometric ratio (Sto) of air is maintained 3 and Sto of hydrogen is varied between 1.4 to1.7. Results show that the benefit of carbon reduction depends on methanol production. By using water separator, the methanol production efficiency increases dramatically. In addition, hydrogen transfer membrane is used to increase stack efficiency and control the temperature of stack chamber and reformer. This further improves benefit of carbon reduction. The proposed hybrid system in this work can be used to power huge residential buildings and some factories.

1 Introduction

Fuel cell is an efficient device to convert molecular energy straight away into electricity. High-temperature solid oxide fuel cell (HT-SOFC) functions in the temperature range of 800-1000 °C. HT-SOFC operation temperature allows its use in a hybrid system with a gas turbine (GT) or micro gas turbine (MGT), or a combined heat and power system. Integration of residual biogas generation system as a source of hydrogen generation by steam methane reforming (SMR) could effectively reduce the cost of hydrogen fuel generation for SOFC. The as-generated hydrogen can be fed to HT-SOFC for industrial power generation as mentioned by Gandiglio et al [1]. The unutilized hydrogen from SOFC can be effectively used for methanol production. Methanol is widely used as raw material for producing formaldehyde, synthetic resins, pharmaceuticals, and pesticides in organic factories. So, the SOFC hybrid systems can be used as a source of power and raw material generation in organic chemical factories. The carbon imprint in power generation and raw material production for the mentioned organic factories can be stockpiled. Such hybrid systems also avoid the mitigation of currency outflow in a factory. But in HT-SOFC, high heat resistant alloys and ceramics are only feasible for balance-of-plant (BOP) components in the HT-SOFC operation range. Therefore, it is significant to reduce the operating temperature to the range of 550-650 °C (intermediate-temperature, IT). Reducing operation temperature favors the usage of low-cost materials for BOP, quick start and off, lowered corrosion rate of metallic components with enhanced endurance.

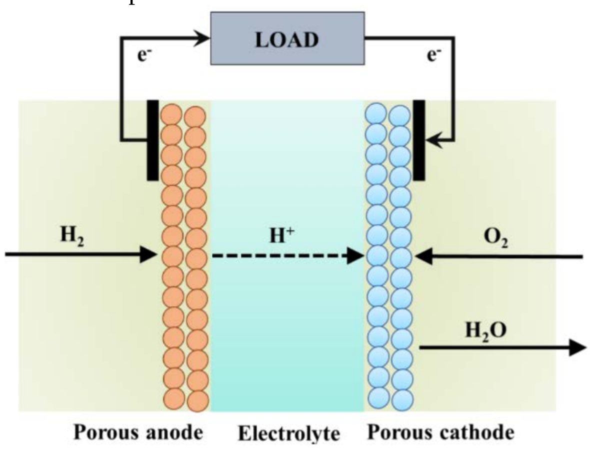

Fig. 1. Schematic of a proton-conducting SOFC.

Proton-conducting SOFC (pSOFC) favors reducing the operation temperature [2]. The mechanism of pSOFC is shown in Fig. 1. The smaller size of proton aids better conductivity compared to an oxide ion in the electrolyte with lower activation energy. Thus, the high fuel utilization at anode with higher hydrogen partial pressure caused higher efficiency of the pSOFC. Based on the comparative thermodynamic analysis of pSOFC and oxygen-ion electrolyte SOFC (oSOFC) investigated by Demin et al. [3, 4], methane and hydrogen fed pSOFC show high chemical to electrical energy conversion compared to oSOFC. Ni et al. [5, 6] notice that the

* Corresponding author: cjtseng@g.ncu.edu.tw

concentration losses in pSOFC and oSOFC are different. pSOFC has low anode concentration and high cathode concentration losses. Water vapor generation at the cathode influences the cathode concentration losses in pSOFC. Moreover, the difference in the performance of oSOFC and pSOFC is observed with larger fuel utilization in ammonia fed SOFCs. The lower steam and higher hydrogen partial pressures of pSOFC compared to oSOFC favors better efficacy of pSOFC than oSOFC. Patcharavorachot et al. [7] has developed and validate a design for j-V curve of pSOFC based on $SrCeO_3$ electrolyte. They also investigated the cell performance with variation in thickness of electrolyte and electrodes in the cell. Results suggest that, the major voltage loss is attributed to the ohmic losses and low proton conductivity of the electrolyte. The anode-supported pSOFCs exhibits superior performance.

The high temperature waste flue gas from SOFC can be used for excess power generation by Rankine/Brayton cycles for heating and cooling purpose (cogeneration/ trigeneration) [8]. In general, a contradictory tendency is observed in the electric and cogeneration efficiency in a co-generation system. However, electric efficiency should be prioritized in the designing and selection of a system, as electric energy is of superior quality compared with thermal energy [9]. Yi et al. simulate 25 kW SOFC integrated reformer system with a CHP and GT/MGT. In SOFC-GT-CHP combined system. A significant decrease in the exhaust heat loss of coal syngas is expected for higher system efficiency. Whereas in replacement of GT with MGT in combined system, electrical efficiency decreases with increase in turbine inlet temperature but the CHP efficiency enhances [10]. In accordance with required energy outcome of the system, the operating conditions of all the components in the hybrid system should be modulated to achieve optimum operating condition [11]. The high temperature operation of SOFC paves way for designing different combinations of systems. Braun et al. discussed the feasibility of SOFC micro combined heat and power generators for daily usage in house hold applications by proper recycling of exhaust gas heat for heating water to 60 ºC along with preheating of input fuel and air [12]. The CO_2 capture and storage units can be attached to the SOFC integrated gasification combined cycles or fuel cells to reduce carbon emission [13-16].

Earlier studies on pSOFC are focused on developing materials or thermodynamic performance of fuel cell system. oSOFC is considered for developing hybrid systems. But, pSOFCs possess high efficiencies compared to oSOFCs. So, there is substantial scope to setup IT-pSOFC hybrid systems for low temperature operation advantages [3, 4]. The low temperature (60 ºC) hot water generation from waste heat can be utilized in residential buildings/complex. The power and cost for hot water generation in huge buildings or complex can be decreased. Thus, IT-pSOFC can be used as power source for buildings. Also, such hybrid systems promise continuous and distributed power supply by avoiding power fluctuations in peak demand.

In this study analysis of IT-pSOFC hybrid systems will be discussed in detail. Activation, concentration and ohmic losses in pSOFC system will be investigated by an electrochemical model. The activation and ohmic losses are evaluated by Butler-Volmer equation and ionic conductivity of electrolyte. Whereas, the concentration losses can be determined by the Fick’s diffusion through porous electrode. Experimental results from literature are used for validation of simulation data. The proposed study includes a 20 kW pSOFC, MGT, methanol production, HTM and heat exchangers to heat water upto 60 ºC by waste heat recovery. The proposed hybrid IT-SOFC designs of this study can be used for huge residential buildings/complex and organic chemical factories.

2 Theoretical model

2.1 Proton-conducting solid oxide fuel cell (pSOFC)

A pSOFC consists of two electrodes separated by an electrolyte. The electrochemical reactions in pSOFC are:

$$\text{Anode: } 2H_2 \rightarrow 4H^+ + 4e^- \quad (1)$$

$$\text{Cathode: } O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad (2)$$

$$\text{Overall: } 2H_2 + O_2 \rightarrow 2H_2O \quad (3)$$

Standard reversible cell potential is considered to evaluate ideal open-circuit voltage:

$$V_r^0 = -\frac{\Delta g^0}{nF} \quad (4)$$

where Δg^0, n and F are the Gibbs free energy change at the standard pressure and temperature, the number of moles of electrons transferred and Faraday constant, respectively.

Effects of temperature and pressure on reversible cell potential can be described as:

$$V_r = V_r^0 - \frac{\Delta s}{nF}(T - T_0) - \frac{\Delta NRT}{nF} ln\left(\frac{P}{P_0}\right) \quad (5)$$

where Δs is the change in entropy. ΔN is the change in the number of mole of gaseous species in the reaction per mole of fuel.

The operation voltage (V_{cell}) is always less than the reversible potential due to irreversible losses and can be expressed as:

$$V_{cell} = V_r - V_{act} - V_{ohm} - V_{conc} \quad (6)$$

where V_{act}, V_{ohm}, V_{conc}, represent the activation, ohmic, and concentration polarizations, respectively.

The sluggish charge transfer reaction across the interface of electrode-electrolyte leads to activation polarization. It is directly related to the rate of electrochemical reaction, which can be determined from the Butler-Volmer Equation:

$$j = j_0\left[exp\left(\frac{\alpha nFV_{act}}{RT}\right) - exp\left(-\frac{\alpha nFV_{act}}{RT}\right)\right] \quad (7)$$

where j_0 is the exchange current density, α the transfer coefficient (=0.5).

Ohmic polarization arises due to electrical resistance in the cell. Ionic losses within electrolyte leads to ohmic losses, which obeys Ohm's law:

$$V_{ohm} = j\frac{\delta_{electrolyte}}{\sigma_{electrolyte}} \tag{8}$$

where $\delta_{electrolyte}$ and $\sigma_{electrolyte}$ are the thickness and ionic conductivity, respectively.

The instantaneous consumption of reactants at electrodes for electrical current output in electrochemical reaction leads to concentration polarization. Also, the reactant availability at the site of reaction due to the limitations in mass transfer influences losses in outcome. V_{conc} is estimated with reference to the concentration of reactant and products at the interface of electrolyte-electrode. In pSOFC V_{conc} can be expressed as:

$$V_{conc,anode} = \frac{RT}{2F}\ln\left(\frac{p_{H_2}}{p^*_{H_2}}\right) \tag{9}$$

$$V_{conc,cathode} = \frac{RT}{2F}\ln\left[\left(\frac{p_{O_2}}{p^*_{O_2}}\right)^{0.5}\left(\frac{p^*_{H_2O}}{p_{H_2O}}\right)\right] \tag{10}$$

where $p^*_{H_2}$ $p^*_{O_2}$, and $p^*_{H_2O}$represent the partial pressure of hydrogen at the anode-electrolyte interface and the partial pressures of oxygen and water vapor at the cathode-electrolyte interface, respectively. They can be determined as:

$$p^*_{H_2} = p_{H_2(a)} - \frac{j\delta^a RT}{2Fp^a D_{a,eff}} \tag{11}$$

$$p^*_{O_2} = p_{O_2(c)} - \frac{j\delta^c RT}{2Fp^c D_{c,eff}} \tag{12}$$

$$p^*_{H_2O} = p_{H_2O(c)} + \frac{j\delta^c RT}{4Fp^c D_{c,eff}} \tag{13}$$

where δ^a and δ^c are anode and cathode thickness respectively. p^a and p^c represent the pressure of anode and cathode, respectively. $D_{a,eff}$ and $D_{c,eff}$ are the effective mass diffusion coefficients at anode and cathode.

2.1 j-V curve validation

The pSOFC experimental data of Iwahara is used for validation of j-V curve [17]. The thickness of electrodes and electrolyte are 50 µm and 500 µm respectively. The proton conductivity is acquired from Potter and Baker [18]. Fig. 2 depicts good estimation of the j-V characteristics of pSOFC operated under normal atmospheric conditions at 800 °C, 900 °C, and 1000 °C.

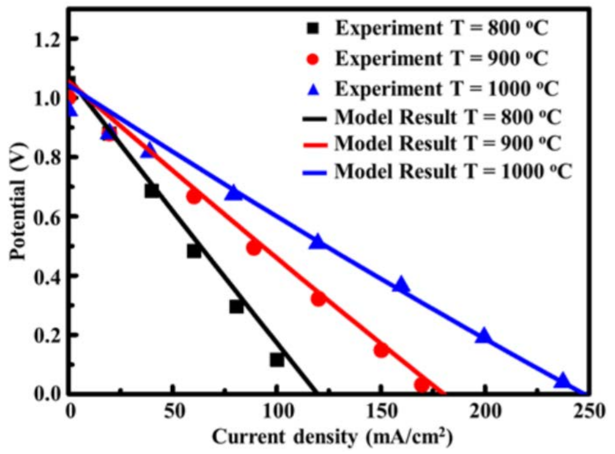

Fig. 2. Comparison between theoretical modeling results and experimental data.

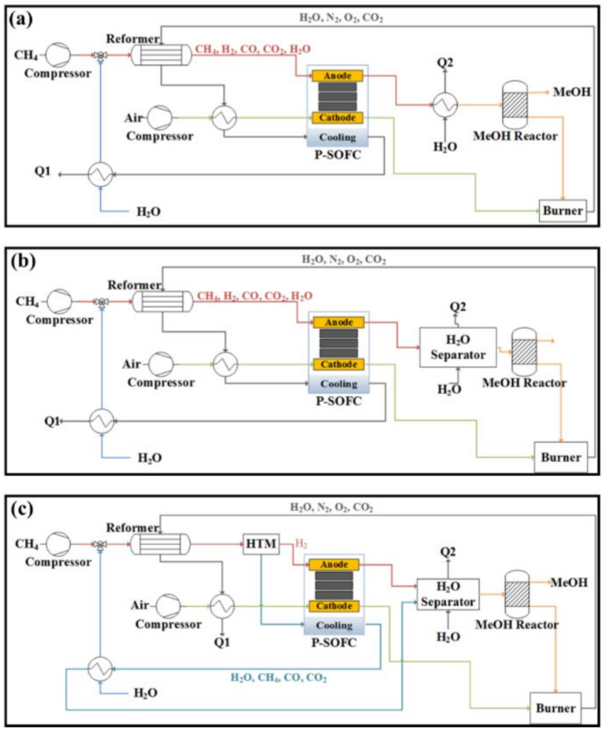

Fig. 3. The IT-pSOFC hybrid system model on (a) initial design (system A), (b) with water separator (system B), and (c) with HTM (system C).

2.2 System simulation model

The IT-pSOFC hybrid system efficacy is simulated by using Matlab/Simulink/Thermolib. Thermolib is a simulation toolbox to design and evaluate thermodynamic systems using Matlab/Simulink software. Fig. 3 shows the schematic of the hybrid system configurations (system A, B and C) designed for this study. In this systems, the reactants are compressed to 2 atm and preheated prior supply to pSOFC stack. The unreacted fuel and air from exhaust of pSOFC stack flows into an afterburner followed by a methanol synthesis reactor for reduction of excess gas. Thereafter, the gas flows around pSOFC to control the stack temperature between 550-650 °C.

Further, water is heated using hot gas for the heat recovery and enhancement of efficiency of the system. The system parameters of this study are shown in Table 1. The following conditions are assumed to simplify the analysis of system:

1. Steady state system
2. Gases are ideal gases
3. Uniform stack temperature

The modeling of each component is described in the further sections.

Table 1. Operating and system parameters for 20 kW IT-pSOFC hybrid system.

System parameter	value
Fuel stoichiometric ratio (Sto_{fuel})	1.4 - 1.7
Air stoichiometric ratio (Sto_{air})	3
Operating pressure (atm)	2
Number of fuel cells	100
Fuel cell active area (m^2/cell)	0.01
Cell voltage (V/cell)	0.68-0.72
pSOFC fuel utilization (%)	90
Compressor isentropic efficiency (%)	70
Heat recover efficiency (%)	90
Inverter efficiency (%)	92

2.3 Compressor

The compressor delivers the required outlet pressure with low-pressure inlet flow. It estimates the thermodynamic state of outlet flow along with the necessary mechanical power consumption of a compressor at a given isentropic efficiency. The enthalpy difference in isentropic change of states to actual enthalpy difference is isentropic efficiency.

$$\eta_{isentropic} = \frac{\Delta\dot{h}_{isentropic}}{\Delta\dot{h}} \quad (14)$$

2.4 Methanol synthesis reactor

Methanol is one of the most common organic chemicals. Its main uses include the production of formaldehyde, synthetic resins, pharmaceuticals, and pesticides. In this study, residual hydrogen from a fuel cell reaction is reformed with residual methane, producing carbon monoxide and carbon dioxide. The methanol synthesis reactor uses carbon oxide, carbon dioxide, and hydrogen to produce methanol. This reaction improves system efficiency and reduces carbon:

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O \qquad \Delta\hat{h}^0_{rxn} = -49.5\ kJ/mol \quad (15)$$

$$CO + 2H_2 \leftrightarrow CH_3OH \qquad \Delta\hat{h}^0_{rxn} = -90.5\ kJ/mol \quad (16)$$

2.5 Afterburner

An afterburner combusts the fuel that remains from the pSOFC. The enthalpy of combustion for hydrogen is based on the following reaction:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \qquad \Delta h = -241.2\ kJ/mol \quad (17)$$

2.6 Hydrogen transfer membrane (HTM)

The hydrogen transfer membrane (HTM) uses proton-conducting electrolyte and transfers hydrogen ions to the other side of the membrane. When the HTM separates the hydrogen, the main driving force is the concentration difference between the two sides of the membrane. This element is not assumed to be represented by ideal components of energy; its gas pressure loss is ignored.

2.7 Water separator

The water separator condenses water vapor from the gas collected; when the tank is full of water, a solenoid switch drains the tank. This element is not assumed to be represented by ideal components of energy; its gas pressure drop and the power required for the solenoid valve switch are ignored.

2.8 Efficiency definitions

$$\eta_{pSOFC} = \frac{P_{DC,pSOFC}}{\dot{n}\times LHV} \quad (18)$$

$$\eta_{sys} = \frac{P_{AC,Net}}{\dot{n}\times LHV} \quad (19)$$

$$\eta_{MeOH} = \frac{n_{MeOH} + LHV_{MeOH}}{\dot{n}\times LHV} \quad (20)$$

where $\dot{n}$ denotes the input molar flow rate of fuel in a system; $P_{DC,pSOFC}$ denotes the output power of the stack calculated from direct current of pSOFC; $P_{AC,Net}$ denotes the overall system power, which is the summation of AC output of pSOFC AC, the low heat value of the methanol product, and the power consumption of compressor;

3 Results and discussion

In this study, three systems with a same SOFC stack is used for simulation. The performance of SOFC in all the systems is proportional to the stack temperature as the conductivity of electrolyte increases with rise in temperature. The three proposed hybrid systems A, B, and C in this study are shown in Fig. 3. In system A, the H_2O present in outlet gases of SOFC anode might decrease the methanol reactor efficiency with a reverse reaction as shown in the equation (15). So, a H_2O separator is used between the SOFC and the input of methanol reactor in system B. The H_2O separator obstructs H_2O entering the methanol reactor, thereby favors in higher methanol forming. The higher temperature of inlet gases in SOFC and methanol reformer favors the maintenance of higher temperature of systems. This might favor in higher efficiency of the system. So in system C, a hydrogen transport membrane (HTM) is used at the inlet of SOFC. The outlet gases of reformer after separation from HTM are passed through cathode side of SOFC as a cooling media for maintenance of SOFC temperature. Also, the temperature of gas increases before it is fed into methanol reactor. The H_2O in the high temperature gaseous passed through SOFC for heat exchange is separated by H_2O separator before fed into methanol reactor. The effects of H_2O separator, HTM and temperature of inlet gases on the performance of SOFC and methanol reactor will be explained further.

3.1 SOFC stack efficiency

In this study for SOFC operation, the stoichiometry of fuel (Sto_{fuel}) is varied from 1.4 to 1.7 with a constant stoichiometry of air (Sto_{air}) as 3. In general, Sto_{air} of 3 is usually preferred in the operation of SOFC stack. The stack efficiency of SOFC is seen in Fig. 4(a) is calculated using the equation (18). It can be clearly seen from Fig. 4(a) that the stack efficiency decreases with increase in Sto_{fuel}. The unconsumed fuel with higher Sto_{fuel} decreases the efficiency of SOFC. From Fig. 4(a), it can be seen that, the stack efficiency of system C is little higher at 1.4 and 1.5 Sto_{fuel} compared to system A and B. The fuel inlet for SOFC in system C is pure H_2 as it passes through the HTM.

3.2 Methanol reactor efficiency

The excess gases from SOFC anode are fed to the methanol reactor. The unconsumed H_2 from the SOFC is used for methanol production. So, the efficiency of methanol production increases with increase in the Sto_{fuel} as seen in Fig. 4(b). But, the system B and C shows higher methanol production compared to system A. Whereas, system C shows higher production compared to system B. System B shows higher production compared to system A as the reverse mechanism mentioned in equation (15) is obstructed with presence of H_2O separator as shown in Fig. 3. Whereas, in system C, the temperature of the gases fed to methanol reactor is higher compared to system B. Also, pure H_2 gas is fed to the methanol reactor in system C compared to the hydrocarbon gas system A and B. So, the methanol production in higher in system C compared to system A and B.

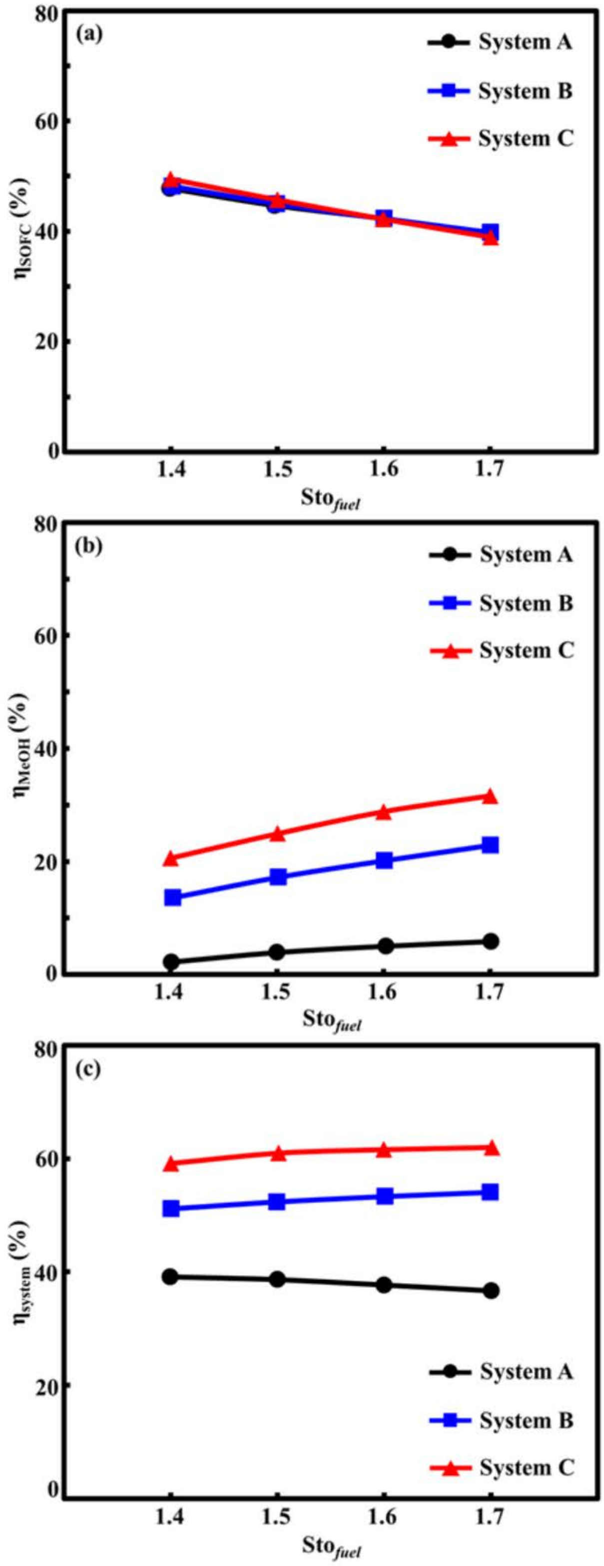

Fig. 4. Effects of Sto_{fuel} on (a) stack efficiency, (b) methanol reactor efficiency, and (c) system efficiency.

3.3 System efficiency

The overall system efficiency comprises of pSOFC output power and the methanol production. The system efficiency of A, B, and C is shown in Fig. 4(c). In system A, the efficiency of system is approximately 36.5-39%, which is lower than the stack efficiency (shown in Fig. 4 (a)), because of the lower methanol production. The methanol production efficiency for system A is approximately 6% (Fig. 4(b)). When the efficiency of methanol production cannot offset the energy losses of other components, the system efficiency declines (Fig. 4(c)). However, in system B, the system efficiency increases by 38% compared to system A with increase in the methanol production efficiency from 6% to 22%. The system efficiency of system B increases with rise in the methanol production and Sto_{fuel} compared to system A. This system efficiency with rise in Sto_{fuel} is in accordance with the equation (20). The system efficiency of system C is 14.8% higher compared to system B. Also seen in Fig. 4(b), the highest methanol production of 31 % is observed for system C in comparison to system A and system B. Thus, the large yield of methanol and net output of system compensates the losses and increases the efficiency of system C.

3.4 Methanol reactor input gases

3.4.1 H_2O mole fraction

H_2O separator is used in system B and D for obstructing the reverse reaction hindering the methanol production as mentioned in equation (15). Thus the increase in methanol production is observed in Fig. 4(b) and as explained in the previous section. The decrease in mole fraction of H_2O with the presence of H_2O separator at the input of methanol reaction can also be observed from Fig. 5(a).

3.4.2 H_2 mole fraction

The production of H_2 depends on the efficiency of steam methane reformer (SMR). The efficiency of SMR depends on the temperature of reforming. The temperature of the reformer also depends on the waste/recycled heat fed to the SMR in the system. The excess gases from the methanol reactor are fed to the burner for generation of heat. The heat generated in burner is fed to the SMR for temperature maintenance. The obstruction of water vapor into the methane reactor has increased the production of methanol and the temperature of outlet gases from methanol reactor. The higher temperature of methane reactor outlet gas with low amount of water vapor fed the burner increases the temperature of the outlet gas of burner. Thus the high temperature is maintained in burner. Further using the burner outlet gas for SMR temperature maintenance increases the efficiency of SMR in system B compared to system A. The excess fuel fed to SOFC stack is the input for methanol reformer. Thus, the H_2 mole fraction for system B is higher compared to system A. Whereas in system C, the passing outlet gases of SMR (except H_2) favors the higher temperature maintenance of methanol reformer compared to system B. So, the efficiency of SMR in system C > system B > system A. Also, the higher mole fraction of unused H_2 from SOFC stack is available for methanol reactor as seen in Fig. 5(b).

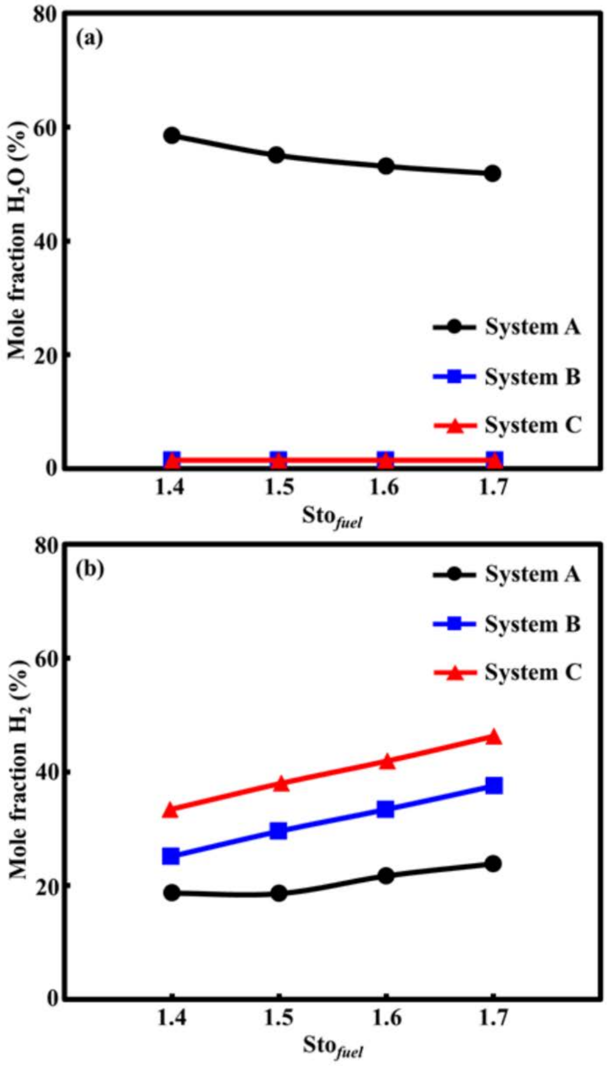

Fig. 5. Effects of Sto_{fuel} on methanol reactor inlet parameters (a) H_2O mole fraction, and (b) H_2 mole fraction.

3.5 Carbon reduction

In this study, the behavior of intermediate-temperature pSOFC hybrid systems is investigated. Low carbon emission is one of the advantages of a fuel cell. The extra H_2 is recovered and combined with carbon to prepare methanol, which further reduces the carbon emission from integrated systems. In this study, the proportion of carbon reduction depends on the system parameters. The amounts of carbon reduction in system A, B and C are 2.6%-7.3%, 17.1%-28.8%, and 25.9%-39.6%, respectively, as shown in Fig. 6. The methanol production tends to increase when extra unconsumed fuel enters the methanol reactor. To find the reason of lower methanol production efficiency in system A, the mole fraction of H_2O is analyzed in the methanol reactor inlet. As seen in Fig. 5(b), the mole fraction of H_2O is approximately 51%-60%. According to equation (15), excessive H_2O is unfavorable for the chemical reaction, and results in poor methanol production efficiency.

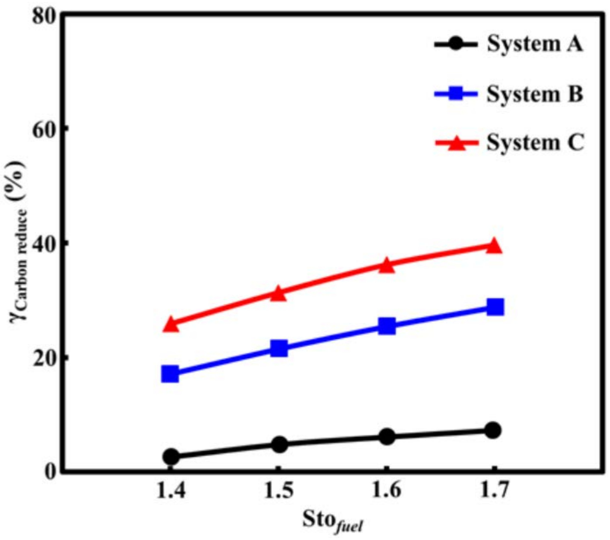

Fig. 6. Effects of Sto_{fuel} on carbon reduction property of systems.

Table 1. The comparison of carbon reduce proportion.

Power plant	**CO_2 emission (kg/kWh)**
System A	0.571
System B	0.402
System C	0.358

However, the H_2O separator is used to raise the methanol production efficiency in system B. As shown in Fig. 5(a), the mole fraction of H_2O is only approximately 1.5% in system B and C; As a result of using H_2O separator, the methanol production efficiency and carbon reduction is increased in system B and C. The carbon reduction in system C is 25.9%-39.6%, which is approximately 8.8%-10.8% higher than that of system B. Hence, system C performs excellent carbon reduction with higher methanol production (Table 2). System C has the largest carbon reduction, and the highest economic benefits; therefore, system C is preferable compared to the other systems.

4 Conclusions

The behavior of IT-pSOFC hybrid system is studied in this work. The hybrid system comprises of a pSOFC stack, a methanol production reactor, and heat exchangers. Heat exchangers are used for waste heat recovery from the burner. The system performance is explored using Matlab/Simulink/Thermolib. Different Sto values are used to control the flow rates of air and hydrogen. Sto values for hydrogen in this study varies between 1.4-1.7. The benefit of carbon reduction is dependent on methanol production. Avoiding the presence of water vapor with H_2 dramatically increases the methanol production efficiency. In addition, HTM, which was used to increase stack efficiency and control the temperature of stack chamber and reformer, further improves the benefit of carbon reduction.

Acknowledgements

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On the use of dynamic state estimation for the optimal control of power system

Alexander Domyshev[1,*], and *Alexander* Tikhonov [2]

[1]Melentiev Energy Systems Institute of SB RAS, Irkutsk,Russia
[2]RUSAL Engineering and Technological Center, LTD, Irkutsk, Russia

Abstract. Investigations of the application of classical methods of dynamic state estimation on the data of a real power system for the purposes of optimal control have been carried out. A modern feature of state estimation for a large power system is that data from the SCADA system are fed to the calculation subsystem with a fairly small frequency. It is shown that the use of classical methods of dynamic state estimation for such problems is limited. The study was carried out using the ergodic theory of a dynamical system.

1 Introduction

The diversification of the energy sector in the Russian Federation and the subsequent forced digitalization were the catalyst for the creation of an intelligent energy system in Russia. Such an electric power system (EPS) contains a significant number of elements, the mode of which is stochastic in time. This is due to the large number of local control devices, the algorithm of which is not defined at the power system level. Along with this, in distribution networks, the problem of optimal control is become even more complicated due to the small number of measuring devices and significant uncertainty of measurements. To solve the problems of operational and emergency control, a mathematical model of the current state of electric grid is used.

At the same time, for the problem of optimal control, and especially for the problem of automatic optimal control, a reliably functioning state estimation algorithm [1] is required that works without human intervention.

In static state estimation, one uses the relationships between physical parameters of the single steady state, but there is additional information about the change in these parameters over time. This information ca n be used by applying dynamic state estimation algorithms. At the same time, the practical application of dynamic state estimation algorithms for optimal control purposes encounters computational difficulties. In this paper, an attempt is made to investigate the possibility of using existing dynamic state estimation. This information can be used by applying dynamic state estimation algorithms on a model of a sufficiently large power system using real telemetry received from a SCADA system.

2 State estimation problem statement

In a static formulation, the assessment of the EPS state is the calculation of the parameters of the state, carried out on the base of SCADA measurements $\bar{y}$.

$$\bar{y} = [P_i, Q_i, P_{ij}, Q_{ij}, U_i, I_i, I_{ij}]$$

The measurements vector includes: modules of nodal voltages U_i, generation of active P_i and reactive power Q_i in nodes, power flows of active P_{ij} and reactive power Q_{ij} through overhead lines and transformers, less often currents at the ends of overhead lines I_{ij} and nodal currents I_i, some integral characteristics of the mode. To obtain nodal injections, in addition to measurements of loads and generation power, pseudo-measurements are used.

The task of state estimation is to find such estimates of the measured parameters y(x) that are closest to the measured values $\bar{y}$. The sum of the weighted squares of the deviations of estimates from measurements is most often used as a criterion for proximity [2].

$$J = [\bar{y} - y(x)]^T R_v^{-1} [\bar{y} - y(x)]$$

where R_v^{-1} is a diagonal matrix of weight coefficients whose elements are inverse to the variances of measurements characterizing their accuracy.

Estimates must satisfy the electrical circuit equations:

$$w(y(x), x) = 0$$

The result of state estimation is the state vector

$$\hat{x} = [\hat{U}_1, \hat{U}_2, \dots, \hat{U}_n, \hat{\delta}_1, \hat{\delta}_2, \dots, \hat{\delta}_n]^T \quad (1)$$

This vector contains the estimated voltages and its angles for each node. n – the total number of nodes in the model of the electrical grid.

Within the framework of the problem of dynamic state estimation, the system is usually considered to be Markov. The change in the state vector of system (1) is considered in the form of the following Markov process:

* Corresponding author: domyshev@isem.irk.ru

$$x_i = F(x_{i-1})+\left[\hat{U}_1, \hat{U}_2, \dots, \hat{U}_n, \hat{\delta}_1, \hat{\delta}_2, \dots, \hat{\delta}_n\right]^T$$

To predict weakly variable components of the system state vector x for a short period of time, a dynamic state estimation is used based on a modification of the Kalman filter.

The Kalman filter is a classic dynamic state estimation method. The essence of the Kalman filter is as follows. Suppose there is a time-varying parameter. The law of its change is known only with a certain error, so that:

$$x_{i+1} = x_i + u(x_i) + \xi_i,$$

where $u(.)$ is the assumed law of variation of x, ξ_i is an uncertain value. Also, at each time step (starting from the first), there are actual measurements of the predicted parameter $z_{i+1} = x_{i+1} + \eta_{i+1}$, containing the measurement error.

The idea behind the Kalman filter is that to get the best approximation to the proper value of x_{i+1}, one need to choose a compromise between measuring z_{i+1} and inaccurate prediction $x_i + u(x_i)$. The measurement is assigned a weight of K_i, and the predicted value is assigned $1 - K_i$, respectively. The Kalman coefficient changes at each iteration and is found by iteratively minimizing the squared prediction error

$$E(e_{i+1}^2) = \frac{\sigma_\eta^2\left(E(e_i^2) + \sigma_\xi^2\right)}{E(e_i^2) + \sigma_\xi^2 + \sigma_\eta^2}$$

and the error-minimizing value of the Kalman coefficient on the next iteration

$$K_{i+1} = \frac{E(e_{i+1}^2)}{\sigma_\eta^2},$$

where σ_η^2 is the variance of the measurement error, and σ_ξ^2 is the variance of the model error.

For the nonlinear model $u(x_i)$, an extended Kalman filter is used [3, 4] or faster methods that approximate nonlinearity, such as the Sigma-point Kalman filter (Unscented Kalman Filter), based on the same-name Unscented transformation.

A modern feature of state estimation for a large power system is that data from the SCADA system is fed to the calculation subsystem with a fairly small frequency. In the power system under consideration, the snapshots of measurements is formed at the 30-minute boundary. If there is WAMS, you can get consistent data much more often. In this case, the status evaluation period can be shortened to 10 seconds. However, for the purposes of automatic optimal control, when the problems of emergency management are not considered, the formation of a snapshots at the 30-minute boundary and, accordingly, the state estimation may be quite sufficient.

The use of classical methods of dynamic state estimation [5] on 30-minute snapshots of measurements obtained from SCADA, as shown by calculations, was not effective. Indeed, the change in load showed a chaotic nature. Fig. 1 shows the change over two days of the measured active load power and its estimates using a static state estimation algorithm. On the ordinate axis, the sequential number of the snapshot (half-hour) is deferred. Changes in values are given for a single node, but the nature of changes is similar for most load nodes in the network.

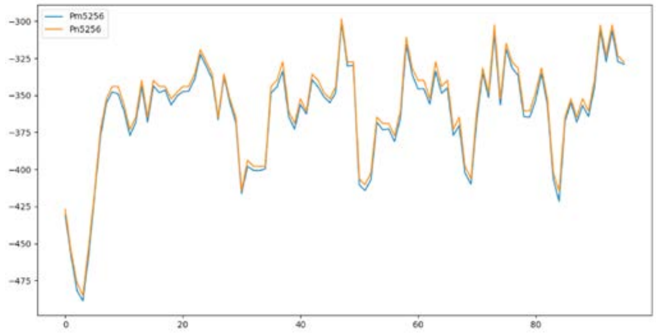

Fig. 1. Measured and estimated load in one of the grid nodes.

Similar chaotic behavior is observed in voltage and power flow measurements (Fig. 2, Fig. 3).

As a result of applying the Kalman filter with a linear or moving average model, we get a mode with a greater error than with static state estimation. In this case, there is either a delay and a roughen of the state (Fig. 4), or in some cases there is a outage of the computational stability of the algorithm. This behavior is explained by the fact that the error of the model ξ_i significantly exceeds the measurement error η_{i+1}.

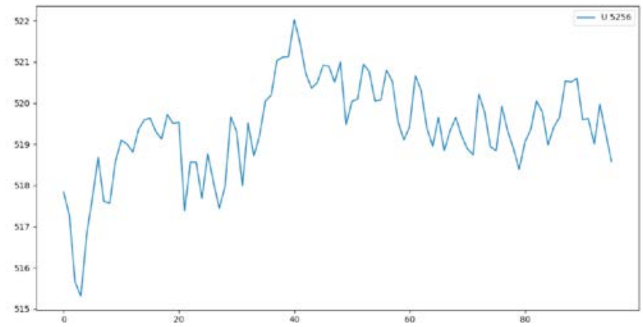

Fig. 2. Measured voltage.

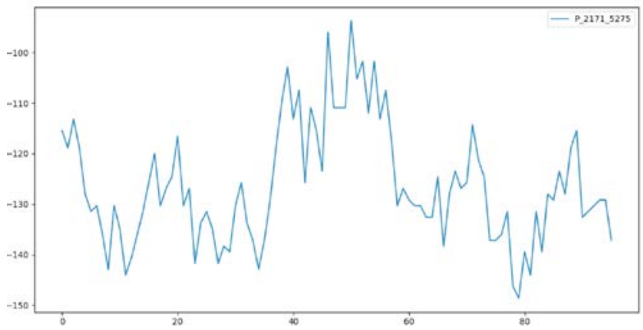

Fig. 3. Measured power flow.

In order to understand the possibility of creating an adequate model for predicting the process of changing sates parameters over time, the ergodic theory [6, 7] of dynamic chaos was applied. The process of changing states was considered as a dynamic system with an unknown control law.

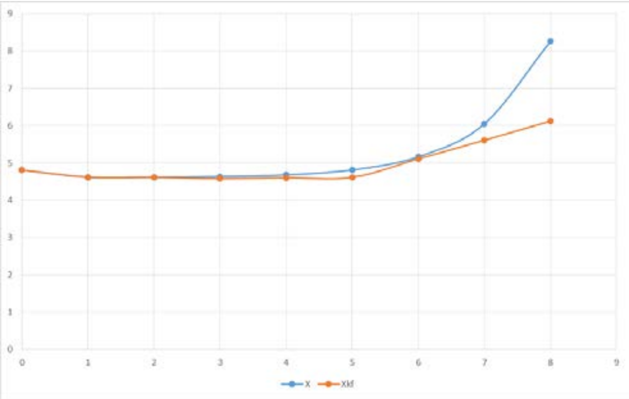

Fig. 4. Lag of the value filtered by Sigma-point Kalman filter. X – measured value, Xkf – filtered value.

To study the behavior of a system in the vicinity of an arbitrary trajectory, we use Lyapunov exponents that characterize the degree of stretching and compression in the phase space of the system's motion (changes in its parameters) along stable and unstable directions (5).

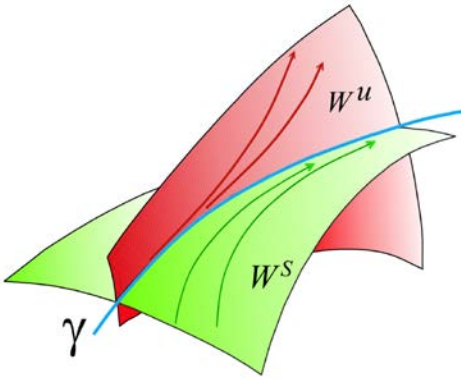

Fig. 5. The trajectory of the system is γ. W^S is a stable manifold, W^U is an unstable manifold of the system's trajectories (the figure is taken from [7]).

Let the dynamics of the system be given by a system of differential equations:

$$\dot{x} = f(x(t), c), \tag{2}$$

where x is a vector of dynamic variables that depend on time t, and c is a set of non-changing parameters. Consider the typical phase trajectory $x(t)$ of the system (2) and the trajectory close to it:

$$x_1(t) = x(t) + \xi(t).$$

The function that defines Lyapunov exponents is written as:

$$\Lambda(\xi) = \lim_{t\to\infty} \frac{1}{t} ln \frac{|\xi(t)|}{|\xi(0)|} \tag{3}$$

For $\xi(0) \to 0$, the values of function (3) are a vector with a dimension equal to the dimension of the phase space n:

$$\Lambda(\xi) = \{\lambda_1, \lambda_2, \dots, \lambda_n\}.$$

If $\Lambda(\xi)$ does not contain positive values, then there is no chaotic component and the evolution of the system is completely predictable.

Obtaining the law of changing of the state parameters in time in the form (2) is impossible due to the complexity of the system under consideration. Therefore, it is necessary to apply the method of reconstructing a dynamic system from the available measurements using Takens' theorem. This theorem substantiates the possibility of reconstructing a strange attractor of a chaotic dynamical system from a sequence of measurements of one of its parameters taken at equal time intervals τ:

$$Z = \{z(t_0), z(t_0 + \tau), \dots, z(t_0 + (m-1)\cdot\tau)\}. \tag{4}$$

This approach to the analysis of time series was mathematically substantiated in the work of F. Takens [8, 9]. Reconstruction of the entire d-dimensional phase space (embedded space) from measurements of one variable is possible due to the fact that all variables of the state vector of the system are tied up in a general nonlinear process.

The maximum Lyapunov exponent is defined as:

$$\lambda_{max} = \lim_{t\to\infty} \lim_{\varepsilon\to 0} \frac{1}{t} \ln\left(\frac{|z(t) - z_\varepsilon(t)|}{\varepsilon}\right).$$

To determine the maximum Lyapunov exponent based on a finite series of measurements (4), we use the algorithm proposed by Rosentein [10]. Consider the representation of time series data as a trajectory in a reconstructed nested space. Individual trajectories of the system movement in the reconstructed space fluctuate along the main trend determined by the Lyapunov exponent spectrum. Then we can consider the distance $\Delta_0 = |z(t_0) - z_\varepsilon(t_0)|$, as a deviation that should grow exponentially over time such that $\Delta_t \approx \Delta_0 \varepsilon^{\lambda t}$. In this case, λ will be equal to the maximum Lyapunov exponent. The spectrum of Lyapunov exponents is calculated as:

$$\lambda_\tau(t) = \lim_{\varepsilon\to 0} \frac{1}{\tau} \ln\left(\frac{|z(t+\tau) - z_\varepsilon(t+\tau)|}{\varepsilon}\right).$$

If the spectrum $\lambda_\tau(t)$ shows a linear increase with the same slope for most of the trajectories, then this slope can be taken as an estimate of the maximum Lyapunov exponent λ_{max} (Fig. 6).

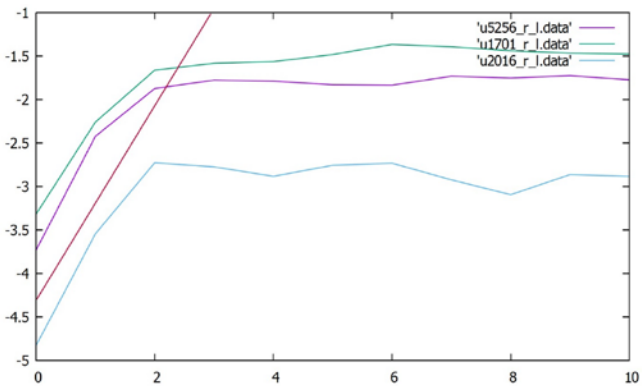

Fig. 6. Determination of the maximum Lyapunov exponent.

As the measurements by which the maximum Lyapunov exponent is determined, it is necessary to take the variable from the state vector of the system that is most influenced by other variables of the system. This will be the voltage value on the high-voltage buses remote from the buses, on which the voltage is maintained by the regulators.

To determine the Lyapunov exponents, the TISEAN library of nonlinear time series analysis was used [11].

The maximum Lyapunov exponent for the power system under consideration, determined from the power system state vector, is $\lambda_{max} = 2{,}238$. Thus, the chaotic behavior of the dynamic system is confirmed.

Given the chaotic behavior of the system, it is important to understand whether it is possible to predict the behavior of a chaotic system and what data set is needed to perform an adequate prediction. The rate of generation of new information in a number of measurements can be related to the rate of growth of distances in the space of measurements according to the work of Pesin [12]. The rate of information generation can be estimated by the value of the average mutual information:

$$I_{AB} = \sum_{a_i, b_i} P_{AB}(a_i, b_i) \log_2 \left(\frac{P_{AB}(a_i, b_i)}{P_A(a_i) P_B(b_i)} \right),$$

where a_i is an event from set A, b_i is an event from set B, $P_A(a_i)$ is the probability of an event from the set A, $P_B(b_i)$ is the probability of an event from the set B, $P_{AB}(a_i, b_i)$ is the mutual probability of events.

If we take measurements $z(t)$ observed at times t as the set of events A, and measurements $z(t+\tau)$ as events of the set B, then from the function of the average mutual information, we can determine the parameters of the series that are optimal for predictions measurements. So, to select the optimal discretization of measurements in [13], the first minimum of the function is found:

$$\mathrm{C}(\tau) = \sum_t |z(t) - \bar{z}| |z(t+\tau) - \bar{z}|,$$

$$\bar{z} = \frac{1}{n} \sum_{t=1}^{n} z(t)$$

With a predetermined measurement discreteness (as it is in the system under study), the size of the measurement vector n used for forecasting can be varied:

$$\min_n \mathrm{C}(n) = \begin{cases} \sum_t |z(t) - \bar{z}| |z(t+\tau) - \bar{z}| \\ \bar{z} = \frac{1}{n} \sum_{t=1}^{n} z(t) \end{cases}$$

From the above calculations (Fig. 7), it can be seen that the first clear minimum appears after the 30th measurement snapshot, which, with a measurement frequency of 30 minutes, approaches the archive depth of one day. Thus, to obtain an adequate forecast in the model function, it is necessary to use more complex models than linear or moving average, which are often used in the Kalman filter.

As rightly noted in [14], the application of dynamic state estimation using the Kalman filter is limited by a slow change in the mode parameters and a forecasting horizon of up to 1 min. Thus, the field of application of the dynamic state estimation proposed in [14] and similar works is limited to the automatic control of power plants, including for the purpose of emergency control.

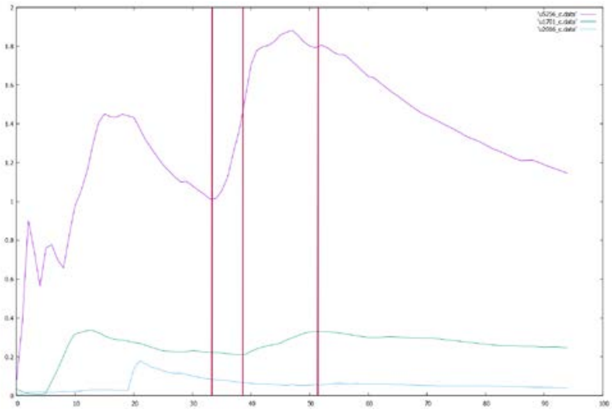

Fig. 7. Determination of the maximum Lyapunov exponent.

For the purposes of optimal control, a model is required that provides a forecast for a time of the order of a day. Such a model can be models based on artificial neural networks. Moreover, there are two options for using such models:

- direct use to obtain a forecast;
- use as a model of system behavior in dynamic state estimation using the Kalman filter.

The second variant of ANN application involves the use of a nonlinear Kalman filter, in particular, a sigma-point filter.

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Statistics of multimoding in optimum compensation of reactive loads of electrical systems

Alexey Gerasimenko[1,*]

[1] Siberian Federal University, Krasnoyarsk, Russia

Abstract. A stochastic approach has been implemented to account for multimodality to optimize the operating conditions of electrical systems. On the basis of the algorithm for optimization of the instantaneous mode and the stochastic model of the load graphs, a mathematical model of the generalized reduced gradient was obtained. The practical implementation of the algorithm was carried out due to its low labor intensity.

Keywords. statistical model, optimal reactive load compensation, generalized reduced gradient method, electrical systems,

1. Introduction

Optimal reactive load compensation (RLC) in the grids of electrical systems (ES) can significantly increase the efficiency of their functioning. The problem solving here requires taking into account the aggregate of steady-state modes (multimoding), obtaining and analyzing the integral parameters of this aggregate, such as energy loss in the system, ranges and diagrams of voltages and reactive power changes in its nodes. Direct optimization of each mode separately, generalization and analysis of economic and mode characteristics of the aggregate of modes dramatically complicates the problem at hand, making it excessively cumbersome and time-consuming. Against this background, the most productive is the gradient methods, proved themselves in operational problems, using the probabilistic-statistical (stochastic) approach, which allows solving problems more strictly than deterministic approaches [1]. A statistical model for accounting the set of steady-state modes [2, 3] combined with a generalized reduced gradient (GRG) method [4, 5] are the basis of the developed optimization method. The basic principles for solving the problem of optimal RLC in terms of the minimum loss of electric energy (EE) is given below.

2. Statistical Model of Electrical Loads

The optimal RLC is formulated as a nonlinear mathematical programming problem [4]; it belongs to the stochastic optimization since loads of the ES nodes are random variables. The stochastic approach of taking into account multimoding [2, 3], caused by the change in electric loads, is implemented based on an analytical model of load changes which is obtained through factor (component) analysis [6, 7]. Electrical loads modelling on the basis of factor analysis allows identifying common and most stable patterns of changing the configuration of load curves, compressing the information regarding the multimoding through a small number of generalizing factors with their subsequent application of them when calculating the EE losses and other integral parameters.

The load diagrams modelling using the principal component analysis is as follows. Based on a representative sample N of initial load diagrams, we determine a moment correlation matrix (MCM) and select M of maximum eigenvalues λ_i and their corresponding eigenvectors $\overline{\upsilon}_i$. These values determine the main factors – generalized (orthogonal) load diagrams (GLD):

$$\mathrm{G}_{kj} = \sum_{i=1}^{N} \upsilon'_{ki}\, \Delta P_{ij} + \sum_{i=1}^{N} \upsilon''_{ki}\, \Delta Q_{ij} \quad j = \overline{1,d}\,,\; k = \overline{1,M}\,, \qquad (1)$$

where: υ'_{ki} , υ''_{ki} are the components of eigenvector $\overline{\upsilon}_k$ of MCM; ΔP_{ij} , ΔQ_{ij} are components j of the centered diagrams of active P_i and reactive Q_i of the loads of node i with d intervals of constancy.

The modelling GLDs are a set of statistically independent basis vectors oriented so that each of them reflects most of the connection of the initial aggregate of load diagrams and contributes most to the variance of the initial variables. Like eigenvectors, GLDs are orthogonal (statistically independent), uncorrelated (unrelated) quantities. They attribute the properties of linearity and additivity to the models, the statistical method, and the whole process of multimoding modelling. Analysis of the GLD configurations for various realizations of the random

* Corresponding author: gerasimenkoaa@yandex.ru

process of changing the loads showed the presence of statistical stability of these factor models, i.e. proximity of the numerical characteristics of the corresponding GLDs of various samples of the original diagrams.

This statistical transformation of MCM helps simulate fairly accurately the original curves of electrical loads P_{ij} and Q_{ij} using known mathematical expectations MP_i and MQ_i and simulated deviations of loads from mathematical expectations in the form of M-linear combinations of statistically stable GLD:

$$P_{ij} = MP_i + \sum_{k=1}^{M} \upsilon'_{ki} G_{kj} ; \quad Q_{ij} = MQ_i + \sum_{k=1}^{M} \upsilon''_{ki} G_{kj} ,$$
$$i = \overline{1, N} , \quad j = \overline{1, d} . \qquad (2)$$

Such a representation of the loads turned out to be effective since obtaining model (2) of acceptable accuracy needs only to take into account up to the first three or four GLDs ($M << N$), which reflect up to 85–95% of the total variance of the initial loads. The modelling error for the interval values of unknown load curves by models (2), being in the range of ± (2–15) %, is not a crucial factor for determining the integral characteristics since its influence decreases as a result of stepwise (iterative) refinement of pseudo-average loads and, accordingly, load diagrams models in the combined algorithm for determining these parameters.

The solution for optimal RLC is based on taking into account the entire set of modes in the form of their integral characteristics, primarily EE losses, which are a target criterion for solving the operational problem with determining the optimal load of existing reactive power sources.

3. Statistical modelling of the set of steady-state modes [2, 3]

The general expression of the EE load losses in the ES with *m*-branches is basically determined by accurate summing (integrating) of power losses ΔP at all time intervals Δt (in all modes) of calculated period T according to the classical expressions:

$$\boldsymbol{\Delta}\mathrm{E}_{ll} = \mathbf{3} \sum_{j=1}^{m} \boldsymbol{R_j} \int_0^T \boldsymbol{I_j^2(t) dt} = \sum_{j=1}^{m} \int_0^T \boldsymbol{\Delta}\mathrm{P}_j(\boldsymbol{t}) \boldsymbol{dt} = \sum_{i,j}^{N+1} \int_0^T \boldsymbol{\Delta P_{ij}(t)\, dt} \approx \sum_{i,j}^{N+1} \quad \sum_{k=1}^{d} \boldsymbol{\Delta P_{ijk}\, \Delta t_k}. \qquad (3)$$

The EE load losses are the sum of the main component M$\boldsymbol{\Delta E}$ determined for the average loads mode, and the variance component $\boldsymbol{\sigma\Delta E}$ which takes into account the deviation of the loads from the average values:

$$\Delta E = M\Delta E + \sigma\Delta E = \Delta P(M\overline{V}, M\overline{\delta})T + \left[\frac{1}{2} \sum_{i=1}^{N} \sum_{j=1}^{N} k(V_i V_j) \frac{\partial^2 \Delta P}{\partial V_i \partial V_j} + \sum_{i=1}^{N} \sum_{j=1}^{N} k(V_i \delta_j) \frac{\partial^2 \Delta P}{\partial V_i \partial \delta_j} + \frac{1}{2} \sum_{i=1}^{N} \sum_{j=1}^{N} k(\delta_i \delta_j) \frac{\partial^2 \Delta P}{\partial \delta_i \partial \delta_j} \right] T , \qquad (4)$$

where $\Delta P(M\overline{V}, M\overline{\delta})$, $k(V_i V_j)$, $k(V_i \delta_j)$, $k(\delta_i \delta_j)$ are power losses, correlation moments calculated for moduli MV and phases $M\delta$ of the voltages at the point corresponding to the mathematical expectations of the loads; $\frac{\partial^2 \Delta P}{\partial V_i \partial V_j}$, $\frac{\partial^2 \Delta P}{\partial V_i \partial \delta_j}$, $\frac{\partial^2 \Delta P}{\partial \delta_i \partial \delta_j}$ – second derivatives of the expression of power losses with respect to the corresponding variables, they have been calculated relevantly to the same point; N – the number of nods in the circuit without a slack bus.

The main component of EE losses is determined by calculating the steady-state mode (SSM) for average loads with high reliability. The greatest difficulty is a complete and simple calculation of the multimoding when calculating the variance component, which is a critical factor in the EE loss analysis in general.

The EE loss expression (4) is featured by the correlation moments of moduli V and phases δ of the voltages, which form the MCM of the voltages, which are obtained on the basis of a system of equations written similarly to the linearized equations of nodal voltages (NVEs):

$$\begin{bmatrix} \partial P_i / \partial \delta_j & \partial P_i / \partial V_j \\ \partial Q_i / \partial \delta_j & \partial Q_i / \partial V_j \end{bmatrix} \begin{bmatrix} \Delta \overline{\delta_i} \\ \Delta \overline{V_i} \end{bmatrix} = \begin{bmatrix} \Delta \overline{P_i} \\ \Delta \overline{Q_i} \end{bmatrix}, \quad i, j = \overline{1, N} , \quad (5)$$

where ΔP_i, ΔQ_i, ΔV_i, $\Delta\delta_i$ – deviations of active, reactive powers, moduli, phases of nodal voltages from their mathematical expectations.

Since the deviations of the voltages and wattages from their mathematical expectations are approximately related by the NVE system (5), the centered random parameters (variations of the voltage phases and moduli) $\Delta\delta_i, \Delta V_i$, same as ΔP_i, ΔQ_i, similarly to (2) are formulated by linear combinations of GLD:

$$V_{ij} = MV_i + \sum_{k=1}^{M} \gamma''_{ki} G_{kj} \quad \delta_{ij} = M\delta_i + \sum_{k=1}^{M} \gamma'_{ki} G_{kj} \quad i = \overline{1, N} , \quad j = \overline{1, d} . \quad (6)$$

After substituting deviation of the mode parameters from expressions (2) and (6) into the system (5), coefficients γ'_{ki}, γ''_{ki}, modeling the deviations of the phases and voltage moduli from the average values are calculated from equations equivalent to the system of linearized NVEs:

$$[J] \times \begin{bmatrix} \overline{\gamma'}_{ki} \\ \overline{\gamma''}_{ki} \end{bmatrix} = \begin{bmatrix} \overline{\upsilon'}_{ki} \\ \overline{\upsilon''}_{ki} \end{bmatrix}, \; k = \overline{1, M} , \; i = \overline{1, N} , \quad (7)$$

where $\upsilon'_{ki} \gamma'_{ki}$, $\upsilon'_{ki}, \upsilon''_{ki}$ are determined with initial (reconstructed) load diagrams and GLD according to (2) as:

$$\upsilon'_{ki} = \frac{1}{d} \sum_{j=1}^{d} G_{kj} \Delta P_{ij} ; \; \upsilon''_{ki} = \frac{1}{d} \sum_{j=1}^{d} G_{kj} \Delta Q_{ij} , \; k = \overline{1, M} , \; i = \overline{1, N} . \quad (8)$$

The stochastic model of load diagrams (1)-(2), (6)-(8) allows expressing the MCM elements of voltages and wattages with modeling coefficients

$$k(\delta_i\delta_j)=\sum_{k=1}^{M}\gamma'_{ki}\gamma'_{kj}\ ;\ \ k(V_i\delta_j)=\sum_{k=1}^{M}\gamma''_{ki}\gamma'_{kj}\ ;$$

$$k(V_iV_j)=\sum_{k=1}^{M}\gamma''_{ki}\gamma''_{kj}\ ;\ \ \sigma^2\delta_i=\sum_{k=1}^{M}\gamma'^{\,2}_{ki}\ ;\ \sigma^2V_i=\sum_{k=1}^{M}\gamma''^{\,2}_{ki}\ . \quad (9)$$

Similar to (9) for the elements, MCMs of wattages are:

$$k(P_iP_j)=\sum_{k=1}^{M}\upsilon'_{ki}\upsilon'_{kj},\ k(P_iQ_j)=\sum_{k=1}^{M}\upsilon'_{ki}\upsilon''_{kj},\ \ k(Q_iQ_j)=\sum_{k=1}^{M}\upsilon''_{ki}\upsilon''_{kj},$$

$$\sigma^2(P_i)=\sum_{k=1}^{M}(\upsilon'_{ki})^2;\ \sigma^2(Q_i)=\sum_{k=1}^{M}(\upsilon''_{ki})^2. \qquad (10)$$

Considering the correlation moments for moduli and phases of voltages (9), the EE load losses (4) are:

$$\Delta E=\left[\Delta P(M\bar{V},M\bar{\delta})+\sigma\Delta P\right]T=\left[\Delta P(M\bar{V},M\bar{\delta})+\frac{1}{2}\sum_{k=1}^{M}\sum_{i=1}^{N}\sum_{j=1}^{N}\gamma''_{ki}\gamma''_{kj}\frac{\partial^2\Delta P}{\partial V_i\partial V_j}+\right.$$

$$\left.+\sum_{k=1}^{M}\sum_{i=1}^{N}\sum_{j=1}^{N}\gamma''_{ki}\gamma'_{kj}\frac{\partial^2\Delta P}{\partial V_i\partial\delta_j}+\frac{1}{2}\sum_{k=1}^{M}\sum_{i=1}^{N}\sum_{j=1}^{N}\gamma'_{ki}\gamma'_{kj}\frac{\partial^2\Delta P}{\partial\delta_i\partial\delta_j}\right]T\ . \quad (11)$$

Analysis of the accuracy of calculating the EE losses by the statistical testing with 2-4 GLD made for samples of test circuits of power grids with 35, 110, 220 kV, a small number of nods (up to 10), and real-world 6–220 kV circuits of power grids within the Krasnoyarsk energy system with up to 25 nods, resulted in finding that these expressions allow to compute load losses with acceptable accuracy: considering significance level of 0.95 for the samples, the average error in calculating EE losses for test circuits was $\boldsymbol{\delta_{av}}$ = –(1,2÷1,7) % with σ2 scattering up to 0.70, and $\boldsymbol{\delta_{av}}$ ±(0,25÷0,45) % with σ^2 scattering up to 0.64 for real-world circuits.

EE losses of idle running N_T of transformers with g_i^T conduction are specified in the initial and optimal modes in accordance with the obtained voltage diagrams (6):

$$\Delta E_X=\sum_{i=1}^{N_T}g_i^T\int_0^T V_i^2(t)dt\approx\sum_{i=1}^{N_T}\sum_{j=1}^{d}g_i^TV_{ij}^2t_j\approx T\sum_{i=1}^{N_T}g_i^TMV_i^2\ . \ (12)$$

Linear system of equations in SSM (5), factor transforming (1), load model (2) and relations (6) – (12), expressing deviations of dependent variables (*δ*, *V*) and their second moments through the corresponding characteristics of independent variables (*P*, *Q*), collectively form a statistical model for the SSM analysis and ES multimolding analysis.

Finding the integral characteristics through the stochastic method (7) - (12) does not require interval calculations of the modes; it comes down to one calculation of the SSM of the electrical system for average loads and an additional solution of three to four systems of linear equations (7) with the implacable Jacobian matrix, which drastically simplifies calculations of multimoding and EE losses in general, in comparison with direct d-calculations of the SSM (3) over the intervals for averaging the electrical load diagrams. The method allows to calculate electric power losses and other integral characteristics with accuracy and reliability sufficient for practice. Moreover, in comparison with the deterministic methods, the tolerance to random errors increases. EE load losses can be calculated via any algorithm computing the SSM which can be supplemented by blocks for determining (7), (8) of the modulating coefficients $\upsilon'_{ki},\ ,\upsilon''_{ki}$ and $\gamma'_{ki},\ \gamma''_{ki}$, which usually make the analysis only, 20 – 40 % more laborious.

4. Mathematical model for stochastic optimization of modes

The basis of the model is the multimode-based GRG constructing apparatus with the statistical accounting of multimoding [8, 9]. While solving the operational problem, we define the minimum of the objective function of the total EE losses (11), (12) under the balance nonlinear equality constraints (NVEs) for the mathematical expectation of mode parameters, and simple inequality constraints

$$Q_i^{\min}\le Q_i\le Q_i^{\max},\ i=\overline{1,G};\ \ V_i^{\min}\le V_i\le V_i^{\max},\ i=\overline{1,N},\ (13)$$

where *G* is a number of nods with sources of reactive power (RP).

Epy constraints (13) all be applied to the entire time interval, i.e. for each mode, which should be controlled in two ways:

1) modelling with GLD for RP (2) and voltages (6) at each optimization step and checking compliance with the constraints (13);

2) calculating of design ranges for variation of the considered parameters, which, considering variances (9), (10), are determined by Chebyshev's inequalities:

$$\left.\begin{aligned}V_i^{\min\,p.}&=MV_i-k_\beta^{\min}\sigma V_i;V_i^{\max\,p.}=MV_i+k_\beta^{\max}\sigma V_i;\\Q_i^{\min\,p.}&=MQ_i-k_\beta^{\min}\sigma Q_i;Q_i^{\max\,p.}=MQ_i+k_\beta^{\max}\sigma Q_i.\end{aligned}\right\}$$

$$\begin{aligned}V_i^{\max\,p.}&\le V_i^{\max};V_i^{\min\,p.}\ge V_i^{\min};\\Q_i^{\max\,p.}&\le Q_i^{\max};Q_i^{\min\,p.}\ge Q_i^{\min}.\end{aligned} \qquad (14)$$

Considering antisymmetric (biased) function of distribution density of V_i, Q_i , the values of k_β, ensuring the minimum error of the interval analysis on average up to 5–10 %, is justified for the range: $k_\beta^{\min}=1{,}45-1{,}55$, $k_\beta^{\max}=1{,}55-1{,}65$ with a significance level of β= 0,90.

Dependent (basic) $\overline{X}$ and independent regulated) $\overline{Y}$ variables that make up the general vector are the key parameters for forming array expression for determining the reduced gradient, and the expectations of mode parameters and active constraints (13) are as follows:

$$\begin{cases}(\boldsymbol{V_{1i}},\boldsymbol{Q_{2j}})\in\overline{\boldsymbol{Y}}\rightarrow\boldsymbol{V_{1i}}\in\boldsymbol{V}_{\text{marg}},\boldsymbol{Q_{2j}}\in\boldsymbol{Q}_{\text{perm}};\boldsymbol{i}=\overline{\boldsymbol{1,p}};\boldsymbol{j}=\overline{\boldsymbol{1,q}};\boldsymbol{p}+\boldsymbol{q}=\boldsymbol{G};\boldsymbol{i}\neq\boldsymbol{j};\\(\boldsymbol{V_{2i}},\boldsymbol{\delta_j},\boldsymbol{Q_{1l}})\in\overline{\boldsymbol{X}}\rightarrow\boldsymbol{i}=\overline{\boldsymbol{1,N-p}};\boldsymbol{j}=\overline{\boldsymbol{1,N}};\boldsymbol{l}=\overline{\boldsymbol{1,p}},\end{cases}\tag{15}$$

where $\boldsymbol{V}_{\text{marg}},\boldsymbol{Q}_{\text{perm}}$ are a set of marginal voltages and admitted values of RM sources respectively; 1 and 2 are the indices of dependent and independent variables; p, q are the number of independent variables within V, Q.

If simple constraints (13) are violated, the basic set changes. This means exchanging corresponding components between vectors $\overline{\boldsymbol{X}}$ and $\overline{\boldsymbol{Y}}$.

The following separation of variables is proposed for the components of eigenvectors and modeling coefficients:

$$\begin{cases}(\upsilon''_{k2i},\gamma''_{k1j})\in\overline{Y}\rightarrow k=1;\ i=\overline{1,q};\ j=\overline{1,p};q+p=G;i\neq j;\\(\upsilon''_{k1i},\gamma''_{k2j})\in\overline{X}\rightarrow k=1;\ i=\overline{1,p};\ j=\overline{1,N-p};i\neq j;\\\upsilon''_{k1i}\in\overline{Y}\rightarrow k=\overline{2,M};\ i=\overline{1,G};\\\gamma''_{ki}\in\overline{X}\rightarrow k=\overline{2,M};\ i=\overline{1,N};\gamma'_{ki}\in\overline{X}\rightarrow k=\overline{1,M};i=\overline{1,N}.\end{cases}\tag{16}$$

In this case, a basic set change is provided only for the variables reflecting multimoding with the first GLD (M = 1).

Using the matrixed linearized system (5), provided the mode is balanced for the active power ($\Delta P_i = 0$), following the illustrated separation of variables (16), with the subsequent grouping of the vectors of the dependent and independent variables, we obtain the system of equations reflecting the parameters of SSM corresponding to the loads expectations:

$$\begin{bmatrix}E&\overline{0}&\overline{0}&A_{12}\\\overline{0}&E&\overline{0}&A_{22}\\\overline{0}&\overline{0}&E&-B_{12}\\\overline{0}&\overline{0}&-B_{21}^{-1}&E\end{bmatrix}\begin{bmatrix}\Delta\overline{\delta}\\\Delta\overline{Q}_1\\\Delta\overline{V}_2\end{bmatrix}+\begin{bmatrix}A_{11}&\overline{0}\\A_{21}&\overline{0}\\-B_{11}&\overline{0}\\\overline{0}&-B_{22}^{-1}\end{bmatrix}\begin{bmatrix}\Delta\overline{V}_1\\\Delta\overline{Q}_2\end{bmatrix}=\overline{0}\tag{17}$$

When constraints are inactive in (13), equations (17) are reduced to equations with identity matrix

$$\begin{bmatrix}E&A_{22}\\\overline{0}&E\end{bmatrix}\begin{bmatrix}\Delta\overline{\delta}\\\Delta\overline{V}\end{bmatrix}+\begin{bmatrix}\overline{0}\\-B_{22}^{-1}\end{bmatrix}\left[\Delta\overline{Q}\right]=\overline{0}\cdot\tag{18}$$

In systems (17), (18), the following matrices are used to relate the dependent and independent mode parameters

$$A=\begin{bmatrix}A_{11}&A_{12}\\A_{21}&A_{22}\end{bmatrix}=\left[\frac{\partial P}{\partial\delta}\right]^{-1}\left[\frac{\partial P}{\partial V}\right];$$
$$B=\begin{bmatrix}B_{11}&B_{12}\\B_{21}&B_{22}\end{bmatrix}=\left[\frac{\partial Q}{\partial V}\right]-\left[\frac{\partial Q}{\partial\delta}\right]A\cdot\tag{19}$$

Following the separation of variables (16), on the basis of expressions (2) and (5) – (7), considering pairwise equivalence of variables γ' and δ, γ'' and V, υ'' and Q, equality constraints (NVEs) taking into account multimolding are the most completely simulated by the system of equations (17) representing mathematical expectations of the parameters being optimized, and the following systems of equations considering deviations of parameters from mathematical expectations:

$$\begin{bmatrix}E&\overline{0}&\overline{0}&A_{12}\\\overline{0}&E&\overline{0}&A_{22}\\\overline{0}&\overline{0}&E&-B_{12}\\\overline{0}&\overline{0}&-B_{21}^{-1}&E\end{bmatrix}\begin{bmatrix}\overline{\gamma'}\\\overline{\upsilon''_1}\\\overline{\gamma''_2}\end{bmatrix}+\begin{bmatrix}A_{11}&\overline{0}\\A_{21}&\overline{0}\\-B_{11}&\overline{0}\\\overline{0}&-B_{22}^{-1}\end{bmatrix}\begin{bmatrix}\overline{\gamma''_1}\\\overline{\upsilon''_2}\end{bmatrix}=\overline{0}$$

$$k=1;\tag{20}$$

$$\begin{bmatrix}E&A_{22}\\\overline{0}&E\end{bmatrix}\begin{bmatrix}\gamma'_k\\\gamma''_k\end{bmatrix}+\begin{bmatrix}\overline{0}\\-B_{22}^{-1}\end{bmatrix}\left[\overline{\upsilon''_k}\right]=\overline{0},\quad k=\overline{2,M}\,.\tag{21}$$

When inserting dependent variables ($\Delta\delta$, ΔQ_1, ΔV_2 and $\boldsymbol{\gamma'}$, $\boldsymbol{\upsilon''_1}$, $\boldsymbol{\gamma''_2}$) into (17), (20) through independent variables (ΔV_1, ΔQ_2 and $\boldsymbol{\gamma''_1}$, $\boldsymbol{\upsilon''_2}$) considering objective function F (11) and component (12) upon transition to infinitesimal increments of the variables, the expression of reduced gradient simulating loads only with the first actively constrained GLD (13), will be:

$$\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\text{п}}=\left[\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\boldsymbol{V_1}}\boldsymbol{F}\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\boldsymbol{Q_2}}\boldsymbol{F}\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\boldsymbol{\gamma''_1}}\boldsymbol{F}\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\boldsymbol{\upsilon''_2}}\boldsymbol{F}\right]-\left[\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\boldsymbol{\delta}}\boldsymbol{F}\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\boldsymbol{Q_1}}\boldsymbol{F}\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\boldsymbol{V_2}}\boldsymbol{F}\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\boldsymbol{\gamma'}}\boldsymbol{F}\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\boldsymbol{\upsilon''_1}}\boldsymbol{F}\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\boldsymbol{\gamma''_2}}\boldsymbol{F}\right]\times$$

$$\begin{bmatrix}\begin{bmatrix}E&A_{22}\\\Theta&E\end{bmatrix}&&\\&\begin{bmatrix}E&\begin{bmatrix}A_{12}\\A_{22}\end{bmatrix}\\\Theta&\begin{bmatrix}E&-B_{12}\\-B_{21}^{-1}&E\end{bmatrix}\end{bmatrix}&\\&&\begin{bmatrix}E&A_{22}\\\Theta&E\end{bmatrix}\end{bmatrix}^{-1}\times\begin{bmatrix}\begin{bmatrix}\Theta\\-B_{22}^{-1}\end{bmatrix}&&\\&\begin{bmatrix}\begin{bmatrix}A_{11}\\A_{21}\\-B_{11}\end{bmatrix}&\Theta\\\Theta&-B_{22}^{-1}\end{bmatrix}&\\&&\begin{bmatrix}\Theta\\B_{22}^{-1}\end{bmatrix}\end{bmatrix}\tag{22}$$

where $\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\text{п}}$ is a $G(1+M)$-dimensional reduced gradient vector with components; $\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\boldsymbol{V_1}}\boldsymbol{F}\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\boldsymbol{Q_2}}\boldsymbol{F}$ and $\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\boldsymbol{\gamma''_1}}\boldsymbol{F}\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\boldsymbol{\upsilon''_2}}\boldsymbol{F}$ are vector-rows $[\boldsymbol{\partial F/\partial Y}]$, each being of total size G; $\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\boldsymbol{\delta}}\boldsymbol{F}$ and $\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\boldsymbol{\gamma'}}\boldsymbol{F}$ are N-dimensional vector-rows $[\boldsymbol{\partial F/\partial X}]$; $\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\boldsymbol{Q_1}}\boldsymbol{F}\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\boldsymbol{V_2}}\boldsymbol{F}$ and $\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\boldsymbol{\upsilon''_1}}\boldsymbol{F}\overline{\boldsymbol{\nabla}}^{\boldsymbol{t}}_{\boldsymbol{\gamma''_2}}\boldsymbol{F}$ are vector-rows $[\boldsymbol{\partial F/\partial X}]$, each of total size N. In expression (22), $2N(1+M)$-dimensional square matrix $[\boldsymbol{\partial W/\partial X}]^{-\boldsymbol{1}}$ and $2N(1+M)\times G(1+M)$-dimensional matrix $[\boldsymbol{\partial W/\partial Y}]$ are used.

The modified model based on GRG method (22) allows stochastic optimization of the objective function F in the space of expectations of the modes parameters, eigenvectors of wattage MCM and modeling coefficients $F=f(Q_i,\delta_i,V_i,\upsilon''_{ki},\gamma'_{ki},\gamma''_{ki})$, taking into account the ES multimoding in a concise form.

5. Multimode-based optimal choice of loading RP sources

An objective function of the total EE losses (11), (12) is determined by the mathematical expectations of the mode parameters, the components of the eigenvectors and modeling coefficients: $F = f(Q_i, \delta_i, V_i, \upsilon''_{ki}, \gamma'_{ki}, \gamma''_{ki})$. It can be minimized by means of modifying GRG method (13) – (22) based on the stochastic model of loads and the set of modes (1), (2), (6) – (10) specifying the active resistance of overhead and cable lines in (11) by the average values of current loads and ambient temperatures for the period under consideration. An optimization step is calculated as a minimum of the values determined from the condition for observing the constraints in the form of simple inequalities for the mode parameters O and V and by the parabolic interpolation method, provided that the EE loss function passes through its minimum inside the constraints. The mode dependent parameters enter the possible domain of mathematical expectations (obtaining a possible point of the optimization trajectory) by means of solving the SSM nonlinear equations through Newton's method. Corrections of dependent variables for average loads are determined from solving the systems of (17), (18), and variables γ', υ''_1, γ''_2, which model the deviations of the optimized variables from the average can be found from the solution of linear systems (20), (21).

The variables found during the optimization allow obtaining:

1. A criterion (objective) function of total EE losses and its components (the value of EE load losses (11) and idle running (12) in the initial and optimal states).
2. Ranges of alteration of the optimized mode parameters (14) taking into account expressions (9) and (10) for variances.
3. Diagrams (curves) of loading of the RP sources (2) and voltages (6) in the system nodes in the given time interval.

6. The main stages of the algorithm for optimal compensation of reactive loads are as follows

The initial data in the optimization problem are simulated (or initial) curves of the active and reactive powers of the nodes (2), presented through average loads using GLD (1). Reactive powers for *G* set of RP sources (including compensating devices) are the main independent variables, determined during the solution process and written in the same form in which the initial diagrams are given (2):

$$Q_{lj} = MQ_l + \sum_{k=1}^{K} \upsilon''_{kl} \Gamma_{kj}, \quad l = \overline{1,G}, \quad j = \overline{1,d}. \qquad (23)$$

Expressions (23) differ from similar expressions (2) in the fact that the diagrams (curves) Q_{lj} of RP generation and, accordingly, expectations MQ_l and coefficients υ''_{kl} are not specified, but they are determined in the process of solving the optimization problem.

The greatest optimal power of compensation at node *i* of *G* taking into account (14) shall be

$$Q_i^{\text{nc}} = MQ_i + k_\beta^{\max} \sigma Q_i. \qquad (24)$$

GRG-based algorithm for optimal compensation of reactive loads starts to work and performs each subsequent optimization step from a possible point $\overline{Z} = (\overline{Y}, \overline{X})$ in accordance with the following steps:

1. Determines a possible vector of the parameters of the basic electric mode corresponding to the load expectations for the initial (starting) point of the optimization search.
2. Computes the objective function and a number of derivatives of the objective function and imbalance functions of $\partial\Phi/\partial Z$, $\partial\Phi/\partial\gamma$, $\partial W/\partial Z$ to model the constraints and form the expression of the reduced gradient and other calculated expressions.
3. Determines the vectors: of the reduced gradient $\overline{\nabla}_r$, the permissible directions of the optimization descent $\overline{\Delta} = (\overline{\Delta}_Y, \overline{\Delta}_X)$ with respect to the independent and dependent variables, and the step size λ of external iterations in the selected optimization direction.
4. Calculates a new vector of the variables as $\tilde{Z}^{(k+1)} = (\overline{Y}^{(k)} + \lambda\overline{\Delta}_Y^{(k+1)}, \overline{X}^{(k)} + \lambda\overline{\Delta}_X^{(k+1)})$ at (k + 1) external step, which in general is infeasible since it is determined by linear translation along $\lambda\overline{\Delta}$ vector relatively to nonlinear constraints of the form of SSM equations.
5. Adjusts the dependent parameters $\overline{V}$, $\overline{\delta}$, $\overline{\gamma}$ to obtain a valid vector of variables $\overline{Z}^{(k+1)}$. The main part of this procedure is the solution of the equations of balance constraints as in (17) for fixed values of the RP sources and the further analysis of the parameters of the basic steady-state mode with subsequent verification of interval constraints (13). If the resulting voltages do not satisfy the controlled constraints (13), it is necessary to obtain new values of the controlled variables (RP sources) by decreasing λ step or by means of fixing the violated limits on the limit values (change of basis), and then re-determine the dependent variables.
6. Controls of the decline of the objective function at (k + 1) iterative step and the fulfillment of the criteria for the termination of the optimization search.

The calculation cycles for 2–6 are iterated until the optimum condition is satisfied i.e. the minimum of the objective function of the total EE losses.

Software for optimization algorithms. These algorithms form the basis of ORESA stochastic optimization software [10] based on algorithms and OPRES instant mode optimization software [11]. ORESA is intended for optimal distributing of reactive loads of existing RP sources over a time interval according to the criterion of minimum EE losses and aims to solve the problems of ES optimal functioning in various mode planning cycles.

Conclusions

We implemented the proposed modification of the generalized reduced gradient method for stochastic modeling of multimode-based electrical systems. The program provides ranges and diagrams of loadings for RP and voltages changes of RP sources and other ES nodes, EE losses in the initial and optimal states avoiding analyzing and optimizing of the modes at each load stationarity interval. The accuracy of ORESA was assessed via statistical tests as a result of direct reproduction of the totality of typical optimal modes on a variety of circuits of 35–220 kV electrical grids and systems: the accuracy achieved for solving this particular operational problem was sufficient for actual practices.

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Development of Methods for Research of Electric Power System Flexibility

Anna Glazunova, *Elena* Aksaeva

Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

Abstract. This paper presents deterministic methods developed to study the flexibility of an electric power system. They rely on the proposition that an electric power system is flexible if power balance is maintained at a considered time. These methods are aimed at determining the combination of the largest loads, which, when exceeded a little, disturb power balance at studied nodes. The paper presents two methods: brute-force optimization and nonlinear optimization. Results obtained using the first method are taken to be a reference for verification of nonlinear optimization output.

1 Introduction

In terms of control of an electric power system (EPS), the flexibility of the EPS that has generating equipment with specific maneuverability characteristics is closely related to its ability to maintain frequency and voltage in the system under uncertainty and variability [1]. Thermal and hydroelectric power plants, which can quickly ramp up and ramp down the load, provide the flexibility of the EPS on the generation side. A variety of load management techniques that have emerged owing to the development of new technologies solve the flexibility problem on the demand side. With the adoption of wind and solar farms, energy storage is becoming an important tool for ensuring flexibility.

A prerequisite for ensuring the EPS flexibility is operating reserves available in the system. The considered reserves or sources of flexibility are:

1. Operating reserves [2], [3], [4].
2. Demand management [5].
3. Energy storage systems [6].

Reserve is used in the case of an unplanned increase or decrease in load. A large number of sources of variable generation (wind, solar) in the EPS require the placement of upward and downward reserves [2]. Authors of [3] provide an overview of the operating reserves used in the USA and Europe. In [4], a methodology for determining the minimum required reserves of Russia's EPSs is given.

Demand-side management is applied to adjust residential load [5], service sector load [6], and industrial load [7].

Energy storage devices are used to store and deliver power during a certain time. Energy storage technologies are based on different physical principles. The following classification of energy storage devices is given in [8]:

– Mechanical: flywheels, hydraulic accumulators, pneumatic accumulators.
– Electric: capacitors and supercapacitors.
– Electrochemical: storage batteries, hydrogen fuel cells, nano-ion cells.

Author of [9] describes Superconducting Magnetic Energy Storage (SMES), which stores energy in a magnetic field created by direct current in a coil with zero electrical resistance, cooled below a characteristic critical temperature.

Researchers in many countries are studying the issues of the flexibility margin, presence, and absence in the power system. There are currently probabilistic and deterministic methods for determining flexibility.

In [11], a deterministic method was proposed to determine the largest variation range of uncertainties at which the power system remains flexible for a specified time within acceptable cost. The flexibility metric is calculated by comparing the obtained range with the target range. In [10], the flexibility residual, which is the difference between the available flexibility and the expected load ramps is calculated for each observation and horizon. Then, the probability that the residual flexibility will be less than zero is determined, which means the probability of insufficient resources in the system. In [11], the flexibility of thermostatically controlled loads (TCLs) when integrated into system-level operation and control is calculated. The authors propose a geometric approach to modeling the aggregate flexibility of TCLs. The set of valid power profiles of individual TCLs is represented by a polyhedron. Aggregated flexibility is calculated as the Minkowski sum. The authors developed an optimization algorithm for approximating polynomial by homotheties of a given convex set represented by a virtual battery model.

The insufficient ramping resource expectation (IRRE) metric to estimate flexibility is calculated in [12]. For each direction and time horizon, a probability distribution of IRRE is formed.

This paper presents deterministic methods developed to study the EPS flexibility. The structure of the paper is as follows. The second section discusses modeling the flexibility of EPS facilities and modeling the archive of loads. The third section presents the ideas of methods, the objective function of calculating the maximum loads and constraints. The fourth section provides a detailed description of the methods for calculating flexibility. The fifth section presents the research results. The sixth section is the conclusion.

2 Modeling the flexibility of EPS elements and load archive

Model of *generator* flexibility of a conventional station

The flexibility available from each generator is determined by the power that can be generated over the considered time horizon and is calculated by the formula [12]

$$F_g = V_{i+} * (t - (1-b) * S_i), \quad (1)$$

where V_{i+} is load ramp time (MW/min), t is the considered time horizon, S_i is the start-up time (hour), b is the binary on-line variable when a generator is on $b = 1$.

Model of battery flexibility

The flexibility available from the battery is determined by its state of charge. If the battery is charged within the specified limits

$$SOC_{\min} < SOC(t) < SOC_{\max}, \quad (2)$$

then the power output is calculated by the formula:

$$F_B = P_{max}, \quad (3)$$

otherwise:

$$F_B = 0 \quad . \quad (4)$$

Model of system flexibility

System flexibility is determined as total flexibility available from all units of flexibility

$$F_S = \sum_1^m F_g + \sum_1^n F_B , \quad (5)$$

where m is the number of generators at conventional stations, n is the number of batteries.

Modeling of load archive

The load at each given node *i* is calculated by the formula [13]:

$$P_i(z_i) = z_i P_i^{min} + (1 - z_i) P_i^{max} \quad , \quad (6)$$

where $0 \le z_i \le 1$, P_i^{max} is the upper limit of load at node *i*, P_i^{min} is the lower limit of load at node *i*.

The archive of loads is formed according to the following algorithm:

1. Set the minimum and maximum values of the active load. Form vectors P^{min} and P^{max}, $P^{min} = (P_1^{min}, P_2^{min} \dots P_l^{min} \dots P_R^{min})$, $P^{max} = (P_1^{max}, P_2^{max} \dots P_l^{max} \dots P_R^{max})$, where R is the number of given load nodes.
2. Set vector z $z = (z_1, z_2, ..z_i, ..z_R)$. Specify the number of steps N, which determines the size of the archive. Calculate the step of changing the load by the formula

$$step = 1/N . \quad (7)$$

Initial condition: z= (0) is the zero vector, k =1 is the step number.

3. Calculate the value of load by (6).
4. If $k = N * R$, go to item 7, otherwise $k = k+1$, go to item 5.
5. Calculate z^{k+1} by

$$z^{k+1} = z^k + step . \quad (8)$$

6. Go to item 3.
7. Determine all possible load values.
8. The end. The result is a modeled archive of loads P^{LOAD}, the dimension of the archive is $[L \times R]$ where $L = C_N^R$.

3 The idea of the methods. Objective function and constraints

This paper presents deterministic methods based on the proposition that an EPS is flexible if a power balance is maintained at the considered time. An increase in the load leads to a decrease in the flexibility of the system, this is why one of the key points in the analysis of the EPS flexibility is the availability of information about the maximum possible loads. The developed methods are aimed at determining the combination of maximum loads which, when exceeded a little, disturb the power balance at the studied nodes.

The objective function is the maximum sum of the differences between the predicted and simulated loads at nodes with uncertainty over a given time. It is written as follows:

$$\sum_{i=1}^{r} (\bar{P}_i - P_i(z_i)) = \sum_{i=1}^{r} \Delta P_i(z_i) \quad \to max \quad (9)$$

where r is the number of nodes with uncertainty.

For clarity of presentation of the constraints used to solve this problem, all nodes are divided into three types:

- Uncontrolled nodes. Generator nodes where control actions are not performed or load nodes at which there is no uncertainty P^{CONST};
- Controlled nodes. Generator nodes where the control actions P^{CA} are performed;
- Nodes with uncertainty. Load nodes at which power changes.

The constraints are as follows:

$$\Delta P_j = 0 \ , \quad (10)$$

$$P_{i-j} < P_{i-j}^{max} \ , \quad (11)$$

$$P_i^{min} < P_i^{CA} < P_i^{max} \ , \quad (12)$$

$$0 \le z_i \le 1 , \quad (13)$$

where in (9) $\overline{P_i}$ is the forecast (pseudo measurement) of active power at node *i*, which has uncertainty; $P_i\ (z_i)$ is the relationship between active power and value *z*, which is responsible for a change in the value of power at node *i*. Constraint (10) is the power balance at node j (any type of node), or the power balance at EPS, (11) is the constraint on line transfer capability; P_{i-j}^{max} is the capability limit of transmission line *i-j*, (12) limits the range of control actions at the controlled node, (13) is a constraint on the parameters of optimization.

4 A detailed description of the developed methods

The paper presents two methods for determining flexibility:

1. Brute-force optimization.
2. Nonlinear optimization.

4.1 The brute-force optimization

The brute force optimization is used to process all combinations of possible loads in EPS to determine load combinations that, when slightly exceeded, make the system inflexible.

The brute force optimization algorithm is described below.

1. Start. The vector of injections is $P = (P^{CONST},\ P^{CA},\ P^{L})$. Calculate a load flow solution (LFS). $P^{ref} = P^{L}$, where P^{L} is a load at the nodes with uncertainty at a given time. Initial conditions are $P^{rab} = P^{ref}$; $i = 1$.
2. Perform the control action P^{CA} according to $P^{LOAD}(i)$
3. Form the vector of injection $P = (P^{CONST},\ P^{CA},\ P^{LOAD}(i))$.
4. Calculate a load flow solution.
5. If the process has converged, go to the next step. Otherwise, go to step 9.
6. Check the constraints (formulas 10-13).
7. If the constraints have been satisfied, go to the next step. Otherwise, go to step 9.
8. Compare the vectors $(P^{rab} - P^{ref}) < (P^{LOAD}(i) - P^{ref})$. When the condition is met, save the vector $P^{LOAD}(i)$, $P^{rab} = P^{LOAD}(i)$. Use Euclidean distance and distance of Chebyshev to compare the two vectors.
9. If $i = i + 1$. $i = L$, go to step 10, otherwise, go to step 2.
10. The end. The result: $P^{LOAD}(i)$ is a combination of the largest loads in EPS, which are possible under the given conditions.

4.2 Nonlinear optimization

Nonlinear minimization refers to the problem of nonlinear programming and is performed in Matlab. As a result, the values of optimization parameters used for the calculation of active power P_i^{calc} at the nodes with uncertainty are determined. In this study, the optimization parameter is z (formula (6)). Therefore, the objective function (9) and constraints (10), (11) should be written using the parameter *z*. Constraint (12) is taken into account by the objective function.

The objective function.

Each element of (9), taking into account (6), can be written as:

$$\Delta P_i(z_i) = P_i - P_i\ (z_i) = \bar{P}_i - P_i^{max} + z_i\left(P_i^{max} - P_i^{min}\right) = D_i + F_i z_i \quad (14)$$

$$\overline{P_i} - P_i^{\max} = D_i \ , \quad (15)$$

$$P_i^{\max} - P_i^{\min} = F_i \ . \quad (16)$$

D_i, F_i remain the constant values during the optimization process.

The objective function can be written as follows

$$D_i + z_i F_i + \ldots D_R + z_R F_R + z_r F_r \to max \quad (17)$$

and after excluding all constant values it has a compact form:

$$\sum_{i=1}^{R}(-F_i z_i) - F_A z_A \to max. \quad (18)$$

Constraints

After some transformation, power balance in EPS

$$\sum_{i=1}^{un} P_i + \sum_{j=1}^{n-un} P_j\left(z_j\right) = 0 \quad (19)$$

can be written as follows

$$\sum_{1}^{n-un} F_j \ \ Z_j = \sum_{1}^{u-un} P_j^{max} + \sum_{1}^{un} P_i \quad , (20)$$

where n is the number of nodes in EPS, un is the number of uncontrolled nodes.

Building the balance and transmission constraints, which are needed to ensure that all state variables be within their limits, requires the values of power flows in the lines. In this study, power flows in the lines are calculated using the PTDF (power transfer distribution factor) method [15]. PTDFs describe how active power flows in lines are changed if power injection at the node is increased or decreased.

The power transfer distribution factor in the line limited by nodes *i*, *j* is calculated in advance as follows

$$k_{i-j} = \Delta P_{i-j} / \Delta P_A(z_A), \quad (21)$$

$$\Delta P_A(z_A) = \sum_{i=1}^{R} \Delta P_i(z_i), \quad (22)$$

where ΔP_A is an increase (decrease) of the active power at the node, where the control action is performed ΔP_{i-j} is an increase (decrease) of the active power flow in line *i-j*, ΔP_i is an increase (decrease) of active power at the node with uncertainty.
For the problem of nonlinear optimization, the coefficients k_{i-j} are the initial data.

The power balance at nodes with uncertainty is compiled as a balance of power increments

$$\Delta P_i + \sum_{j=1}^{G} \Delta P_{i-j} = b, \quad (23)$$

$$\Delta P_{i-j} = \Delta P_A(z_A) k_{i-j}. \quad (24)$$

where ΔP_A is an increase (decrease) of active power at node *A*, ΔP_{i-j} is power flow increments, *G* is the number of adjacent nodes, b is convergence tolerance. Given (14), (24), the constraint at node *i* is written as:

$$F_A Z_A \sum_{j=1}^{g} k_{i-j} + F_i Z_i + (P_i - P_i^{max}) \sum_{j=1}^{G} k_{i-j} = b \quad .(25)$$

Active power flows in lines are monitored according to (11)

$$P_{i-j} + k_{i-j} \Delta P_A(z_A) < P_{i-j}^{max} \quad (26)$$

when transferring constant values to the right-hand side (taking into account (14) for i = A), constraint (26) has the form

$$F_A k_{i-j} z_A, < P_{i-j}^{max} - P_{i-j} - k_{i-j}(P_A - P_A^{max}) \,. \quad (27)$$

4.3 Determination of EPS flexibility

The flexibility of EPS is determined as follows:

$$F_S = \sum_{i=1}^{R} (P_i^{calc} \quad - P_i^{forec}). \quad (28)$$

where P_i^{calc} is a calculated (simulated) value of the active load at node *i*; P_i^{forec} is a forecast of active load at node *i*. If

$$F_s > 0,$$

then EPS is flexible.

5 Case study

5.1 Describing a test scheme and scenario

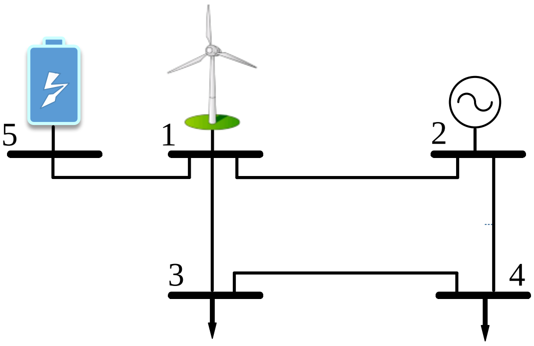

Fig.1. Test scheme

Calculations are performed using a scheme consisting of 5 nodes and 5 lines (figure 1). Nodes 3 and 4 are the nodes with uncertainty. Node 1 stands for a wind farm. Node 5 is a battery. Node 2 (conventional plant) is a controlled node where control actions are power generation required to ensure balance in the EPS, given the forecast of generation from the wind farm and the power supplied by the battery. Nodes 1 and 5 are considered to be uncontrolled.
The calculations are performed according to the scenario: it is necessary to determine a combination of the largest loads at nodes 3, 4 four minutes ahead with known:

- forecasts of load values at nodes 3 and 4 (P^{forec}), which are assumed to be the lower load limits;
- forecast of active power output at the wind farm;
- forecast of active power output at the battery;
- maximum load values, which are the upper load limits;
- maximum value of active power generation at node 2;
- capacity limits of transmission lines.

It is assumed that it takes 4 minutes for the entire available reserve at the conventional plant to be switched on and that the battery produces maximum power.

Table 1. Initial data (MW).

Number of nodes	P^{max}	P^{min}	P^{forec}
1			
2	32	20	20
3	37	23	23
4	23	13	13
5			

The flexibility of a 5-node EPS is calculated by two methods: the brute-force optimization and non-linear optimization. The results of the first method are taken to be a reference.

5.2 The brute-force optimization applying

Using this method, the vector of active loads is determined among 900 pre-created vectors that differs as much as possible from the forecasted loads when the following constraints are met: iteration convergence tolerance is 0.05 MW (0.05 MVAr), the upper limit of power generation at node 2 is 32 MW, active power flows in all lines should be within transfer capability. The difference between the two vectors is measured by the Euclidean distance and the Chebyshev distance. As a result of applying this method, the load flow solution with the maximum possible loads at nodes 3 and 4 is calculated. Figure 2 shows the values of active power injection which are the results of the calculation of three load flow solutions: the obtained loads at nodes 3 and 4 are equal to the forecast loads (Steady state); the obtained loads at nodes 3 and 4 are the maximum loads according to Euclidean distance (SSeuclidean) and Chebyshev distance (SSchebyshev), respectively.

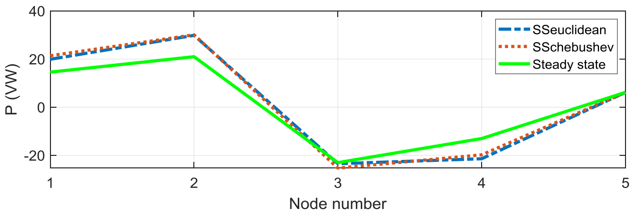

Fig. 2. The active power injections

5.3 Nonlinear optimization applying

Solving the problem which applies the nonlinear optimization, developed in Matlab, can be divided into several steps.
Step 1. Calculate coefficients (k_{i-j}) according to (21).
Step 2. Describe the objective function and constraints in the equivalent forms which are suitable for the programs, developed in Matlab.
The objective function

$$\left(\bar{P}_2 - P_2(z_2)\right) + (\bar{P}_3 - P_3(z_3)) + (\bar{P}_4 - P_4(z_4)) \to max \quad (29)$$

in an equivalent form is written as follows:

$$-z_2F_2 - z_3F_3 - z_4F_4 \to max. \quad (30)$$

Similar transformations are performed for constraints.
EPS active power balance:

$$P_1 + P_2(z_2) + P_5 - P_3(z_3) - P_4(z_4) = 0 \quad (31)$$

is:

$$F_2Z_2 + F_3Z_3 + F_4Z_4 = P_3^{max} + P_4^{max} - P_2^{max} - P_1 \ - P_5 \quad (32)$$

Active power balance at nodes 3,4

$$\Delta P_3 + \Delta P_{3-1} + \Delta P_{3-4} = 0, \quad (33)$$

$$\Delta P_4 + \Delta P_{4-2} + \Delta P_{4-3} = 0, \quad (34)$$

are transformed into the equations:

$$F_2Z_2(k_{3-1}+k_{3-4}) + F_3Z_3 = (P_3 - P_3^{max}) + (P_2 - P_2^{max})(k_{3-1}+k_{3-4}) + b \ . \quad (35)$$

$$F_2Z_2(k_{4-2}+k_{3-4}) + F_4Z_4 = (P_4 - P_4^{max}) + (P_2 - P_2^{max})(k_{4-2}+k_{3-4}) + b \ . \quad (36)$$

Transmission constraints

$$P_{i-j} + k_{i-j}\Delta P_2(z_2) < P_{i-j}^{max} \quad (37)$$

are transformed into the following inequalities:

$$F_2k_{1-2}z_2, < P_{1-2}^{max} - P_{1-2} - k_{1-2}(P_2 - P_2^{max}) \ , \quad (38)$$

$$F_2k_{1-3}z_2, < P_{1-3}^{max} - P_{1-3} - k_{1-3}(P_2 - P_2^{max}) \ , \quad (39)$$

$$F_2k_{1-5}z_2, < P_{1-5}^{max} - P_{1-5} - k_{1-5}(P_2 - P_2^{max}) \ , \quad (40)$$

$$F_2k_{2-4}z_2, < P_{2-4}^{max} - P_{2-4} - k_{2-4}(P_2 - P_2^{max}) \ , \quad (41)$$

$$F_2k_{3-4}z_2, < P_{3-4}^{max} - P_{3-4} - k_{3-4}(P_2 - P_2^{max}) \ . \quad (42)$$

Optimization parameters constraints are:

$$0 \le z_2 \quad \le 1, \quad (43)$$

$$0 \le z_3 \quad \le 1, \quad (44)$$

$$0 \le z_4 \quad \le 1. \quad (45)$$

The objective function in the Matlab codes is:
[z,fval]=fmincon(@funn,z0,ineq_l,ineq_r,A,B,zmin,zmax)
;
Function f= funn; $f = -F_2z_2 - F_3z_3 - F_4z_4$; initial approximation of optimization parameters is :$z0 = [0\ 0\ 0]$.
A compact matrix formulation is used for representing constraints.
Equality constraints (A, B) are:

A			B
F_2k_{1-5}	0	0	$(P_2 - P_2^{max})k_{1-5}$
$F_2(k_{1-3} + k_{3-4})$	F_3	0	$\bar{P}_3 - P_3^{max} + (P_2 - P_2^{max})(\sum_{j=1}^{G} k_{ij})$
$F_2(k_{4-2} + k_{3-4})$	0	F_4	$\bar{P}_4 - P_4^{max} + (P_2 - P_2^{max})(\sum_{j=1}^{G} k_{ij})$
F_2	F_3	F_4	$\sum_1^{u-un} P_j^{max} + \sum_1^{un} P_i$

Inequality constraints (L, R,) are:

L			R
F_2k_{1-2}	0	0	$P_{1-2}^{max} - P_{1-2} - k_{1-2}(P_2 - P_2^{max}$
F_2k_{1-3}	0	0	$P_{1-3}^{max} - P_{1-3} - k_{1-3}(P_2 - P_2^{max})$
F_2k_{1-5}	0	0	$P_{1-5}^{max} - P_{1-5} - k_{1-5}(P_2 - P_2^{max})$
F_2k_{2-4}	0	0	$P_{2-4}^{max} - P_{2-4} - k_{2-4}(P_2 - P_2^{max})$
F_2k_{3-4}	0	0	$P_{3-4}^{max} - P_{3-4} - k_{3-4}(P_2 - P_2^{max})$

Step 3. Perform optimization. The result is a vector of optimization parameters (z) with given constraints.
Step 4. Interpret the results. Calculate the load values at nodes 3, 4, and the generation at node 2, according to formula (6). Figure 3 shows the active power values at nodes 2, 3, 4 before (SS), and after (SS max) optimization.
Step 5. Check if the obtained state variables meet the given limits. If the result is negative, invalid state variables are assumed to be corrected.

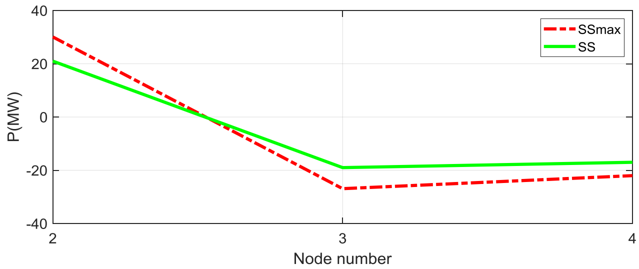

Fig. 3 Active power at nodes 2, 3, 4 before (SS) and after (SS max) optimization

5.4 Analysis of results

The results obtained by the two methods are summarized in Table 2. The last line shows the flexibility calculated by (28) using different methods. Table 3 presents the values calculated by the formula:

$$\Delta F_{dist} = \left|F_{nonl} - F_{dist}\right| \quad , \qquad (46)$$

where F_{dist} is the EPS flexibility (F_s Table 2) calculated by the brute-force method using Euclidean distance (8.8MW) or Chebyshev distance (9.3MW), F_{nonl} is EPS flexibility (12.9 MW, Table 2) calculated by nonlinear optimization.

Table 2. Result of calculations (MW).

	Initial data		**Calculated data**		
Number of nodes	Forecast P_i^{forec}	Max P_i^{max}	Brute force P_i^{calc}		Nonlinear P_i^{calc}
			euclid	cheb	
1	13.9				
2	21	30	31		30
3	-23	*37*	**-23.4**	**-25.5**	**-26.9**
4	-13	*25*	**-21.4**	**-19.8**	**-22**
5	6.2	6.2	6.2		
F_s			8.8	9.3	12.9

Table 3. Absolute difference between two values of flexibility.

Difference	$\Delta F_{dist(i)}$ **(MW)**		$\sum \Delta F_{dist}$ **(MW)**
	Number of nodes		
	3	4	
$F_{nonl} - F_{eucl}$	3.5	0.6	4.1
$F_{nonl} - F_{cheb}$	1.4	2.2	3.6

The active powers, which are the result of three load flow solution problems and the result of the nonlinear optimization, are shown in Figure 4.

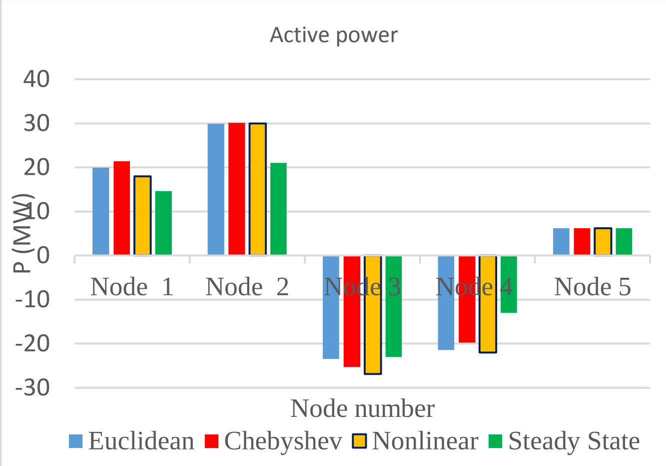

Fig. 4. Diagram of active power

Analysis of the results presented in Table 2 and Figure 4 shows that

• Comparison of the given maximum loads (italics) with the maximum possible loads calculated by different methods (bold) shows that the loads calculated using nonlinear optimization are closer to the given maximum loads;

• The flexibility of the considered EPS is 12.9 MW (formula 28) according to nonlinear optimization, 8.8 MW and 9.3 MW according to the brute-force method when using the Euclidean distance and Chebyshev distance, respectively, as a metric.

Table 3 shows that the nonlinear optimization results are closer to the results obtained by the brute-force method in the case of the Chebyshev distance used as a metric (4.1> 3.6).

Findings have revealed that the calculation of load flow solution in the case where the result of nonlinear optimization is used as the initial data, requires that reactive power be added at node 3 for all variables to be within given limits.

6 Conclusion

The paper describes the methods for determining the flexibility of the electric power system: the brute-force and nonlinear optimization. In the brute-force method, the Euclidean distance and the Chebyshev distance are used as a metric for comparing the two vectors. For nonlinear optimization, a function developed in Matlab is used.

The nonlinear optimization results are analyzed. The analysis shows that the loads calculated using nonlinear optimization are closer to the given maximum loads. The study indicates that to ensure the reactive power balance in the EPS at the obtained load values, it is necessary to increase the reactive power at node 3.

A comparative analysis of the results has shown that the reference for the verification of the nonlinear optimization output should be the results calculated by the brute-force algorithm based on the Chebyshev distance as a metric.

An algorithm was developed to create an archive of loads required for the brute-force method.

Acknowledgment

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REFORMING THE ELECTRIC POWER INDUSTRY OF RUSSIA: MATTERS OF CONCERN, CHALLENGES, AND SOLUTIONS

Valerj Stennikov[1], and *Vladimir* Golovshchikov[1, *]

[1] Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk

Abstract. The results of reforms in the Russian electric power industry and the main problems facing the industry that hinder not only its development, but also reduce the efficiency of its operation are presented. The analysis of the current regulatory framework in the electric power industry is provided.It is shown that the ongoing process of digitalization and intellectualization of the electric power industry will fail to attain its full potential unless large-scale technological modernization of the industry is implemented, and both directions should be pursued simultaneously. The wholesale and retail electricity and capacity markets created, as a result of the electricity reform are of low efficiency and call for introducing significant changes. In order to carry out the necessary transformations, some priority measures are proposed to improve the state of affairs in the Russian electric power industry and ensure its prospective development.

Introduction

The problems accumulated over time in the electric power industry of the Russian Federation (RF), caused by the ongoing reform of the industry, for many years keep going the discussion among the academic and engineering community and representatives of authorities at various levels, from federal to municipal [1-10].

At that, both issues of conceptual nature (ways and methods of development of the industry, competition, market relations) and current issues, including equipment health and modernization, informatization, tariff formation, etc. are covered.

At present, the process of digitalization of the country's economy in general and the electric power industry in particular is growing in intensity at the initiative of Russia's top leadership. Various rationales are given to substantiate this direction of development, the most common of which is that "digitalization is a driver of electric power industry development and a step towards introducing artificial intelligence into the industry". In recent years, almost all major events in Russia on the electric power industry have included in their agenda digitalization issues ranging from standardization, to cyber security, to plans for the future. [11, 12]. The importance of the "digitalization of the electric power industry" is beyond any doubt, as it can have a synergistic effect. With its introduction the possibility of moving away from predictive and preventive maintenance (PPM) to repairs based on the analysis of equipment health, which is enabled by the mature digital fault detection system [12], is considered. This will make it possible to extend the operation of a significant number of power facilities, whose official service life has already expired, by applying "risk-oriented management". The national leader in the Russian Federation with respect to digitalization in the power industry is PJSC Rosseti that has developed and has been implementing "The vision statement of digitalization of grids for 2018-2030" with the required amount of investment of 1.3 trillion rubles.

While supporting the digitalization of the electric power industry as a promising direction, it is necessary to pay attention to the existing numerous problems in the industry, many of which should have been solved by now [13]. In order to successfully implement the process of digitalization of the electric power industry and obtain the greatest effect from its results, it is necessary to solve a set of technical, organizational, economic, regulatory, and other issues. First of all, it is required to analyze the goals and objectives of the reform of the industry, assess its results, and identify the most negative aspects. On the basis of this analysis one is to formulate (or notably adjust the existing approaches) the Vision statement of the electric power industry operation and development, establish an appropriate model, and, on their basis, develop an appropriate strategy and specific plans for its implementation, which will organically incorporate the digitalization of the industry.

The prime movers behind the reform of the electric power industry, who were part of the Russian leadership in the late 1990s and early 2000s, were known to rely on poorly studied international experience of similar

* Corresponding author: vladgo@isem.irk.ru

reforms and believed that the establishment of competitive relations in the industry will ensure its efficient development. Conceptual and legislative support for the electric power industry reform process at the first stage was provided by the following documents: 1) Vision statement "Strategies of RAO UES of Russia" (Vision statement "5+5" (1998-2003 and 2003-2008). The main goals of the "5+5" vision statement were aimed at improving the financial condition of the then unified electric power holding company RAO UES of Russia. These objectives had largely been met by 2008. Technological development issues were unfortunately sidelined. Perhaps this was due to the fact that their urgency was significantly reduced as a result of a decrease in consumer demand caused by the slump in industrial production. However, this only pushed back the need for technical re-equipment of the electric power system and aggravated the situation under growing demand for electricity. The next stage of reforming the electric power industry was regulated by such documents as Resolution of the Government of the Russian Federation No. 526-p "On reforming the electric power industry" (July 2001); 3) Federal Law No. 35-FZ "On the electric power industry" (2003). They set the goals, objectives, and directions of the reform, while the assessment of the consequences of these objectives was again not carried out. As a result, despite certain advances, a number of anticipated results were not achieved.

1. Efficient competitive markets for electricity and heat have been created on neither the production nor consumption sides. Major energy companies and shareholders have enjoyed significant preferential advantages in these markets.
2. Cross-subsidization (between energy consumer groups and territories such as "Far East", "Crimea", etc.) has been retained. There are more and more examples of "the manual override" based on instructions from "the very top" in various areas of life in the country.
3. The balance of interests of all players of energy markets is not ensured. The primary benefits were secured by generating and power supply companies. At the same time, CHP plants operating in two markets, those of electricity and heat, found themselves at a disadvantage. The peculiarities of their operation, as well as those of heat supply in general, were ignored during the reform.
4. Efficient fuel markets for power plants have not been formed. Gazprom is in possession of an absolute monopoly in the gas market. The situation in the coal market is slightly better, but the monopolistic pressure is felt there as well.
5. Tariffs for electricity and heat (capacity) for end consumers continue to grow, with rates generally exceeding the inflation rate.
6. Proclaimed measures to reduce costs of generating, grid, and power supply companies fail to work as the basis for tariff reduction.
7. The development of the electric power industry is due to the growth of tariffs for consumers, while market mechanisms (bonds, shares, etc.) are practically not employed.
8. Coordination and efficient management of most of the country's power sector was lost after the reorganization of the RAO UES holding company. The fragmentation of the industry into many companies of different sizes and lack of competition has led to inefficient operation and development of the electric power industry. The energy industry is gradually losing its infrastructure functions, becoming a mere supplement of some industries and even that of some major consumers.
9. The Ministry of Energy of the Russian Federation has failed to develop into a full-fledged hub of expertise and governance of the electric power industry (the oil and gas industry are at the top of the Ministry's agenda).
10. The aging process of the main energy facilities (at least 60 percent on average) shows no signs of abatement and outpaces the ongoing efforts to modernize and develop the energy facilities, despite the introduction of such arrangements as Capacity Delivery Agreements (CDA) and CDA+ (for the modernization of heat power industry facilities), RAB regulation (Fair ROI), the current tariff policy, etc.
11. The existing and constantly growing legal and regulatory framework governing relations in the electric power industry proves extremely complex and oftentimes inconsistent.
12. The law enforcement practice of some important legal acts (e.g. Federal Law No. 261-FZ "On Increasing Energy Efficiency", Decree of the Government of the Russian Federation No. 511-r, etc.) is unsatisfactory.
13. Constructive feedback given by the academic and engineering community on how to improve the situation in the electric power sector is received and heard by official authorities, but decisions are either not made or implemented too slowly.

The negative results of the electric power industry reform (with some of them listed above) that continues in the sluggish fashion to this day, are due to the fact that the decisions made were not thought out well enough, with the specifics of the Russian electric power industry and many years of previous experience of successful operation of the electric power industry ignored. This could not but have a negative impact on results and the achievement of targets.

Among the priority measures contributing to the overcoming of negative processes and the consistent transition of the electric power industry to a new innovative path of its development, the following should be highlighted:

- Analysis and evaluation of the results of the electric power industry reform, including all issues discussed within the framework of the discussion held by the academic and engineering community [1, 2, 14-16].
- Creation of a working group to summarize the results of the reform and develop practical mandatory measures to eliminate its negative consequences [1, 2].

At the same time, it is necessary to start implementing priority measures:

1. Ensuring that all power plants can enter the wholesale and retail energy and capacity markets.
2. Consolidation of territorial (distribution) power grid companies on the basis of the most efficient of them, which is a mandatory requirement as per Decree of the

Government of the Russian Federation № 511-r (dated April 3, 2013).
3. Providing power grid companies with an opportunity to carry out power sales activities based on economic feasibility, as there is no real competition among power supply companies for consumers.
4. Consolidation of retail electricity and heat markets into the "Unified retail electricity and capacity market" that ensures a positive effect for all players of this market [17].
5. Gradual transformation of the wholesale electricity and capacity market into a balancing market.
6. Formation of differentiated tariffs in the integrated power grid for services related to electric power transmission via the grids. Such tariffs should factor in the real costs of electricity transmission to specific consumers.
7. Ensuring unconditional financial responsibility for quality and reliability of power supply.
8. Embarking on the most up-to-date technological directions in the development of the electric power industry, including "digital technology", "smart power systems", "artificial intelligence", etc., the implementation of which is reasonable to launch in the form of pilot projects with the analysis of the results thus obtained and further development of the projects.

Conclusion

The main goals and tasks of reforming the Russian electric power industry, formulated more than two decades ago, have not been achieved. Efficient competitive electricity and capacity markets have been created on neither the production nor consumption sides. Hopes for attracting capital have not been fulfilled either as all development is carried out at the expense of consumers.

For the efficient development of the industry, it is necessary to analyze thoroughly the results of the reform. Based on the analysis and taking into account the already available constructive feedback, one is to develop a new vision statement for the development of the Russian electric power industry, while factoring in both the internal situation and external trends, including challenges and threats. The new vision statement should provide guidelines for the development of the strategy of the Russian electric power industry and specific plans for its implementation. Some important and urgent directions can be implemented in the short term (a year or two) and medium term (three to five years).

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Models for the development of multi-level gas supply systems

Nikolay Ilkevich[1], *Tatyana* Dzyubina[1, *], *Zhanna* Kalinina[1]

[1]Melentiev Energy Systems Institute of Siberian branch of Russian Academy of Science (ESI SB RAS), department of pipeline and hydraulic systems, Lermontov street 130, Irkutsk, Russia, 664033

Abstract. The article shows the relevance of hierarchical modeling in substantiating the optimal development of the gas industry in modern conditions. The questions of aggregation of calculation schemes of gas supply systems are considered. A set of mathematical models is proposed that allows us to consider it at three levels of the hierarchy, taking into account the improvement, refinement and detail of the information base being developed. Models are considered: 1) optimization of the structure of gas supply systems; 2) optimization of se-zone gas consumption, analysis and synthesis of reliability; 3) optimization of parameters of the main gas-wire taking into account reliability.

The created information base on gas supply systems of the Russian Federation includes dynamics of development of demand for natural gas in the domestic and foreign markets, aggregated technical and technological, cost and reliability characteristics of system objects (main gas lines, fields, underground gas storage facilities) and forecasts of gas production.

On the basis of mathematical models, studies of the development of multi-level gas supply systems in Russia for the period up to 2030 are performed: the rates and directions of development of the gas transport structure, commissioning of new fields and optimal gas flows through the Russian Federation are substantiated. A systematic assessment of the means of regulating seasonal unevenness of gas consumption and the means of ensuring the reliability of the North-Western district of the Russian Federation was carried out.

1 Introduction

The unified gas supply system (UGSS) of Russia is a unique system of large size, which is not equaled in the world. The problem of hierarchical modeling of its optimal development began to be studied at the end of the last century [1, 2], and continues to be studied now, including in the ISEM SB RAS [2-4]. Questions of multilevel modeling are also raised abroad [5-17]. Various tasks of forecasting the world and national development of gas supply systems (GSS) are solved (gas flow models are usually used), each at its own hierarchical level. There are world energy [5-7] and gas models[8-14], models of the European [15, 16] and national market [17]. Gas flows, demand, production, gas prices, and the necessary new capacities of gas transport corridors and gas liquefaction plants are projected for different perspectives. Information exchange of data can be carried out between individual models of different hierarchical levels.

The size and complexity of the GSS, various aspects of their functioning and development make it necessary to consider them at different levels of the hierarchy, taking into account the improvement, refinement and detail of the information base being developed. Therefore, research in the field of multi-level modeling of development in the gas industry is an urgent task.

The object of research is the gas industry, which includes gas supply systems that supply consumers with hydrocarbon gases – the most important raw material resource for obtaining chemical products and environmentally friendly types of energy.

The article considers hierarchical modeling of optimal development of multi-level gas supply systems, including mathematical models of their development, models of reliability analysis and synthesis, and optimization of object parameters with regard to reliability.

2 Aggregation of gas supply companies

Aggregation of the calculation scheme is understood as modeling of the real gas supply scheme in an enlarged form [18]. Such a scheme should reflect the real scheme with a certain accuracy, preserving its required properties. The resulting aggregated scheme is characterized by a smaller number of nodes and connections, which makes it easier to analyze the results in order to develop the necessary solutions and use the information for calculations in mathematical models.

The GSS is represented as a directed graph and is considered as a set of three sub-systems: gas sources, main transport networks, and consumers.

The source objects are all enterprises that supply gas to the main transport network: integrated gas treatment plants, gas chemical complexes and underground gas storage facilities (UGS) that operate on gas extraction. A

* Corresponding author: tvleo@isem.irk.ru

gas producing enterprise is designated as an aggregated source unit, where gas production is determined by the total production of the fields.

Gas main transport enterprises consist of sections of main gas pipelines (MG), including the linear part (LP) and compressor stations (CS) located on it. Aggregated multi-line MG are represented as single-line arcs, which are characterized by the total capacity of gas pipelines and the total length of all MG going from one node to another.

Consumer objects take gas from main gas pipelines, as well as UGS, if they are working for gas injection at the moment in question. Consumption nodes are aggregated on an administrative and geographical basis, with the Russian Federation's constituent entities serving as consumers. The demand for natural gas of the aggregated consumer is determined from the condition of equality of needs in the initial and aggregated schemes.

If the CS does not match the aggregated consumer node, it is designated as a branch node in the diagram. This node is necessary to correctly reflect the main gas flows in the diagram. The need for gas in the branch node is not set. The entire need of the subject is concentrated in the consumer node.

To determine the aggregated technical and economic characteristics of each arc and node of the aggregated calculation scheme, we use statistical data from PJSC Gazprom [19], and also take the original technical and economic information on existing gas production and gas transportation enterprises.

The final operation for forming the design scheme is "gluing" all aggregated schemes into one, "gluing" is carried out along the boundaries of the gas transportation enterprises. For example, a complex multi-line UGSS (Fig. 1) is presented as an aggregated calculation scheme. Existing large-scale projects of gas transport systems are superimposed on the aggregated existing scheme of the UGSS by the years of the planned periods. Thus, a redundant aggregated calculation scheme is created that reflects the stages of development of the GSS for the studied perspective (Fig. 2).

Based on the data [19], an information base is also being developed for multi-level modeling of the development of Russian gas supply systems for the period up to 2030 [4]. It shows the demand for gas in the nodes of the scheme, the upper limits on production and transport, as well as costs and coefficients showing the gas consumption for own needs and leaks. It also provides estimates of the dynamics of demand for natural gas in the Russian Federation and its export supplies (the state and prospects for the development of gas supply markets in the Russian Federation); technical and economic indicators for existing and new gas production enterprises and gas transportation systems.

The completed methodological developments allow us to set and solve complex tasks for the optimal development of gas supply systems in the future.

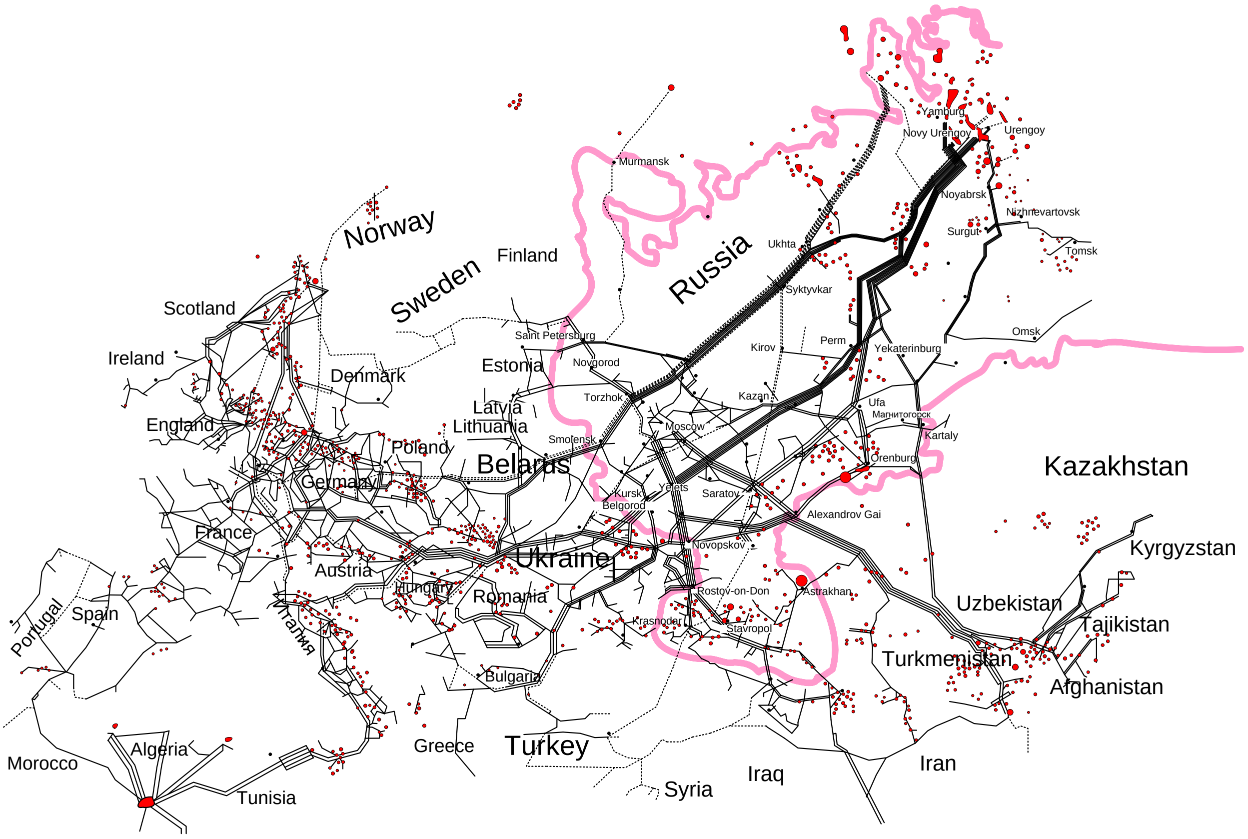

Fig. 1. Unified gas supply system.

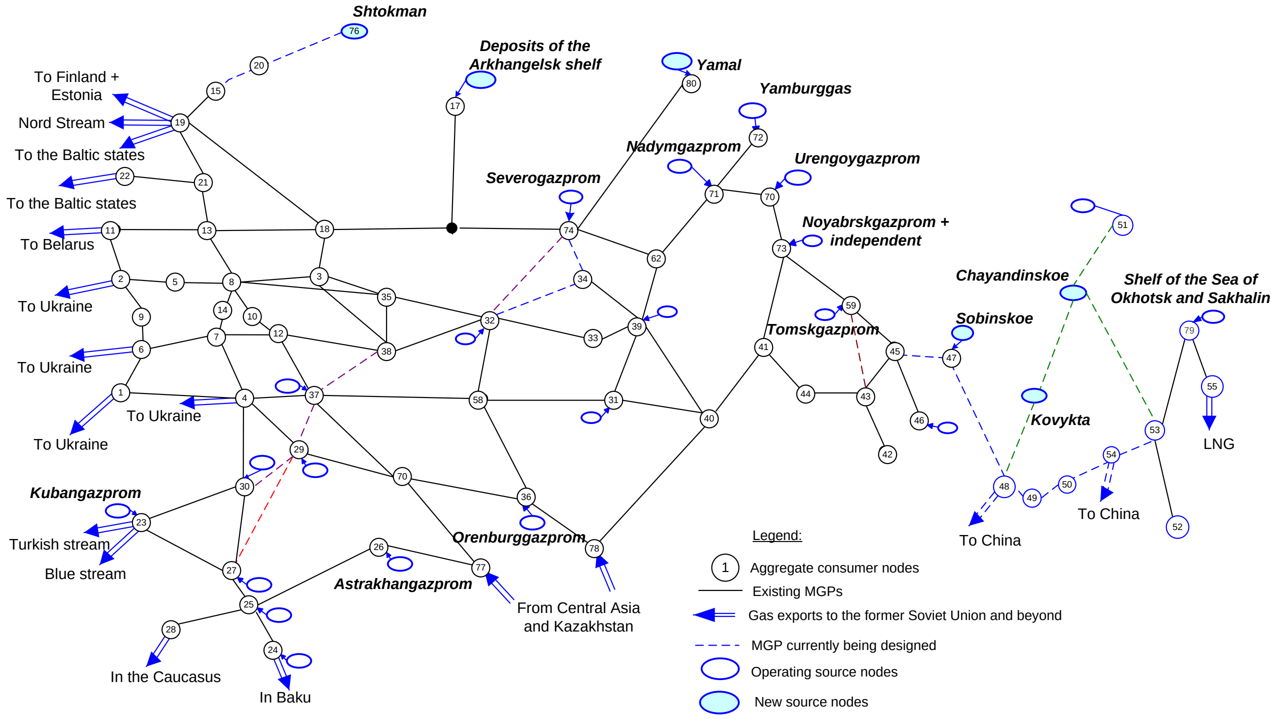

Fig. 2. Redundant aggregate calculation scheme of the GSS of the Russian Federation.

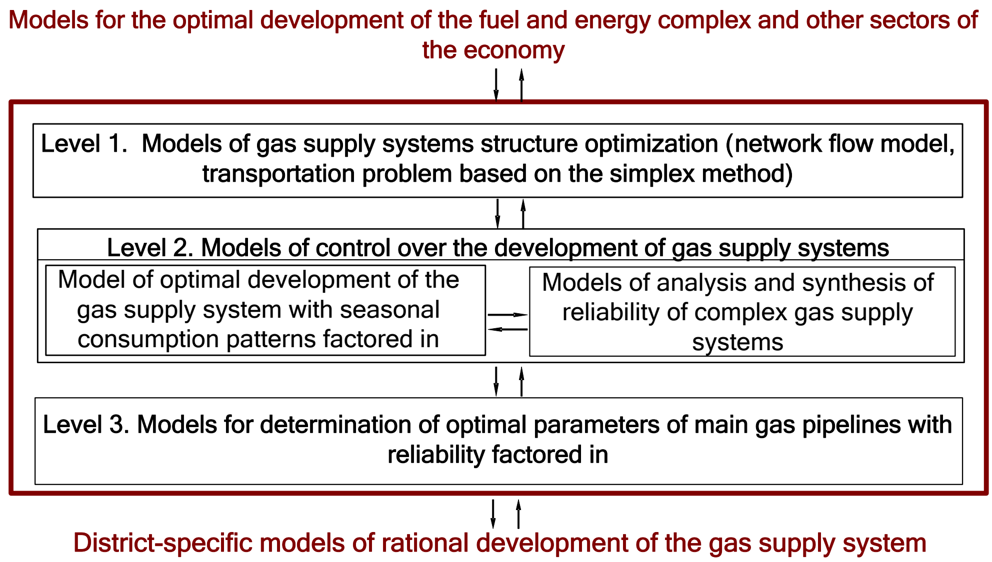

Fig. 3. Models for solving problems of optimal development of gas supply systems.

3 Aggregation Complex tasks of optimal development for the future

Fig. 3 shows the models developed at ISEM SB RAS for solving problems of optimal development of gas supply systems and their interaction at three levels of consideration [4].

Model for optimizing the structure of the gas supply system. This network flow model allows you to find the optimal gas supply plan when there is a fixed demand for gas from consumers. It is solved at the first level of the hierarchy.

The generalized flow simulation problem is written as follows:

$$\sum_{(i,j)} \left(c_{ij} x_{ij} + k_{ij} y_{ij} \right) \to \min$$

$$\sum_i \lambda_{ij} x_{ij} - \sum_i x_{ji} = \begin{cases} -v, & j = s \\ 0, & j \neq s,t \\ w, & j = t \end{cases}$$

$$l_{ij} \le x_{ij} \le d_{ij} + y_{ij}, \quad (i,j) \in U,$$

$$0 \le y_{ij} \le g_{ij}, \quad (i,j) \in U.$$

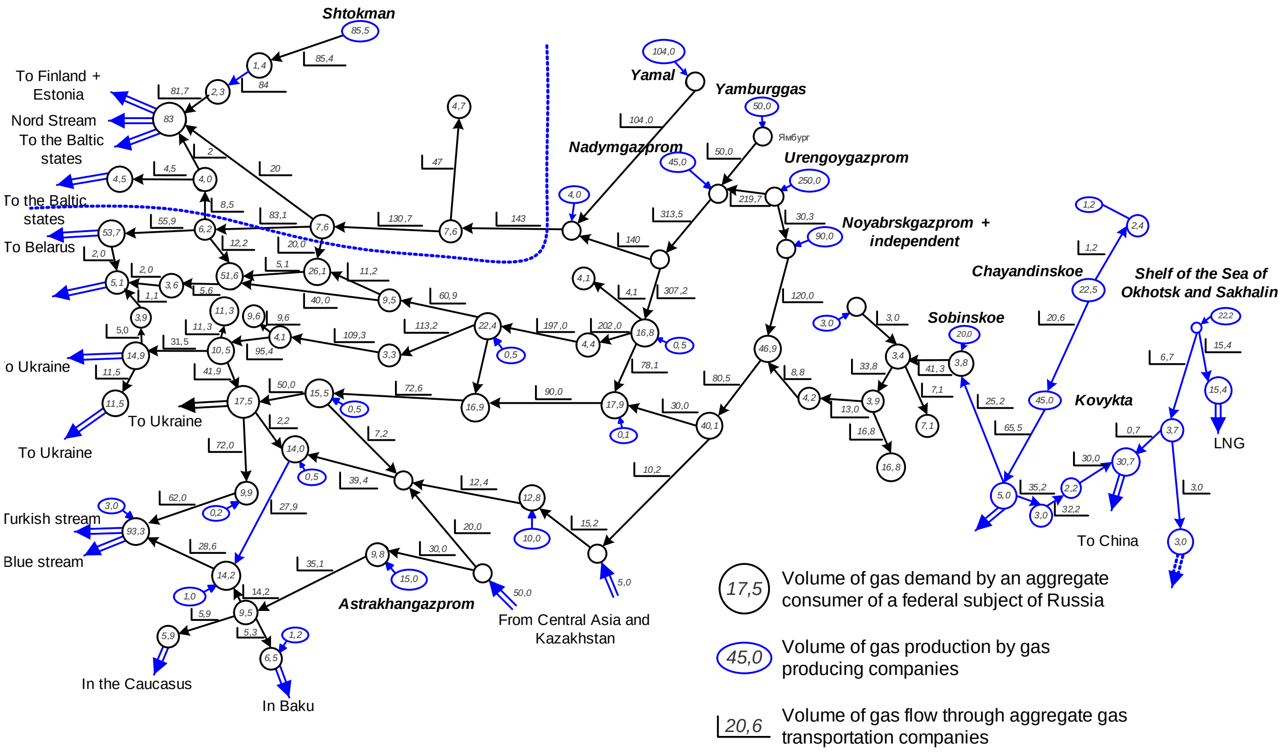

Fig. 4. Optimal volumes of gas production and transportation for the average scenario of consumption in the Russian Federation and export in 2030, billion cubic meters m / year.

As an optimality criterion, the minimum costs for the production, transport and delivery of gas to consumers are considered, the limitations are the production capacities of existing and new enterprises and the requirements to meet the minimum demand from consumers, provided that the balance of gas supply and withdrawal at the network nodes is maintained. This is the minimum cost flow problem, solved by the modified Basaker-Gowan algorithm [1].

Based on the data of the created information base, calculations were performed showing the optimal volumes of gas production and transportation for the average scenario of consumption in the Russian Federation and exports for 2020, 2025 and 2030. The calculation for 2030 is shown in Fig. 4, which shows the optimal volumes of gas production by gas producing enterprises and the volumes of gas flows through aggregated gas transmission enterprises.

The dotted line in Fig. 4, the scheme of gas supply to the Northwestern Federal District was highlighted. Using this diagram as an example, the detailed solutions of models of problems of lower levels of consideration will be shown.

A model for regulating the seasonal unevenness of gas consumption. Using this model, the solution obtained for the annual period at the top level of the hierarchy is detailed by seasons for summer and winter.

The model is a system of linear equations and inequalities that consistently describe the processes of production, transport, storage and consumption of gas by seasons:

$$\sum_{i=1}^{n}\sum_{\tau=1}^{T}(c^P_{i\tau}x^P_{i\tau}+c^T_{i\tau}x^T_{i\tau}+c^x_{i\tau}x^x_{i\tau}+\sum_{l=1}^{L}c^U_{i\tau l}x^U_{i\tau l}+c^b_{i\tau}x^b_{i\tau}+u_{i\tau}z_{i\tau})\to \min;$$

$$\sum_{\tau=1}^{T}(a^P_{i\tau}x^P_{i\tau}+a^T_{i\tau}x^T_{i\tau}+a^x_{i\tau}x^x_{i\tau}+\sum_{l=1}^{L}a^U_{i\tau l}x^U_{i\tau l}+z_{i\tau})=\sum_{\tau=1}^{T}(x^{-T}_{i\tau}+a^b_{i\tau}x^b_{i\tau}+b_{i\tau}),$$

$$0\le a^P_{i\tau}x^P_{i\tau}\le d^P_{i\tau};0\le a^T_{i\tau}x^T_{i\tau}\le d^T_{i\tau};0\le a^x_{i\tau}x^x_{i\tau}\le d^x_{i\tau};0\le a^U_{i\tau}x^U_{i\tau}\le d^U_{i\tau}$$

The model can take into account constraints on limited resources: fuel oil (d^f), coal (d^c), total capital investment (k) and metal (M).

$$0\le\sum_{i=1}^{n}\sum_{\tau=1}^{T}\sum_{l=1}^{L}a^U_{i\tau l}x^U_{i\tau l}\le d^f;$$

$$0\le\sum_{i=1}^{n}\sum_{\tau=1}^{T}(\sum_{l=1}^{L}a^U_{i\tau l}x^U_{i\tau l}+a^b_{i\tau l}x^b_{i\tau l})\le d^c;$$

$$0\le\sum_{i=1}^{n}\sum_{\tau=1}^{T}(k^P_{i\tau}x^P_{i\tau}+k^T_{i\tau}x^T_{i\tau}+k^x_{i\tau}x^x_{i\tau}+\sum_{l=1}^{L}k^U_{i\tau l}x^U_{i\tau l}+k^b_{i\tau l}x^b_{i\tau l})\le k;$$

$$0\le\sum_{i=1}^{n}\sum_{\tau=1}^{T}\mu_{i\tau}x^T_{i\tau}\le M\ ,$$

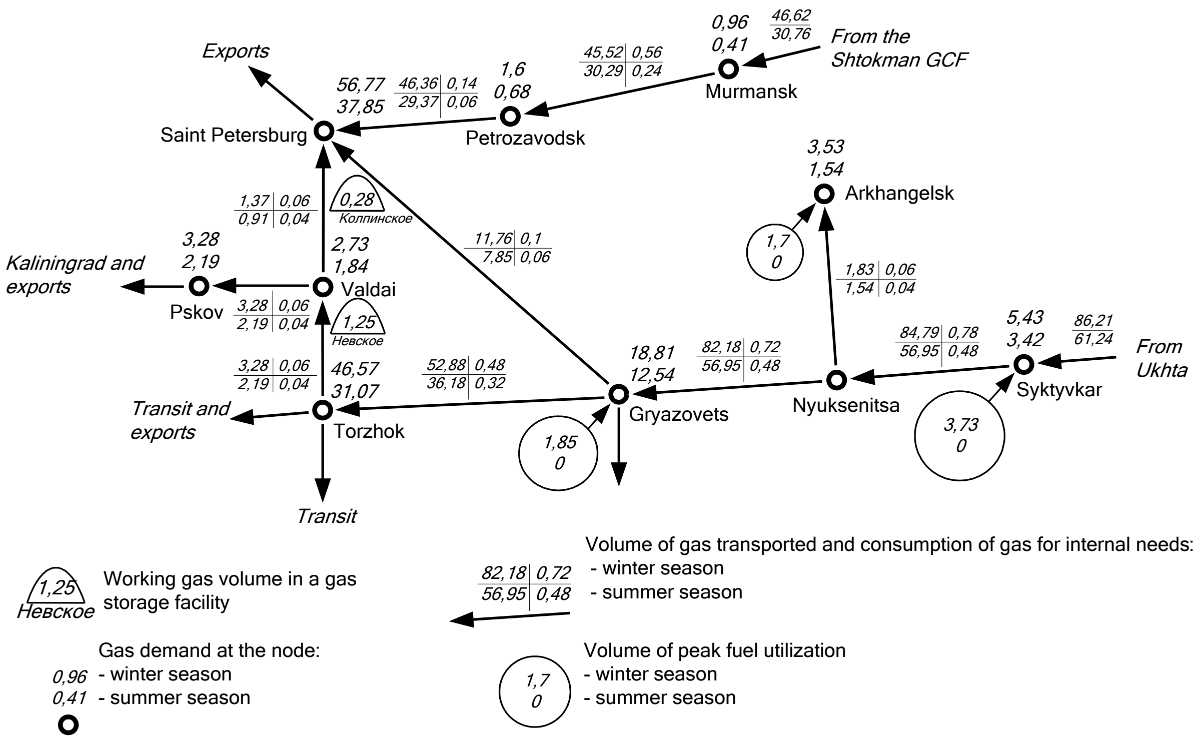

Fig. 5. Regulation of seasonal irregularity of gas supply in the Northwestern Federal District in 2030, million tons of fuel equivalent.

The criterion is the minimized function of costs for production, transportation, storage and use of gas; the following expression shows the condition for equality of flows of production, transport, storage and consumption of gas; then there are restrictions on gas flows; for investment; on metallurgy.

As a result of solving this problem by standard methods of linear programming by seasons of the year, the productivity of fields, gas transmission enterprises and underground gas storage facilities is determined.

On the model of regulation of seasonal unevenness, a detailed scheme of gas supply to the North-Western Federal District in 2030 was calculated (Fig. 5). It shows rational volumes of transported gas and gas consumption for own needs in winter and summer periods, volumes of storage and use of gas in underground storage facilities and volumes of peak fuel use.

Reliability synthesis model for a complex gas supply system. This detailed solution is the initial information for modeling the rational reliability of the GSS. For this, a two-stage methodological approach is proposed, in which the following tasks are solved [20]:

Stage 1. Determination of equivalent reliability characteristics for main gas pipelines, fields and underground gas storages, as well as for structures storing gas and other fuel reserves at consumers, allowing them to replace gas. For this, the models for analyzing the reliability of GSS facilities are used.

Stage 2. Optimization of gas supply system backup means. The problem of determining the optimal combination of redundancy methods that satisfy in each node of the design scheme the balances of incoming and outgoing mathematical expectations of the productivity of objects that provide consumers with volumes of gas and reserves of other fuel with a given reliability and given restrictions is formulated as follows:

$$\sum_{(i,j)\in U}\left(c_{ij}x_{ij}+k_{ij}y_{ij}\right)+p_j z_j \rightarrow min$$

$$\sum_{i\in \Gamma_j^+}\left(\lambda_{ij}x_{ij}+\pi_{ij}y_{ij}\right)+\alpha_j z_j-\sum_{j\in \Gamma_j^-}x_{ji}=\begin{cases}-Q, \ j=s;\\ 0, \ j\neq s,t;\\ B, \ j=t.\end{cases}$$

$$0\le x_{ij}\le d_{ij}; \quad 0\le y_{ij}\le d_{ij}^r-d_{ij}; 0\le z_j\le Z_j .$$

The minimum of the objective cost function is considered as a criterion. Shows the balances of the arrival and departure of the capacities of objects with existing redundancy and with additional reserve funds for these objects, as well as taking into account reserves of reserve fuel. For each node, a balance of incoming and outgoing capacities must be observed (Kirchhoff's first law). The last line shows the two-way performance limits for objects. The problem is solved by standard linear programming methods.

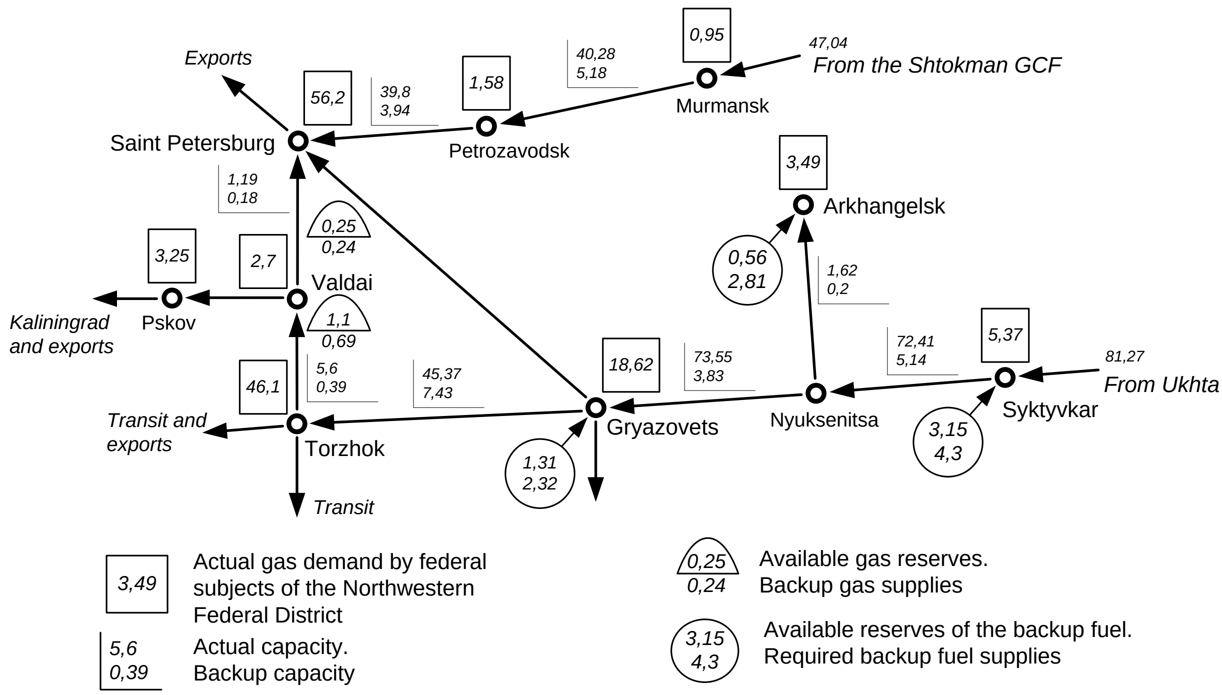

Fig. 6. Optimal supply redundancy of the gas supply system of the Northwestern Federal District in the winter period of 2030.

In fig. 6 shows the results of optimization of the system reliability of the Northwestern Federal District in the winter period for 2030, which detail the solution to the problem of seasonal unevenness. To ensure the actual gas demand in the subjects of the Northwestern Federal District with a supply ratio of 0.99, it is necessary to create additional reserve productivity in addition to the actual productivity of the elements, as well as reserves of reserve fuel for a number of consumers in the district, as shown in Fig. 6.

Model for determining the optimal parameters of the main gas pipeline, taking into account reliability. The General process of selecting optimal MG parameters involves:

1. Alternative consideration of ways of development for the future of the object under consideration.
2. Analysis of its reliability.
3. Optimal choice of a rational option based on the calculation of technical and economic characteristics and integrated reliability indicators.

The problem of determining the rational parameters of the designed MG, taking into account reliability, is generally formulated as follows.

Based on the average daily MG capacity (*Q*), its technical and process (*T*), reliability (*N*), and technical and economic performance indicators (*E*), the basic scheme of the MG and redundant final backup methods (*r*) to determine the diameters of a line for line pipes, the number of CSs and installed GPUs (gas pumping unit) that would maximize income *Z* from gas sales, provided that the specified reliability standard of P^* of gas supply is to be complied with.

$$Z = f(T, N, E, r) \to \max$$

$$P = y(Q, N, r) \geq P^*$$

The average daily calculated capacity (*Q*) is determined based on the annual calculated capacity of the MGP taking into account the coefficient of non-uniformity of gas consumption. For MGs without underground gas storage (UGS) facilities at the consumers' end, it is typically assumed to be 0.85, while for branch lines of the trunkline it is 0.75.

Technical and process indicators (*T*) are as follows: the MG length, the list of the number of lines and corresponding diameters, the list of standard sizes of rated GPU capacity (the number of considered options for LPs and CSs).

Reliability indicators (*N*) are understood as the rate of failure and recovery of LPs and GPUs. As a normative reliability indicator of gas pipeline P^*, we take reliability factor K_n. Its current value (*P*) is the ratio of the mathematical expectation of performance to its rated value:

$$K_n = \frac{M[Q]}{Q_n}.$$

Technical and economic indicators (e) are defined as: specific annual operating costs and capital investment in LP MG; specific annual operating costs and specific annual capital investment, proportional to the installed capacity of the compressor station; specific metal investment.

As a result of solving this problem of synthesis (optimization) of the structural reliability of the designed

MG, the following parameters are determined: the number of pipeline threads; the corresponding optimal diameters; the number of CS; the number and length of linear sections; the number of working and reserve GPU on each CS; the optimal nominal capacity of the GPU; metal deposits in the LP.
The number of all possible variants of the designed MG is equal to the product of the numbers of options LP MG and sizes of GPU for KS and the maximum number of backup units to cs, which should not exceed number of operating units.
The formulated problem can be considered as a combinatorial optimization problem. Engineering research experience shows that the number of options for the development of the gas pipeline is relatively small, and all of them can be viewed by ordinary search.
Table shows the results of parameter optimization taking into account the reliability of the Kovyktinskoye gas transmission system – Irkutsk – Beijing.

Table. Optimization of gas transportation system parameters Kovykta GCF - Irkutsk - Beijing, with reliability factored in.

Parameter	Kovykta GCF - Irkutsk	Irkutsk-Beijing
Top	25	25
Bottom	20	20
Diameter and number of lines	1220x2+1420	1420
Pipeline length, km	470	2170
Number of CSs	2 (3)*	16
Number of installed GPUs	9	6
Number of backup GPUs	3	3
GPU type	GPA-Ts-16	GPA-Ts-16
Resulting reliability	0.978	0.974
Capacity of a single CS	128.5	82.9
Specific capital expenditures per 1 km, million doll.	2.35	2.32
Net present value, mln. USD	36,035	25,263
Internal rate of return, %	58.9	25.2
Year of loan repayment	7	7
Metal inputs, thous. tons	886	1634

Conclusions

1. Taking into account the General issues of aggregation of enterprises of gas supply systems, hierarchical modeling of optimal development is considered, namely: 1) optimization of the GSS structure; 2) optimization of seasonal gas consumption, analysis and synthesis of reliability; 3) optimization of object parameters taking into account reliability.
2. Based on the proposed method of multi-level modeling of the gas supply system development, optimization calculations were made: gas production and transport volumes for the average scenario of consumption in the Russian Federation, rational seasonal unevenness of gas consumption in the North-Western Federal district, gas

supply system reservation in the North-Western Federal district in winter, optimal parameters of the Kovyktinskoye GCM – Beijing mg.

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Monitoring and analysis of SCADA and WAMS data for EPS digitalization

Irina Kolosok[1], *Liudmila* Gurina[1, *]

[1] Melentiev Energy Systems Institute of SB RAS, Irkutsk, Russia

Abstract. The properties of electric power systems (EPSs) are currently in the process of digital transformation, which should be taken into account when controlling them. Despite the numerous advantages of the digital transition, there are still problems with quality of the data used to control the EPS, and they are to a greater extent associated with the cybersecurity threats to the EPS information and communication infrastructure. The paper demonstrates the effect of changes in cybersecurity properties of the information and communication infrastructure on the quality of data streams coming from SCADA and WAMS, and reveals their complex interaction. The need has arisen to assess the quality of data during cyberattacks on systems for collecting, transmitting and processing the information. An algorithm is proposed to assess the quality of measurements based on the fuzzy logic.

Keywords. Quality of data, SCADA, WAMS, cyber attacks, fuzzy logic.

1 Introduction

The transition to the models of cyber-physical electric power systems (EPSs) is due to the digital transformation of the electric power industry, the interaction processes in which rest on new information and communication technologies, and digital models [1]. The cyber-physical system acquires new properties and distinctive features that must be taken into account to control it. In this context, such systems not only keep on facing the stability problems in terms of cybersecurity, but these problems become even more pronounced in terms of reliability requirements because of the increased vulnerability to cyberattacks on the information and communication subsystems [2,3]. The relevance of providing the EPS control with timely and reliable information is emphasized by the need to develop new methods and models for data representation based on artificial intelligence technologies.

Currently, the electric power system control is based on both SCADA measurements and synchronized vector measurements coming from WAMS measuring devices. The quality of SCADA and WAMS measurements is crucial not only for the development of automated control systems but also for the smooth operation of EPSs. The quality of information data flows is understood as the degree of completeness and reliability of information providing the required accuracy in the EPS control.

The paper proposes a method for processing measurement information based on the theory of fuzzy sets, given such cyber security requirements of the SCADA system and WAMS as timeliness, integrity, availability, and cyber resilience and confidentiality [4]. The development of the approach involved an analysis of the cyber-physical system properties and the identification of possible cyberattacks that reduce the quality of information data flows.

The paper shows that the incompleteness and inaccuracy of information increase due to cyberattacks on the SCADA system and WAMS, which can lead to the development and implementation of incorrect control actions and the adverse consequences for the EPS operation [4].

In the proposed method, an algorithm is developed to analyze the operating parameters based on fuzzy rules. This algorithm can also be used as a preliminary stage for data processing as a barrier to "bad" data in the state estimation of an EPS.

In the proposed method, an algorithm is developed to analyze the operating parameters based on fuzzy rules. This algorithm can also be used as a preliminary stage for data processing as a barrier to "bad" data in the state estimation of an EPS.

The use of artificial intelligence technologies in the analysis and processing of information flows will improve the efficiency of the EPS control and reliability.

2 Digital transformation of the properties of cyber-physical electric power systems

In Russia, as in other countries, the development of EPS is aimed at creating a cyber-physical system based on a single digital environment (CIM model), and introducing cybersecurity technologies and intelligent control methods in order to improve the reliability and transparency of EPS operation.

* Corresponding author: gurina@isem.irk.ru

The CIM (Common Information Model) based on the ODM (Open Model for Exchanging Power System Simulation Data) data format allows building models of any complexity, which can then be converted to any known data format or any new data format using additional plug-ins. ODM is an open model for data exchange in the modeling of power systems. ODM is an international open standard for data exchange in modeling and calculation of EPS, which supports dynamic calculations [5]. Based on CIM models, the IT infrastructure integrating the intelligent information, computing, and telecommunication environments should provide two-way communication between the information-communication and process subsystems of the cyber-physical EPS.

Transparency of the EPS operation requires the implementation of new systems for the collection, transmission and processing of information flows; the development of technologies and methods for modeling the studied processes and obtaining reliable real-time data on operating conditions for the control of EPSs.

The transition to the intelligent control of EPSs and the growing needs to monitor and analyze data, call for digital data processing technologies based on artificial intelligence methods:

- artificial neural networks and genetic algorithms;
- logical programming;
- ontological engineering;
- fuzzy logic, etc.

Despite all the obvious advantages of the digitalization of electric power systems, it makes them more vulnerable to cyberattacks, which is associated with a large scale (including spatial fragmentation) of the process part and the multicomponent nature (devices for collecting, transmitting and processing information at all levels of control) of the information and communication infrastructure of cyber-physical EPSs and their information interaction. At the level of hardware and software support of control, the risk of the occurrence of hidden threats is growing. The integration of IT infrastructure technologies contributes to the increase in the number of cyberattacks [4].

EPS control is based on data from the SCADA and WAMS. Cyberattacks aimed at the components of these systems or two-way data flows of information-communication and process systems can disrupt not only the control functions but also cause failures in the EPS operation.

The study in [4] demonstrates the effect of poor information quality, which results in false visualization of EPS operating conditions and generation of incorrect control actions due to cyberattacks on SCADA system and WAMS. Data quality analysis can determine the type of cyberattack and identify overlooked vulnerabilities.

3 The quality of data flows of the SCADA system and WAMS

The large-scale EPS monitoring involves both SCADA system and WAMS, in which the measurements come from PMU devices. In these conditions, the EPS can be controlled based on

- SCADA measurements;
- WAMS measurements;
- Mixed measurements.

Technologies of synchronized phasor measurements can increase the observability of the system and provide more accurate and timely information for control.

The quality of information data flows is understood as an extent to which the information is complete and reliable, which provides the required accuracy of solutions for control of EPS operating conditions.

In [6], the information for the EPS control is classified as follows:

- deterministic;
- probabilistic;
- uncertain.

Deterministic information is based on the laws of cause and effect relationships and is conditioned by a numerically unambiguous specification of the types of equipment, its composition and rated parameters.

Probabilistic information describes the stochastic nature of a change in the operating condition, the totality of the electric network components, which corresponds to a given behavior of EPS.

Uncertain information is divided into four groups:

- ambiguous;
- unknown;
- insufficient;
- unreliable.

The ambiguity of information refers to its multivariance due to various methods used to obtain and describe it. The lack of information about the components and operating parameters due to technical and physical factors leads to uncertainty. Various extents to which the information is unknown and insufficient reflect the incompleteness of information. Information unreliability arises when the model does not correspond to the modeled process, when there are measurement errors, data inaccuracy, etc.

However, the joint use of SCADA and WAMS measurements requires that the following issues be solved:

- high computational load;
- big data;
- weak conditionality of covariance matrices.

There arise serious data quality and cybersecurity problems that have complex interactions. A decrease in data quality, for example, can be a consequence of a successful cyberattack. At the same time, an analysis of data quality can determine the type of cyberattack and identify overlooked vulnerabilities [7]. To check the cybersecurity properties, it is necessary to develop methods for analyzing the data quality of SCADA and WAMS.

In this regard, the influence of cyberattacks on data quality was analyzed taking into account violations of cybersecurity properties [8] (Fig. 1).

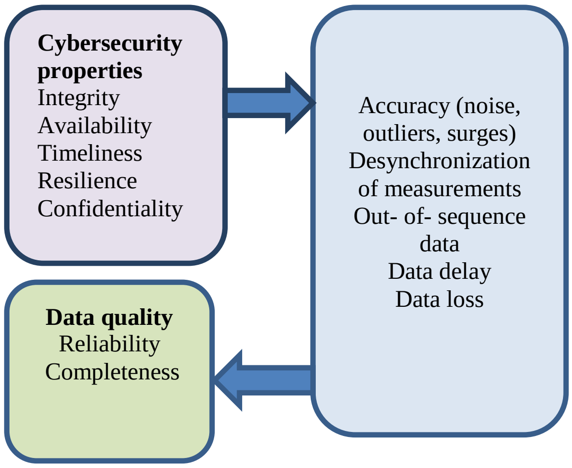

Fig. 1. The impact of cyberattacks on data quality.

In [5], a criterion for the quality of information and a method for its determination on the basis of the theory of fuzzy sets were introduced. The authors of [9], depending on the level of SCADA and WAMS measurements completeness and reliability, propose the measurement models for EPS state estimation. Consideration of the impact of cyberattacks on the completeness and reliability of information required the extension of a list of factors to assess the data quality. The study in [10–14] examines possible cyberattacks on information collection, transmission, and processing systems, reveals their vulnerabilities, and shows how the violations of the cyber security properties of the SCADA systems and WAMS affect the EPS control functions [4]. These studies indicate the need to take into account the following factors of the impact the cyberattack on the SCADA system and WAMS has on data quality:
- sequence;
- timeliness of data;
- data consistency.

The timeliness of data in real time reflects the uncertainty of information. Data consistency must be considered when SCADA and PMU measurements are used jointly.

4 A fuzzy system for data flow processing considering the cybersecurity properties of the SCADA system and WAMS

The proposed algorithm for evaluating data quality is based on the following algorithm:
1. Determine the level of information reliability;
2. Determine the level of information completeness;
3. Assess the information quality.

To determine the levels of reliability and completeness of information, we specify the linguistic variables (accuracy, sequence, consistency, timeliness, adequacy), determine the term sets and give their semantic definition. The developed fuzzy system for assessing the quality of measurement data is presented in Fig. 2.

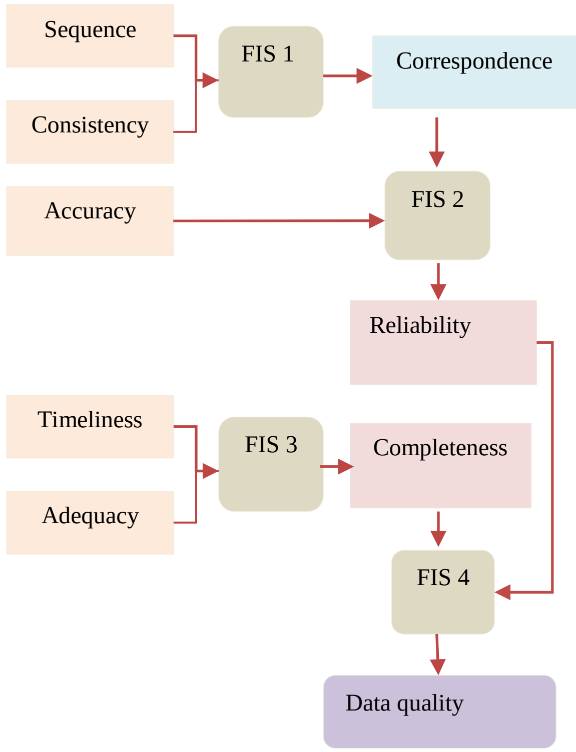

Fig. 2. Fuzzy system of data quality assessment.

5 Case study

A fuzzy system has been built to assess the quality of information, given the problems of EPS state estimation arising from cyberattacks on SCADA system and WAMS [15, 16].

The semantic description of input and output linguistic variables is presented in Tables 1-4.

Table 1. Levels of factors affecting the reliability of information.

Level	Accuracy	Sequence	Consistency
Low 0-0,25	The measurements contain errors due to cyberattacks, including those that cannot be detected	The sequence is broken	Data are not consistent
Medium 0,25-0,75	The measurements contain errors due to cyberattacks, which can be detected by the bad data detection methods	Sequence is broken but there is a possibility of elimination (duplication, comparison)	Data are not consistent, but there is the possibility of duplication and restoration

High 0,75-1	The measurements contain errors resulted from the errors of measuring devices, etc., which do not affect the accuracy of the EPS state estimation	Sequence is not broken	Data are consistent

Table 2. Levels of factors affecting the completeness of information.

Level	Timeliness	Adequacy
Low 0-0,25	Big delay	No data
Medium 0,25-0,75	Delay with the possibility of considering in measurement models	Data loss is not significant for solving the problem
High 0,75-1	Measurements arrive without delay	Sufficient number of measurements are received

Table 3. Completeness and reliability of data.

Level	Completeness	Reliability
Low 0-0,25	The system is not observable	Doubtful
Medium 0,25-0,75	Ability to calculate missing measurement values	Erroneous
High 0,75-1	Excessive measurements	Reliable

Table 4. Data quality.

Level	Quality
Low 0-0,25	Network is unobservable and/or measurements are unreliable
Medium 0,25-0,75	The use of bad data detection methods, validation of measurements, filtering errors, restoration of measurement flows, consideration of information aging will allow EPS state estimation with required accuracy
High 0,75-1	Full reliable flow of information

Figures 3-5 demonstrate the obtained three-dimensional surfaces of completeness, reliability and quality of information.

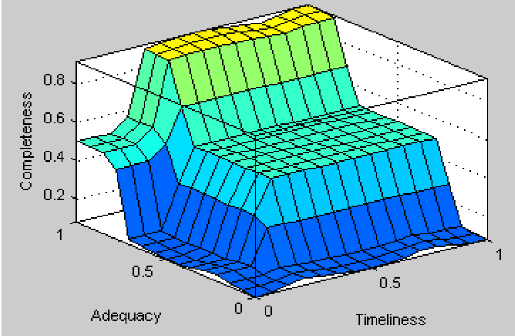

Fig. 3. Fuzzy system of data quality assessment.

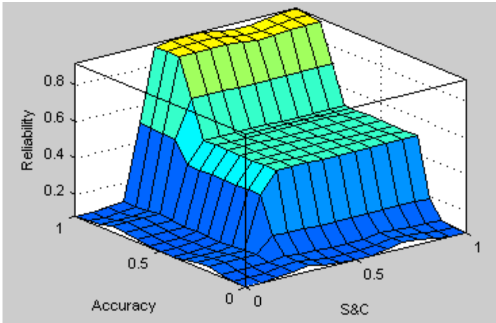

Fig. 4. The dependence of the information reliability on the data accuracy, sequence and consistency.

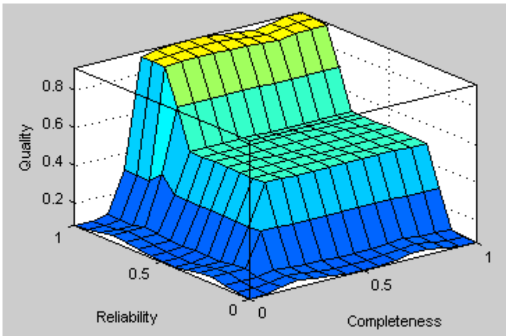

Fig. 5. Quality of measurements.

As can be seen from the graphs, the low level of any of the input factors caused by cyberattacks affects the quality of information (blue color), This especially affects the reliability of measurements.

This justifies the need to analyze the data when solving the state estimation problem, taking into account additional factors as a preliminary stage of data processing.

6 Conclusion

The EPS properties associated with the creation of a cyber-physical system are analyzed. The studies have shown an increased vulnerability of such systems to cyber attacks on information and communication infrastructure.

The interdependence between the cybersecurity properties of the SCADA system and WAMS and the quality of measurements is shown. An algorithm is proposed for assessing the data quality given violations of cybersecurity properties as a preliminary stage in EPS state estimation.

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Analysis of pricing mechanisms in a microgrid with active electric energy storages

Vsevolod Korepanov[1,*] and *Tatiana* Vaskovskaya[1,2]

[1]V.A.Trapeznikov Institute of control sciences of RAS, 117997, Profsoyuznya 65, Moscow, Russia
[2]National Research University "Moscow Power Engineering Institute" 111250, Krasnokazarmennaya 14, Moscow, Russia

Abstract. A model of power market with a simple market clearing price mechanism on microgrid is considered. Market participants are consumers, prosumers with energy storage systems (ESS), and the power company as a guaranteed supplier. Prosumers charge their ESS in the first off-peak period with low prices from the power company and can decrease their demand or sell energy in the market through discharging the ESS in the second peak period. The strategic behavior of participants and their influences on a system state are postulated as the goal of work. Some use cases and model elements are discussed.

1 Introduction

The microgrid idea allows us to think about creating a micro market – local electricity market at the lowest level, the household level. It arose in connection with the growing popularity and falling prices for renewable sources (solar, wind, etc.) and energy storage (chemical batteries, hydroelectric storage, etc.) - let us call all these elements "microenergetics". At the same time, the critical factor from which the desire to create a market arises is that a household can become an electricity producer rather than just a consumer, i.e., it can transfer the excess of its sources of energy to other households in the microgrid. Such a network participant is usually called a prosumer.

The interest of large energy companies to research and create microgrid technologies and subsidizing purchases by households is related to the smoothing of temporary peaks in energy consumption connected with microenergetics. At the same time, when using only energy storage systems (ESS), the total consumption of the prosumer increases due to the inevitable loss of power in work processes of the ESS. For the energy company, there is a double interest: smoothing peaks + growth in total consumption of customers who use only energy storage devices.

In [1], a hierarchy of models for analysing price mechanisms in energy markets was proposed from a strategic point of view – decomposition of complex control problem into a number of elementary, basic problems [2]. There are cases with fixed demand and active producers, with active demand, with active parties owning several producers and/or consumers, and various mechanisms of pricing and competition. Two-node models with electricity transfer between nodes are considered separately. The models are analysed using game theory, mechanism design, and business games with dedicated students.

In this paper, we aim at a similar analysis with an emphasis on other aspects: microgrid and prosumer. We will try to outline the simplest model that will contain the required properties and based on the models in [3] and [4]. Basically our prosumers modelling similar to [4] and [5] but our goal and market modelling are slightly different. In [4], the market price is a linear function and a future price is a random variable, the power company choose a base market price as a leader in Stackelberg game. In [5] the market price is based on historical data, the ESS and a peer-to-peer market of prosumers are compared to basic interaction of prosumers with the power grid.

2 Model

Let us consider a consumers set $C = \{1, \dots, m+n\}$, a prosumers set $P = \{1, \dots, n\} \subset C$ and one «big» guaranteed supplier M. Let us consider the local market model with the standard market mechanism for determining the Market Clearing Price (MCP) [6]. The supplier M can provide electricity for all needs of the local electricity market.

Further, firstly, due to the presence of prosumers, both consuming and producing processes should be considered. We should not fix the overall demand. Secondly, since the prosumer separate consumption and production of energy in time, it is necessary to consider at least two periods of time, for example, the off-peak and the peak periods or, conventionally, the first and second periods $t \in \{1, 2\}$. Note that the temporal aspect was not considered earlier in [2]. The peak period is characterized by an increase in consumer energy demand

* Corresponding author: moskvo@ya.ru

and price and an increase in the price of the single supplier M. According to [7], the use of the ESS in the wholesale market makes it possible to flat locational marginal prices. However, a microenergetics ESS can produce such an effect only with massive deployment. In our work, the prices of the single supplier remain different.

Each consumer (including a prosumer) $i \in C$ has a demand profile in each period: $d_i(1) < d_i(2)$ and the maximum prices at which he is ready to buy energy: $p_i(1) \le p_i(2)$. A prosumer can either reduce its demand during the period by discharging the ESS and increase it by charging the ESS . The prosumer i has ESS with a capacity S_i. Then the prosumer can change its power demand from $(d_i(t) - S_i)$ to $(d_i(t) + S_i)$. The prosumer can also produce some electricity volume $g_i(t) \in [0, S_i]$ by price p_i^g(t) as a generator in the market.

The goal function of the prosumer is the total of electricity sales revenue, the cost of purchasing electricity in the local market, and the fixed cost of maintaining microenergetic devices, while the devices can help both increase revenue and reduce costs:

$$f_i(s_i, g_i) = \sum_{t=1}^{2} -(d_i(t) + s_i(t) - g_i(t))P(t) - 2cS_i, \quad (1)$$

where $P(t)$ is the price of energy in the micro market during the period t, $s_i(t) \in [-S_i, S_i]$ is the volume of energy discharged from the ESS (if the value is negative) or the volume of energy charged from the power grid (if the value is positive) in the period t, $g_i(t)$ is energy of the ESS passed to the market as a generator, c is the unit cost of maintaining the ESS of volume S_i for one period.

Denote the initial stored energy as $s_i(0) \in [0, S_i]$. Then the following physical restrictions can be introduced:

$$0 \le s_i(0) + s_i(1) - g_i(1) \le S_i \quad (2)$$

$$0 \le s_i(0) + s_i(1) - g_i(1) + s_i(2) - g_i(2) \le S_i \quad (3)$$

Note, that charging and discharging ESS in the same period does not make sense. Suppose a consumer wants to get profit from the charge and the subsequent discharge from the ESS. Since energy buying/selling in this period will occur at the same price, the player will not gain anything from this operation in total. Moreover, taking unavoidable energy losses in ESS into account makes it completely unprofitable. Therefore, we don't consider the case $g_i(t)\, s_i(t) > 0$.

The goal function of the energy company should, in addition to accounting for an income from sales of energy on microgrids, consider the reduction in consumption during the peak period, since even a small peak-consumption reduction in each microgrid will have a significant cumulative effect, which is not captured by the energy company goal function from [4], for example.

3 Examples

Let us consider the example in figure 1.

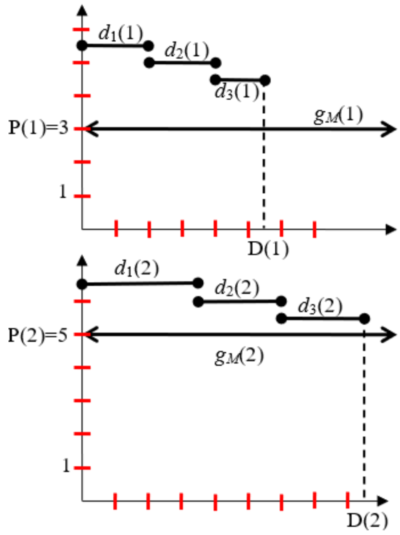

Fig. 1. Example with 3 consumers

In general, since consumption and prices are higher in the second period, then the market price in the second period is higher. The values of the goal functions of consumers 1 and 2 are equal to -23.5 and -18.5 respectively (without considering fixed costs for the ESS).

Suppose that consumers 1 and 2 bought the ESS and became prosumers. They charge them in period 1 because of the low price of the supplier M, and in period 2 they use it to reduce their demand or to sell a part of the ESS energy in the market as a generator. It seems reasonable that it is profitable for a prosumer to first fully meet his demand in period 2 and to give an ESS surplus to the market. Consider an example $d_1(2) = 3.5$, $S_1 = 5.5$, $d_2(2) = 2.5$, $S_2 = 3.5$, $d_3(2) = 2.5$. Suppose that prosumers 1 and 2 fully cover their demand in period 2, and they sell the excess as producers: $g_1(2) = 2$ and $g_2(2) = 1$ in the market at a price of 3.5. Then the market price in the second period will be $P(2) = 3.5$. This situation is shown in figure 2a.

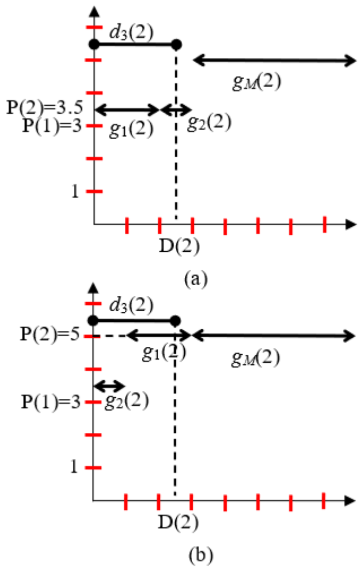

Fig. 2. Situation change due to ESS in period 2

In this situation, the goal functions of the prosumers are -15.5 and -14.75 taking into account the increased consumption in period 1 for charging the ESS (but excluding fixed costs). From a game-theoretic point of view, this situation is unstable: prosumers can increase the value of the goal functions by raising the market price up to 5 by raising the price for their generation g_i. In this case, it is more profitable for prosumer 2 to set a price lower than prosumer 1 - then he will be able to sell the entire volume $g_2(2)$. For example, the Nash equilibrium (one of) will be the situation shown in figure 2b. In this situation, prosumer 2 sells the entire available volume of energy, while prosumer 1 does not. In order to sell it, the price for $g_1(2)$ must be lower than 3.5, which will not bring him an increase in the goal function.

At the same time, we see that the market price has not become lower, but the goal functions of prosumers have improved, and overall demand has decreased, which is good for the energy company and the social welfare increases. Moreover, in the second peak period, this market does not need additional external energy at all since the total generation of the ESS exceeds the total demand.

Let us consider situation when a prosumer can increase the market price through decreasing its capacity – so called "power withdrawal". Prosumer 2 in figure 3c decreases its capacity from 2 kW to 1 kW in figure 3d. As a result, the market price increased from 3.5 to 5.

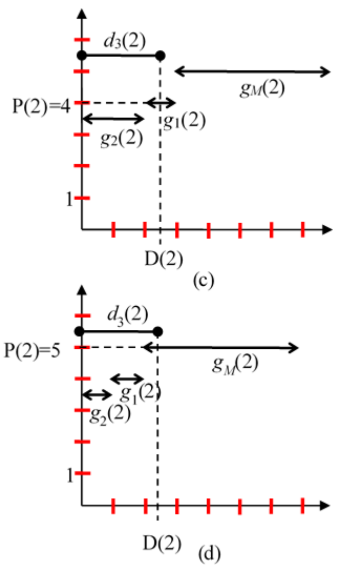

Fig. 3. Start situation (c) and power withdrawal (d)

4 Conclusions

We are constructing a basic model of a microgrid market to investigate game-theoretic behaviour of prosumers. There are many possibilities to expand the model for real-life cases:

• to consider more periods, prosumers,

• to take into account ESS physic: e.g., 3*charging speed ≈ discharging speed,

• to choose a subsidy model and other pricing mechanisms see [6, Section 3.3].

In each case, we should describe prosumers' behaviour and equilibrium; therefore, understanding of the utility and goal function of active participants is crucial.

For example, an increase in consumption cannot reduce the price in the market, and an increase in generation cannot increase the price. So, when we consider the model with several prosumers, only because of their number, a situation may arise when prices in the off-peak and peak periods converge so much that the use of storage would be economically impractical. Then perhaps a game-theoretic situation such as a game of entering the market [8] will arise, where prosumers will have to coordinate.

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Development and evolution of methods for optimizing the modes of heating networks

Alexandr Lutsenko[1,*], and *Nikolay* Novitsky[1]

[1] Melentiev Energy Systems Institute of SB RAS, Pipeline Department, 664033 Irkutsk, Russia

Abstract. Both in Russia and abroad, energy efficiency problems are relevant, while heat supply systems have significant energy saving reserves, which can be realized by organizing optimal operating modes. In practice, the task of planning modes of heat supply systems is solved by multivariate mode calculations, while the choice of methods for organizing the modes is assigned to the specialist performing the calculations, which does not guarantee the optimality of the obtained modes. Automation of solving these problems is complicated by a number of factors. For these reasons, there are no methods and software systems suitable for wide practical application. This determines the relevance of developing separate methods and programs for calculating optimal modes of heat supply systems. The subject of this article is the tasks and methods of optimizing operation modes of heat supply systems using several objective functions at the same time. The object of application is hydraulically inextricable heat supply systems. It is assumed that the temperature schedule on heat source is set, the heat losses in the networks are eliminated, and their residual value can be neglected. In this case, the task is to optimize the hydraulic mode.

1 Introduction

Both in Russia and abroad, energy efficiency problems are relevant, while heat supply systems (HSS) have significant energy saving reserves [1], which can be realized by organizing optimal operating modes. In practice, the task of planning HSS modes is solved by multivariate mode calculations [2], while the choice of methods for organizing the modes is assigned to the specialist performing the calculations, which does not guarantee the optimality of the obtained modes. Automation of solving these problems is complicated by a number of factors: high dimension HSS [3, 4], nonlinearity of the involved flow distribution models, the presence of several objective functions, etc. For these reasons, there are no methods and software systems suitable for wide practical application. This determines the relevance of developing separate methods and programs for calculating optimal HSS modes.

Recently, attention has been paid to optimizing HSS modes, but the bulk of research in this area is not applicable in the general case. Some works (for example, [5]) are devoted to HSS of small dimension. Many works ([6, 7] etc.) use an approximation of the dependence of the objective function value on the mode parameters selected as a basis, which greatly complicates the correct accounting of discrete variables related to the composition of the operating equipment. In other cases, to overcome the dimension problem, aggregation of HSS schemes is used, which prevents taking into account the whole set of constraints and does not guarantee the required accuracy of solutions. A common approach is to use ready-made solvers. The main disadvantage of this approach is the impossibility of adapting methods to the specifics of tasks, which leads to too high computational costs. For example, in [8, 9] the physical model of the network was created in the Simulink / Matlab environment, the CPLEX solver is used to calculate the mode, and the ReMIND software is used for optimization. The use of genetic and evolutionary algorithms requires even greater computational costs. For example, in [10] , a nested iterative cycle is used to minimize the cost of pumping the coolant. In the internal loop, the allowable mode is calculated using the SIMPLE algorithm. Using the genetic algorithm, the parameters determining the mode are changed on the external cycle. In a number of works, narrowly targeted objective functions are used, which does not allow applying the achieved results in the general case. For example, in [11] the total fuel consumption at heat sources (HS) is minimized. In [6, 7] , the problem of optimal control of pumps at pumping stations (PS) was solved in order to minimize the consumed electric power. Basically, tasks related to operational management are considered, for example, [11 – 13]. Note that, there are practically no works on the problem of planning HSS modes of real dimension that occurs during the preparation for the heating season.

The subject of this article is the tasks and methods of optimizing HSS operation modes using several objective functions at the same time. The object of application is hydraulically inextricable HSS. It is assumed that the temperature schedule on HS are set, the heat losses in the networks are eliminated, and their residual value can be

* Corresponding author: luc_alex@mail.ru

neglected. In this case, the requirements for providing consumers with thermal energy is reduced to the need to maintain their required coolant flows, and the task is to optimize the hydraulic mode (HM). The case of parallel operation of the same type of pumps on PS is considered as usual for HSS.

2 Problem statement

In order to optimize the HM HSS, it is necessary to find control actions that implement the mode that meets the admissibility requirements and reaches the set optimization goals. Energy saving requirements can be reduced to minimize the economic objective function. Minimizing the complexity of network preparation and reducing possible coolant leaks and the risks of emergency situations can be reduced to minimizing additional places for flow control and minimizing the total pressure in the network.

2.1 The mathematical formulation of the problem.

The main elements of HSS are pipeline sections, PS, consumers, HS, and ramification units. In the technological scheme (single-line representation, Fig. 1), pipeline sections and PS are represented by branches, and HS, consumers and ramification units are represented by nodes. In the design scheme (two-line representation, Fig. 2), the pipeline sections are depicted as two branches (supply and return pipelines), PS - as a branch with PS, consumers - as branches between the supply and return pipelines. HS can be modeled on the design scheme as a branch between the supply and return pipelines with a PS and a heating unit installed on it, the optimization of the operation mode of which represents a separate independent task [14]. We denote the set branches of the design scheme that model PS as I_{PS}, consumers – as I_C and pipeline sections – as I_{PL}. Then $I_{PL} \cap I_{PS} = I_{PL} \cap I_C = I_{PS} \cap I_C = \varnothing$ and $I_{PL} \cup I_{PS} \cup I_C = I$ – the set of all branches, $|I| = n$. We also introduce J - the set of all nodes of the design scheme, $|J| = m$.

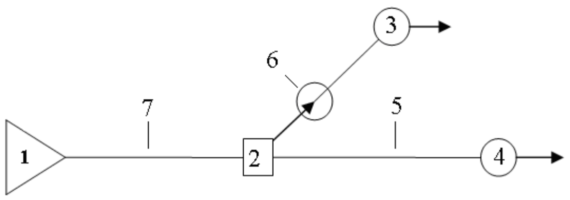

Fig. 1. An example of a technological scheme. 1 - HS; 2 - ramification unit; 3.4 - consumers; 5, 7 - pipeline sections; 6 - PS.

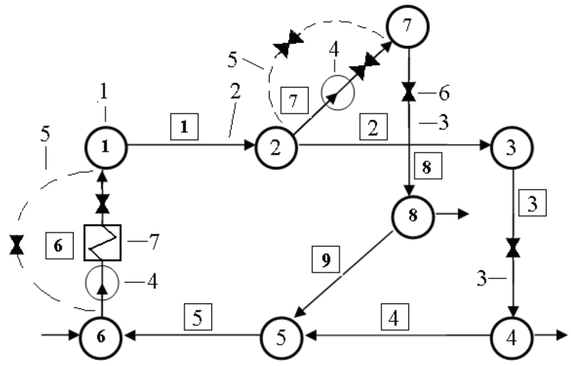

Fig. 2. An example of a design scheme. In circles, the numbers of nodes are indicated, in squares, the numbers of branches. 1 - node *j*, 2 - branch *i*, 3 - consumer, 4 - PS, 5 - bypass line, 6 - application point of the flow control means, 7 - heaters.

2.1.1 Controlled flow distribution model.

As the initial model, we will use the controlled flow distribution model [15], which consists of equations analogous to Kirchhoff's laws and equations describing the laws of the coolant flow over individual network elements:

$$\mathbf{U}(\mathbf{R},\mathbf{u}) = \begin{pmatrix} \mathbf{U_1}(\mathbf{x},\mathbf{Q}) \\ \mathbf{U}_2(\mathbf{P},\mathbf{y}) \\ \mathbf{U}_3(\mathbf{y},\mathbf{x},\mathbf{u}) \end{pmatrix} = \begin{pmatrix} A\mathbf{x}-\mathbf{Q} \\ \mathbf{A}^T\mathbf{P}-\mathbf{y} \\ \mathbf{y}-\mathbf{h}(\mathbf{x},\mathbf{z},\boldsymbol{\gamma},\boldsymbol{\kappa}) \end{pmatrix} = 0 \,. \quad (1)$$

The following notation is used here: A – incidence $m \times n$ -matrix of a connected oriented graph of the HSS design scheme; $\mathbf{Q}$, $\mathbf{P}$ – m-dimensional vectors of nodal flow rates and pressures; $\mathbf{x}$, $\mathbf{y}$ – n-dimensional vectors of flow rates and pressure drops on the branches; $\mathbf{h}(\mathbf{x},\mathbf{z},\boldsymbol{\gamma},\boldsymbol{\kappa})$ – n-dimensional vector function with elements $h_i(x_i,z_i,\gamma_i,\kappa_i)$, $i=\overline{1,n}$ approximating the dependence of the pressure drop on the flow rate on the branch; $\boldsymbol{\gamma}$ - vector of relative frequencies of rotation of the impellers of the pumps (or their diameters), we call the change in this parameter frequency regulation; $\boldsymbol{\kappa}$ - vector of the number of pumps turned on at the PS; $\mathbf{z}$ - vector of relative hydraulic resistances (for example, increased by throttling). $\mathbf{R}$={$\mathbf{P}$,$\mathbf{Q}$,$\mathbf{x}$,$\mathbf{y}$} – set of variables corresponding to the mode parameters; $\mathbf{u} = \{\mathbf{z},\boldsymbol{\gamma},\boldsymbol{\kappa}\}$ – set of variables corresponding to control actions.

In the case of parallel operation of the pumps on the PS, as an approximation of the hydraulic characteristics of the *i*-th branch, we can take [15]:

$$h_i(x_i,z_i,\gamma_i,\kappa_i) = z_i s_i x_i |x_i| / \kappa_i^2 - \gamma_i^2 H_i \,. \quad (2)$$

The following notation is used here: s_i – hydraulic resistance, H_i – pressure increment created by pumps on PS. In (2), for modeling the absent or forbidden to change the control action, one can equate the corresponding variable constant. In addition, (2) can be considered as a generalization of the hydraulic characteristics of a controlled pipeline section if: $\kappa_i = 1$, $H_i = 0$, $\gamma_i = 1$.

In case any mode parameter depends on the external environment, the corresponding variable is fixed. We call such parameters the boundary conditions. For HSS, such parameters are the pressure in the make-up nodes (nodes in which the coolant enters the HSS to compensate for the loss of coolant and withdrawals) and flow rates in all other nodes.

The requirements of the admissibility of the HM and the feasibility of control actions can be written as [15] $\underline{P}_j \le P_j \le \overline{P}_j$, $\underline{y}_i \le y_i \le \overline{y}_i$, $\underline{z}_i \le z_i \le \overline{z}_i$, $\underline{\gamma}_i \le \gamma_i \le \overline{\gamma}_i$, $\kappa_i\gamma_i\underline{\chi}_i \le x_i \le \kappa_i\gamma_i\overline{\chi}_i$, $\kappa_i \in \mathrm{K}_i$, $i \in I$, $j \in J$, where $\underline{P}_j, \overline{P}_j$, $\underline{y}_i, \overline{y}_i$, $\underline{\gamma}_i, \overline{\gamma}_i$ and $\underline{z}_i, \overline{z}_i$ - margins of change P_j, y_i, γ_i and z_i; $\mathrm{K}_i = \{0,1,2,...,K_i\}$, K_i - number of pumps installed on PS; $\underline{\chi}_i, \overline{\chi}_i$ - margins of change x_i with $\gamma_i = 1$, $\kappa_i = 1$. We introduce a vector of Boolean variables **δ**, whose components δ_i control the presence or absence of throttling on the i-th branch of the design scheme. We also replace the inequality $\underline{z}_i \le z_i \le \overline{z}_i$ by $\underline{z}_i \le z_i \le \underline{z}_i + (\overline{z}_i - \underline{z}_i)\delta_i$. Then the system of constraints takes the form

$$\begin{aligned}&\underline{P}_j \le P_j \le \overline{P}_j,\ \underline{y}_i \le y_i \le \overline{y}_i,\ \underline{z}_i \le z_i \le \underline{z}_i + (\overline{z}_i - \underline{z}_i)\delta_i,\\ &\underline{\gamma}_i \le \gamma_i \le \overline{\gamma}_i,\ \kappa_i \in \mathrm{K}_i,\ \kappa_i\gamma_i\underline{\chi}_i \le x_i \le \kappa_i\gamma_i\overline{\chi}_i,\ i \in I,\ j \in J.\end{aligned} \quad (3)$$

2.1.2 Objective functions.

The variable component of the maintenance costs is $F_C = F_C^{EP} + F_C^F$, where F_C^{EP} is the cost of electricity for pumping coolant to PS, F_C^F is the fuel costs for heating the coolant. We denote $I_{HS} \subset I_{PS}$ as the set of HS. Then $F_C^{EP} = \sum_{i \in I_{PS}} c_i^{EP} N_i$, $F_C^F = \sum_{i \in I_{HS}} c_i^C B_i$, where c_i^{EP}, N_i – the price of electricity and its consumption, c_i^F, B_i – the price of fuel and its consumption. For a given temperature schedule of HS, fuel consumption can be represented as a known function of the coolant flow rate. We approximate it by a square trinomial: $B_i(x_i) = \alpha_{0,i} + \alpha_{1,i}x_i + \alpha_{2,i}x_i^2$ [16]. The electrical power consumption on a separate PS is $N_i(x_i, \gamma_i, \kappa_i) = \beta_{0,i}\kappa_i\gamma_i^3 + \beta_{1,i}\gamma_i^2 x_i + \beta_{2,i}\gamma_i x_i^2 / \kappa_i$, $i \in I_{PS}$ [15]. Here $\beta_{0,i}$, $\beta_{1,i}$, $\beta_{2,i}$ - approximation coefficients of the dependence of the electric power consumption by an individual pump on the coolant flow rate, provided $\gamma = 1$. Then the economic objective function will take the form $F_C(\mathbf{x}, \boldsymbol{\gamma}, \boldsymbol{\kappa}) = \sum_{i \in I_{PS}} c_i^{EP}\left(\beta_{0,i}\kappa_i\gamma_i^3 + \beta_{1,i}\gamma_i^2 x_i + \beta_{2,i}\gamma_i x_i^2 / \kappa_i\right) + \sum_{i \in I_{HS}} c_i^C\left(\alpha_{0,i} + \alpha_{1,i}x_i + \alpha_{2,i}x_i^2\right)$. The objective function of the number of control actions is $F_z(\boldsymbol{\delta}) = \sum_{i \in I_{PL}} \delta_i$ [17], and the indicator of the general pressure level is $F_P(\mathbf{P}) = \sum_{j \in J} P_j / m$ [17].

2.1.3 Consideration of multiobjectiveness

In preparation for the heating season, you need to find an HM that meets the requirements: 1) minimum maintenance costs; 2) the minimum complexity of adjustment activities; 3) the lowest level of pressure in HSS to minimize leaks, unproductive costs and risks of emergency situations. These requirements are listed in order of importance.

The following are known: topology of the design scheme; border conditions; coefficients of hydraulic and power characteristics ($\beta_{0,i}$, $\beta_{1,i}$, $\beta_{2,i}$, s_i, H_i, $i \in I$); flow rate coefficients HS ($\alpha_{0,i}, \alpha_{1,i}, \alpha_{2,i}$);permissible limits of change of continuous variables; sets of possible values of integer variables (K_i, δ_i, $i \in I$); the cost of electricity for each PS ($c_i^{EP}, i \in I_{PS}$) and the cost of fuel for each HS (c_i^F , $i \in I_{HS}$). It is required to determine the parameters of the optimal HM (**P**, **Q**, **x**, **y**) and the control actions necessary for its implementation (**z**, **γ**, **κ**, **δ**).

The specific mathematical formulation of the problem depends on the approach taken to account for multiobjective. As the main approach, it is proposed to use the vector optimization method in accordance with ordering of the requirements for HM by degree of importance.

Then the task is to find the parameters of the mode and the control actions that satisfy the following conditions: (1), (3), $F_C = F_C^*$, $F_z = F_z^*$ and $F_P = F_P^*$. Here: $F_C^* = \min F_C$ under constrains (1), (3); $F_z^* = \min F_z$ under constrains (1), (3) and $F_C = F_C^*$; $F_P^* = \min F_P$ under constrains (1), (3), $F_C = F_C^*$ and $F_z = F_z^*$. We write this problem as:

$$\min_{lex}\left(F_C, F_z, F_P\right) \text{ under constrains (1), (3).} \quad (4)$$

3 Hierarchical approach to optimizing HSS hydraulic modes

To solve the problem of dimensionality of problem (4), the authors proposed a hierarchical approach to optimizing HM HSS [18], which allows us to separate the various types of discrete variables (integer and Boolean) and objective functions for various problems. This approach includes the following steps: 1) decomposition of HSS into main (MHN) and distribution (DHN) networks; 2) the search for the limits of permissible changes in the mode parameters at the decomposition point; 3) optimization of the MHN mode, taking into account the restrictions obtained in the previous step; 4) optimization of DHN modes taking into account the parameters of the MHN mode at the decomposition point.

The basic principles of HSS decomposition are as follows. MHN contains all HS, PS and multi-loop part of the network in a single-line representation. DHNs include tree-like passive networks to users. The decomposition point is the point where DHN joins the MHN in a single-line representation and two nodes in a bilinear representation, one of which is the connection point of the MHN and DHN supply pipelines, and the second is the return (Fig. 3). For MHN, the decomposition point is a generalized consumer with bilateral restrictions on the pressures in the supply and return piping and on the difference in these pressures. For DHN, the decomposition point is a generalized heat source.

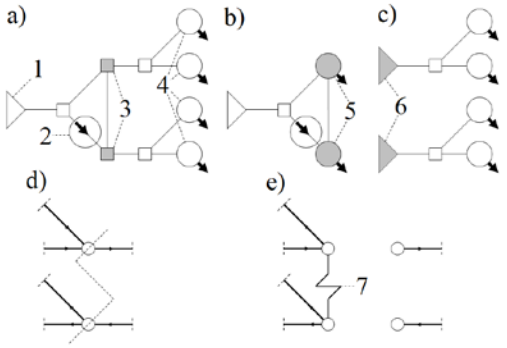

Fig. 3. Illustration of the principles of decomposition of the HSS. a) a single-line representation of an HSS; b) MHN; c) DHN; d) nodes of the division of hierarchical levels in a two-line representation; e) the result of decomposition on a fragment of a two-line representation. 1 - HS; 2 - PS; 3 - nodes of decomposition; 4 - consumers; 5 - generalized consumers; 6 - generalized HS; 7 - a branch with an equivalent characteristic replacing DHN.

Note that the economic objective function is related to the HM parameters and control actions that are relevant only to MHN. In practice, adjustment activities related to the installation of regulators, throttling washers, etc. occur only on DHN. This allows for the MHN to solve the following problem instead of problem (4):

$$\min_{lex}\left(F_C, F_P\right) \text{ under constrains (1), (3).} \quad (5)$$

Due to the branched configuration, there is a fixed, easily computable flow distribution for DHN, as well as the ability to reduce the design scheme of DHN to one branch due to the equivalenting of serial and parallel branch connections. Therefore, instead of (1), we have:

$$\mathbf{U}\left(\mathbf{R},\mathbf{u}\right)=\begin{pmatrix}\mathbf{A}^T\mathbf{P}-\mathbf{y}\\ \mathbf{y}-\mathbf{h}(\mathbf{x},\mathbf{z},\boldsymbol{\gamma},\boldsymbol{\kappa})\end{pmatrix}=0 \quad (6)$$

and problem (4) takes the form [19]:

$$\min_{lex}\left(F_z, F_P\right) \text{ under constrains (6), (3).} \quad (7)$$

The study of the Pareto set of the following problem is also of practical importance:

$$\min\left(F_z, F_P\right) \text{ under constrains (6), (3).} \quad (8)$$

The task of finding the limits of permissible changes in the mode parameters at the decomposition point is six optimization problems to be solved for each DHN: $\min P_1$, $\max P_1$, $\min P_m$, $\max P_m$, $\min\left(P_1-P_m\right)$, $\max\left(P_1-P_m\right)$. Here j = 1 is the connection node of the supply pipelines MHN and DHN, and $j = m$ is the return. All problems are solved under constrains (6) and (3).

4 Optimization methods used in the hierarchical approach

Given the approach used to take into account multicriteria, the optimization problem HM MHN (5) is reduced to the sequential solution of two problems:

$$\min F_C \text{ under constrains (1), (3) and } \delta_i=0, i\in I_{PL} \quad (9)$$

$$\min F_P \text{ with (1), (3), } F_C=F_C^* \text{ and } \delta_i=0,\ i\in I_{PL} \quad (10)$$

To solve problem (9), the authors developed a method [15], the essence of which is as follows. A triple nested iteration loop is used. The allowable HM is calculated on the internal cycle using the internal points method developed at ESI SB RAS [20, 21]. On the middle cycle, the value of the objective function is minimized by the bisection method. On the external loop, κ_i values are searched by the continuous branch and bound method. Variables κ_i are considered continuous on two internal iterative cycles, and on the external, their discreteness is achieved.

Problem (10) is solved similarly to problem (9) with the only difference being that an additional condition $F_C=F_C^*$ is imposed and F_P is minimized.

To optimize HM DHN (task (7)), the authors developed a loop reducing dynamic programming method [19]. The essence of this method is as follows: 1) for each branch, all permissible pressure drop trajectories are constructed, while trajectories that have the same pressure drop (y_i) but different pressures in the end nodes are considered different; 2) using special techniques of equivalent serial and parallel connection of branches, the design scheme and these trajectories are minimized (with rejecting both unacceptable and non-optimal pressure distribution options) to one branch with a single pressure drop trajectory corresponding to the optimal solution; 3) restoration of this solution to the original DHN scheme.

Potentially, this method can solve the problem of finding the limits of permissible changes in the mode parameters at the decomposition point in one application of this method for each DHN. At the moment, work is underway to adapt it to solve this problem. Previously, this problem was solved as 6 separate optimization problems for each DHN [18]. Each of these problems was solved using a double nested iterative loop. The allowable HM was calculated on the internal cycle using the internal point method, and on the external, the parameter under study was minimized or maximized.

5 Investigation of the properties of the Pareto set of the optimization problem of the hydraulic mode of distribution heating networks

We show that the Pareto set of problem (8) is discrete. We associate with each value of the vector $\boldsymbol{\delta}^*$ the value of $\tilde{F}_P\left(\boldsymbol{\delta}^*\right)$, equal to the minimum F_P, attainable at (6), (3) and $\boldsymbol{\delta}=\boldsymbol{\delta}^*$. If conditions (6), (3) and $\boldsymbol{\delta}=\boldsymbol{\delta}^*$ are incompatible, we set $\tilde{F}_P\left(\boldsymbol{\delta}^*\right)=\infty$. For all $\boldsymbol{\delta}$ giving the same value of F_z, we choose the best (smaller) value of $\widehat{F}_P(F_z)=\min\left(\tilde{F}_P(\boldsymbol{\delta})\,|\sum\delta_i=F_z\right)$. We discard all

Table 1. PS pumping equipment's coefficients of characteristics

PS	Number of pumps	H	s	b_0	b_1	b_2	b_3
1	3	120	0,0000375	160	0,0706	0,000135	-0,0000001
2	5	80	0,00004	40	0,16	0	0
3	3	120	0,000125	60	0,24	0	0
4	2	60	0,0001	30	0,09	0	0

$\widehat{F}_P(F_z)$ satisfying at least one of the conditions: 1) $\widehat{F}_P(F_z)=\infty$; 2) $\widehat{F}_P(F_z)\geq\widehat{F}_P(F_z-k)$, $k>0$. The resulting set of points will be the Pareto set of problem (8). Obviously, it is a set of points on the plane F_P-F_z.

In [17], problem (7) was considered. To minimize F_z, the discrete branch-and-bound method was used, and among all variants with the same F_z value, variants with a lower F_P value are considered earlier than variants with a large F_P value. Thus, the Pareto set of problem (8) is found. An example of such a set is presented in Fig. 4.

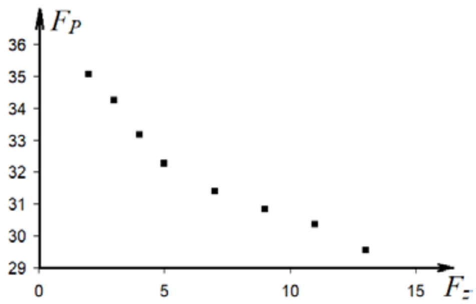

Fig. 4. An example of a Pareto set of optimization problems for DHN modes.

6 Inverse Assignment Method

The method of successive concessions [22] as applied to (5) is as follows. For each objective function (F_C, F_z, F_P) assignments (ΔF_C, ΔF_z, ΔF_P) are assigned, then the tasks are solved in series: 1) $F_C^*=\min F_C$ under constrains (1), (3); 2) $F_z^*=\min F_z$ under constrains (1), (3) and $F_C\leq F_C^*+\Delta F_C$; $F_P^*=\min F_P$ under constrains (1), (3), $F_C\leq F_C^*+\Delta F_C$ and $F_z\leq F_z^*+\Delta F_z$.

In practice, sometimes the problem arises of minimizing the economic objective function with restrictions on F_z:

$$\min F_C \text{ under constrains (1), (3) and } F_{zk}\leq F_{zk}^*. \qquad (11)$$

Here k is the DHN number, F_{zk}^* is a certain maximum number of control actions on the passive sections of the network for the k-th DHN, set by the specialist performing the calculations. Note that this problem is the inverse of the problems that arise when applying the method of successive concessions.

To solve this problem using a hierarchical approach to optimizing HM HSS, it is sufficient to require that the condition $F_z\leq F_{zk}^*$ be satisfied when searching for the limits of permissible changes in the mode parameters at the decomposition point for the k-th DHN.

7 Example of hierarchical optimization of hydraulic mode

The method described above was tested on the Baikalsk HSS calculation model (Fig. 5), in which part of the DHN was replaced by generalized consumers, the number of pumps in PS-2 was increased to five, and frequency regulation was allowed on all PSs. On the PS-1, the pumps are installed on the supply pipeline, for the rest of the PS - on the return. The number of pumps installed on the PS, their coefficients of characteristics are given in table 1.

HSS has one HS, and all PS receive electricity at the same prices, so the electric power consumption by PS was the economic objective function. Optimization of HM HSS was carried out for the load case corresponding to the winter mode of operation of the HSS of Baikalsk. The calculations were carried out in accordance with the hierarchical approach to optimizing HM HSS.

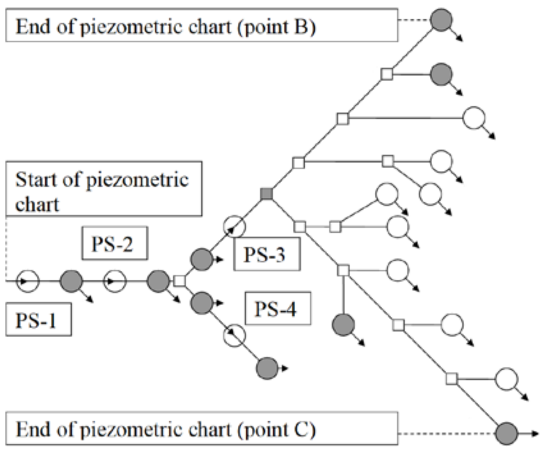

Fig. 5. Single-line representation of the HSS of Baikalsk

Table 2 shows the optimization results for HM MHN. It can be seen that the cost of pumping the coolant decreased by one and a half times. The number of controls on passive network sections after optimization was equal to one for the entire HSS considered.

Table 2. The optimization results for HM MHN

Calculation option	Power Consumption (KW)	Average pressure (m water)
Feasible HM	491,5	56

Cost reduction	307,5	54,6
Pressure reduction	307,5	43,49

In fig. Figure 6 shows a piezometric graph of the optimal HM of a given HSS. Vertically shows the pressure in the pipeline, horizontally - the distance from HS. The vertical dashed line indicates the decomposition point. To the left of it is a piezometric graph of the MHS, to the right - DHS (the solid line for the AB route, the dotted line for the AC route). Rectangles indicate areas corresponding to PS (left) and throttling (right).

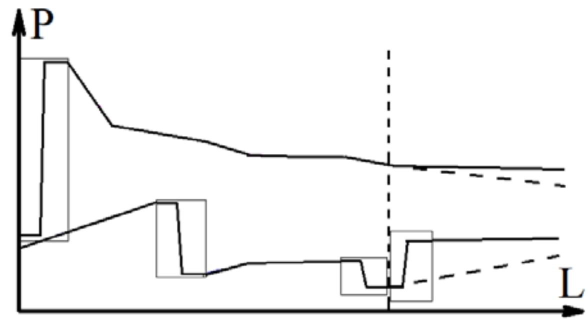

Fig. 6. The piezometric graph

8 Findings

The characteristic of the tasks of the organization of the HSS operating modes related to the development of commissioning measures in preparation for the next heating season is given. The optimization nature of these tasks is revealed, as well as the multi-purpose nature. A generalized mathematical formulation of the optimization problem for the hydraulic mode of the HSS is presented, which is a mixed, discrete-continuous optimization problem of large dimension with a vector objective function.

The characteristic developed by the authors of the hierarchical approach to optimizing the HSS modes is given, which provides both overcoming dimensional problems and significantly simplifying the general formulation for problems solved at different levels of the hierarchy.

A review of the developed methods for optimizing the MHN and DHN modes is presented, which have a rational combination of computational efficiency and guaranteed global solution, both with regard to taking into account the discreteness of part of the variables and the presence of several objective functions.

For the first time, an attempt is made to study the properties of the Pareto set of the formulated problem of optimizing DHN modes. A method for finding it is proposed. An original method of backward concessions is proposed within the framework of the developed hierarchical approach in the presence of a vector objective function.

A numerical example is given illustrating the performance and advantages of the proposed approach and methods for optimizing the hydraulic modes of the HSS.

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Development Of Digital Twins And Digital Shadows Of Energy Objects And Systems Using Scientific Tools For Energy Research

Lyudmila V. Massel[1], *Alexey G. Massel*[2*]

[1] Doctor of Technical Sciences, Professor, Chief Researcher, Head of department of Artificial intelligence system, MESI SB RAS, Lermontov str. 130, Irkutsk

[2] Ph.d., Senior Researcher, department of Artificial intelligence system, MESI SB RAS, Lermontov str. 130,

Abstract. The article discusses an approach to the construction of digital twins and digital shadows, based on the use of scientific tools for complex energy research in Russia. It is proposed to use, as their basis, mathematical models of energy systems and software systems and databases developed at the Energy Systems Institute of SB RAS, for calculations using these models. For each area of research, an ontological model is developed, over which mathematical and information models are built and integrated, as the basis of digital twins and digital shadows of energy objects. In turn, scientific prototypes of digital twins and digital shadows can be used in complex energy studies. To support this research, a modified architecture of the multi-agent intelligent environment is proposed. It is considered as the basis of the future IT infrastructure that integrates modern information and intelligent technologies and implements a new approach to building digital twins and digital shadows using scientific tools.

Keywords. Energy systems, mathematical model, ontological model, intelligent technologies, digital twin, digital shadow

Introduction

In connection with the spread of digital energy concepts in Russia, the importance of strategic decisions on the development of interconnected technological and information and telecommunications infrastructures is increasing. Institute of Power Systems. Melentiev SB RAS (MESI SB RAS) traditionally conducts complex energy research, the results of which can be used to substantiate strategic decisions on the development of the energy sector.

To substantiate and support the adoption of such decisions, it is advisable to use intelligent information technologies and modern digitalization trends. Among the latter, digital twins and digital shadows are important.

The article examines these concepts and an approach to the construction of digital twins and digital shadows, based on the use of scientific tools for energy research: mathematical and information models, software systems and databases. A multi-agent instrumental environment for research support is described, combining mathematical and semantic methods, models and software developed at MESI SB RAS. It is proposed to develop and include in this environment scientific prototypes of digital twins and digital shadows that can be used in research. This allows us to view this environment as the foundation of the future IT infrastructure, integrating modern information and intelligent technologies and introducing a new approach to building digital twins and digital shadows using scientific tools.

1 Hierarchical systemic studies of energy industry

MESI SB RAS is one of the leaders in the field of system research in the energy sector of Russia. The main scientific directions of ISEM SB RAS: theory of the creation of energy systems, complexes and installations and their management; scientific foundations and mechanisms for implementing the energy policy of Russia and its regions. Within the framework of these areas, the following studies is being carried out: of energy systems (electric power, gas, oil, oil products, heat power); of energy security of Russia; of regional energy issues; of interconnections of energy and economy; of promising energy sources and systems; research in applied mathematics and computer science [1].

Until recently, the main research tool was mathematical modeling and a computational experiment. In connection with the new development trends of the Russian energy sector (Smart Grid and Digital Energy), much attention is paid to the development and application of intelligent information technologies. The Digital Economy Program being implemented in Russia is now being actively developed. The federal project "Digital Energy Industry" is a part of this Program. The authors decide that the federal project "Digital Energy

* Corresponding author: amassel@isem.irk.ru

Industry” does not pay enough attention to such areas as intelligent support of strategic decisions making on the development of the technological infrastructure of the energy sector and ensuring cyber security of critical energy facilities. Below we consider in more detail the first direction. A major role in strategic decisions making should be played by their scientific justification, for which the scientific achievements of the institute can be used.

Traditionally, the MESI SB RAS uses a hierarchical research scheme in which at aggregated level researches of the fuel and energy complex (economic and mathematical models are used), and at the next more detailed levels Sstudies industry energy systems (physical and mathematical models are used) (Fig. 1). These models must coordinated. Research on forecasting the development of the fuel and energy complex is carried out at the top level, taking into account the results obtained in studies of the development of industrial energy systems at the following levels. The scheme includes a number of blocks, each of which corresponds to a set of mathematical methods, models, and software systems that are used to perform computational experiments using these methods and models [2].

To use the results of these studies for substation of strategic decisions on energy sector development, it is necessary to carry out a formal integration of software and information support in order to improve the hierarchical technology to justify the development of the energy industry as a whole and its industry and territorial components, while the main attention should be paid to the development of software and information interfaces between tasks in the horizontal (between energy systems) and vertical (Energy Systems - Fuel and Energy Complex - External Conditions).

The development and implementation of such interfaces should provide the following advantages of a complex hierarchical research technology: a) maintaining (with the necessary refinement of the required software tools) confidentiality of the main detailed data arrays supporting specific tasks; b) formalization and thereby accelerating the exchange of information and ensuring the uniqueness of exchanged data; c) a certain unification of the information models used in solving various problems, which will need to be implemented when coordinating and developing interfaces; d) in general, an increase in “harmony” and the validity of the hierarchical technology for substantiating the development of energy industry and its components.

In [3], an approach to solving this problem was proposed, but the concepts of digital twins and digital images were not used in it. At the end of the article, the main provisions of the previously proposed and described here approaches will be compared.

Further, the main concepts of the latest trends in the development of digital technologies are considered: digital twins and digital shadows, digital models and digital images.

2 Digital twins and digital shadows

The latest trend in the development of digital technology is the creation of digital twins. It is claimed that the “digital twins” has entered the top ten major strategic technological trends of 2019. The concept of a digital twins has several definitions. The concept of a digital double has several definitions, a review of which was performed, for example, in [4], based on sources [5-14].

Consider the definition of the chief engineer of the Intelligent Networks division of Siemens company by E. Litvinova: “A digital twin is a real display of all components in the product life cycle using physical data, virtual data and the interaction data between them, that is, a digital twin creates a virtual prototype of a real object with which you can conduct experiments and test hypotheses, predict the behavior of an object and solve the problem of managing its life cycle ” [15]

According to experts [4], digital twins can be divided into three types:

1. Digital Twin Prototype. This is a virtual analogue of a real existing element. It contains information that describes a specific element at all stages — from the requirements for production and production processes during operation to the requirements for the disposal of the element.

2. Digital Twin Instance . It contains information on the description of the element (equipment), that is, data on materials, components, information from the equipment monitoring system.

3. Digital Twin Aggregate. It combines a prototype and an instance, that is, it collects all available information about the equipment or system.

For companies that operate electrical networks, the most relevant Digital Twin Instance. It is based on a mathematical model of network. Such a Digital Twin Instance can contain information about the technical parameters of the equipment used (cables, transformers, switches, etc.), the date of its commissioning, geographical coordinates, data from measuring devices. This information is used to carry out calculations for connecting new consumers, as well as various calculations of electric networks. For example, the calculation of modes, short circuit currents, coordination of relay protection settings and others.

For electric networks, the Digital Twin Instance includes a database with information about the network, which is integrated with other IT systems of the energy company (SCADA, geographic information system, asset management system, etc.). A Digital Twin Instance should synchronize data received from different sources, so that they exactly match the current state of the electrical network.

From the point of view of the construction area, digital twins of the product, process and system are distinguished [4]. A “digital product twin” is a virtual model of a specific product. “Digital process twins” - these models simulate production processes. The “digital system twins” are the virtual models of the system at a whole (for example, a digital twin of factory).

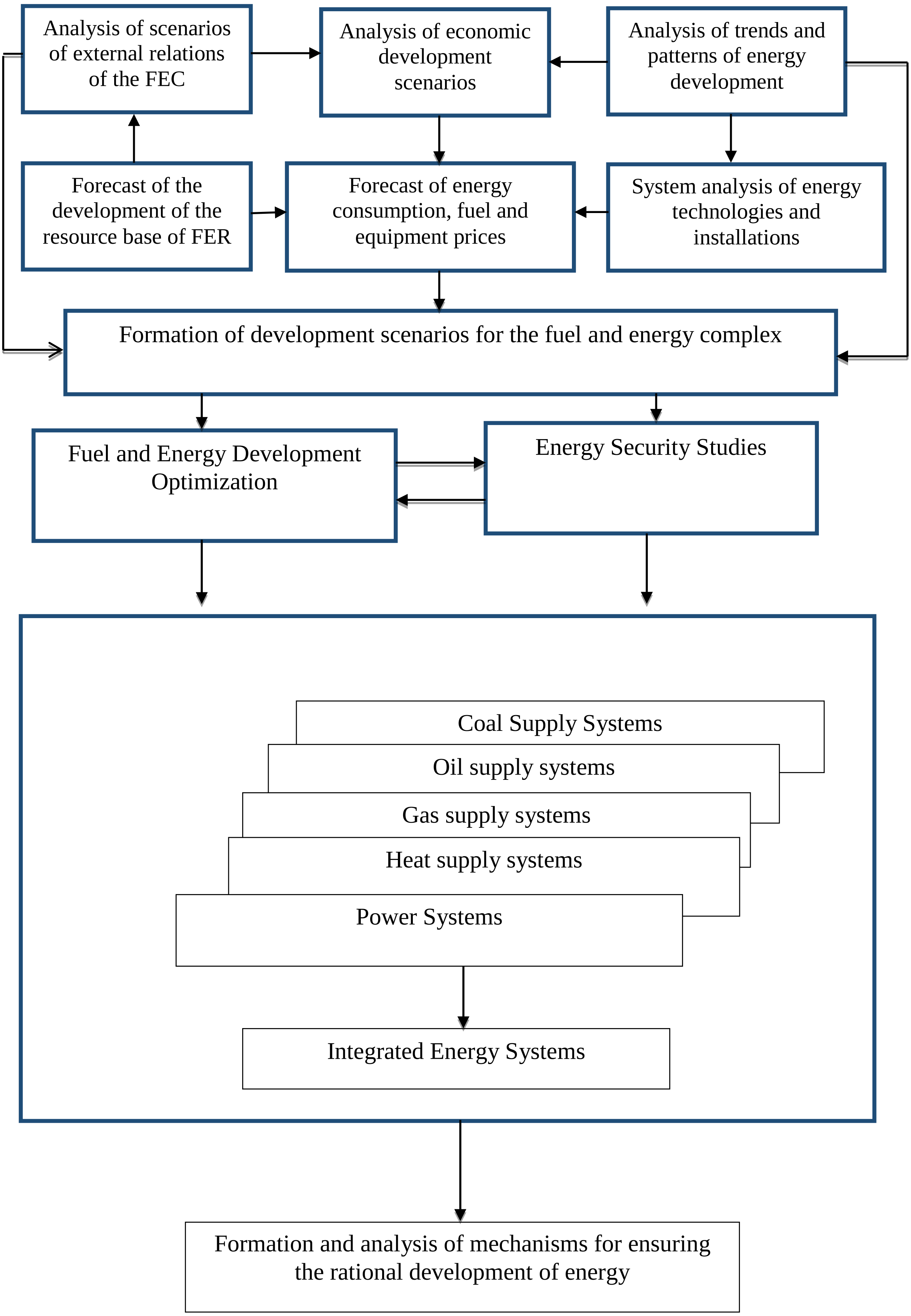

Fig. 1. The general scheme of hierarchical studies to substantiate the development of energy industry

In addition, the term digital shadow is used. A digital shadow can be defined as a system of relationships and dependencies that describe the behavior of a real object, as a rule, under normal working conditions and contained in excess big data obtained from a real object using industrial Internet technologies. A digital shadow is able to predict the behavior of a real object only in those conditions in which data was collected, but it does not allow simulating other situations. Comparison of digital twins and digital shadows is considered, for example, by A. Borovkov [16].

3 Transition from mathematical and informational models (computer programs and databases) for energy research to digital twins and digital shadows.

Based on the analysis of the sources cited and their own experience in the development of intelligent DSS and research infrastructure, the authors propose the following approach to the organization of system research in the energy sector using modern digitalization trends.

Justification of the possibility and feasibility of such a transition can be confirmed by a digital twin scheme based on an ontological model, which is a generalization of the scheme proposed by Dr.Sci. S.P. Kovalev (IPU RAS) with coauthors [17, 18] (Fig. 2).

In this scheme, it is important for us that the layer of mathematical models of the digital twin “gathers” over the ontological model. If we return to hierarchical studies to justify the energy development at ISEM SB RAS, it seems that on the basis of ontological and mathematical (physic-technical) models of industrial energy systems, digital twins of these systems can be constructed. Digital shadows are developed on the basis of information models, at the first stage, in the form of databases. After solving the issues of providing mathematical and simulation models with data, the issues of information interaction with data streams and conducting computational experiments on digital twins, they can be recommended for practical use in the management of the corresponding energy systems.

We can suggest the following stages of the transition to "digital twins" in the study of energy systems:

1) analysis of existing mathematical models and computer programs implementing them (software systems);

2) ontological engineering of the subject area (the corresponding power system) and the construction of its ontological model;

3) determination of the initial data or data flows (composition, sources of receipt, the possibility of obtaining operational data, databases, etc.), as a basis for building digital shadows, and their interaction with mathematical models;

4) modification, if necessary, of mathematical models and reengineering of software systems (if they moved into the category of legacy software);

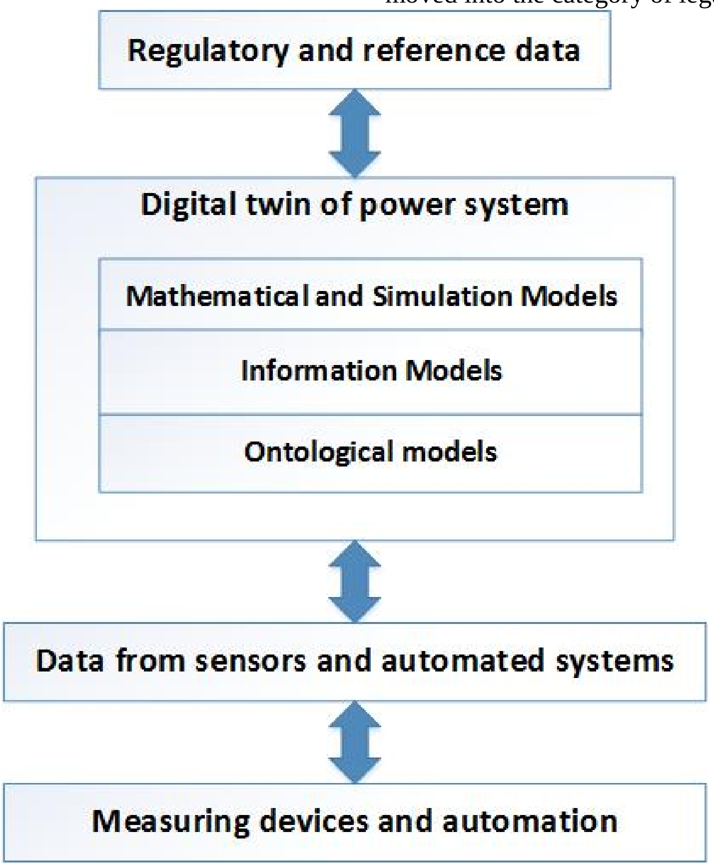

Fig. 2 . Energy system digital twin architecture.

5) development, based on the reengineered digital programs, web-applications and web-services for the development of digital twins.

6) development of digital twins prototypes of energy systems

The general final stage: the creation of IT infrastructure for hierarchical integrated researches using digital twins and digital shadows.

4. Infrastructure for support complex research in the energy sector using digital twins and digital shadows.

The basis of the infrastructure for conducting hierarchical comprehensive research in the energy sector using digital twins and digital images can be the modified architecture of the multi-agent intellectual environment (Fig. 4), proposed by the authors earlier in [3].

The levels (stages) of energy systems research and tools supporting them are shown in Fig. 3.

The following research levels (stages) and the supporting tools are identified:

1. The level of information analysis (using semantic modeling), supported by Intelligent IT environment.
2. The level of collective implementation of coordinated decisions (can be used semantic modeling, methods for coordinating decisions and others) - is supported by the Intelligent Support System for Collective Expert Activity [19].
3. The level of substantiation of decisions (the options proposed at the previous stage are calculated using traditional software systems for research on Fuel and Energy Complex and Energy Systems).
4. The level of presentation of the proposed solutions (using visual analytics and cognitive graphics).

The integration of tools is carried out using the knowledge management language (KML), which is considered as a simplified version of the previously developed language of situational management (Contingency Management Language - CML) [20]. Knowledge Management Language is used for integration of these components and for call of the required component.

The main components (agents) of MAIE are:

1. Software Systems and Data Bases for research of the fuel and energy complex together with Software and Data Bases, for example, for energy security research.
2. Data and Knowledge Warehouse.
3. Intelligent IT-environment for supporting of semantic modeling [21].
4. Intelligent system for supporting of collective expert activity.
5. Software component for visual analytics (GEO-visualization component).
6. Repository for descriptions storage of all intelligent and information resources supported by MAIE.
7. Knowledge Management Language (KML) to ensure the interconnection and interaction of all components (agents) of MAIE.
8. Portal – Ontological Knowledge Space.

The modification of this schema consists in the fact that software systems in the upper blocks of the circuit will be replaced with digital twins prototypes and databases became of digital shadows prototypes. This allows us to view this environment as the foundation of the future IT infrastructure, integrating modern information and intelligent technologies and introducing a new approach to building digital twins and digital shadows using scientific tools.

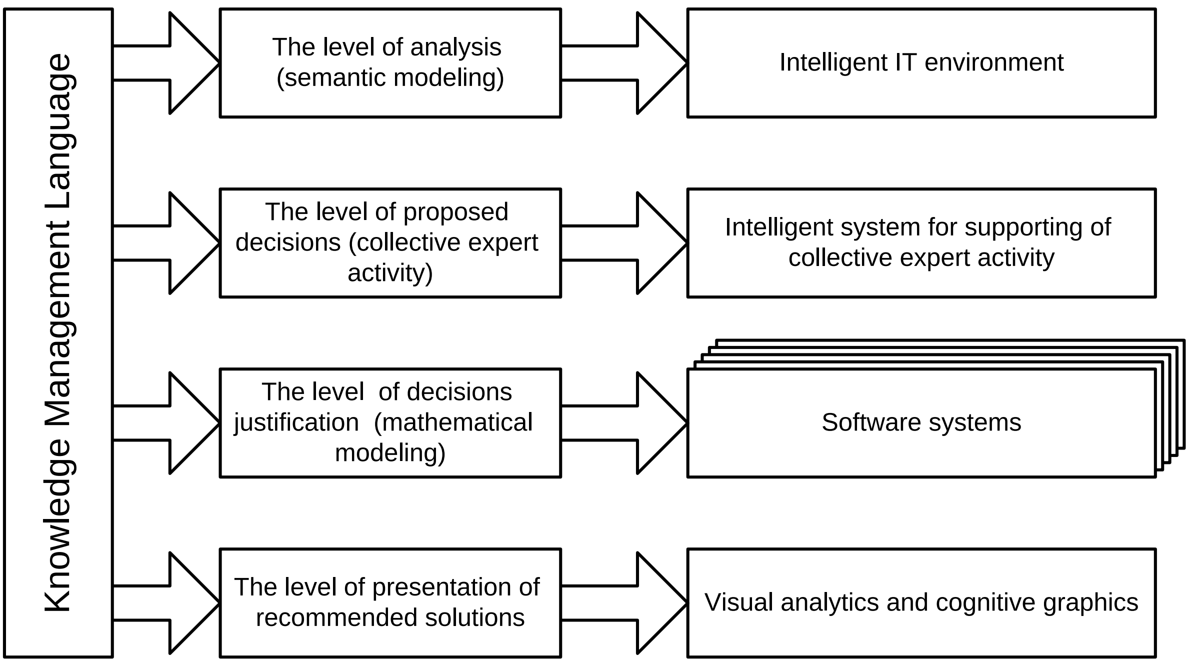

Fig. 3. Levels (stages) of energy systems research and tools supporting them.

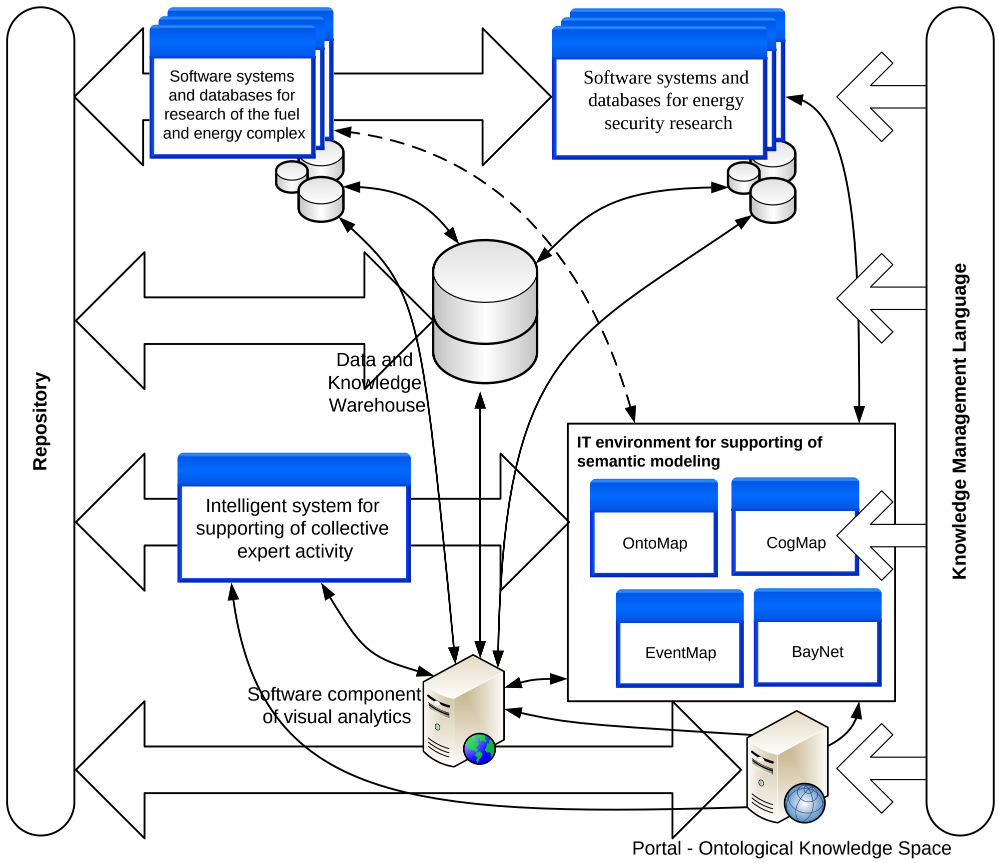

Fig. 4. The architecture of the multi-agent intelligent environment (MAIE) as the basis of the IT-infrastructure for support of complexes energy research using digital twins and digital shadows

Conclusion

1. One of the main trends of digitalization are considered: digital twins and digital shadows.

2. It is proposed to use the integration of mathematical, information and ontological models in energy research as base for costruction digital twins and digital shadows.

3. The stages of transition from mathematical models, software systems and databases to digital twins and digital shadows are determined.

4. An infrastructure is proposed to support complexes energy research using digital twins and digital shadows.

5. The modified architecture of a multi-agent intelligent environment as the basis of a new IT-infrastructure for energy research is considered.

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Control of Power Prosumer Based on Swarm Intelligence Algorithms

Pavel Matrenin[1*], *Vadim* Manusov[1], and *Dmitry* Antonenkov[1]

[1]Department of Industrial Power Supply Systems, Novosibirsk State Technical University, Novosibirsk, Russia

Abstract. The development of renewable energy and Smart Grid leads to the emergence of prosumers or power generating consumers, which are involved in the processes of bidirectional exchange of electricity and information. The work is devoted to the problem of optimal control of a power generating consumer in Smart Grid. The distinctive research features are the solution of the optimal control problem in conditions of difficult prediction of wind power plant generation, the usage of Swarm Intelligence algorithms to build a system of control rules, and the study of the obtained models on data from two different generating consumers: one on about Russky Island, the second on Popov Island (Far East). We selected a list of priority rules as a decision-making model and applied Particle Swarm Optimization, Bees Algorithm, and Firefly Optimization to build and optimize this model. The computer modeling with the usage of two mounts dataset showed that the proposed approach could significantly increase the revenue of the generating consumers considered.

1 Introduction

The development of renewable energy and Smart Grid leads to the emergence of prosumers or power generating consumers (GC), which are involved in the processes of bidirectional exchange of electricity and information [1, 2]. GC needs to control not only electrical load but also the flow of generated power. It significantly increases the complexity of its control tasks [3, 4].

The problem of the optimal GC control has a number of issues that lead to high complexity:

• GC operates under conditions of stochastic change in the generation of electricity by renewable sources and, to a lesser extent, of its consumption;

• the control problem has a high dimensionality of the solution search space;

• the objective function is not an analytical expression, is need to be calculated algorithmically.

Much modern research has been devoted to optimal control in Smart Grid networks with distributed generation and renewable energy sources. However, the optimal control is carried out at the level of a supersystem in them, and not individual GC. The frameworks to real-time coordinate load scheduling, sharing, trading were considered at studies [5, 6]. A.C. Luna et al. [7] proposed an energy management system for coordinating the operation of distributed household prosumers with renewable energy sources. H. Mortaji et al. [8] proposed smart-direct load control and load shedding based on autoregressive integrated moving average time-series prediction model and Internet of Things concept.

A number of articles propose a stochastic game approach for the problem of energy trading between smart grid prosumer. L. Ma et al. [6] used the energy management model on cooperative game theory. S.R. Etesami et al. [9] formulated the interaction among prosumers as a stochastic game, in which each prosumer seeks to maximize its payoff, in terms of revenues and proposed an optimal strategy for utility companies. The Stackelberg game approach for Smart Grid Energy Management (Energy sharing management) was considered at [10, 11].

Such management allows taking into account data on all participants in the distributed electric power system, but there is a risk associated with the high level of centralization of the control system. Thus, modern studies primarily consider the principles of constructing the entire Smart Grid power system and the interaction rules for multiple GCs. Out research focuses on optimizing the control rules for a single GC with a difficult prediction of generation using Swarm Intelligence (SI) algorithms.

The SI algorithms are known to effectively solve large-scale nonlinear optimization problems, including problems of power systems. The most commonly used SI algorithm is Particle Swarm Optimization (PSO); paper [12] provides a comprehensive survey on the usage PSO for power system applications. Other SI algorithms are also applied to different optimization problems in power system design and control [13-15]. In this research, three SI algorithms: PSO, Bees algorithm (BA), and Firefly optimization (FFO).

* Corresponding author: pavel.matrenin@gmail.com

2 The Problem Statement

2.1 GC Power System

In this research, we considered two large GC: the power system of Russky Island and the power system of Popov Island. Both islands are located in Peter the Great Gulf in the East Sea (Fig. 1). High wind speed makes it possible to create wind power plants up to 16 MW on Russky Island and up to 20 MW on Popov Island [16].

Russky Island belongs to the territorial composition of Vladivostok. It is located about two kilometers from the coast in Peter the Great Gulf, which is part of the Sea of Japan (the smallest distance between the continental part and the island is 800 meters). Russky Island is separated from the Muravyov-Amursky Peninsula by the East Bosphorus. From the west, the island is washed by the waters of the Amur Gulf, and from the east and south side by the waters of the Ussuri Gulf. In the southwest, the island is separated from the other Popov island by the Stark Strait.

The island is 97.6 km2, its length is about 18 km, and its width is about 13 km. The population of the island is approximately 25,000 inhabitants.

Popova Island (named after Admiral A.A. Popova) is located in Peter the Great Gulf of the Sea of Japan, 20 km from Vladivostok and 0.5 km southwest of Russky Island. About 3,000 people live on the island, mainly in the two villages of Stark and Popova.

Fig. 2 and Fig 3. show curves of own consumption of Russky GC and Popova GC and possible wind power generation of GCs according to the estimates of [16]. Fig 4. shows the results of adding these curves. The demonstrated fragment of data corresponds to twenty days from 01.06.2017.

From the charts above it is possible to notice the following:

• the forms of the electricity generation curves are very close since both islands are located very close, and their wind speeds are also close;

• the load curves concerning to generation are radically different; the Russky GC always has a deficit, the Popova GC still has a surplus;

• in case of consideration of two consumers together, we have the third type of load / generation pattern – in general, the GC system has a deficit, but sometimes there is a surplus.

Thus, different management strategies may be required depending on the characteristics of GC or GC hub.

2.2 Optimal Control

The task of optimal control is to create a control system (subject) that implements a sequence of actions on a controlled object in the environment to achieve the best possible quality specified by one or more criteria (Fig. 5); the controlled object is a specific part of the world around which the control subject can purposefully influence [17]. Control always occurs during a certain period of time, while the controlled object passes from one state to another.

Fig. 1. Russky and Popova Islands.

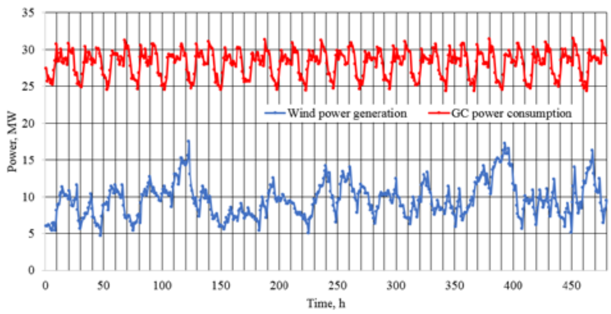

Fig. 2. Consumption and generation of Russky GC.

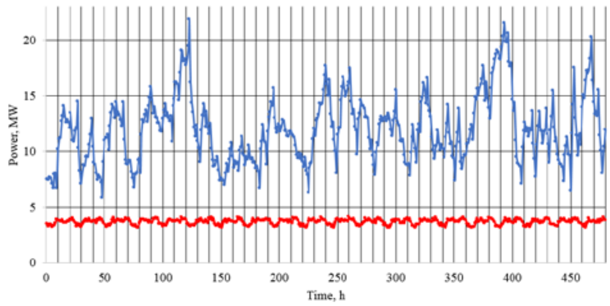

Fig. 3. Consumption and generation of Popova GC.

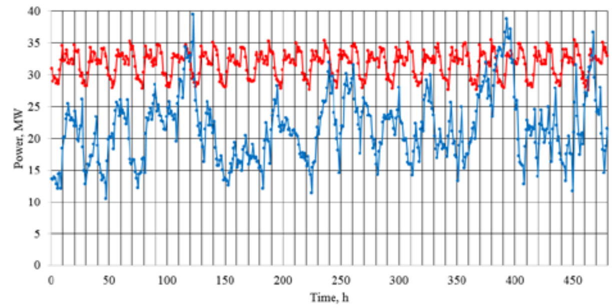

Fig. 4. Aggregated consumption and generation of both GC.

The state of the controlled object is characterized by a set of parameters that can change over time:

$$S(t) = \{s_1(t), s_2(t), ..., s_n(t)\}. \quad (1)$$

Thus, there is a vector of functions. Each function shows the parameter changing over time. These functions in the explicit form are unknown. In addition, there is a control system that provides control.

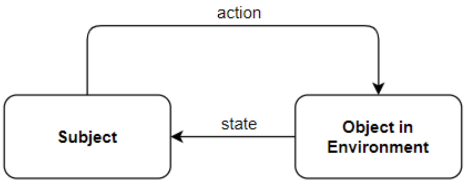

Fig. 5. Interaction between a subject and an object.

The control can also be defined as a vector of functions:

$$A(t) = \{a_1(t), a_2(t), ..., a_m(t)\}. \qquad (2)$$

The notations S from "state" and A from "action" are used.

The optimal control problem, in general, can be written as follows:

$$A^{opt}(t) = \arg\min_{A(t)\in A^{pos}} \int_{t_0}^{t_T} f\left(t, S(t), A(t)\right)dt \qquad (3)$$

• $A^{opt}(t)$ is the required optimal control; it defines values of the control parameters at each time moment (in the considered task, when and how much GC must sell or buy, charge or discharge);

• A^{pos} is the area of permissible values of control parameters;

• $f(t, S(t), A(t))$ is a continuous-time cost function, in the considered task, it gets GC's total electricity costs: purchases from the own generation + purchases from the other GC and an external power system – sale to other GC and the external power system.

• t_0 and t_T are the period of time considered.

2.3 GC Optimal Control task

For GC, the state parameters can be defined as follows:

• own consumption, MWh (s_1);

• wind power plants generation, MWh (s_2);

• charge level of power storage, MWh (s_3).

Control parameters can be defined as follows:

• the amount of electricity that is currently exchanged by the GC with an external power system (purchase or sale), MWh (a_1);

• the amount of electricity that is currently being transferred by the GC with the neighboring GC (purchase or sale), MWh (a_2);

• the amount of electricity that the GC is currently charging or discharging from the power storage, MWh (a_3).

The control does not affect the state parameters associated with the GC consumption and generation, but it directly affects the charge of the power storage. In the considered task, the time step is set equal to one hour. So, each day contains 24 values of the state parameters and 24 values of the control parameters. A daily sample is shown in Fig. 6.

Due to the high complexity of power systems in an explicit analytical form, the function $f(t, S(t), A(t))$ cannot usually be obtained, especially integral of this function. But it is possible to calculate the function algorithmically. In the case of GC control, this function is piecewise continuous, since the time step is 1 hour. The task (3) can be written without an integral, in the form of a sum, and the function $f(t, S(t), A(t))$ is nothing more than the difference between the revenues from the sale of electricity of a GC and the costs of its purchase, generation, and power storage in all hours into the time period. However, even in this case, the analytical expression for $f(t, S(t), A(t))$ is difficult to write, since the price of electricity is a piecewise constant function, the exchange of electricity with a neighboring GC supply depends on its state and controlling them. Thus, the calculation of the value of $f(t, S(t), A(t))$ should be performed algorithmically:

$$A^{opt}(t) = \arg\min_{A(t)\in A^{pos}} \sum_{t=t_0}^{T} revenue\left(t, S(t), A(t)\right) \qquad (4)$$

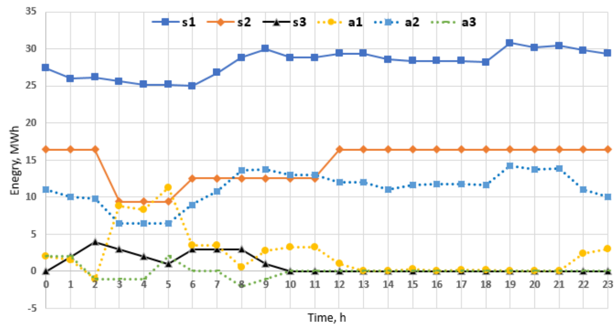

Fig. 6. Sample of daily state-action curves of Russky GC.

3 The Research Method

3.1 Heuristic-Rule-based control

All possible control actions could be described by dividing them into four groups. The following designation is used:

• *power_wind* – GC wind power plant generation at the considered hour;

• *power_gc* – GC consumption at the considered hour;

• *dif* – the difference between the GC generation and consumption at the considered hour;

• *storage* – the amount of energy that needs to be charged (> 0) or discharged (<0) at the considered hour;

• *now_ storage* – the energy stored in the power storage at the considered hour;

• *max_ storage* – the maximum amount of energy that can be stored in the power storage (constant, GC parameter);

• *max_ storage _h* – the maximum amount of energy that can be added to the power storage in one hour (constant, GC parameter);

• *sale_ storage* – coefficient that regulates the balance of purchase and charging (parameter should be tuned in the optimization process

• *sale_unload* – coefficient that regulates the balance of sales and use of discharging (parameter should be tuned in the optimization process);

• *sale_buy* – the amount of energy that is sold (> 0) or purchased (<0) at the considered hour.

Thus, we have the four cases of possible control actions:

1. Charge_Sell (it's possible if generation > consumption).
   1.1. *dif* = *power_wind* - *power_gc*;
   1.2. *storage* = min(*max_storage* – *now_storage*, *max_storage_h*, *dif*);
   1.3. *storage* = *storage* * *sale_storage*;
   1.4. *now_storage* = *now_storage* + *storage*;
   1.5. *sale_buy* = *dif* – *storage*.
2. Charge_Buy:
   2.1. *dif* = *power_wind* - *power_gc*;
   2.2. *storage* = min(*max_storage* – *now_storage*, *max_storage_hour*);
   2.3. *storage* = *storage* * *buy_storage*;
   2.4. *now_storage* = *now_storage* + *storage*;
   2.5 *sale_buy* = *dif* – *storage*.
3. Discharge_Sell:
   3.1. *dif* = *power_wind* - *power_gc*;
   3.2. *storage* = *now_storage*;
   3.3. *storage* = *storage* * *sale_unload*;
   3.4. *now_storage* = *now_storage* – *storage*;
   3.5. *sale_buy* = *dif* + *storage*.
4. Discharge_Buy (it's possible if generation < consumption):
   4.1. *dif* = *power_wind* - *power_gc*;
   4.2. *storage* = min(–*dif*, *now_storage*);
   4.3. *storage* = *storage* * *buy_unload*;
   4.4. *now_storage* = *now_storage* – *storage*;
   4.5. *sale_buy* = *storage* – *dif*.

The choice of actions should depend on the state of the GC, but it is enough to get answers to two questions. The first is connected with determining whether the GC is in a state of excess or deficiency of energy? The second is also related to the fact that the price of electricity changes throughout the day. Although various billing schemes are possible, a two-zone tariff is considered in this research, the daily tax is from 7 a.m. to 11 p.m., and at other hours it is a night tax, cheaper one. Thus, it's needed to get answers to the questions:

1) Excluding accumulation, does the generation of the GC wind power plant more than the GC consumption (diff> 0)?

2) Is there a special time period now?

The GC control takes into account the possibility of using two intervals as special periods (from $time_1$ to $time_2$ and from $time_3$ to $time_4$), the values of the boundaries of the time intervals are parameters adjusted during the optimization process.

As a result, we have four possible cases at each hour:

• (diff < 0) AND NOT (special_time_period);
• (diff > 0) AND NOT (special_time_period);
• (diff < 0) AND (special_time_period);
• (diff > 0) AND (special_time_period).

When creating a GC control based on rules, we get 12 rules of the form IF <condition>, THEN <action>

The number of rules is 12 since the second and third actions can be performed under any of the four conditions, and the first and fourth under two conditions (2 * 4 + 2 * 2 = 12). In addition, the GC control model has four balance factors: *buy_unload*, *sale_unload*, *buy_storage*, *sale_storage*, and four moments as the boundaries: $time_1$, $time_2$, $time_3$, $time_4$.

To control using these rules, we need to determine the procedure for their verification and compliance, that is, rule priorities. Decision making begins with checking of the highest priority rule. If its condition is satisfied, then the corresponding action of this rule is implemented. Otherwise, the next priority rule is checked, and so on until the end of the rule list. The conditions are designed in such a way that when you go through the list of rules, you will surely find one whose condition will be satisfied. As a result, to build a controller, it is necessary to determine the order of the rules by setting priorities (pr_i) and the tuned parameters specified above:

$$Solution = [pr_1, \ldots, pr_{12}, buy\_unload, sale\_unload, buy\_storage, sale\_storage, time_1, \ldots, time_4]$$

3.2 Swarm Intelligence

It is not always possible to determine the Swarm Intelligence algorithm that is most suitable for a solved task [15]. Therefore, the use of only one algorithm can give a solution whose effectiveness is not satisfactory for the optimization criterion. In this case, the researcher cannot determine the effectiveness without using other algorithms for comparison. Therefore, three Swarm Intelligence algorithms were applied: the Particle Swarm Optimization (PSO) algorithm, the Firefly Optimization (FFO) algorithm, and the Bees algorithm (BA) (not Artificial Bee Colony Optimization). Descriptions of the algorithms precisely in the form in which they are applied in this research are given in.

3.2.1 Particle Swarm Optimization

The Particle Swarm Optimization algorithm was first proposed by J. Kennedy and R. Eberhart in 1995 [18]. Then it was improved by Kennedy, Eberhart, and Shi [19]. PSO is based on a bird flocks' behavior. A flock acts coordinated according to a number of simple rules. Every bird (called particle) coordinates own movements with the movements of whole flocks. In the PSO algorithm, every particle is denoted by a position vector, a velocity vector, and a value of the criterion. The vectors of position and velocity of all particles are updated according to a number of rules taking into account the best position of a particle, and the best position of the whole swarm. Also, the algorithm uses inertia weights of the particles, velocities restriction and the stochastic deviations.

According to the scheme of the swarm algorithms description [15], the PSO algorithm may be represented by a tuple $\{S, M, A, P, I, O\}$.

1. A set of particles (particles) $S = \{s_1, s_2, \ldots, s_{|S|}\}$, $|S|$ is number of particles. At j-th iteration i-th particle is characterized by the state $s_{ij} = \{X_{ij}, V_{ij}, X^{best}_{ij}\}$, where $X_{ij} = \{x^1_{ij}, x^2_{ij}, \ldots, x^l_{ij}\}$ is the variable parameter vector (particle position), $V_{ij} = \{v^1_{ij}, v^2_{ij}, \ldots, v^l_{ij}\}$ is the velocity

vector, $X^{best}_{ij} = \{b^1_{ij}, b^2_{ij},..., b^l_{ij}\}$ are the best (by value) fitness-functions of the particle position among all the positions it took during the algorithm operation from the 1st to the *j*-th iterations, *l* is the number of variable parameters.

2. Means of indirect exchange is vector $M = X^{best}_j$ is the best value of the variable parameters vector derived among all particles from the 1st to the *j*-th iterations of the algorithm.

3. Algorithm *A* describes the steps of the PSO algorithm.

3.1. Generation of initial population (iteration number $j = 1$):

$X_{i1} \leftarrow random(0,1),\ i = 1, …, |S|,$

$V_{i1} \leftarrow random(0, v_{max}),\ i = 1,…|S|,$

$X^{best}_{i1} \leftarrow X_{ij},\ i = 1, …|S|,$

where *random*(0, 1) is the vector of random numbers with dimensionality *l* (dimensionality of solution search space) uniformly distributed from 0 to 1.

3.2. Calculation of fitness- functions. The criterion calculation takes place in the mathematical model of the problem where X_{ij} vectors are entered from algorithms and the results are returned to the algorithm through the interface {*I*, *O*}.

$X^{best}_{ij} \leftarrow X_{ij} \mid f(X^{best}_{ij})<f(X_{ij}),\ i = 1, …, |S|,$

$M \leftarrow X_{ij} \mid f(M) < f(X_{ij}),\ i = 1, …, |S|,$

3.3 Particles' movement with respect to the tolerance region and to the velocity limitation:

$V_{ij+1} \leftarrow V_{ij}\omega + \alpha_1(X^{best}_{ij} - X_{ij})random(0,1) + \alpha_1(M - X_{ij})random(0,1)\ (i = 1, …, |S|).$

$V_{ij+1} \leftarrow \beta \mid V_{ij+1} > v_{max}\ ,i = 1, …, |S|.$

$V_{ij+1} \leftarrow -\beta \mid V_{ij+1} < -v_{max}\ ,i = 1, …, |S|,$

where α_1, α_2, ω, v_{max} are algorithm parameters.

$X_{ij+1} \leftarrow X_{ij} + V_{ij+1}\ ,\ i = 1, …, |S|.$

$X_{ij+1} \leftarrow 1 \mid X_{ij+1}>1\ ,\ i = 1, …, |S|.$

$X_{ij+1} \leftarrow 0 \mid X_{ij+1}<0\ ,\ i = 1, …, |S|$

3.4. If at the *j*-th iteration a stop-condition is satisfied, then the value *M* is transmitted to output *O*, or the transition to iteration 3.2 takes place.

4. Vector $P = \{\alpha_1, \alpha_2, \omega, \beta\}$ comprises the coefficients of algorithm *A*, which influences the particles' movement in the search space. Coefficients α_1 and α_2 define the degree of accounting the individual and group experience of the particles, respectively. Coefficient ω characterizes inertial properties of the particles, and coefficient v_{max} defines limitations for the maximum velocity.

5. Identifiers *I* and *O* are input and output of the PSO algorithm for interaction with the problem considered.

3.2.2 Bees Algorithm

The Bees Algorithm Bee Colony Optimization algorithm was researched and developed by a number of authors in 2005 [20]. It is based on the simulation of the behaviour of bees in their searching for nectar and the indirect exchange of information between bees. Bee swarm sends several scouts in random directions to search for nectar. Returning, scouts report on the areas found in the field with flowers containing nectar, and on them fly out the other bees. In this case, the more on the site of nectar, the more bees go to it. However, the bees can randomly deviate from the chosen direction. After the return of all the bees in the hive, information exchange and sending of bees again.

According to the description scheme of swarm algorithms, the BA algorithm may be represented by a tuple {*S, M, A, P, I, O*}.

1. A set of particles (bees) $S = \{s_1, s_2, …, s_{|S|}\}$. At the *j*-th iteration the *i*-th particle is characterized by the state $s_{ij} = \{X_{ij}\}$, where $X_{ij} = \{x^1_{ij}, x^2_{ij}, …, x^l_{ij},\}$is the variable parameters vector (the particle position), *l* is the dimensionality of the solution search space.

2. Means of indirect exchange *M* is a list of the best and perspective positions found in the j-th iteration, $M = \{N_{ij}^b, N_{kj}^g\},\ i = 1, ..., n^b,\ k = 1, ..., n^g$.

3. Algorithm *A* describes the steps of the BA algorithm.

3.1. Generation of initial population (*j*=1) is fulfilled only for a subset of particles termed scouts:

$X_{i1} \leftarrow random(0,1),\ i = 1, …, n^s,$

where n^s is the number of scout particles. Other particles are considered as inactive this time (only at the first iteration).

3.2. Calculation of fitness-functions. The criterion calculation takes place in the mathematical model of the problem where X_{ij} vectors are entered from algorithms and the results are returned to the algorithm through the interface {*I*, *O*}.

$X^{best}_{ij} \leftarrow X_{ij} \mid f(X^{best}_{ij})<f(X_{ij}),\ i = 1, …, |S|,$

3.3. Particles' movement. Among all particles n^b particles with the best values of target function are chosen, and then, in the rest of the set, n^g particles with the best values are chosen. On the basis of this positions, the lists of the best and perspective positions $M = (N_{ij}^b, N_{kj}^g)$ are generated, found at the (*j*–1)-th iteration. Herewith, the distance between any two positions in *M* over each coordinate in the solution search space must be not less than the values of parameter *rx*. Worker particles are sent to the vicinity of these positions. c^b of particles are sent to the vicinity of each best position and c^g are sent to the vicinity of each perspective position. Thus, the positions of all worker particles are determined as follows:

$X_{(i-1)cb+k\ j} \leftarrow N^b_{ij-1} + random(-1, 1)\cdot rad,\ i = 1,…, n^b,\ k= 1,…, c^b,$

$X_{nb\cdot cb+(i-1)cg\ +\ k\ j} \leftarrow N^b_{ij-1} + random(-1, 1)\cdot rad,\ i = 1,…, n^g,\ k= 1,…, c^g,$

where n^s, n^b, n^g, c^b, c^g, *rad* are the parameters of the algorithm.

In this case, scout particles are sent to random positions the coordinates of which are random values uniformly distributed in the tolerance range:

$X_{nb\cdot cb+ng\cdot cg\ +\ i\ j} \leftarrow random(-1, 1)\cdot rad,\ i = 1,…, n^s$

3.4. If at the *j*-th iteration a stop-condition is satisfied, then the value X^{best}_i is transmitted to output *O*, or the transition to iteration 3.2 takes place.

4. Algorithm parameters used in this description form vector $P = \{n^s, n^b, n^g, c^b, c^g, rad, rx\}$. The coefficient *rad* defines particle scattering in sending to the best and prospective positions, coefficient *rx* defines minimum possible distances between these positions.

The value for the expression $n^s + n^b c^b + n^g c^g$ is equal to the total number of the swarm particles ($|S| = n^s + n^b c^b + n^g c^g$). The selection of the algorithm parameters heavily affects the quality of derived solutions, so in order to increase the algorithm efficiency it is necessary to adapt parameters.

3.2.3 Firefly Optimization

Firefly Optimization was proposed by Xin-She Yang in 2010 [21]. This algorithm as all Swarm Intelligence algorithms is based on the particles (fireflies) movement in the search searching space. Let's consider the objective function minimum problem of the following type $f(X)$, where X is a vector of varied parameters which can get the values from some D area. Each particle is specified by the value of X parameter and value of an optimized function $f(X)$. Thus, the particle is a feasible solution of the considered optimization problem.

As the algorithm is based on watching for fly's behavior, each particle is considered to see the "light" from their neighbors, but the brightness of the "light" depends on the distance between particles. For the process of solution finding to be converged to the optimum, each particle in its movement takes into account only those neighbors having a better value of $f(X)$ criterion. But for the algorithm not to degenerate into greedy heuristics, it is necessary to have particles' stochastic movement.

According to the description scheme of swarm algorithms, the FFO algorithm may be represented by a tuple $\{S, M, A, P, I, O\}$.

1. Set of particles (fire-flies). $S = \{s_1, s_2, \ldots, s_{|S|}\}$, $|S|$ is a number of particles. At iteration j the i^{th} particle is specified by the state $s_{ij} = \{X_{ij}\}$, where $X_{ij} = \{x_{1ij}, x_{2ij}, \ldots, x_{lij}\}$ is a vector of the varied parameters (particle's position), l is a number of the varied parameters.

2. Means of indirect exchange is vector M is particles' brightness.

$M = \{f(X_{1j}), f(X_{2j}), f(X_{|s|j})\}$

Brightness is determined by the optimality criterion. This vector ensures the indirect experience exchange among particles.

3. Algorithm A describes the steps of the ACO algorithm.

3.1. Generation of initial population (iteration number $j = 1$):

$X_{i1} \leftarrow random(G(X)),\ i = 1, \ldots, |S|$,

where random($G(X)$) is a vector of equally distributed random variables meeting the restrictions of searching space.

3.2. Calculation of fitness-functions. The criterion calculation takes place in the mathematical model of the problem where X_{ij} vectors are entered from algorithms and the results are returned to the algorithm through the interface $\{I, O\}$.

$m_{ij} \leftarrow f(X_{ij}),\ i = 1, \ldots, |S|$

$X_j^{best} \leftarrow X_{ij} \mid f(X_{ij}) \le f(X_j^{best})$

3.3 Particles' movement:

$X_{ij+1} \leftarrow X_{ij} + v(X_{ij}, X_{kj}) \cdot (X_{ij} - X_{kj}) + \alpha \cdot random(0, 1) \mid m_{kj} \le m_{ij},\ i, k = 1, \ldots, |S|,\ i \ne k$,

if $G(X_{ij+1}) = 0,\ X_{ij+1} \leftarrow X_{ij},\ i = 1, \ldots, |S|$,

Where random ∈ [0, 1], and $G(X)$ is used in this case as the predicate showing if X belongs the area of admissible solutions.

The function $v(X_{ij}, X_{kj})$ defines the attractiveness of k particle for i particle with j algorithm iteration:

$v(X_{ij}, X_{kj}) \leftarrow \beta \cdot (1 + \gamma \cdot r(X_{ij}, X_{kj}))^{-1}$

where $r(X_{ij}, X_{kj})$ is Cartesian distance between particles.

3.4. If at the j-th iteration a stop-condition is satisfied, then the value $X^{best}{}_i$ is transmitted to output O, or the transition to iteration 3.2 takes place.

4. Vector $P = \{\alpha, \beta, \gamma\}$ are coefficients of the algorithm. Coefficient α determines the influence degree of stochastic algorithm nature. Coefficient β sets the degree of attraction between particles with zero distance between them i.e. defines the particle's mutual influence. Coefficient γ controls the dependence of attraction on the distance between particles.

3.3 Application the Swarm Intelligence Algorithm for GC optimal control

For applying SI algorithms, it is necessary to determine the mapping of the particle coordinate (X) in the search space solution to the solutions of the solved task. In this case, the solution is the control actions $A(t)$, as shown in expression (1). Each element of the vector X is bounded from 0 to 1 [15]. The priorities are real numbers from 0.0 to 1.0, so $pr_i = x_i$, $i = 1, ..., 12$. The parameters *buy_unload*, *sale_unload*, *buy_storage*, *sale_storage* also take values from 0.0 to 1.0, so they are mapped in the same way. To set values of $time_1, ..., time_4$, we use rounded down values of $24x_{17}, \ldots, 24x_{20}$.

The FFO algorithm requires comparing each particle to each other, so the number of operations quadratically depends on the number of particles. The PSO and BA have a linear relationship. We reduce the number of FFO particles to equalize the calculation time. At the same time, we increase the number of iterations of the FFO algorithm to equalize the number of calculations of the objective function. As a result, the number of particles is reduced four times, and the number of iterations is increased four times compared to the PSO algorithm and the BA. The parameters of the SI algorithms are given in Table 1.

Table 1. Parameters of the SI algorithms

Alg.	Particles	Iteration	Heuristic coefficients
PSO	200	500	$\alpha_1 = 1.5$ $\alpha_2 = 1.5$, $\omega = 0.7$, $\beta = 0.5$
BA	200	500	$n^s = 60$, $n^b = 6$, $n^g = 1$, $c^b = 20$, $c^g = 20$, $rad = 0.01$, $rx = 0.05$
FFO	50	2000	$\alpha = 0.05$, $\beta = 1$, $\gamma = 0.5$

4 Results and Discussion

4.1 Computational Experiment

Computational experiments were carried out while considering the GC of Russky and Popov Islands (GC_R, GC_P, respectively). Table 2 shows the prices used in the simulation.

Table 2. Prices used in the simulation

Power flow	Price, rubel / MWh	Price, $ / MWh
Wind generation	500	6,67
Power storage discharging	100	1,33
Sale (daily rate)	3200	42,7
Sale (daily rate)	1400	18,67
Buy (daily rate)	2700	36,00
Buy (daily rate)	900	12,00

To evaluate the effectiveness of the rule-based control model built by the Swarm algorithms, we compared them with a base constructed manually by an expert. The main advantage of using SI is an automatic adaptation to the profiles of production and consumption of each GC. Therefore, the expert rules were constructed one time for the general case.

Obviously, in the problem under consideration, control is impossible without power storage. Because without it, GC has to sell electricity at times of excess and buy at times of shortage, and there are no other options. Therefore, control efficiency is limited by the capacity of the power storage. Due to the limitation of capacity and the use of tariff simulation with only two rates (day, night), the reduction in energy consumption or the increase in income (this is the same thing) is not very large. Thus, for results clarification, we did not compare the absolute values of the cost of electricity according to criterion (4), but the benefits that control gives regarding the situation without power storage.

In section 2.1, three cases are considered: the control of a GC of Russky Island, GC of Popova Island, and an integrated system of both GCs. For each situation and each algorithm, modeling was performed on data for two summer months (Fig. 2-4).

4.2 Simulation results

Table 3 shows the results. Each SI algorithm was launched 20 times, and in 17-18 launches out of 20 gave the same result. This result is used as a summary. The results without the use of power storage are shown in rows with the label "No" in the "Algorithm" column, and the results of control using the expert rules are labeled as "Expert". Also, Fig. 7 visualizes the benefits of using the rule-based model optimized by the SI.

It can be seen that the difference varies greatly depending on the profile of production and consumption. For the GC of Russky Island, there is a situation of electricity shortage, so control does not make a large contribution. For the Popova Island GC, on the contrary, there is an excess of electricity; therefore, it is necessary to determine the best moments for the sale of electricity and the balance between sale and accumulation.

The most interesting situation is when a joint system of two GCs is controlled together. First, in this case, the profile is more complicated (Fig. 4), since there are moments of both excess and shortage of electricity. Secondly, the power storage capacity is two times higher due to the combination of storages of both GC in a single power system. Thirdly, the combined GC has a higher generation and consumption, since, it is evident that all quantitative indicators will be more top.

The results of all applied SI algorithms are very close, even without adjusting the heuristic parameters. It can be explained by the relatively low complexity of the task from the point of view of optimization theory since there are not many control options.

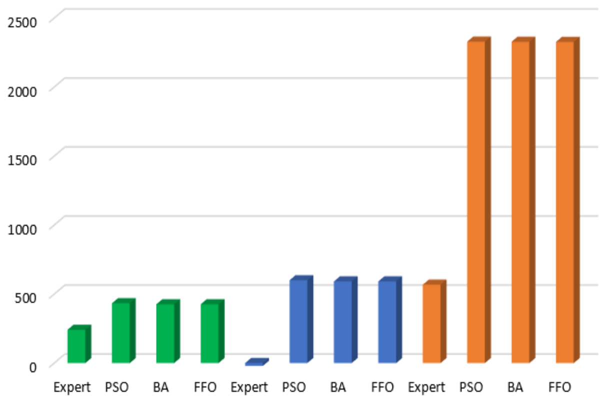

Fig. 7. Algorithms' results. The histogram shows the monthly profit ($) of power storage usage with the different algorithms of optimize control rule-based model. Left 4 bars shows results for GC_R, central 4 bars – for GC_P, right 4 bars – for GC_{R+P}.

Table 3. Algorithms' results

Case	Algorithm	Cost, thousands $	Monthly Profit, thousands $
GC_R	No	580.3	-
GC_R	Expert	579.8	0.241
GC_R	PSO	579.4	0.43
GC_R	BA	579.5	0.43
GC_R	FFO	579.5	0.43
GC_P	No	-41.6	-
GC_P	Expert	-41.5	0
GC_P	PSO	-42.8	0.6
GC_P	BA	-42,8	0.59
GC_P	FFO	-42,8	0.59
GC_{R+P}	No	452,0	-
GC_{R+P}	Expert	450,4	0.57
GC_{R+P}	PSO	447,3	2.33
GC_{R+P}	BA	447,3	2.33
GC_{R+P}	FFO	447,3	2.33

5 Conclusion

In this research, we have applied Swarm Intelligence algorithms to optimize the heuristic-rule-based control model (optimize priorities of rules and numerical values of the model coefficients) for optimal control of generating consumers with wind power plants. The computer simulation showed that SI allowed to increase the profit of power storage usage 1.8–4.1 times compared with the rules build by experts. The simulation results confirmed that it is appropriate to apply the SI algorithms to increase accuracy of heuristic-rule-based model, and perform adaptation to a given generating consumer.

The proposed control model allows to get the robust control in a particular situation, which can be easily transferred to other climatic conditions and GC features. For future work, we plan: firstly, to complicate a GC model and a model of GCs interaction; secondly, to apply the Q-learning method for the optimal control of GC; thirdly, make comparisons with existing methods using larger dataset.

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A LAW AND ECONOMICS ASPECTS OF THE IMPLEMENTATION OF SMART GRID IN THE RUSSIAN FEDERATION, PROBLEMS AND PERSPECTIVES OF THEIR USE

Strenin Danil[1,*] and *Maydibor* Daria[2]

[1] Financial University under the Government of the Russian Federation, Faculty of Law, 49 Leningradsky Prospekt, 125993, Moscow, Russia
[2] Financial University under the Government of the Russian Federation, Faculty of Economics and Business, 49 Leningradsky Prospekt, 125993, Moscow, Russia

Abstract: In the course of this work, the authors considered the features and prospects of introducing smart energy systems in the Russian Federation, highlighted the legal problems that arise during the implementation of technologies, suggested possible solutions to them and made recommendations for the effective implementation of this activity.

The 21st century is the century of new technologies, the century of introducing innovations in all spheres of public life. Modern energy does not stand aside. One such innovation is Smart Grids. By Smart Grids we mean an automated set of algorithms that independently monitors and distributes electricity flows to achieve maximum energy efficiency, as well as other tasks.

The emergence of a new generation of Smart Grids is caused by the following reasons:

- distribution of generation, as well as an increase in the volume of technologies used based on renewable energy sources;
- the emergence of new methods of managing consumer services, innovative energy storage technologies;
- the discovery of new approaches in the field of energy supply and distribution during the use of highly intelligent automated systems;
- the advent of new applications working with data analytics on high-voltage networks.

The idea of smart energy systems is embodied in the form of a single set of devices that make it possible to achieve automation of the processes of activity of energy companies and utilities, as well as provide the ability to carry out high-quality monitoring and control of the two-way energy flow along the entire length of the production chain - from a power plant to the end consumer. Along with the two-way power transmission channels, the system has two-way data exchange channels that receive information from the object and transmit control commands to it.

This smart system uses sensors, counters, analytical tools and digital controls. The data from the sensors enter the information systems, which, analyzing the incoming information, are able to make decisions about whether to change the route of electricity flows, the mode of operation of household appliances or industrial installations in order to consume a valuable resource - electricity - as efficiently as possible and ultimately avoid energy collapses.

The introduction of Smart Grid in the energy sector provides optimization of productivity, prevention of downtime and quick recovery from power outages. For consumers, this transformation opens up the possibility of managing their own energy consumption at the level of individual electrical appliances connected to the network.

The evolution of Smart Grid technologies can be visualized and viewed in two stages. The first - modernization - completed by 2015, should include various equipment for transmission and measurement, examples of which are measuring instruments, transformers, capacitors and plugs, and partly automated control systems. The latter are at the junction of the described stages and are widely used in the transition to the second - a breakthrough through integration with information and communication technologies. Examples of these systems are SCADA and PMUs systems, voltage sensors, Demand Side Management, power distribution automation. Currently, an advanced measuring infrastructure in the form of smart meters, price-dependent consumption, energy management, and also the so-called microgrids: ultra-advanced current limiters, energy storage, smart devices, and power management platforms [1].

Transformation of the electric power industry segments allows achieving the following effects: increasing production capacities and providing power to remote and isolated regions, reducing losses arising in the process of transmission and transformation of electricity; reduction of peak network loads during power distribution and, as a result, reduction of operating costs and losses. In addition, the transformation of the segments will allow for accurate metering of consumption, and in the business environment to meet the growing requirements for environmental friendliness and energy efficiency of production, integrate electricity

* Corresponding author: strenin@mail.ru

markets, introduce integrated intelligent management of both demand and consumption, as well as manage and supply to the market surplus energy, where former consumers will become producers of electricity.

Practical measures for the transition to the Smart Grid should become a necessary component of the entire technological process of renewing the electric power industry in Russia. So, replacing old equipment with a similar or technically progressive new one is not enough for the effective implementation of the transition - the primary task is to introduce it into the energy Internet, which will allow it to be embedded in the active part of innovative systems for managing economic interactions and technological processes, to apply it not only on the local, but also at the regional, federal and even national levels.

Implementation of the action plan for the implementation of smart measuring systems will allow achieving a number of socio-economic effects:

• changes in the export diversification index, GDP structure, as well as building up the export potential of the state through the formation of a sustainable export flow of software, equipment, smart energy systems services and integrated engineering services. The gross turnover of domestic enterprises in the markets of “target countries” is estimated by analysts at $ 40 billion in 2035 [2];

• strengthening the positions of domestic companies in the international arena and the global energy market through the introduction of EnergyNet technologies;

• potential reduction of technical losses by up to 50% through the installation of more high-tech metering devices and targeted network repair, the volume of required capacities - up to 80%, operating costs - up to 10% due to a decrease in the number of employees and maintenance and repair volumes, a decrease in consumer debt by up to 30-50% due to timeliness of payment [3];

• achievement of a higher quality of power supply, development of household and industrial segments of the equipment energy efficiency market;

• development of the information technology industry, various areas of engineering in key areas, the formation of a talent pool in the field of high-tech industries, training of specialists with skills to work in global markets;

• savings on energy marketing activities arising from the introduction of new financial technologies that allow automating the settlement processes, resulting in a reduction in the cost of energy consumption.

However, smart grids cannot be implemented ignoring the world experience, both technological and organizational and economic. Table 1 highlights the main technologies of strategies for the implementation of smart grids in 4 leading countries in this direction.

Table 1 Characteristics of smart grid implementation strategies [1]

Country	Key technologies used
England	1. Implementation of smart meters, creation of applications for monitoring and control; 2. Priority for the use of renewable energy sources, gradual integration into network infrastructure systems; 3. Regular diagnostics of power supply voltage; 4. Application of thermal energy storage systems.
India	1. Development and implementation of SCADA / Energy Billing, Energy Auditing & ABT Meter Interface / DMS / EMS and other technologies; 2. Real-time collection, processing of information and redistribution of energy; 3. Analysis of network visibility using open access and the Independent Power Producers (IPPs) system; 4. Dispatch control with data transmission technology using VSAT.
USA	1. Application of the Advanced Power Distribution System (DMS); 2. Implementation of automated switches at distribution centers; 3. Launch of remote control and monitoring of equipment at substations; 4. Installation of new components to stabilize and raise the level of the technical condition of the network.
Sweden (automation of the smart grid of the seaport in Stockholm)	1. Improvement of the Peak Load Management (DSM) system; 2. Widespread introduction of RES; 3. Electrification of the bay, ship docks, docks; 4. Automation of systems of structures and buildings of port services; 5. Improving the quality and efficiency of energy storage systems.

It should be noted that today a significant part of smart grid technologies developed and successfully implemented abroad, in particular, in the West, cannot be applied in Russia and the CIS countries due to the significant differences in domestic and Western electric power infrastructures that have not yet been eliminated. That is why, taking into account the specifics of large domestic power grid complexes, in Russia at this stage of

[1] Compiled by the authors based on [1].

technological development, it is advisable to only partially introduce smart power systems, which are aimed at solving the key existing problems and tasks of the industry.

Russia has great potential for the development, implementation and use of smart energy technologies. Acceleration of the development of Smart Grid principles can be both borrowing an integrated approach used in the leading countries in the implementation of smart energy systems technologies, and international cooperation with them. All participants of the energy market will have to make efforts in a coordinated and coordinated way, as it is difficult to create a single intelligent power system, working in a different way. It was necessary to work together within the energy value chain, which should unite the interests of generators, distribution networks, marketing companies and consumers. The value chain assumes that new market players will have to share basic information with each other in real time, while at the same time enabling consumers to obtain key information on price conditions, loading modes, savings in time and other important parameters for engaging consumers in the optimization process of the entire grid. In this process, the State has an important role to play, which should take on the functions of coordination, support and incentives. In addition, in practice, the effectiveness of the creation at the government level of institutions responsible for the creation, development and use of technologies in the field of monitoring and accumulation of renewable energy, the development of mechanisms for attracting both public and private investments, the launch of various educational programs in this area for the population, support and financing of projects has been proven.

Smart grids can include new renewable energy sources, such as wind turbines and solar panels. They can also be used locally with distributed energy sources or network-connected electric vehicles. All of these elements of a single system are managed by the necessary software-but-hardware tools, such as a high-performance computing system that allows real-time information to be processed, streaming tools that allow it not to store vast amounts of incoming information, but to filter it, process it in a necessary way and make management decisions. Another important aspect that is not being given sufficient attention is ensuring the security of the "reasonable" power grid that we are striving to build. The more data, data and information, the greater the threat of external intruders to have a negative impact on the grid. Therefore, we can expect an increase in investments in providing integrated (at the junction of physical and digital networks) security.

The potential effects of the large-scale application of smart grids in Russia include an increase in the competitiveness of the domestic energy-intensive industry, which will make up the main share in the national economy for at least 15 years [3]. In addition, the implementation of reliable, flexible networks will lead to increased efficiency in the use of today's infrastructure. It is expected that investment needs over the next 5 years will decrease to 30% [1], while the savings will be redistributed and directed to the further development of technologies.

In addition, smart power systems can be considered as an important tool in the implementation of the Energy Strategy of the Russian Federation until 2035, in particular, its priorities. Among the key authors identified the following areas:

• reduction and minimization of the negative impact on public health and the environment;

• increasing the efficiency and rationality of using the potential of the fuel and energy complex;

• supporting and ensuring the development of competition, transparent pricing mechanisms in the energy market;

• increasing and ensuring the energy and information security of individual regions and the entire state as a whole.

It is worth noting that in Russia the smart grid market is just emerging, so in domestic practice there are not so many examples of their implementation. The experience of implementing Smart Grid in such cities and regions of Russia as Ufa, Sergiev Posad, Kaliningrad Region, and the Republic of Bashkortostan can be called successful.

The transition to Russia's Smart Grid will help to restrain the growth of electricity prices until 2035 by increasing generating and network capacity, quantitatively reducing energy losses to 70-80% and reducing the need for new capacity to 60-70% [1]. In addition, the above will significantly reduce the accident rate in the engineering infrastructure, improve the level of energy security and quality of life of the population as a whole.

However, the introduction of intelligent power systems in Russia is complicated by some legal problems. Let's take a closer look at them.

As we know from historical experience, any positive economic changes associated with the automation of production have negative consequences for some categories of citizens. In the case of the widespread use of intelligent power grids, there will be a reduction in the number of employees who, up to a certain point, have performed the working functions of the intellectual power grid. The termination of the employment contract in this case will take place on the basis of section 2 of Article 81 of the Russian Labor Code [4].

Since the widespread introduction of smart power grids is expected, we believe that a large number of employees in this industry will acquire the category of unemployed. In this regard, we propose the adoption of a federal law obliging the employer in the case of the introduction of automated systems in the energy sector of the economy six months before the planned reduction to provide an opportunity at the expense of the organization to take specialized courses of shift profession to employees who fall under the reduction or pay a premium of n-number of monthly salaries. These proposals allow observing the norms of Article 75 of the Constitution, taking into account the amendments made to it [5].

This problem is acute not only for the energy sector, but also for all sectors of the economy subject to digitalization and robotization. In this case, the presence of a special federal law will protect the legal rights of citizens and reduce the further growth of poverty and unemployment[6].

It may seem that another way to solve this problem is to introduce an additional tax on the use of weak artificial intelligence in various types of production and the redistribution of funds to citizens who need them. A similar initiative was announced by the Institute of Progressive Education on July 24, 2020. However, such actions will ultimately lead not to an improvement in the life of the population, but to a slowdown in the growth of technological development of the entire robotics industry and the use of artificial intelligence systems.

The reason for this will be the fact that the mentioned industry at this stage of its existence is just emerging, despite all the successes achieved. A nascent industry always requires large and long-term public and private investment, which in turn means that each cash flow will directly affect the pace of development. And now let's say that under such conditions, this branch of the economy, the industry for which the future will be subject to a constant tax burden from the state, redistributes 13-15% of its potential income not to improve production technology or improve the quality or quantity of potential tests of its products, but to pay taxes[7]. Of course, taxes are important for the state, but this instrument should be used with extreme caution[8].

It would be optimal to subject this industry to minimal taxation only when it becomes, firstly, more significant in terms of GDP formation and, secondly, much more profitable than it is now[9].

Another problem that arises during the digitalization of public life is the rather high probability of a technical failure of the program. Even a minor programmer error in the code can lead to the collapse of the energy system. To prevent this from happening, it is necessary to give the weak artificial intelligence, on the basis of which the smart grid functions, the possibility of practice in real life, allowing to identify such errors and correct them. Thus, we came to the first paradox of a real error - artificial intelligence will make mistakes in the real world, which can have extremely negative consequences, but in order to avoid such consequences, it must make mistakes as many times as possible in order to be able to foresee its possible mistakes in the future.

The best way to solve this problem without harmful consequences would be to use virtual space to test weak artificial intelligence. Artificial intelligence in this case will not be able to harm the real budget system, but only that which has no physical embodiment in the ordinary world. However, for the problem to be solved, it is necessary to complicate the virtual space with all the variety of existing social relations, which is the next problem - the lack of necessary technologies in the world.

Today we cannot, without distorting, completely “digitize” the world around us, with all its social subjects, since the behavior of one particular person or any natural phenomenon depends on an infinite number of factors, most of which cannot be described in the language of mathematical models on which it is built the virtual reality.

The only way to solve this problem is to use “limited weak artificial intelligence”. In this case, the problem of digitizing the whole world for testing it does not arise, we can limit the scope of its application, thereby simplifying the reality in which it should exist, which in turn will cause simplification to the possible limits of the virtual space in which it should pass tests. This means that there is no need to test in the real world, which in turn protects it.

At present, there are many ways to test weak artificial intelligence and its simulation. This largely depends on the application of low AI. Therefore, voice assistant is not tested separately in virtual space, but is put into our life immediately.

This makes sense, because their actions may pose the least danger to society, and in order to function better, they must "talk to as many people as possible.". The key factor in testing low AI in daily life is the initial restrictions imposed by developers.

For example, a voice assistant "Alice" can't insult you. This option and the corresponding vocabulary set don't exist in her software or so-called "core.". Alice uses two modes of communication - polite intonation and jokes. We draw attention to this seemingly insignificant fact, as it shows one of the avenues for the development of all legal science in the future.

When the two subjects come into contact in daily life, their way of communication is not strictly restricted by the law. Only when they are absolutely necessary can they communicate as they think necessary. But it should not infringe on each other's rights. The law also does not specify the language an entity can use or not use in private conversations. But when we talk about a person talking to a voice assistant, the main moderator is not the law of the Russian speaking country, A user agreement between an individual and a company that owns the technology.

Yes, of course, the agreement is based on the legal system of the host country, but it contains more restrictions, If a person wants to take advantage of the company's technology, he must abide by the user agreement.

By analogy, smart energy systems must also be considered. If they're private companies, The limits and rules of their activities should be determined in advance at the legislative level, in close cooperation with the relevant professionals, How they have to work. Such restrictions will help protect humans from possible errors in artificial intelligence. In addition, the introduction itself must be carried out step by step, so that people can adapt to the new energy reality and make artificial intelligence think Consistency in all cases. At the same time, the gradual adoption of this technology can also avoid fatal errors - if the program fails, it will not be completely destroyed and rewritten, But only two steps back can theoretically save enough resources. However, if there are dangerous consequences of society and mistakes have occurred, what should we do?

The next significant problem is the legal responsibility of the corporation and individual individuals for the operation of the automated power system. In modern domestic law, there is no mechanism for bringing a virtual program to justice. However, we are considering such a system, which, as we said earlier, is a limited weak artificial intelligence, which means there is no volitional criterion for perceiving existing reality, and in the absence of a person's will, it cannot be a subject of an offense..

Let's suppose that the actions of the power system led to an environmental disaster. In this case, it will be necessary to identify the reasons for such actions. There may be several of them - an error in the software of an intelligent energy system, unfair actions of an energy company or individual individuals.

In the first case, the specific programmer or the company that released the program will bear legal responsibility. An energy enterprise in such circumstances will not be liable, but if there is negligence in its actions, we assume the possibility of bringing the enterprise itself to responsibility [6].

In the second situation, the company whose actions or omissions caused damage to the environment will be directly held liable. Similarly, with case 3, a certain person will be held accountable, in whose actions there is guilt.

But what if the actions of the programmers, the energy company, and specific individuals were correct, and the reason for the disaster was the decision of the intelligent energy system itself? What if the program considered a disaster to be more preferable than, say, the likely loss of a utility? Such an example cannot be regulated by modern law, and, of course, any actions that cause harm must be stopped and must bear consequences. In such a confluence of circumstances, we propose to use the analogy of law and use the concept of joint legal liability existing in the current legislation.

By this analogy, both the author of the program and the enterprise itself should be subject to responsibility, and the novelty will be the fact that that between these subjects there was initially no conspiracy to commit an offense, their guilt is relative, but their joint actions led to the onset of negative consequences. It will also be necessary to change the program that made the error. It will also be permissible to expand the subject of the offense to the owner of patent rights for the intellectual energy system program in the event that the enterprise or the direct author of the program does not have such rights, since before the direct use of his patent for a monetary remuneration, he had to make sure of its safety.

Above, we described the theoretical concept of legal liability for an error in an intelligent power system. Let's consider the problem from a practical point of view.

The system of tripartite legal liability developed by us can be applied in the framework of civil law relations in order to determine the subject, obliged to compensate for the harm caused indirectly by his actions. In this case, the civil liability of the three parties indicated above will be subsidiary in nature, and the main obligated person will be the enterprise itself.

From the standpoint of criminal law, the subject of a crime cannot be a legal entity, which means that it is possible to bring to criminal responsibility specific individuals, and not the enterprise itself. These individuals should include those who are responsible for testing the smart grid and running it. The subjective side of the crime will be expressed in criminal negligence or in criminal negligence in all cases when the intentions of the perpetrators were not aimed at the direct fact of committing an environmental crime. If intentions were nevertheless directed, the subjective side will be expressed in direct intention. The object of the crime in each case will be different, but the most likely object will be public relations arising in the field of ecology and the environment.

In administrative law, legal entities can act as the subject of an offense, which makes it possible to bring the energy company itself to justice. The key in this case will be the proof of the fact of the connection between the intelligent energy system and the energy corporation.

Russian legislation allows several types of liability to be applied to the offender at the same time. In the situation we are considering, legal responsibility in the event of an error in the smart power system that led to negative consequences will be distributed as follows:

• the owner of the patent for the smart power system, its author and the enterprise using this system will be brought to civil liability;

• the enterprise that made a mistake in the intelligent power system will be brought to administrative responsibility;

• specific individuals who had the duty to control the testing of the program and are responsible for its use will be brought to criminal responsibility.

The fact of an error in the smart grid program will cause the utility to shut down for a while.

This fact can negatively affect public well-being in view of the importance of the energy industry for socio-economic relations. This can be avoided by the presence of either a certain number of reserve personnel, or the use of another intelligent system. The second option is preferable in our case. The key in this matter is the fact that it must not be the system that made the mistake. Therefore, the energy company needs to develop 2 systems in parallel: one main and one additional, and if the first makes a serious mistake, it should stop, and the emergency one should start working.

Thus, in the course of this scientific work, we analyzed the ways to solve the problem in other states, considered the prospects for the introduction of intelligent energy systems in Russia and proposed ways to solve some legal and technical incidents associated with this implementation.

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Technological forecasting related to the energy sector: a scientometric overview

Alexey V. Mikheev[1,*]

[1] Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, 130, Lermontov str., 664033, Irkutsk, Russia

Abstract. Scientometric review of trends and key points of technological forecasting related to the energy sector is carried out in this study. Using co-keyword, co-citation techniques to analyze a set of research and review articles indexed in the Scopus database, clustered networks were built to understand content relationships and research topic evolution within the 2000-2019 period. This study provides an overview of future-oriented research efforts and trends in the energy technology knowledge domain.

Keywords: energy technology, technological forecasting, scientometric analysis, visual analytic, VOSviewer, CiteSpace.

1. Introduction

Technology forecasting is usually determined as decisive and systematic attempts to anticipate and understand the potential direction, rate, characteristics, and effects of technological changes, especially invention, innovation, adoption, and use [1]. In [2] the group of experts systematizes methods and forms of technology forecasting within a future-oriented technology analysis framework. They distinguish several overlapping forms of technology forecasting such as:

- technology monitoring, watch, alerts (gathering and interpreting information);
- competitive intelligence (converting that information into usable intelligence);
- technology forecasting (anticipating the direction and pace of changes);
- technology roadmapping (relating anticipated advances in technologies and products to generate plans);
- technology assessment (anticipating the unintended, indirect, and delayed effects of technological changes);
- technology foresight (effecting development strategy, often involving participatory mechanisms).

In recent decades, the works [3] and [4] review the families of technology forecasting methods, its relationships, and applications. Nevertheless, there are no general overviews of technology forecasting evolution applied to the energy sector. This research tries to investigate the impact of energy technology forecasting in the scientific literature.

The energy technology forecasting concept is not always used to imagine prospects and the coming advances in the energy area. Many works anticipating future energy technologies use “technological change” or widely discussed “energy transition” toward sustainable development by transitioning from fossil-based to zero-carbon energy resources [5]. So these concepts should be additionally involved in the consideration.

The main goals of this study:

- summarizing the recent existing research efforts on energy technology forecasting;
- helping to systematically understand the co-citation documents, term clusters, and keywords clusters, as well as the knowledge pattern of energy technology forecasting;
- quantitative estimation of the status quo and development trend of energy technology forecasting;
- visualization of the research landscape of technology forecasting in the energy area.

2. Methodology, data, and tools

The methodology of the study is a scientometric analysis joint with supporting visualization to provide an in-depth understanding of the research structure and trending topics in energy technology forecasting. The scientometric analysis is a well-established technique to construct a knowledge map of the specific area over a large massive dataset of scientific literature. An example of a scientometric review of global research on

* Corresponding author: avmiheev@gmail.com

sustainability and sustainable development can be found in [6]. General workflow of scientometric analysis includes several sequential steps:

1. Publications data retrieval related to a specific problem or knowledge area.
2. Data cleaning manually or automatically to remove irrelevant publications.
3. Scientometric quantitative analysis applying various metrics like betweenness centrality, burst strengths to construct different co-occurrence networks. The network examples are co-authorship network, co-word network, co-terms network, co-citations network, and others. Further cluster analysis over the constructed networks is also a part of the scientometric approach.
4. Knowledge domain visualization and in-depth analysis to obtain status-quo of research, discover emerging trends, hidden interrelations, and other valuable outputs.

In the study, the Scopus database was selected as the most comprehensive and easy-to-use data source. A search in the database was carried out using the base word “energy” and a specific set of additional words related to concepts of future-oriented technology analysis. The last concept has fuzzy semantics and includes such terms as “technology forecasting”, “technology foresight”, “technology monitoring”, “technology roadmapping”, “technology trend”, “technology assessment”, “technology change”, “technology transition” and so on. Symbol “*” is inserted instead of the end of some words to satisfy a fuzzy search. The publications with the language “English” and document type as “Article”, “Review” from reviewed and trusted journals were selected. We consider the period 2000–2019 when the rapid growth of publications in the Scopus database is observed.

The final query text inserted in the bar of “Advanced search” of the Scopus search engine is presented below.

```
TITLE-ABS-KEY ( energy AND ( "technol* forecast*" OR "forecast* technol*" OR "technol* trend*" OR "technol* monitoring" OR "technol* chang*" OR "technol* transit*" OR "technol* transform*" OR "emerging energy technol*" OR "technol* assess*" OR "technol* roadmap*" OR ( technolog* AND "future prospect*" ) ) ) AND (LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "re" )) AND (LIMIT-TO ( LANGUAGE , "English" ) )
```

To avoid including irrelevant documents, for example from medical science, the search results were filtered to remove the subject areas far from “Energy” like “Medicine”, “Nursery”, “Computer Science”, “Arts and Humanities”, etc. On the other hand, since the “energy” is a multidisciplinary topic, such subject categories as “Engineering”, “Chemistry”, “Environmental Science”, “Social Science”, “Material Science” and so on also remain under consideration.

The search with this query gives 3448 articles. Fig. 1 presents the document statistics by years, countries, and sources provided by the standard Scopus tool.

To investigate semantic content, key topics, and its corresponding interrelations the two scientometric techniques were used in this study, namely, co-citation analysis and co-term (keyword) analysis.

In this paper, two software tools are used for scientometric analysis. First, VOSviewer software pays special attention to displaying large bibliometric maps in an easy-to-interpret way [7]. Another one is CiteSpace, which is a very powerful and extremely featured application for analyzing and visualizing co-citation scientific networks [8]. The software developed by Chaomei Chen has rich possibilities to identify the emerging trends and general points in a specific domain.

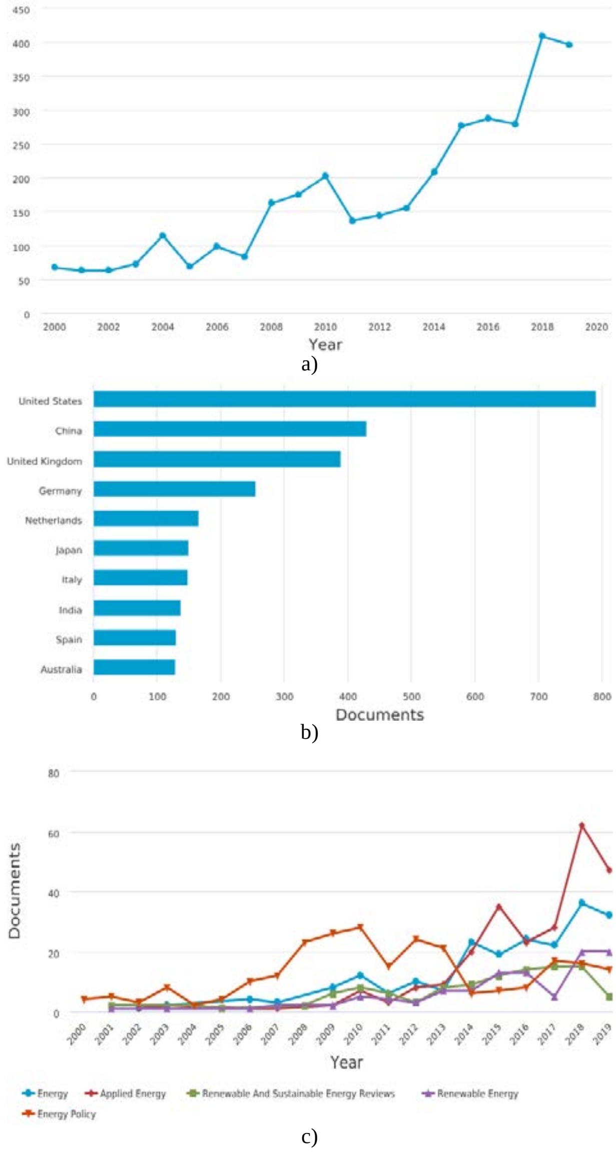

Fig. 1. The number of articles on energy technology forecasting in the Scopus database: (a) during period 2000–2019, (b) country distribution, (c) most productive journals.

3. Results of scientometric analysis

Initially, the co-occurrence network based on the article's keywords was generated with VOSViewer. General terms like "article", "review", "technology" were excluded from the keywords list summarized from all articles. The visualization of the clustered network graph is shown in Fig. 2.

Several colored clusters found over the keywords network reflect the main research topics of two recent decades. Technological change implies the advancement of renewable energy resources such as wind energy and solar energy (mixed violet and blue clusters). The red cluster contains another class of renewable energy technologies based on biomass. The bioenergy cluster is linked to renewable solar and wind technologies through hydrogen technologies including fuel cells. The green cluster presents energy policy issues including planning and market development for renewable energy sources on the one hand. On the other hand, climate change and emission control issues are directly related to environmental protection and carbon dioxide emissions topics located in the yellow cluster. Such general terms as energy efficiency, energy conversion, energy consumption, performance assessment, electric power system development, and other issues remain important research topics.

Generating a co-citation network using CiteSpace software with default parameters is the next step of the analysis. For the correct construction of the co-citation network, the publications of the years preceding 2000 were also included to consider previous research impact. Co-citation network in Fig. 3 presents an evolution of technology forecasting research from 2000 to 2019 years. It's observed that the presented co-citation graph becomes sparser during the last decade 2010-2020.

The list of top 47 papers having the strongest citation burst is shown in Fig. 4. These papers are sorted by start year of burst to show the dynamics of the "hottest" documents and its corresponding topics along with the considered period. The main theme of these papers is a discussion about appropriate technological changes as responses on the global problems of climate change and sustainable development of the world economy. Types of almost all highly cited works are reviews, surveys or theory foundation books.

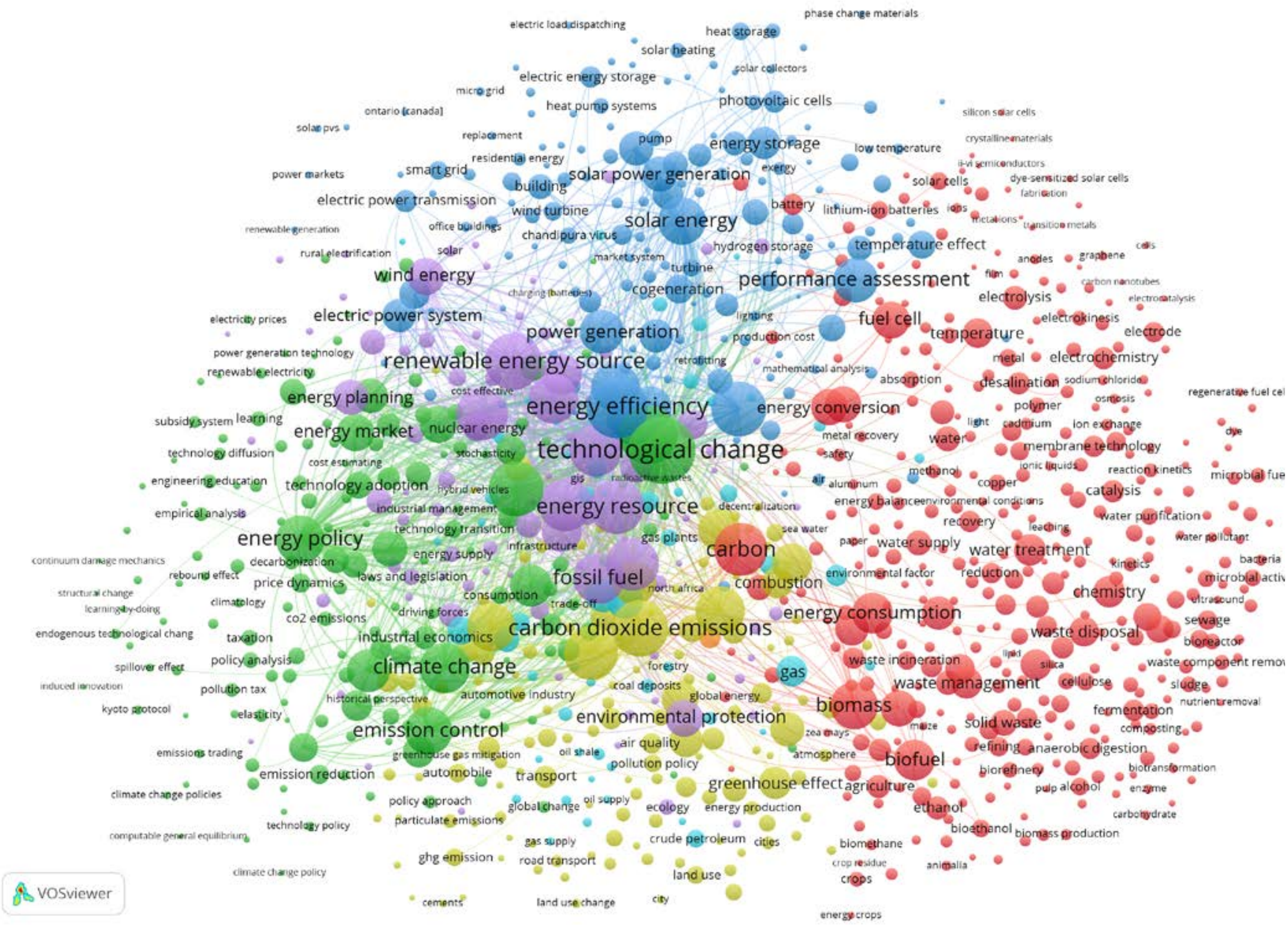

Fig. 2. Colored clusters of keywords co-occurrence network generated using VOSviewer software.

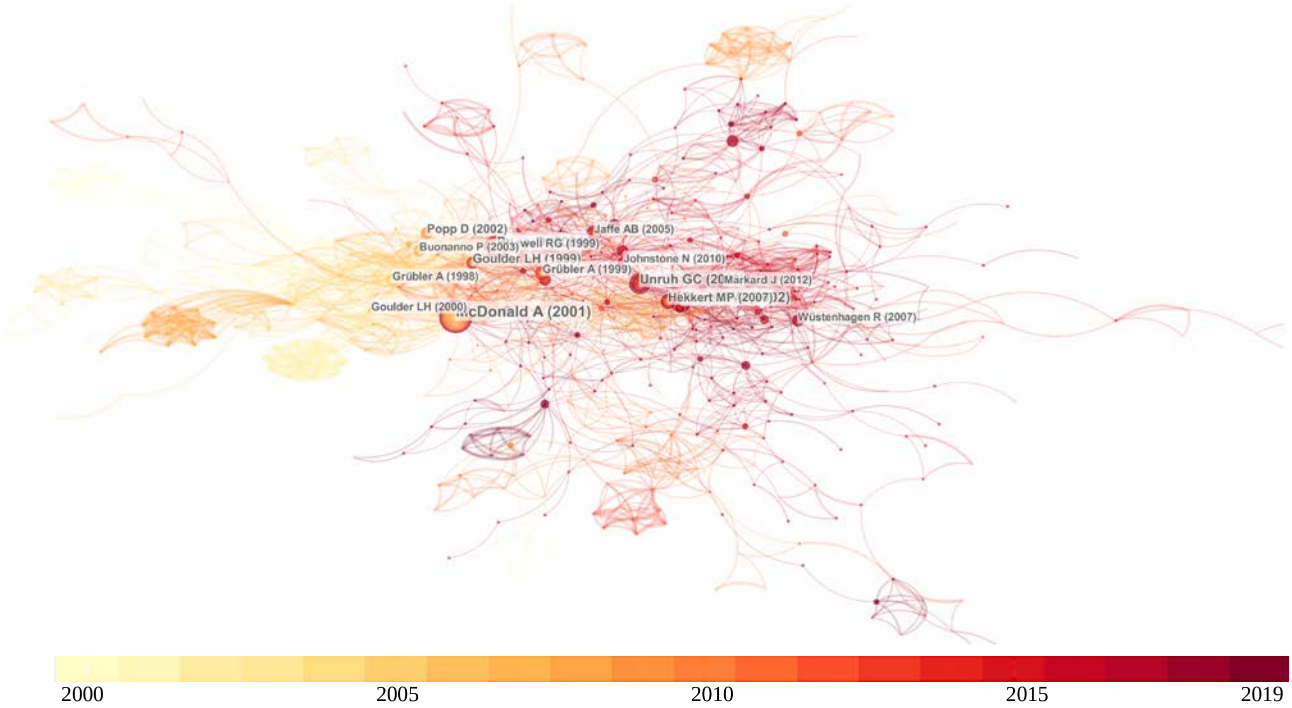

Fig. 3. Co-citation network from publications of Scopus database over period of 2000-2019 years.

References	Year	Strength	Begin	End
Messner S, 1997, Endogenised technological learning in an energy systems ..., V7, P291-313	1997	5.1843	**2000**	2004
Grübler A, 1998, Technology and Global Change @ , V0, P0	1998	7.6396	**2000**	2007
Nakicenovic N, 1998, Global Energy Perspectives @ , V0, P0	1998	3.4511	**2000**	2004
McDonald A, 2001, Learning rates for energy technologies @ ENERGY POLICY ..., V29, P255-261	2001	8.5072	**2002**	2012
Goulder LH, 2000, Optimal CO2 abatement in the presence of induced technological ..., V39, P1-38	2000	5.5228	**2002**	2008
Goulder LH, 1999, Induced technological change and the attractiveness ..., V21, P211-253	1999	4.1715	**2003**	2009
Mattsson N, 1997, Assessing new energy technologies using an energy system ..., V21, P385-393	1997	3.1934	**2003**	2004
Newell RG, 1999, The induced innovation hypothesis and energy-saving ..., V114, P941-975	1999	3.6389	**2004**	2008
Argote L, 1990, Learning curves in manufacturing @ SCIENCE, V247, P920-924	1990	4.4955	**2004**	2007
Grubb M, 2002, Induced technical change in energy and environmental ..., V27, P271-308	2002	3.5716	**2004**	2008
Popp D, 2001, The effect of new technology on energy consumption ..., V23, P215-239	2001	3.5856	**2004**	2006
Jacobsson S, 2000, The diffusion of renewable energy technology, V28, P625-640	2000	3.9312	**2005**	2010
Kemp R, 1998, Regime shifts to sustainability through processes of ..., V10, P175-195	1998	3.9312	**2005**	2010
Nordhaus WD, 1994, Managing the Global Commons, V0, P0	1994	3.1554	**2005**	2006
Gerlagh R, 2003, Gross world product and consumption in a global warming ..., V25, P35-57	2003	5.1502	**2005**	2008
Popp D, 2002, Induced innovation and energy prices @ AMERICAN ECONOMIC ..., V92, P160-180	2002	8.3398	**2005**	2010
Popp D, 2004, ENTICE, V48, P742-768	2004	7.6643	**2005**	2009
Buonanno P, 2003, Endogenous induced technical change and the costs of ..., V25, P11-34	2003	8.7436	**2005**	2008
Acemoglu D, 2002, Directed technical change @ REVIEW OF ECONOMIC STUDIES ..., V69, P781-809	2002	3.1912	**2006**	2010
Rip A, 1998, Technological change @ HUMAN CHOICE AND CLIMATE CHANGE ..., V2, P0	1998	4.0037	**2007**	2010
Stern N, 2007, The Economics of Climate Change, V0, P0	2007	3.4291	**2008**	2011
Markard J, 2008, Technological innovation systems and the multi-level ..., V37, P596-615	2008	3.5256	**2009**	2010
De Piante Henriksen A, 1997, A technology assessment primer for management of technology ..., V13, P615-638	1997	3.5939	**2011**	2012
Färe R, 1994, Productivity growth, technical progress, and ..., V84, P66-83	1994	4.0341	**2011**	2014
Kern F, 2008, Restructuring energy systems for sustainability?, V36, P4093-4103	2008	3.302	**2012**	2014
Grübler A, 1999, Dynamics of energy technologies and global change @ ..., V27, P247-280	1999	3.6705	**2012**	2014
Ferioli F, 2009, Use and limitations of learning curves for energy technology ..., V37, P2525-2535	2009	3.2291	**2012**	2013
Nemet GF, 2006, Beyond the learning curve, V34, P3218-3232	2006	3.4727	**2012**	2018
Johnstone N, 2010, Renewable energy policies and technological innovation ..., V45, P133-155	2010	6.3747	**2013**	2017
Chung YH, 1997, Productivity and undesirable outputs, V51, P229-240	1997	5.1062	**2013**	2016
Fischer C, 2008, Environmental and technology policies for climate mitigation ..., V55, P142-162	2008	4.8062	**2014**	2018
Wüstenhagen R, 2007, Social acceptance of renewable energy innovation, V35, P2683-2691	2007	3.7744	**2014**	2020
Markard J, 2012, Sustainability transitions, V41, P955-967	2012	5.0054	**2014**	2017
Acemoglu D, 2012, The environment and directed technical change @ AM ..., V102, P131-166	2012	3.2681	**2014**	2020
Kriegler E, 2014, The role of technology for achieving climate policy ..., V123, P353-367	2014	3.4436	**2015**	2017
Geels FW, 2011, The multi-level perspective on sustainability transitions ..., V1, P24-40	2011	3.9079	**2016**	2020
Jacobson MZ, 2011, Providing all global energy with wind, water, ..., V39, P1154-1169	2011	3.8205	**2016**	2017
Jacobsson S, 2006, The politics and policy of energy system transformation ..., V34, P256-276	2006	5.3655	**2016**	2018
Peters M, 2012, The impact of technology-push and demand-pull policies ..., V41, P1296-1308	2012	3.2731	**2016**	2017
Su B, 2012, Structural decomposition analysis applied to energy ..., V34, P177-188	2012	4.0555	**2017**	2020
Turnheim B, 2013, The destabilisation of existing regimes, V42, P1749-1767	2013	3.1737	**2017**	2018
Chu S, 2012, Opportunities and challenges for a sustainable energy ..., V488, P294-303	2012	3.7045	**2017**	2018
Kivimaa P, 2016, Creative destruction or mere niche support?, V45, P205-217	2016	3.1737	**2017**	2018
Luo X, 2015, Overview of current development in electrical energy ..., V137, P511-536	2015	4.3839	**2017**	2020
Ang BW, 2004, Decomposition analysis for policymaking in energy, V32, P1131-1139	2004	3.7045	**2017**	2018
Nykvist B, 2015, Rapidly falling costs of battery packs for electric ..., V5, P329-332	2015	6.081	**2018**	2020
Rubin ES, 2015, A review of learning rates for electricity supply technologies ..., V86, P198-218	2015	5.5589	**2018**	2020

Fig. 4. Top 47 papers with strongest citation bursts. Most intensive citation period is selected by red color.

There are several key topics identified from top-cited papers. First, the *learning rates* of energy technologies to assess forthcoming technological changes were the most important subject of interest for researchers. A highly cited research study [9] by Alan McDonald and Leo Schrattenholzer considers assembled data on cost reductions for many energy technologies to estimate learning rates. The work [10] by G.F. Nemet discusses the factors influencing cost reductions in photovoltaics. A comprehensive review of learning rates for electricity supply technologies [11] is highly cited in past 3 years. Understanding of nature of learning rates remains a key hot topic during all period 2000 – 2019.

The *directed technological change* related to is another topic widely discussed (see for example [12]). The challenge of restructuring energy systems to provide *sustainable technological transition* with large-scale involvement of *renewable energy sources* receives special attention as an important issue of energy policy [13].

Conclusions

A preliminary scientometric overview was carried out for the research domain of energy technological forecasting. General trends of technology forecasting in the energy sector were quantitatively estimated and visualized. The findings show the research spectrum from environmental policy issues like climate change and emission control to a set of alternative energy technologies including renewable solar, wind, biomass, and hydrogen technologies. However, to discover non-evident topics and relationships the deeper analysis is needed together with further comprehensive critical review similar to the methodology used in [14]. This analysis can also be improved on the base of the iterative procedure using preliminary prepared hierarchical concept maps or applied ontologies of energy technologies and forecasting methods.

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Using the flexibility of EPS as a means of improving the system reliability of power systems in modern conditions

Alexey Osak[1,*], *Elena* Buzina[1]

[1]ESI SB RAS, 664033 Lermontov str., 130, Irkutsk, Russia

Abstract. Scientific research in the field of EPS flexibility has recently been intensified, and this flexibility is considered in a fairly broad setting. It is important to note that the issues of EPS flexibility are not new, but the term "flexibility" was not used to refer to this issue before, although all the main issues were considered within the framework of the topic of system reliability and development of EES, and the issue of continuity of modern research with previous scientific research and existing scientific results is important. Traditionally, one of the aspects of system reliability has been the power security of the EPS, which refers to the ability of the system to withstand sudden disturbances without unintended impacts on electricity consumers. At the same time, the analysis of power security was mainly performed only in the volume of the system-forming power gird of the EPS. For the power systems of the future, the importance of power security increases significantly, but as an analysis of the power security of the system-forming and distribution power grids together. For a number of years, the authors have been engaged in research in the field of mode reliability using the method of calculating EPS modes taking into account discrete and interval characteristics of mode parameters. This method allows us to study the properties of controllability of power systems of the future in the required problem statement.

Introduction and problem statement

Recently, scientific research in the field of Electric Power System (EPS) flexibility has been intensified, and this flexibility is considered in a fairly broad setting [1, 2]. In accordance with [3]: Flexibility describes the degree to which a power system can adjust the electricity demand or generation in reaction to both anticipated and unanticipated variability. Flexibility indicates the capacity of a power system network to reliably sustain supply during transient and large imbalances. A techno-economic definition by International Energy Association states that, power system flexibility is the ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales, from ensuring instantaneous stability of the power system to supporting long-term security of supply [4, 5].

It is important to note that the issues of EPS flexibility are not new. Previously, the term "flexibility" was not used to refer to this issue, although all the main issues were considered within the framework of the topic of systems reliability and development of EPS [6-8]. Accordingly, the issue of continuity of modern research with previous scientific research and existing scientific results is important.

In the traditional electric power industry, the main emphasis in the field of system reliability of power plants was placed on the maneuverability of high-capacity generating equipment and sufficient reserves of capacity of inter-system and intra-system main power grids. The nature of load changes over time (over a year, over a week, over a day, over an hour, over a minute) was fairly predictable and was determined by the types of consumers, including the type of production at an industrial enterprise. Unscheduled deviations from the forecast mode were also predictable, because the main reason for them was an emergency shutdown of equipment, which allowed us to normalize such perturbations (normative perturbations in stability analysis [9]), and also allowed us to apply the rich experience of studying the hardware reliability of elements of the EPS [10]. In such conditions, it was possible to plan and implement the required properties of the power plant quite effectively, even in the long term, both in terms of the controllability of power grid elements and the maneuverability of generating objects. To ensure system reliability, the tasks of determining the optimal volumes of hot and cold reserves at power plants were solved. These aspects, in fact, provided the required flexibility of the EPS (primarily due to large-scale generation and main electric grids), and the effectiveness of the traditional approach within the previous technological structure has been confirmed by practice.

In modern conditions, when there is a mass construction of small power plants using renewable energy sources, the volume of installation of power storage devices is increasing, consumer electrical installations are changing (they are becoming adaptive

* Corresponding author: osakalexey@mail.ru

and intelligent), there is a process of mass appearance of electric vehicles, and it is necessary to review traditional provisions in the field of system reliability. The problem is caused by the sharply variable and unreliable predictable of nature of the EPS loads curve, since the EPS load capacity is defined as the difference between the current load of electric receivers and generators power of consumers. Small utility consumers are not involved in operational dispatch control and the prospect of their involvement in the future is unlikely. As a result, there is no dialogue between consumers and energy companies, so the reasons and motives for changing consumer loads, including abrupt ones, are unknown to energy companies. In the case of an active consumer with its own generation using renewable energy sources, there may be a situation of a sharp transition from the mode of issuing electricity to the grid to the mode of maximum load consumption and oppositely, and this will happen without notifying energy companies.

Special attention should be paid to the development of electric transport (electric vehicles). If the entire current fleet of the country is converted from internal combustion engines to electric drive, it will require about a 3-fold increase in power generation. Of course, the scenario of 100% switching to electric transport is unlikely, but it is also quite likely that the transfer of 10% of vehicles to electric drive will require a 20% increase in electricity consumption, and at the expense of increasing the load on the distribution grids.

Therefore, the traditional approach, where the flexibility of EPS was provided at the level of reserves of large-scale power plants and main electric grids with the general passivity of distribution grids, will not ensure the system reliability of the power systems of the future. It is not a problem to provide the required reserve in the future at the level of large-scale power plants and capacity of main electric grids, the problem will be in the transmission and distribution of electricity to consumers. It will require either a multiple increase in the capacity of distribution grids, or the use of new approaches to ensure system reliability due to the flexibility of the EPS on the part of distribution grids and active consumers.

In addition to new trends with active consumers, electric transport and distributed low-power generation, there are also traditional problems of covering peak loads, as well as the problem of maintaining the parameters of the electric regimes within acceptable limits in repair and post-emergency regimes in EPS. In the cold season, the maximum load is associated with electric heating (as the main or additional means of heating), in the warm season, the maximum load is associated with cooling (air conditioning). In Russia, there are regions, in particular the Irkutsk region, where the share of electric heating is very high, including many localities where electric heating is the dominant method of heating premises. Analysis of the load schedules of real power systems shows that during periods of cooling, which in total amount to about 1-3 weeks per year, there is almost a 2-3-fold increase in loads in distribution grids, compared with the average level of loads in the autumn-winter period.

Accordingly, the transmission capacity of distribution electric grids is selected based on the maximum consumption (maximum load) and non-exceeding of the long-term permissible current of the grids elements in the event of a possible failure of any one grids element (criterion "N-1"). Due to the lack of automation tools, distribution grids are traditionally built as a radial grid with branches and a small number of cross-links forming rings. For this reason, for medium-voltage distribution grids, reliability requirements against the background of the rare use of ring circuits, leads to the fact that the power supply to consumers is usually carried out by two parallel power lines (air or cable). As a result, in a normal scheme, even in the maximum load mode, grids elements (power lines and transformers) are loaded no more than 50%, and at the average annual load level, the load of grids elements usually does not exceed 15-30% of the permissible value. In cities, medium-voltage power lines are mostly made with expensive cable lines with a long repair period if it is damaged. In rural areas with low population density, medium-and low-voltage power lines are long. Both factors significantly increase the unit cost of urban and rural power lines per unit of electricity consumed. Thus, the capacity of the distribution grid is excessive, which increases the capital and operating costs for the construction, reconstruction and operation of electric grid, which are included in the electricity transmission tariff.

If the load increases, which may be caused by the construction of new residential or non-residential facilities, or the mass appearance of new electric receivers of significant total capacity, such as electric vehicles (if their total number increases), the existing radial structure of the electric grid will not allow using the existing excess capacity of the grid. Therefore, it is necessary to build new or increase the capacity of existing electric transformer substations and power lines, which in turn will lead to an increase in electricity transmission rates. While maintaining the traditional approach, the new transformers and power lines will also operate in low-load mode most of the time. Thus, the effectiveness of the traditional approach is quite low, which is paid for by consumers.

Since its inception, distribution electric grids are non-automated and poorly observed objects, in contrast to the main electric grids and power supply grids of the most responsible industrial enterprises. This fact is due to the high cost, low reliability and low efficiency of the automation and remote control devices available at that time. Over the past decades, there has been a rapid and high-quality leap in the development of computer technology and digital communications, which allows you to create affordable, highly efficient automation tools at any level. Accordingly, there is a prerequisite for mass automation, intellectualization and digitalization of distribution grids, since this will reduce the cost of developing distribution grids.

For the electricity industry of the future it is crucial to select the optimal regimes control in normal conditions, and the control of emergency and forced regimes. Under normal conditions, the main way to influence active consumers is economic motivation, when due to discounts and surcharges to the price of electricity, a large number of active consumers are encouraged to manage their consumption according to the optimal scenario. At the same time, unlike traditional wholesale and retail markets (B2B market), the main players are quite small active consumers (B2C market), who will be ready only for simple rules of the game with a minimum amount of formal requirements and reporting documentation for them. It is important to understand that these objective circumstances will impair the reliability of the forecast for the control of EPS regimes.

The situation is even more complicated for active consumers with emergency and forced regimes in the EPS. The main players are small consumers, who will not be involved in operational dispatch control. accordingly, energy companies will not be able to get information about the technical condition, accidents and repairs of such active consumers. If the high-power generating equipment, as well as the equipment of power grid companies, have requirements for reliability, requirements for their operating conditions in emergency modes, as well as requirements for their readiness in maximum load modes (readiness to pass the autumn-winter period), then the low-power generation equipment, as well as electrical installations for managing the mode of active consumers, can not be normalized in terms of the requirements for their operation in emergency modes, as well as the requirements for their readiness in maximum load modes. Accordingly, there is a very high probability of mass failure of small generation and controlled elements of active consumers during emergency and post-accident modes in the EPS (electromechanical and transient processes, voltage and frequency deviations), as well as under extreme climatic factors. Accordingly, it is impossible to talk about the guarantee of the volume of system services provided by active consumers. It can be assumed that under normal conditions, most of the time active consumers will manage their consumption according to a relatively optimal scenario in accordance with the factors of economic incentives from energy companies. But there will also be time periods when active consumers will lose their activity, or will not act according to the optimal scenario accordingly, the EPS should be prepared for such a turn of events, ensuring both system reliability and reliability of power supply to consumers. Therefore, the key feature of the future power systems is the ability to operate in wide operating conditions, including forced operation of individual elements and sections of the distribution grid.

It is assumed that the greatest economic effect of digitalization and intellectualization of electric distribution grids will be in the following aspects:

- in the wide use of ring modes of distribution grids, with automatic or automated control of the ring grid topology,
- automatic control of the reactive power regimes in a wide range (maintaining optimal voltage levels in any circuit-mode situations),
- in the managing the demand of active consumers, including through electric vehicles (coordinated management of the charging process of electric vehicles and their use as energy storage devices in emergency situations).

Power system security in new conditions

Traditionally, one of the aspects of system reliability of EPS has been the power system security, which refers to the ability of the system to withstand sudden disturbances without unintended impacts on electricity consumers. At the same time, the analysis of power system security was mainly performed only in the volume of the system-forming grid of the EPS. For the power systems of the future, the importance of power system security increases significantly, but as an analysis of the power system security of a jointly system-forming and distribution grids.

The authors propose to use an iterative two-level system for calculating and optimizing electrical regimes, where information is exchanged at the intersection of levels not by specific values of parameters of electrical modes, but by acceptable ranges and optimal (target) values of parameters of electrical regimes. This approach methodically brings together the traditional approach, where the system reliability of the EPS was ensured by optimal volumes of hot and cold reserves at power plants, with a new approach to managing the flexibility of the EPS. For the energy of the future, the managed resource is not only the range of possible generation capacity at large power plants (taking into account the hot and cold reserve), but also the range of controlled changes in load capacity in distribution grids.

The authors have been engaged in research in the field of power system security for a number of years. To solve this problem, it is proposed to use the method of calculating EPS regimes repeatedly tested on other tasks, taking into account the discrete and interval characteristics of the regimes parameters [11, 12]. This method allows us to study the controllability properties of future power systems in the required task statement.

In general, the balanced steady state parameters as well as their functions should be as close as possible to values $V \to \hat{V}$, these values are defined as discrete characteristics of the regimes parameters. They can be measurements, planned values of regimes parameters, forecast values, etc. Elements of $v_i \in V$ are characterized by two parameters $\{\hat{v}_i, \hat{\sigma}_i\}$. In the case of measurement, $\hat{\sigma}_i$ means the dispersion of $\hat{v}_i$, in other cases, it may be the permissible deviations of v_i from $\hat{v}_i$, specified as a percentage.

In addition, the G regimes parameters should be in some intervals of their $G \to [\underline{G}, \overline{G}]$ values, if possible. Accordingly, each interval variable g_i is characterized by four parameters $\left\{\underline{g}_j, \underline{\sigma}_j, \overline{g}_j, \overline{\sigma}_j\right\}$, where $\underline{g}_j$, $\overline{g}_j$ – upper and lower interval limits; $\underline{\sigma}_j$, $\overline{\sigma}_j$ – boundary dispersions. From $\underline{\sigma}_j$, $\overline{\sigma}_j = 0$ it follows that $\underline{g}_j \le g_j \le \overline{g}_j$. The control range of controlled items (see Item 2), security restrictions (see Item 3-4), the volume control actions (see Item 5-6) are specified using these interval limits.

The current load and generation values, as well as various expected (recommended, optimal) values of voltages, generations and loads of nodes, currents and flows through the branches can be set either by discrete parameters of the V, or by interval parameters of G with the values of dispersions (relative deviations) selected by taking into account the ranking of the importance of the recommended constraints or the severity of the control actions. By setting the current load and the active power of the generation by the discrete parameters of V, in the simulation of the emergency perturbation first of all will be found the controlling effects, not related to the change in the load and the generation of active power. And only if it is impossible to bring the regimes into the permissible area, the resource controlling effects will be used to reduce the load and change the generation.

Because of the need to rank the role of variables y_i in the functioning of the system, it is necessary to take them into account repeatedly in the G with different boundary characteristics and percentage rates $(\underline{\sigma}_{ij}, \overline{\sigma}_{ij})$. Accordingly, the wider the range, the lower the percentage rates. The possibility of simultaneous assignments to the same parameter regime of restrictions in the form of discrete values of the expected values of V and several interval ranges G with different values of variance (percentage variance) makes it quite flexible to influence the results of the calculation of the variation of the controlling effects. Using this method, it is possible to perform the analysis of PS security, assessing the control of PS and finding different ways of automatic or operational control allowing PS to move from pre-emergency to acceptable post-emergency mode in the event of emergency disturbances.

To characterize the proximity measure of $V \to \hat{V}$, $G \to \left[\underline{G}, \overline{G}\right]$, the weighted least squares function is commonly used:

$$f = \sum_i^n a_i^2 + \sum_i^m b_i^2 \qquad (1)$$

where $a_i = \dfrac{v_i - \hat{v}_i}{\hat{\sigma}_i} \cdot k_{vi}$;

$b_i = \dfrac{g_i - g_i^*}{\sigma_i^*} \cdot k_{gi} \cdot k_i$;

The coefficients k_{vi}, k_{gi} take into account the regulating effect of interval variables on the variables v_i и g_i. If there is a regulating effect of some interval variable g_j on another variable, for example, v_i, it exists if the variable g_j does not reach one of the boundaries. Therefore $k_{vi_{gi}} = 1 - k_j$.

In the accepted approach, $0 \le d\left(g_i\right) \le 500$ depends on the distance of g_i from the interval boundaries, on the value of f and on the course of the computational process.

$$g_i \le \underline{g}_i \to \left\{k_i = 1;\ g_i^* = \underline{g}_i;\ \sigma_i^* = \underline{\sigma}_i\right\};$$

$$g_i \ge \overline{g}_i \to \left\{k_i = 1;\ g_i^* = \overline{g}_i;\ \sigma_i^* = \overline{\sigma}_i\right\};$$

$$\underline{g}_i < g_i < \overline{g}_i \to \left\{\begin{array}{l} g^*_i = 1;\ g_i^* = g_i;\ \sigma_i^* = \underline{\sigma}_i \cdot \alpha + \overline{\sigma} \cdot (1-\alpha)\ ; \\ 0 < \alpha < 1; \\ k_i = \dfrac{1}{1 + d\left(g_i\right)} \end{array}\right\};$$

The steady state of PS is usually described by the equations of balance of currents or powers in the grid nodes and in vector form:

$$W\left(X, Y\right) = 0 \qquad (2)$$

here, the vector Y is a vector of independent parameters of the regime, which at the stage of solving the formula (2) take specific values. X is the vector of dependent parameters on the vector Y. This implicit dependency is indicated by:

$$X = X\left(Y\right).$$

The solution of the problem is reduced to finding such a vector Y, at which:

$$\min f(Y)$$

and

$$w(X, Y) = 0.$$

Sequential calculations are performed using the above method both for the system-forming grid and for each section of the distribution grid (connected to the main grid, but not connected to other sections of the distribution grid) with a search for regulatory disturbances. On the basis of each calculation, the required intervals of boundary regimes parameters at the junction of the system-forming and distribution network are determined. If you cannot enter regimes parameters in a valid region, requires the modification of the adjustment ranges of controlled parameters, which allows to determine optimal automatic control options, and if that's not enough, the definition of requirements for the development of the means of control of this part of the grid.

Conclusion

In this study, the authors made the following conclusions:

1. The task of ensuring EPS flexibility is a development of the traditional tasks of ensuring system reliability. Therefore, it is necessary to ensure the continuity of modern research in the field of EPS flexibility with previous scientific research and existing scientific results.

2. Researchers in the field of EPS flexibility should develop their research areas in order to harmonize the newly introduced terminology and concepts with existing developments in the field of system reliability.

3. Researchers in the field of system reliability should develop their research areas to take into account current trends in distribution grids, accounting for small power generation and active consumers.

4. The Flexibility of the power systems of the future, in its balance aspect, will be provided largely due to active consumers and distributed generation of low power, including installed at consumers. But, these processes have not led to lower system reliability of the EPS or reduction of reliability of power supply of consumers, requires the development of distribution grids in terms of their observability, to provide automatic flow control of active and reactive power (banding grids, provision of reactive power sources, provision and installation of a automatic of regimes and emergency control).

5. For the power systems of the future, the importance of power system security increases significantly, but as an analysis of the power system security of a jointly system-forming and distribution grid. It is proposed to use an iterative two-level system for calculating and optimizing electrical regimes, where information exchange between levels is carried out at the interface in the form of transmitting acceptable ranges and optimal (target) values of regimes parameters. Mathematical and software tools for solving the problem in this setting are proposed.

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Medium-term scheduling of electric power system states under a wholesale electricity market

Natalia Aizenberg[1], and *Sergey* Palamarchuk

Melentiev Energy Systems Institute SB RAS,Irkutsk, Russia

Abstract. The paper focuses on the development of a mathematical model for scheduling electric power system (EPS) states for the medium-term period divided into several time intervals. The model allows calculating the equilibrium state in the EPS, in which each supplier receives the maximum profit from the electricity supply to the wholesale market. The price levels in the EPS are determined by finding the maximum value of the social welfare given the balance constraints at the EPS nodes and the constraints on feasible state variables over several time intervals. Approaches to solving the multi-interval problem of search for an equilibrium states are considered. The approaches involve building a system of joint optimality conditions for electricity suppliers in the considered time intervals. The equilibrium state is found either by directly solving such a system or through an iterative search. The paper demonstrates the results of the medium-term scheduling of the state by an example of a simplified electric power system.. electric power system..

1 Introduction

Scheduling (forecasting) of states in electric power systems (EPSs) is an important task of operational dispatch control [1]. The states are scheduled for the short-term (for a coming day), medium-term (for a month, quarter, year), and long-term (for a period of up to 5 years) periods. The scheduling period is divided into time intervals (days, months, quarters).

In the medium-term scheduling, for all operating areas and all time intervals the System Operator determines [1]:

- electricity and power balances,

electrical connection diagrams and schedules of planned repairs of equipment at power plants; power lines and substations; relay protection devices; communication channels and control systems,

- state parameters to be maintained in time intervals of the scheduling period,
- transfer capabilities of electrical network cutsets, considering agreed repair schedules and meeting the requirements of reliability and power quality,
- types and volumes of services to ensure system reliability,
- activities in the case of planned and possible unplanned operating conditions of the power system.

The medium-term scheduling of EPS states takes into account:

- current and projected tariffs for electric and thermal energy,
- data on the results of trading in the wholesale electricity and capacity market (OREM), given the supply volumes stipulated in bilateral electricity purchase and sale agreements,
- characteristics of electrical networks, including transfer capabilities, losses, maximum allowable values of transmitted power,
- consumption rates of hydro resources for hydroelectric power plants (HPPs).

The load is distributed between the generating facilities according to the criterion of the minimum total costs for electricity buyers in the price zones of the wholesale electricity market. Traditionally, this aim was achieved by reducing the total costs associated with electricity production at thermal power plants. A larger-scale introduction of market relations in the electric power industry, a change in the structure of market participants and improvement in the rules of operational dispatch control have led to the modernization of the statements of scheduling problems and the change in the methods and algorithms for solving them [2]. New problem statements should take into account the facts that [3]:

- Electricity consumption in the medium term has price elasticity [4, 5]. System operator should more carefully model the behavior of market prices and consider the possible reaction of consumers to their change;
- Most suppliers seek to maximize their profits. They do not aim at achieving the minimum total costs of electricity production in the electric power system;
- Individual power plants are part of generating companies (GenCos) that pursue their corporate goals. Scheduling of the EPS states should not take into

[1] Corresponding author: ayzenberg.nata@gmail.com

account the individual interests of power plants but rather their behavior as part of a generating company;

- Individual suppliers can influence market prices. Electricity markets are markets with imperfect competition. Scheduling of the ESP state should allow for the oligopolistic nature of the wholesale market, in which the scheduling of generation by one supplier should take into account a possible behavior of other GenCos.

For the medium-term scheduling, one should consider the constraints that relate individual time intervals. This applies to the possibilities of changes in the generated power in each or several intervals, and to the constraints on the amount of electricity generated, energy resources consumed, and on the volume of stored energy [6].

This paper aims to introduce a new statement of the problem of medium-term scheduling of energy system states, which meets the conditions of the domestic wholesale electricity and capacity market and factors in the desire of electricity suppliers to achieve maximum profit. The focus is on the scheduling of the states in several time intervals given the inter-interval constraints and refinement of electricity prices at the nodes of its generation and consumption. The methods of solving the optimization problem are proposed and the EPS state scheduling results are demonstrated by a simplified example of a power system.

The first part of the paper discusses and formulates the problem statement. The second part describes possible approaches to balancing the interests of suppliers. One approach suggests building and solving a system of equations and inequalities consisting of optimality conditions for profit maximization by each supplier and social welfare maximization. The other approach uses an iterative method of approaching equilibrium. The third part of the paper is concerned with the numerical studies of the developed model capabilities. In addition, we analyze the qualitative differences in the calculation results depending on either presence or absence of inter-interval constraints and the type of the considered competition in the electricity market.

Nomenclature

The following notations are used in the text to describe the problem of medium-term scheduling of energy system states:

t is number of time interval;

T is the number of considered time intervals in a scheduling period;

M is the number of time intervals with the interconnected state variables;

Δt is the duration of time interval t;

I_n^t is a set of numbers of nodes considered in time interval t;

$\mathfrak{R}_i^t$ is a set of numbers of nodes connected to node i;

I_g^t is a set of numbers of nodes with generation;

I_d^t is a set of numbers of nodes with electricity consumption;

I_f is a set of numbers of nodes from I_g^t, whose power plants are part of the f-th GenCo;

P_{gi}^t is the power generated at node i in interval t;

P_{gimax}^t is the maximum allowable value for P_{gi}^t;

V_{gi}^M is the amount of generated electricity over M intervals;

$V_{gi\,max}^M$, $V_{gi\,min}^M$ are the minimum and maximum amounts of generated electricity over M intervals;

P_{di}^t is the power consumed at node i in interval t;

p_i^t is the electricity price at node i in time interval t;

Q_{gi}^t is the water flow through the turbines of the i-th HPP in interval t;

$Q_{gi\,max}^M$, $Q_{gi\,min}^M$ are the maximum and minimum allowable volumes of water drawdown from a reservoir of the i-th HPP or an allowable amount of fuel consumed at the i-th thermal power plant over M intervals;

P_{ij}^t is the power flow between nodes i and j in interval t;

$P_{ij\,max}^t$ is the maximum allowable value for P_{ij}^t;

Δ_{ij}^t is the share of losses from flow P_{ij}^t in tie line i-j in interval t;

GK is a set of generating companies.

2. A mathematical model of medium-term scheduling of EPS states

Adequate representation of the electrical network and nodal prices is of great importance for scheduling of EPS states. In the practice of operational dispatch control, the consideration of the EPS steady states usually involves full nonlinear load flow models, including the equations of active and reactive power balances at the network nodes. Such models factor in the values of voltage magnitudes and phases, the transformation ratios of transformers, and the values of generated and consumed reactive power.

It is difficult to ensure a relatively accurate specification of such data in the medium-term scheduling in the time intervals that are remote from the time of modeling. The use of full non-linear power flow models with a large number of time intervals in complex power systems can prove too time-consuming.

Simplified load flow modeling is justified for scheduling the expected EPS states. The simplified models factor in only active power distribution. Reactive power distribution is considered to be balanced and well known. In simplified models, power losses are most often represented as fractions of active power flows along the lines.

The proposed model of medium-term scheduling considers the simplified modeling of the steady states in EPS. The model is characterized by the following properties:

- electricity suppliers (GenCos) are interested in maximizing profits over the entire considered scheduling period [7],
- scheduling of the states allows attaining an equilibrium of the suppliers' interests. In the obtained state, GenCo does not seek to change the found values of the generating capacities P_{gf}^t,

- scheduling takes into account the inter-interval constraints relating the state parameters of several considered time intervals. Such constraints affect the levels of locational market prices, increase the dimension of the optimization problem, and can significantly increase the complexity of solving it.
- scheduling of the states involves determining the values of nodal prices for electricity, which allows modeling a change in the consumed power P_{di}^t in each time interval t.

The statement of the medium-term scheduling problem is as follows. Maximize the profit of individual generating companies over the entire scheduling period

$$S_f = \sum_t^T \sum_{i \in If} (P_{gi}^t p_i^t - C_i^t(P_{gi}^t)) \rightarrow$$

$$\rightarrow \max, \; f \in GK, \qquad (1)$$

where $P_{gi}^t p_i^t$ is the revenue of the company from electricity sale in the amount of $P_{gi}^t \geq 0$ at prices p_i^t, $i \in I_g^t$, $C_i^t(P_{gi}^t)$ is the function of costs for electricity production at node *i*.

Maximum of function (1) is determined following the constraints on the power flow values that provide:

Balances of active power at nodes of the network

$$P_{gi}^t - P_{di}^t(p_i^t) - \sum_{j \in \Re i} (P_{ij}^t - (1 - \Delta_{ji}^t) P_{ji}^t = 0,$$

$$i \in I_n^t. \qquad (2)$$

Bans on countercurrent power flow in one tie-line

$$P_{ij}^t P_{ji}^t = 0, \;\; i \in I_n^t, \; j \in \Re_i^t, \; j > i. \qquad (3)$$

Constraints on power generation at a node with generation

$$P_{gi\,max}^t \geq P_{gi}^t, \;\; i \in I_g^t, \qquad (4)$$

$$P_{gi}^t \geq P_{gi\,min}^t, \;\; i \in I_g^t. \qquad (5)$$

Constraints on power flow in tie-lines

$$P_{ij\,max}^t \geq P_{ij}^t, \;\; i \in I_n^t, \; j \in \Re_i^t, \; j > i, \qquad (6)$$

$$P_{ij}^t \geq P_{ij\,min}^t, \; i \in I_n^t, \; j \in \Re_i^t, \; j > i, \qquad (7)$$

$$P_{ij}^t \geq P_{ji}^t, \;\; i \in I_n^t, \; j \in \Re_i^t, \; j > i, \qquad (8)$$

$$P_{ij}^t \geq 0, \;\; P_{ji}^t \geq 0, \; i \in I_n^t, \; j \in \Re_i^t, \; j > i. \qquad (9)$$

Constraints (2) - (9) are considered for all intervals $t = 1, \dots, T$.

The system of equalities and inequalities (2) - (9) models steady state in the electric power system. Such a model factors in power losses in the network ties-lines Δ_{ij}^t and does not require presetting the directions of flows P_{ij}^t and P_{ji}^t. The sought variables in problem (1), (2) - (9) are generation volumes P_{gi}^t, $i \in I_g^t$, consumption volumes P_{di}^t, $i \in I_{d,}^t$ values of power flows P_{ij}^t, P_{ji}^t, $i \in I_n^t, j \in \Re_i^t$, $j > i$ in the tie-lines of the EPS equivalent circuit and nodal prices p_i^t, $i \in I_n^t$ in all intervals $t = 1, \dots, T$.

GenCos combine the individual power plants. The paper does not consider the case where one of the power system nodes has power plants that belong to different GenCos. We assume that suppliers (GenCos) behave independently in the market. Collusions between them and corporate behavior within the industrial groups are not considered in the paper. We assume that the price offers of suppliers correspond to their actual costs of electricity generation. The distortion of the presented price offers to increase company's profit is not taken into account in the paper.

The complexity of medium-term scheduling in a market environment stems from the need to simultaneously consider several time intervals. In this case, the inter-interval constraints relating the state parameters of several considered time intervals may participate in the optimization problem to be solved. Such constraints affect the levels of locational market prices, increase the dimension of the optimization problem, and can significantly increase the complexity of solving it.

In our research, we consider the following inter-interval constraints:

- constraints on the amount of generated electricity $V_{gi}^M = \sum_{t \in M} P_{gi}^t \Delta t$ over *M* intervals

$$V_{gi\,min}^M \leq V_{gi}^M \leq V_{gi\,max}^M, \qquad (10)$$

where $V_{gi\,max}^M$, $V_{gi\,min}^M$ are maximum and minimum allowable amounts of electricity generated over *M* intervals at node i;

- constraints on the amount of energy resources consumed at node *i* over *M* intervals

$$Q_{gi\,min}^M \leq \sum_{t \in M} Q_{gi}^t \leq Q_{gi\,\max}^M. \qquad (11)$$

Constraints (10), (11) are added to constraints (2) - (9) in the statement of the medium-term scheduling problem. Other types of inter-interval constraints, namely, the constraints on the amount of energy stored in different types of storage systems and changes in the power generated over *M* intervals are considered in [6].

Another difficulty of the medium-term scheduling is related to the dependence of consumption volumes P_{di}^t on the levels of nodal electricity prices. Demand for electricity for most consumers in the medium term has significant elasticity [4, 5]. Therefore, System operator must take into account the reaction of wholesale consumers to changes in market prices. The medium-term scheduling should, where possible, allow for the consumer demand functions that accurately reflect their behavior when prices change at consumption nodes.

The difficulty of considering the demand elasticity when scheduling power flows in a market environment arises because the dual variables to constraints (2) when solving the optimization problem with objective function (1) do not correspond to the values of nodal marginal prices for electricity in the considered power system. To determine the values of nodal prices, we need to solve an auxiliary optimization problem with an objective function that reflects the maximum social welfare. The auxiliary problem

$$W = \sum_t^T \left(\sum_{i\in I_d} P_{di}^t \cdot p_i^t(P_{di}^t) - \sum_{i\in I_g} C_i^t\left(P_{gi}^t\right) \right) \rightarrow$$
$$\rightarrow \max, \qquad (12)$$

with constraints (2) - (9) is solved in each time interval t. In (12) $p_i^t(P_{di}^t)$ is an inverse demand function at node i in interval t. Nodal prices p_i^t correspond to dual variables $\lambda_i^t,\ i \in I_n^t$ to balance constraints (2) of the auxiliary problem (12), (2) - (9). The auxiliary problem is solved according to the technique of determining the hourly nodal prices, which is used by the Commercial operator of the domestic wholesale market [8].

For the medium-term scheduling, the auxiliary problem should factor in the inter-interval constraints (10), (11). The introduction of these constraints affects the levels of nodal prices for electricity p_i^t. Below, problem (12), (2) - (11) is called an extended auxiliary problem.

Summarizing the material of the section, it is worth noting that the medium-term scheduling of the power system states is reduced to simultaneously solving the extended auxiliary problem (12), (2) - (11) relative to the nodal prices p_i^t and general scheduling problem (1), (2) - (11) that involves determining variables $P_{gi}^t, i \in I_g^t,\quad P_{di}^t, i \in I_d^t,\ P_{ij}^t, P_{ji}^t,\ i \in I_n^t,\ j \in \Re_i^t,\ j > i$ in all intervals t=1,..,T.

One of the features of the medium-term scheduling problem is the lack of reliable information on the operation conditions for the power system in the upcoming time intervals. Apart from the unforeseen situations with the availability of the generation and network equipment, the uncertainty in the operation conditions is caused by changes in consumer bids for the volumes of electricity to be purchased from the market. It is difficult to predict the inflow of water into the reservoirs of the hydroelectric power plants and set the required levels of their lower pools several months in advance. Approximate information about the prospective levels of wholesale electricity prices reduces the quality of medium-term scheduling of power system states.

The lack of unambiguous data on the operation conditions requires the formulation of stochastic statements of the scheduling problem and the use of stochastic optimization methods. The development of such statements and methods is beyond the scope of the presented research and relates to the prospective line of our study. In this paper, the information on the operation of the wholesale market and the operation conditions of the energy system in the medium term is considered to be known and reliable.

2. Methods for solving the problem of medium-term scheduling in a wholesale market environment

One of the possible approaches to solving the above problem is the development of a mathematical model in the form of a system consisting of the Kuhn-Tucker optimality conditions [9] for the following problems: a) profit maximization by suppliers (1), and b) extended auxiliary problem (12) with constraints (2) - (11).

Let us formulate the Kuhn-Tucker conditions for auxiliary problem (12), (2) - (11). Constraints (3) are considered for the case where the directions of flows are predetermined. We introduce the incidence matrix E between the nodes with elements (13). If electricity flows from node i to node j, the element e_{ij} of matrix E^t equals 1, if it goes in a reverse direction, the element e_{ij} of the matrix equals -1, if there is no flow, $e_{ij}^t \ = 0$.

$$e_{ij}^t = \begin{cases} 1,\ if\ P_{ij}^t \geq 0; \\ -(1-\Delta_{ji}^t),\ if\ P_{ji}^t \geq 0; \\ 0,\ if\ P_{ij}^t = 0. \end{cases} \qquad (13)$$

Consider the inverse demand functions in each time interval at the nodes with electricity consumption to be specified in a linear form:

$$p_i^t(P_{di}^t) = h_{di}^t - l_{di}^t \cdot P_{di}^t,\ i \in I_d^t,\ t = 1, \dots, T. \quad (14)$$

Assume that the cost function for electricity production for each supplier is quadratic:

$$C_{gi}^t\left(P_{gi}^t\right) = a_{gi}^t + b_{gi}^t \cdot P_{gi}^t + c_{gi}^t \cdot \left(P_{gi}^t\right)^2,$$

$$i \in I_g^t,\ \ t = 1, \dots, T.$$

The objective function of the auxiliary problem (12), given (14), has the form:

$$W = \sum_t^T \left(\sum_{i\in I_d^t} P_{di}^t \cdot (h_i^t - l_i^t \cdot P_{di}^t) - \right.$$
$$\left. \sum_{i\in I_g^t} C_i^t(P_{gi}^t) \right) \rightarrow max,$$

where the first term in parentheses is demand P_{di}^t at node i, multiplied by price $p_i^t(P_{di}^t)$. The objective function is concave with respect to variables P_{di}^t and $P_{gi}^t,\ i \in I_n,\ t = 1, \dots, T$. Therefore, under the linear constraints (2) - (11), the problem has a unique solution [10].

Denote by $\lambda_i^t, \mu_i^t, \theta_{ij}^t, \gamma, \rho$ the dual variables for constraints (2) - (11). The Kuhn – Tucker optimality conditions [11] for the extended auxiliary problem (12), (2) - (11) are a mixed system of equalities and inequalities:

$$\lambda_i^t \cdot \left(P_{gi}^t - P_{di}^t - \sum_{j\in \Re_i^t} e_{ij}^t \cdot P_{ij}^t \right) = 0,$$

$$i \in I_n,\ t = \overline{1,T}\,; \quad (15)$$

$$\mu_{gi}^t \cdot \left(P_{gi\max}^t - P_{gi}^t\right) = 0, \quad i \in I_g,\ t = \overline{1,T}; \quad (16)$$

$$\theta_{ij}^t\left(P_{ij\,max}^t - P_{ij}^t\right) = 0, i \in I_n, j \in \Re_i^t,\ t = \overline{1,T}; \quad (17)$$

$$\gamma \cdot \left(V_{gi\,max}^M - \sum_{t=1}^M P_{gi}^t \cdot \Delta t\right) = 0, i \in I_g,$$

$$i \in I_n,\ t = \overline{1,T}\,; \quad (18)$$

$$\rho\left(Q_{gi\,max}^M - \sum_{t=1}^M Q_{gi}^t\right) = 0,\ i \in I_g,\ t = \overline{1,T}\,; \quad (19)$$

$$\left(P_{gi}^t - P_{gi\,min}^t\right) \cdot (-\lambda_i^t - \gamma_{gi}^1 \cdot \Delta t + \mu_{gi}^t + b_{gi}^t +$$

$$+2c_{gi}^t P_{gi}^t) = 0,\ i \in I_g,\ t = \overline{1,T}; \quad (20)$$

$$P_{di}^t(\lambda_i^t - h_{di}^t + 2l_{di}^t \cdot P_{di}^t) = 0\ , i \in I_d,\ t = \overline{1,T}; \quad (21)$$

$$\left(P_{ij}^t - P_{ij\,min}^t\right)\left(\lambda_i^t \cdot e_{ij}^t + \theta_{ij}^t\right) = 0,$$

$$i \in I_n, j \in \Re_i^t,\ t = \overline{1,T}\,; \quad (22)$$

$$P_{gi}^t \geq P_{gi\,min}^t,\ i \in I_g,\ t = \overline{1,T}; \quad (23)$$

$$P_{di}^t \geq 0,\ i \in I_d, t = \overline{1,T}; \quad (24)$$

$$P_{ij}^t \geq P_{ij\,min}^t,\ i \in I_n,\ j \in \Re_i^t,\ t = \overline{1,T}\,; \quad (25)$$

$$P_{gi\max}^t - P_{gi}^t \geq 0, \quad i \in I_g,\ t = \overline{1,T}; \quad (26)$$

$$P_{ij\,max}^t - P_{ij}^t \geq 0,\ i \in I_n,\ j \in \Re_i^t,\ t = \overline{1,T}\,; \quad (27)$$

$$P_{gi\,min}^t \geq 0, P_{ij\,min}^t \geq 0, i \in I_n, j \in \Re_i^t, t = \overline{1,T}\,; \quad (28)$$

$$V_{gi\,max}^M - \sum_{t=1}^M P_{gi}^t \cdot \Delta t \geq 0\ ,\ i \in I_g,\ t = \overline{1,T}; \quad (29)$$

$$Q_{gi\,max}^M - \sum_{t=1}^M Q_{gi}^t \geq 0,\ i \in I_g,\ t = \overline{1,T}\,; \quad (30)$$

$$\mu_{gi}^t \geq 0, \quad i \in I_{gi},\ t = \overline{1,T}; \quad (31)$$

$$\theta_{ij}^t \geq 0, \quad i \in I_n,\ j \in \Re_i^t,\ t = \overline{1,T}\,; \quad (32)$$

$$\gamma,\ \rho \geq 0. \quad (33)$$

By solving the system (15) - (33) we can obtain prices $p_i^t = \lambda_i^t$ at each node $i \in I_n$, for time intervals $t = 1, \dots, T$ of the scheduling period. These prices will be borne in mind by supplier f when solving the problem of maximizing the total profit (1) for the entire scheduling period under conditions (15) - (33). To form optimality conditions for the general problem (1), (2) - (11), it is necessary to supplement system (15)-(33) with the first-order conditions of function (1)

$$\nabla S_f\left(P_{g_f}, \Lambda\right) = 0,\ f \in GK, \quad (34)$$

where $\nabla S_f(\cdot)$ *is* a gradient of function (1) for the f–th supplier, Λ is a vector of dual variables λ_i^t. Then the Kuhn-Tucker optimality conditions for the general scheduling problem take the form of system (34), (15) - (33). Solving system (34), (15) - (33) ensures the combination of optimality conditions for the main problem (1), (2) - (11) and the extended auxiliary problem (12), (2) - (11).

The method of compiling system (34), (15) - (33) to determine the actions of suppliers is called the construction of a complementary model [12, 13]. It can be used by generating companies to make offers for participation in auctions of the wholesale electricity market.

Compiling and solving system (34), (15) - (33) is a difficult task. Therefore, although the need for medium-term scheduling of the EPS states arose long ago, the algorithms for solving such problems are still under development [14, 15]. This is due to some hindrances. The profit function of the supplier (1) has a bilinear term, i.e. revenue from the sale of electricity $P_{gi}^t \cdot p_i^t$ (here $p_i^t = \lambda_i^t$), which complicates solving problem (34), (15) - (33) and can lead to ambiguity of equilibrium solutions [16].

Also, the approach that involves the formation of joint optimality conditions requires solving cumbersome systems of equations/inequalities, which is difficult for the schemes of real electric power systems due to the large dimension and high computational effort of solving the problem (34), (15) - (33). For an electric power system with 100 nodes, 80 tie-lines, and 20 generation nodes integrated into 4 generating companies, scheduling of the states in 3 time intervals will require building and solving a system with more than 20,000 equations and inequalities.

The second possible approach to solving the problem of medium-term scheduling is to iteratively find an equilibrium of the supplier's interests. This is a fairly well-known approach [17, 18]. Similarly to the previous approach, the Kuhn-Tucker system of conditions (15) - (33) is formed for an extended auxiliary problem. Further, at each iteration, one (not all) supplier solves the problem of profit maximization (1), considering the output of other players to be unchanged. After that, the found power P_{g_f} of the *f*-th supplier is fixed. At the next iteration, another *k*-th company maximizes its profit knowing the generated power of the others. The procedure is repeated until all suppliers come to a state of equilibrium when none of them has an incentive to unilaterally change their generated power. The number of iterations in one calculation cycle is equal to the number of suppliers. The process of finding a solution consists of the following steps.

1. Set the initial values of consumed power $P^t_{di0},\ i \in I_d$ in all time intervals.
2. By solving the problem (1), (2) - (11) for $t = 1, ...,T$, determine the initial values P^t_{gi0} , $i \in I_f$ of all suppliers and values of the transmitted power P^t_{ij0} , $i,j \in I_n$.
3. For one company f_1 determine the optimal values of the output in all time intervals by assuming that generated power of the other suppliers $f_i \neq f_1$ is known and fixed. To this end solve problem (34), (15) - (33), in which condition (34) is written only for f_1. After that fix the power generated at the nodes of company f_1 and consider the next supplier $k \neq 1$.
4. Solve problem (34), (15) - (33) for the k-th supplier. Fix the values of its generated power and switch to $(k+1)$-th supplier. After all $P^t_{gi},\ i \in I^t_g$, $t = 1, \dots, T$ suppliers are found, go to the next cycle of calculations.
5. Repeat steps 3 and 4 until either the specified maximum number of calculation cycles is reached or an equilibrium solution is found. The latter can be defined as the EPS state, in which in the next cycle of calculations the previously found solution does not change or changes little.

Despite the fact that the equilibrium for the described model is theoretically not always unique [13, 17], for a wide range of characteristics of real power systems, we can expect that the equilibrium state will be found using the described iterative procedure [12].

3. A numerical study of the mathematical model capabilities

A numerical study was carried out on the example of a simplified power system with two suppliers and four power lines (Fig. 1). Section 3.1 presents the results for two options: a) maximization of social welfare, considering the inter-interval constraints (15)-(33), and b) optimization of social welfare, not considering the inter-interval constraints (15)-(28), (31), (32). For the maximizing social welfare, it is enough to calculate prices and volumes for the entire scheduling period only in the extended auxiliary problem. If provided from suppliers information is reliable, the obtained result will correspond to the maximum social welfare.

Section 3.2 discusses the effect of imperfect competition in the electricity market on the scheduling results. The option of scheduling a power system state under the imperfect competition involves the calculation of an equilibrium state in which each supplier is aimed to reach a maximum of its profit. For numerical study in section 3.2, the calculations are carried out using an iterative approach to solving problem (34), (15) - (33).

Initial information.

Figure 1 presents a simplified scheme of a power system. The scheduling period is assumed to consist of 3 time intervals t = 1, 2, 3. Both suppliers in the system are thermal power plants.

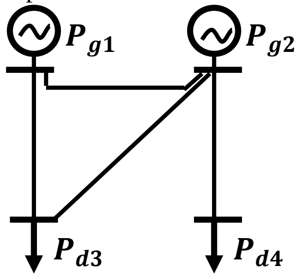

Fig.1. A scheme of the power system.

At nodes 1 and 2, there are generators with the same cost characteristics of electricity generation in all time intervals:

$$C_{g1}(P_{g1}) = 54200{+}72P_{g1}{+}4(P_{g1})^2,$$

$$C_{g2}(P_{g2}) = 21000{+}42.1P_{g2}{+}5.6(P_{g2})^2.$$

At nodes 3 and 4, electricity is consumed with demand characteristics that vary depending on the time interval:

For $t = 1$: $P^1_{d3} = 800 - 0.15\,p^1_3$,

$P^1_{d4} = 1600 - 0.38\,p^1_4$.

For $t = 2,3$: $P^{2,3}_{d3} = 930 - 0.15\,p^{2,3}_3$,

$P^{2,3}_{d4} = 1900 - 0.38\,p^{2,3}_4$.

The fractions of power losses of flows in the lines are the same in all time intervals:
Δ_{1-2} =0.1, Δ_{1-3} =0.12, $\Delta_{2\text{-}3}$ =0.06, Δ_{2-4} =0.08.

Durations of time intervals in the considered example: Δt^1= 720, Δt^2= 744, Δt^3= 720 hours.

Solving the problem of medium-term scheduling one can set integral constraints that relate state parameters of several time intervals. The considered example requires the fulfillment of the constraint on the total electricity output at node 2 for the intervals t=1 and t=2. The inter-interval constraint looks like $P^1_{g2} \cdot \Delta t^1 + P^2_{g2} \cdot \Delta t^2 \leq V^{1+2}_{g2\,max}$. If there is a hydroelectric power plant in the power system under consideration, the integral constraints can be set on the total volumes of water drawdown over several time intervals or the entire scheduling period.

Table 1 shows the minimum and maximum allowable values of generated and transmitted electricity in all intervals of the considered scheduling period.

Table 1. Limiting values of variables.

Variable	The minimum value in the intervals			The maximum value in the intervals		
	t_1	t_2	t_3	t_1	t_2	t_3
P_{g1}	20	20	40	120	140	180
$P_{g2,}$	0	40	40	280	320	320
P_{1-2}	40	40	10	250	270	300
P_{1-3}	10	10	10	120	125	140

P_{2-3}	5	10	15	200	250	280
P_{2-4}	0	10	15	200	250	260

The maximum total electricity output at node 2 in the intervals *t*=1 and *t*=2, $V_{g2\,max}^{1+2}$= 416 GWh.

Table 2 shows the projected demand volumes. This is the reference information. If the optimal demand volumes obtained in the calculations differ significantly from the projected values, such an optimal option is rejected.

Table 2. Projected values of consumed power

Parameter	Power values P_{di}^{t} in the intervals, MW		
	t_1	t_2	t_3
P_{d3}^{1}	160	180	190
P_{d4}^{1}	180	220	230

3.1. Influence of inter-interval constraints on scheduling results

The calculations are carried out and their results are compared with and without the inter-interval constraints (IIC).

Calculation 1. Scheduling of EPS states without the inter-interval constraint. The problem of maximizing social welfare

The calculation of the equilibrium without constraints (10), (11) entails solving the problem formulated using the Kuhn-Tucker conditions (15) - (28), (31), (32). The search for a solution is carried out iteratively with the alternate fixing of the power generated by suppliers. The results are presented in Table 3.

Table 3. The results of the calculation of EPS states without inter-interval constraints while maximizing social welfare.

Variable	Values of variable, MW in the intervals			Prices at nodes, Rub/MW in the intervals			
	t_1	t_2	t_3		t_1	t_2	t_3
P_{g1}	120	140	180	p_1	2786	3291	3179
P_{g2}	262	310	299	p_2	2976	3515	3395
P_{d3}	162	184	194	p_3	3166	3740	3612
P_{d4}	184	223	239	p_4	3242	3821	3741
	Values of flows						
P_{1-2}	40	40	40	P_{2-3}	98	102	75
P_{1-3}	80	100	140	P_{2-4}	200	243	260

Calculation 2. Scheduling with inter-interval constraint (10). The problem of maximizing social welfare.

The calculation of the equilibrium with constraint (10) entails solving the problem formulated using the Kuhn-Tucker conditions (15) - (29), (31) - (34). The calculation is given to show how inter-interval constraints can affect the results of the scheduling of states. In this example, an additional constraint (35) is imposed on the electricity generation of the second supplier at intervals 1 and 2. Table 4 presents the calculation results obtained by solving system (15) - (33) for the entire scheduling period *T*.

Table 4. The results of the calculation of the EPS state with the inter-interval constraint for 3 time intervals while maximizing social welfare.

Variable	Values of variables, MW, in the intervals			Prices at nodes, Rub/MW in the intervals			
	t_1	t_2	t_3		t_1	t_2	t_3
P_{g1}	120	140	180	p_1	2814	3316	3179
P_{g2}	254	302	299	p_2	3006	3542	3395
P_{d3}	160	182	194	p_3	3198	3768	3612
P_{d4}	179	219	239	p_4	3268	3849	3741
	Values of flows						
P_{1-2}	40	40	40	P_{2-3}	96	100	75
P_{1-3}	80	100	140	P_{2-4}	195	238	260

A comparison of the results of Calculations 1 and 2 shows that when the inter-interval constraint (Table 4) is taken into account, the prices in the intervals *t*=1 and *t*=2 are higher than the corresponding prices in Table 3. In the time interval *t*=3, prices remained unchanged. In Calculation 2, the generated powers P_{g2} in the intervals *t* = 1 and *t* = 2 were reduced. Thus, the inter-interval constraints have a significant impact on the outcome of the medium-term scheduling of EPS states.

3.2. Scheduling under imperfect competition

Calculation 3. Scheduling of the EPS states with an inter-interval constraint. Imperfect competition.

In the conducted studies, the imperfect competition means the manifestation of oligopolistic properties of the electricity market. Scheduling of the electricity generation by individual suppliers aims to maximize profits given the possible behavior of other generating companies.

To search for a state that ensures a balance of interests of suppliers, we solved problem (34), (15) - (33) using an iterative procedure based on successively solving problems (34), (15) - (33) for suppliers 1 and 2. The results presented in Table 5 are obtained in 3 iterations.

Table 5. The results of the power system states scheduling with obtaining the equilibrium state

Variable	Values of variables, MW in intervals			Prices at nodes, Rub/MW in intervals			
	t_1	t_2	t_3		t_1	t_2	t_3
P_{g1}	120	140	180	p_1	3299	3220	3299
P_{g2}	260	307	285	p_2	3524	3477	3524
P_{d3}	161	184	188	p_3	3749	3698	3749
P_{d4}	184	222	232	p_4	3242	3830	3779
	Values of flows						
P_{1-2}	40	40	40	P_{2-3}	102	69	102
P_{1-3}	80	100	140	P_{2-4}	242	252	242

The results of Calculation 3 show that under imperfect competition when the scheduling of states is reduced to finding a balance of interests of suppliers, the nodal prices for electricity (Table 5) increase in comparison with the prices of maximizing social welfare (Table 4). In the considered example, due to oligopolistic manifestations in the market, suppliers can raise prices by 2-4%. This option provides the highest profit for suppliers and low amount of social welfare (Table 6). Consideration of such effects when scheduling medium-term states was the aim of this research.

Table 6. Supplier profits and social welfare amounts for the markets with different competition

Profit	Welfare maximization without IIC (15)-(28), (31), (32) **Calculation 1**	Welfare maximization with IIC (15)-(33) **Calculation 2**	Imperfect competition with IIC (34), (15)-(33) **Calculation 3**
Supplier 1	907 423	909 755	918 542
Supplier 2	1 361 999	1 367 369	1 392 410
Social welfare	3 808 183	3 806 129	3 800 130

Conclusion

The paper presents a mathematical model of medium-term scheduling of EPS states. The task is complicated by the need to allow for many time-varying factors and limitations. Changing EPS operation conditions include the balances of electricity and power, the implementation of repair schedules for generation and network equipment, the values of transfer capabilities of lines and cutsets, and the results of trading in the wholesale market.

Considering the properties of modern wholesale electricity markets, the formulated model factors in the interests of electricity suppliers that seek to maximize their profit in the case of medium-term scheduling. When scheduling, the constraints on the state parameters in each considered interval and inter-interval constraints relating the state parameters in several time intervals are met.

The methods of solving the problem of medium-term scheduling are considered. The methods include the formation of a complementary system of equalities and inequalities, which consists of Kuhn-Tucker optimality conditions for maximizing the social welfare and maximizing the profits of suppliers. Two methods for solving the formed problem are found. The first one seeks a solution to the entire complementary system, while simultaneously determining the equilibrium values of prices, output, demand, and transmission. The second one searches for a solution in an iterative way that converges to the sought state gradually, solving at each step the problem for one supplier only.

The numerical studies of the proposed mathematical model capabilities have been carried out using a simplified EPS as an example. For comparison, the calculations were performed for two problems: a) maximizing social welfare, and b) scheduling the states under an imperfect competition market. The numerical studies have confirmed the proposition that under imperfect competition, electricity suppliers can increase market price levels, and thus reduce the value of the social welfare.

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Technologies for mathematical and computer modeling to automate the process of operational states development for heat supply systems

Zoya I. **Shalaginova**[1*], *Vyacheslav V.* **Tokarev**[1] , *Oksana A.* **Grebneva**[1], and *Aleksandr V.* **Lutsenko** [1]

[1]Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences (ESI SB RAS), 130 Lermontov Str., Irkutsk 664033, Russia

Abstract. This article proposes the new technology for development of operational states for HSS of arbitrary structure and dimension. Technology is based on multilevel modeling and a new method for adjustment calculation of thermal hydraulic states. It is implemented in the information and computer complex «ANGARA-HN». Technology includes checking the permissibility of states, calculating the throttling devices on the network and inputs of consumers' buildings. It allows calculating large systems with intermediate stages of regulation, developing adjustment measures to improve the quality of heat supply and consumer provision, reducing circulation flow rates and pressure in networks. The development of modeling methods is carried out in the following directions: taking into account the new composition of equipment, including mixing pumping stations; development of nontraditional methods of calculation, such as object-oriented modeling; development of tasks of hierarchical optimization and identification of state parameters, as task of rising for model adequacy; development of task for finding of sectioning variants for multi-circuit heat network with several sources. The application of methodological and software developments makes it possible to obtain both an economic and a social effect by identifying and realizing of the energy saving potential, improving the quality and reliability.

1 Introduction

Russian heat supply systems (HSS) are unique in their scale and complexity engineering structures. They unite many different types' elements that are developed over time and are dispersed over a large territory. The presence in the systems of heat sources (HS) of various types (CHP, boilers), pumping stations (PS), central or individual heat substations, many different consumers, including subsystems for heating, ventilation and hot water supply, lengthy main (MHN) and distribution heating networks (DHN), operating under constantly changing conditions, determine the complexity of the tasks of organizing and controlling of states.

The tasks of calculating of the thermal hydraulic states of HSS, the permissibility and optimization of the states are basic for the analysis and quantitative substantiation of decisions on organization of HSS operational states. At the same time, methodological, algorithmic and software of these tasks have to satisfy the following requirements: 1) adequacy to real physical processes and properties of the initial information; 2) reliability, which guarantees of solutions with predetermined accuracy; 3) high-performance; 4) the ability to solve problems of large dimension; 5) universality and adaptability with respect to the arbitrary structure of the calculation object, the laws of the medium flow, changes in the statements of calculation problems and design conditions. These requirements are dictated by: increasing complexity and dimension of HSS; introduction of new equipment; limited decision-making time based on calculations in dispatch control; the need of multivariate calculations in solving design and operation problems; the use of models and algorithms for flow distribution calculating in solving of other more complex problems (optimal synthesis, reconstruction, states control, identification, etc.). Automation of decision-making processes for the organization of HSS operational states is of fundamental importance, since the choice of methods for organizing of the states, the quality and optimality of decisions made in practice, depends on the experience and qualification of the engineer by state and the complexity of the calculation object.

2 Overview of the methodological base and characteristics of software for the development of HSS operational states

Currently, there are many methods for calculating both the hydraulic [1-5] and thermal hydraulic [6-13] states of the HSS. At the ESI SB RAS on the basis of the formulated and scientific direction – the theory of hydraulic circuits (THC), it has accumulated unique experience in creating methodological and software solutions for solving problems of calculation and

* Corresponding author: shalaginova@isem.irk.ru

optimization of HSS [5,8-13, etc.]. To date, developed system of mathematical models and methods has been created for calculating and analyzing of the thermal hydraulic states of the HSS [11-20]. A new technique and a set of high-speed algorithms have been developed for calculating of HSS states with an arbitrary number and placement of automatic control devices [10]. The methodology for adjustment calculation of thermal hydraulic state for the organization of HSS operational states includes checking the permissibility of states, calculating throttling devices on the network and inputs to the buildings of consumers, taking into account the differentiated amendments to flow rates for compensating of heat losses in the network. The technique allows developing adjustment measures to improve the quality of heat supply and consumer provision; reduce circulation flow rates and reduce network pressure.

In the ESI SB RAS, the informational and computer complex (ICC) «ANGARA-HN» [21] has been developing for many years to automate the analysis and decision-making processes in the design, operation, and dispatch control for systems of an arbitrary structure and dimension. In the framework of the ICC, the technology for the development of operational states of large HSS with intermediate control stages [20] was implemented. It is based on multilevel modeling [8] and the technique of adjustment calculation of thermal hydraulic state [10].

The priority directions for the development of modeling methods and software are: accounting for the new composition of equipment [22] development of non-traditional calculation methods, such as object-oriented modeling [16,17]; problems of optimization [23] and identification [24], as well as adequacy of the HSS model to the real state; automation of the processes of analysis and development of operational states [25].

3 Technology for the development and organization of large HSS states based on multilevel modeling methods

The technology for the development of operational states of large HSS is based on multilevel modeling [8,12,20]. The proposed approach provides the possibility of a practical solution to the problem of quantitative substantiation of decisions on the organization of states for HSS of arbitrary dimension and structure, including HSS with intermediate control levels. It allows overcoming the contradictions between the high dimension of the problem and the requirements of the integrity and visibility of the object, applying the technology of parallel computing, which significantly reduces the calculation time. The approach is based on the methods of equivalenting and decomposition of design schemas and tasks and involves multilevel data organization and organization of single and multilevel calculations. The methodological base for high-performance multilevel adjustment calculations of thermal hydraulic states takes into account all the requirements for their permissibility [10,12,19].

The process of state development using this implemented in ICC «ANGARA-HN» technology (Fig. 1) can be divided into the following stages: 1) development of a multilevel computer model of HSS, including MHN and DHN design schemas, information on the types and parameters of its elements , as well as restrictions on the state parameters; 2) analysis of the initial information; 3) analysis of current state and network bandwidth with given parameters of HS and central heat substation (CHS); 4) analysis of state violations; 5) development of measures for organizing an permissible state (entering of the state into an permissible area).

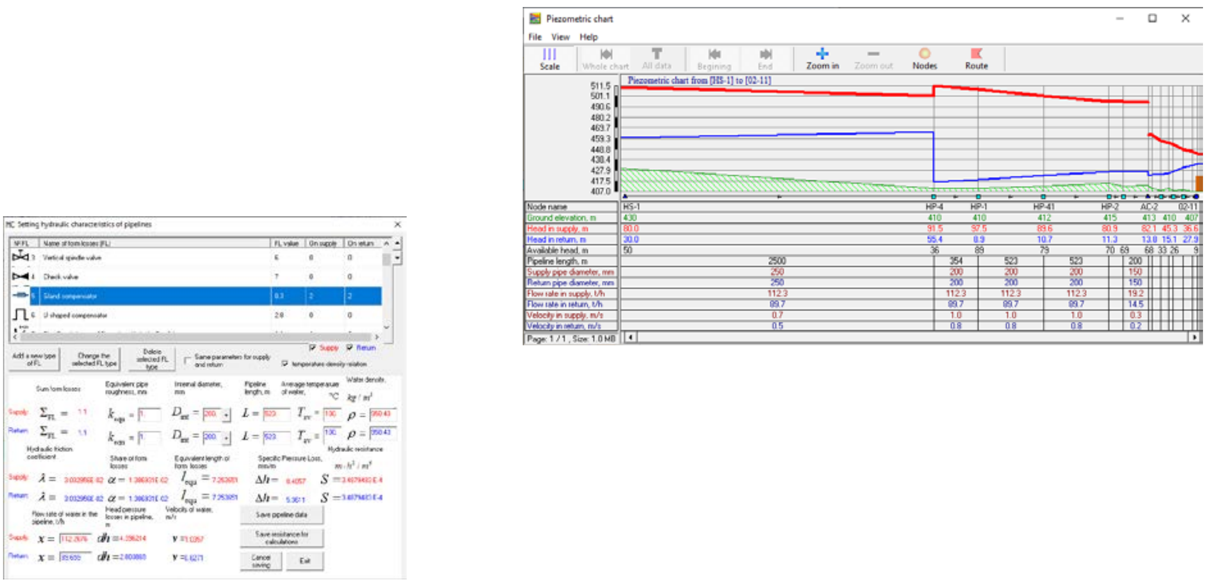

Fig. 1. Results of multilevel hydraulic calculation.

Based on the analysis of the current state of HSS under current operating conditions, «bottlenecks», state violations are identified and a quantitative assessment of the current level of consumer supply is made. The analysis of the current state, as well as the development of controls, is based on calculations of hydraulic and thermal states. Typically, such calculations are divided into adjustment and checking. The main purpose of the adjustment calculation is to find such controls that will allow the run of given water flow rates with current water temperature through the HSS customer systems, subject to technological restrictions on the water parameters – pressure at all nodes of the system, the pressure at the consumer inlets and the water velocity.

When analyzing the state of heating networks, temperature state are important for accounting: cooling of the water along the transportation path; shortage of thermal energy among consumers; selection of measures to compensate for heat losses in the network (increase in water flow rate or entering an amendment to the temperature chart). The result of the adjustment calculation of the heating network is a state in which given heat loads of all consumers and other restrictions are provided. Restrictions arise from the requirements of permissible operating conditions of the equipment.

Entering the state into an permissible area is a difficult task and requires the use of multivariate or optimization calculations by technological and economic criteria. In practice, it is not always possible to create the permissible and even more optimal state only by regulators. In some cases, it may be necessary to reconstruct the whole system or its elements.

Checking calculations of operational states are carried out in order to determine deviations of the state parameters from the required values in non-design conditions, including the degree of consumers' provision.

The application of the developed technology in practice made it possible to identify a great potential for energy saving and significantly improve the quality of heat supply in many cities [26].

4 Development of methods for mathematical modeling of HSS states to ensure their adequacy and optimality

4.1 States optimization

Recently, the problems of energy efficiency have become increasingly relevant, and HSS have significant reserves of energy saving [27], which are caused by the nonoptimality of their operating states. Automation of solving of the problem of HSS states optimization is complicated by a number of factors: the large dimension of HSS [28], the nonlinearity of the involved flow distribution models, the need to take into account several objective functions, the presence of discrete variables of different types, etc. Therefore, there are no methods and software systems suitable for optimization of states for HSS of real dimension. This determines the relevance of developing methods for optimizing of HSS states.

During optimization, it is considered that temperature charts for HS are set, heat losses in networks are eliminated, and their residual value can be neglected. At the same time, the requirements for a sufficient supply of thermal energy to consumers are reduced to the need to maintain the required heat carrier flow rates for consumers, and the task is to optimize the hydraulic state. The case of parallel operation of pumps of the same type at the PS is considered. This case is typical for HSS.

Substantially, the task of optimizing of the HSS hydraulic state is to find control actions that ensure the implementation of state that corresponds to the permissibility requirements and the specified optimization goals. Energy saving requirements can be reduced to minimizing a single economic objective function, which is used as a variable component of the costs for maintaining of the state [29]. The desire to minimize the complexity of adjustment measure and reduce possible water leaks and the risks of emergency situations can be reduced to minimizing additional places of flow control and minimizing the total pressure in the network.

To overcome the dimension of problem, to separate different types of discrete variables and objective functions by different tasks, a hierarchical approach to optimizing of the HSS hydraulic state was proposed [30]. The method consists of the following steps: 1) decomposition of HSS into MHN and DHN; 2) the search for the limits of permissible changes of the state parameters in the decomposition point; 3) optimization of MHN hydraulic state, taking into account the restrictions obtained in the previous step; 4) optimization of DHN hydraulic state taking into account MHN hydraulic state. The MHN level includes all HSs, PSs, and the multi-circuit part of the network. The DHN level includes branched passive networks to end consumers. The decomposition point is the point of connection of DHN to MHN in a single-linear representation and two nodes in the bilinear. One of these nodes is the junction of the supply pipelines of MHN and DHN, the second – return. For MHN, the decomposition point is an aggregated consumer with a given water flow rate and two-sided restrictions on the pressures in the supply and return pipes, as well as the difference in these pressures. For DHN, the decomposition point is aggregated HS.

The search for the limits of permissible changes in the state parameters at the decomposition point is as follows. The water flow rates at the decomposition point are easily found based on the flow rates of consumers and nodal flow rates in the DHN [30]. The search for minimums and maximums of pressures in the supply and return pipelines, as well as the pressure difference between them, is carried out by solving of six optimization problems [30].

As a rule, HSSs are designed in such a way that no additional controls are required when optimizing of hydraulic state of MHN. This task is to minimize the economic objective function. For this, a triple nested iteration loop is used. On the internal cycle, the

* Corresponding author: shalaginova@isem.irk.ru

permissible hydraulic state of MHN is searched, on the average, the minimum of the economic objective function with by the continuous variables, and on the external, the discrete variables are selected that are responsible for the number of turned pumps on PS by the continuous method of branches and boundaries [29].

When optimizing the hydraulic state of DHN, the number of additional flow control points and the overall pressure level in the network are minimized. To solve this problem, an independent dynamic programming method has been developed with circuit equivalents [31], based on the Bellman optimality principle [32] and the ability to reduce dimension of DHN design schema to one branch by unification of parallel and sequential branches.

The hierarchical approach to optimization of HSS hydraulic state presented in the report has the following advantages: 1) the possibility of optimization hydraulic state for HSS of real dimension; 2) the possibility to simultaneously use several objective functions that correspond to real practical problems; 3) high performance and accuracy compared to the approaches of other teams of authors.

4.2 Simulation of mixing pumping stations

HSS schemas in large cities include control elements such as mixing PS. These elements are used to lower the temperature in the supply pipeline by mixing of water from the return pipeline. This allows realizing a transition to a lower temperature chart of quality control. Mixing PS is common in HSS, which have many compactly located consumers with low heat load and direct connection. In this case, to increase throughput capacity, the MHN from the HS to the mixing PS can operate according to an increased temperature chart.

In a number of cities, a multistage cascade change in temperature chart is used. For example, the heat carrier is supplied from the source in transit according to the schedule 170/70ºC to the mixing PS located at the entrance to the city. Then, with the help of cascade of mixing PSs, the temperature chart is lowered to 150/70ºC, 130/70ºC and ultimately in front of the group of directly connected consumers to 95/70ºC.

Since, the water flow rate through the mixing PS depends on the temperature of the mixed water, and it, in turn, depends on the flow distribution and heat losses in the network. It is not possible to determine the flow distribution in one calculation of hydraulic and thermal condition, an external iteration cycle is required, in which the stop criterion will be achievement of the required temperature of mixed water with a given accuracy. In addition, to calculate the temperature distributhin in HSS, it is necessary to apply special methods and stopping criteria. This is because closed flow circuits appear in the network. In the case of cascade mixing, these circuits are embedded [33].

At the nodal temperatures fixed at the k-th iteration of the external cycle, the hydraulic state are calculated. In this state, the flow rate of the mixed water through the mixing PS is uniquely determined by the flow rate of the network water in the supply pipeline before mixing PS and the mixing coefficient.

Thus, when calculating of the hydraulic state, a pipeline with mixing PS can be considered as a pipeline with an active pressure. As well as this pipeline is a flows ratio controller (FRC) by the temperature of mixed water.

The statement of the problem of adjustment calculation of hydraulic state is as follows. Given: design schema; hydraulic characteristics for all its branches; nodal flow rates in (m–1) nodes; vector of known pressure increments for active elements (acting pressures of HSs, PSs and mixing PSs); mixing ratios for the mixing PS; pressure in one of the nodes. It is required to determine the flow rates and pressure drops across all branches, as well as nodal pressures in (m-1) nodes that satisfy the operational states of the mixing PS.

When the adjustment calculation of the thermal hydraulic calculation is carried out, the mixing unit (with the mixing PS) is modeled by a temperature controller. This controller has fixed temperature at the mixing PS outlet. In this case, the task of the adjustment calculation of thermal hydraulic state is joined to determining the flow distribution in the network to ensure the required loads of consumers, including the flow rate of water mixed from the return pipeline.

The proposed methodology is based on a combination of the following calculation stages [22]: 1) decomposition of the calculation of the thermal hydraulic state into hydraulic and thermal state calculations; 2) the use of fictitious FRC with a given mixing ratio of flows at the mixing PS output when calculating of hydraulic state; 3) fixing of the temperature at the outlet of the mixing PS in the calculation of thermal state; 4) correction of the FRC setting according to the results of the thermal state calculation; 5) iterative implementation of p. 2-4 until the stabilization of the mixed water flow rate with a given accuracy.

The proposed approach is implemented in a modified module for calculating the flow distribution using the relay method for calculating of the hydraulic circuit with controlled parameters. It allows determining the thermal hydraulic state of HSS with the mixing PS without using decomposition design schema of the network, which requires a laborious coordination of the boundary parameters in the points of decomposition.

4.3 Sectioning of multi-circuit heating networks

HSS of large cities, as a rule, have a multi-circuit structure. Valves on the multi-circuit network, control elements, changing the parameters of HSs and PSs allow the redistribution of flows. Due to redundancy, HSS of multi-circuit structure has greater reliability then the radial structure. However, in normal states the HSS are preferred to operate by a branched (radial) schema, without heat transfer flows between the heat mains. Each main has a unique composition of connected consumers.

Such a scheme simplifies the processes of network adjustment, detection and localization of accident sites.

To convert the operation schema of a multi-circuit heating network from a multi-circuit to a radial one, it is necessary to determine the places for cutting the circuits (sectioning of the schema), while minimizing the increase in energy costs to create a hydraulic state for the HSS.

In ICC «ANGARA-HN», the task of finding a sectioning variant for multi-circuit heating network with several HSs is formalized [33]. The task of sectioning is posed as optimization. The search for promising sectioning involves multivariate calculations of thermal hydraulic state. This solves the problem of finding the permissible state. The main criteria in the task of HSS sectioning are technological criteria. As such a criterion can use the value of hydraulic power expended on circulation in HSS. This value is definitely determined through the hydraulic power of HS.

The loss of hydraulic power at fixed flow rates, determined from the loads of consumers. Hydraulic power can be divided into two parts – the required and the excess. The total value of the required hydraulic power for consumers is constant, and for each consumer depends on the required differential pressure (available pressure) at the inlet to the consumer and the design flow rate of network water. The excess pressure drop at HS is equal to the excess pressure drop of the consumer dictating by this parameter. The product of the excess differential pressure of the network water and its flow rate is the excess hydraulic power of HS. The task is to find a sectioning variant in which the sum of excess hydraulic powers of all HSs for HSS will be maximum.

The methodology for solving of the problem of searching for rational sectioning of HSS consists in the sequential implementation of the following points: drawing up and calculating of HSS schema without sectioning; search for a sectioning variant near the nodes of the flows gathering; redistribution of flows between HSs; redistribution of flows within independent fragments of network.

Various sequential of variant search for sectioning have been investigated, based on network sectioning close to flows gathering nodes. To automate the solution of the problem of searching for rational sectioning, it was necessary to solve and implement the following sub-tasks as part of ICC «ANGARA-HN»: calculation of the flow distribution for HSS schema without sectioning; search for flows gathering nodes and ranking of branches included in these nodes by flow rate; calculation of the minimum required available pressure for aggregated consumers; search for dictating consumers according to various criteria; implementation of a scheme of iterative calculations of hydraulic state to determine rational sectioning.

When testing the methodology with a real example, it was possible to find a sectioning variant that reduces the total loss of generated hydraulic power at CHP by 3%, compared with the variant obtained by the method of simultaneous network sectioning at the points of flow gathering.

4.4 Ensuring the adequacy of HSS models

Not knowing the true values of the actual characteristics and parameters is the main deterrent to the effective application of mathematical and computer modeling methods to ensure the adequacy of HSS models to their real state.

In practice, this problem is solved by conducting special active tests. However, this does not alleviate the problem described above due to the poor regulation of the conditions for the testing used in tests methods, as well as the lack of a guarantee for obtaining of the results of the required completeness and accuracy.

The tasks of determining the HSS characteristics coefficients from the measurement results are tasks of parametric identification. To solve such problems, methods are potentially applicable [34-39]. However, their use in conditions of passive observations of the normal functioning of HSS does not guarantee an optimal solution due to the lack of used measuring devices and the small range of variation of the states involved for identification.

To develop HSS operational states, at the first stage, it is proposed to check the adequacy of the mathematical models, using the energy systems developed and developed at ISEM SB RAS methods of the active identification for HSS [40-43]. The technique is a sequential (step-by-step) planning strategy when the next experiment is planned taking into account the information obtained after processing the results of the previous experiment.

Vector of state parameters $\mathbf{R}$ consists of vectors of independent $\mathbf{X}$ and dependent $\mathbf{Y}$ parameters of model. Hence, the model in general can be written as $U(\mathbf{Z}) = U(\mathbf{R}, \boldsymbol{\alpha}) = U(\mathbf{X}, \mathbf{Y}, \boldsymbol{\alpha}) = 0$. So vector of dependent parameters is $\mathbf{Y} = F(\mathbf{X}, \boldsymbol{\alpha})$, where F – is an implicit function. The determinant of the covariance matrix of element parameters ($\det \mathbf{C}_{\boldsymbol{\alpha}}$) acts as an optimality criterion. This criteria is the function of independent state parameters $\mathbf{X}$, elements parameters $\boldsymbol{\alpha}$, and as well as it depends on measurement devices [34]. Each step of active identification technique (Fig. 2) includes solving of following tasks: 1) state planning [42]; 2) measurement devices placement [43]; 3) test; 4) processing of test results [34].

As an additional criterion for assessment the adequacy of the model, it is proposed to use the criterion of minimizing the maximum response variance $\gamma = \max_j \frac{\hat{\sigma}_j^2}{\tilde{\sigma}_j^2}$. The value of the proposed criterion shows how many times the variance of the estimate of an unmeasured parameter $\hat{\sigma}_j^2$ more variance of its direct measurement $\tilde{\sigma}_j^2$.

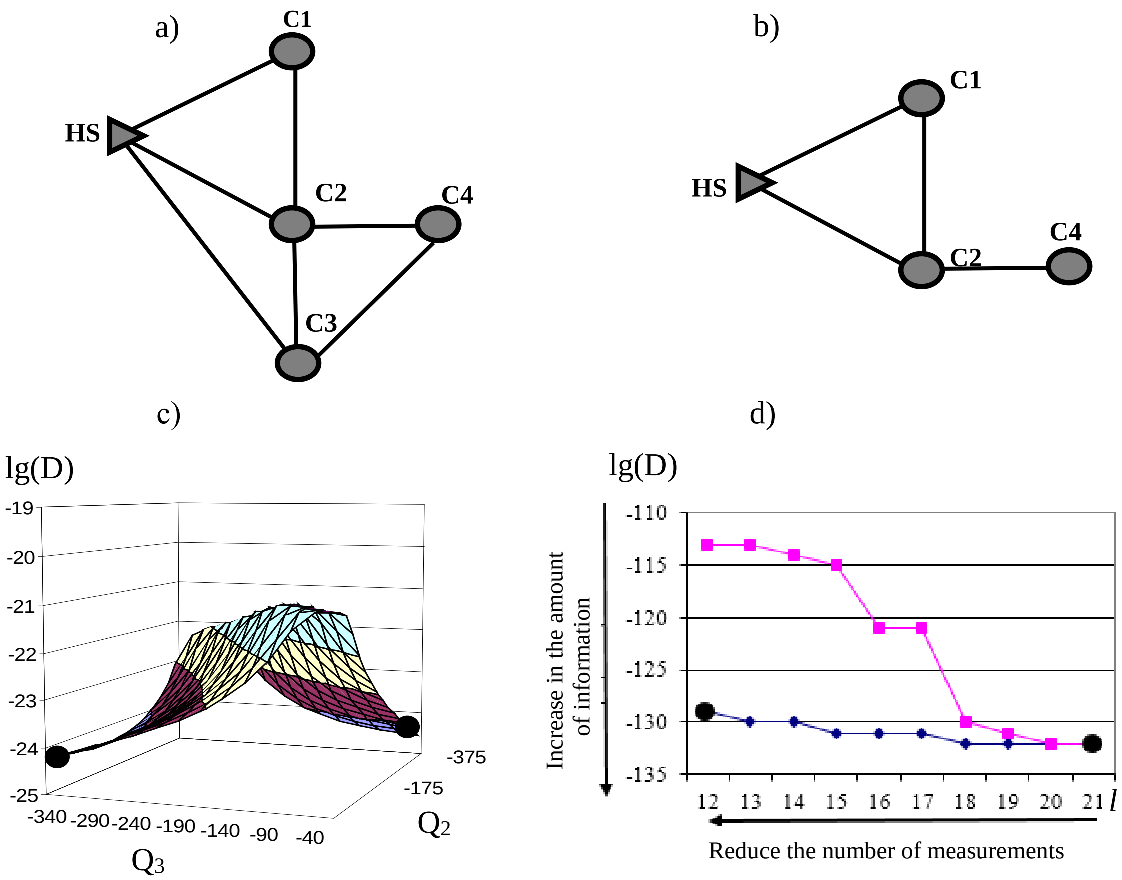

Fig. 2. Illustration of the methodology for active identification of HSS: a) the initial scheme of HSS; b) a fragment of HSS for testing; c) an illustration of the multicriteria of the task of state planning; d) illustration of the search for the optimal composition of measurement devices (C is the consumer; D is the information criterion; Q is nodal flow rate; *l* is the number of measurement devices).

When solving of the task, the obtained values of the additional criterion are compared with the necessary (required) accuracy of the predictive properties of the model, i.e., its adequacy (Fig. 3).

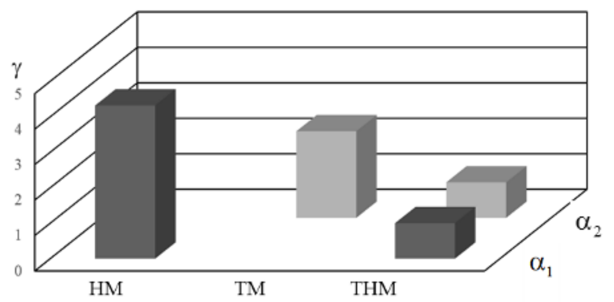

Fig. 3. Diagram of prediction errors by types of used models (HM – hydraulic model; TM – thermal model; THM – thermal hydraulic model; α – elements parameters, index 1 for hydraulic state, index 2 for thermal state).

The effectiveness of the proposed method consists in minimizing the number of experiments to obtain the required or the maximum achievable in accuracy predictive properties of HSS model.

The proposed technology for identifying of HSS with an appropriate level of software implementation allows providing a qualitatively new level of model adequacy and the effectiveness of their application in solving various problems.

5 Practical use

The application of the abovementioned methodological and software developments allows obtaining both economic and social effects by identifying and realizing the potential of energy and resource conservation in organizing the operation states of HSS, improving the quality and reliability for supply of the population and industry with thermal energy. The development results have found effective application in the design, dispatch, optimization of HSS states in various enterprises [26,44,45]. Using the proposed methodological apparatus, calculations were made on the development of states and adjustment measures in many Russian and foreign cities, such as Irkutsk, Petropavlovsk-Kamchatsky, Taishet, Angarsk, Bratsk, Baikalsk, Cheremkhovo, Zheleznogorsk-Ilimsky, Ust-Kut, St. Petersburg , Ulan Bator (Mongolia), Darkhan (Mongolia), Dnepropetrovsk (Ukraine) and many others. The implementation of the planned measures in these cities made it possible without significant capital investments in the reconstruction of networks to normalize the heat supply to consumers; significantly improve its quality; reduce circulation flow rates; reduce the risks of emergencies due to compliance with the requirements of technological permissibility of states and obtain a significant energy saving effect.

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Methodology for the Optimal Development of District Heating Systems: Theoretical and Practical Research

Valery Stennikov[1], *Ivan* Postnikov[1,*], *Andrey* Penkovskii[1], *Ekaterina* Mednikova[1]

[1] Melentiev Energy Systems Institute of SB RAS, 664033, Lermontov st., 130, Irkutsk, Russia

Abstract. The paper presents a synthesis of research results on the development of scientific and methodological support for the comprehensive solution of the main technical, economic and organizational problems of designing, functioning and development of modern district heating systems (DHS). These studies were conducted at the Melentiev Energy Systems Institute of SB RAS (Irkutsk city) by the scientific team of the Laboratory of Heat Supply Systems. Within the framework of the developed scientific and methodological support, the following basic problems were solved: optimization of levels of district heating in DHS with feasibility study for connecting new consumers, selection of optimal forms and models of heating market for DHS, comprehensive analysis and ensuring (optimization) reliability of DHS taking into account the fuel supply of heating sources (HS), and other additional problems. Based on the developed scientific and methodological ensuring following practical researches were carried out on existing DHS schemes of cities of the Irkutsk region: optimal management of DHS in Angarsk, Irkutsk region, taking into account the diverging interests of heating market participants; determination of the optimal scale of development of the existing DHS in Irkutsk based on the optimization of the effective heat supply radius taking into account the reliability of heating to consumers; comprehensive reliability analysis of DHS in Shelekhov of Irkutsk region, taking into account the fuel supply to HS.

1 Introduction

In Russia, heat supply has great social, economic, energy and ecological importance. Russia produces about 44% of the world total heat energy produced in district heating systems (DHS). Here the largest potential of energy saving is concentrated (175–190 million tce, more than 20% of the total consumption of boiler and oven fuel in the country). Realization of this potential necessitates the solution of two interrelated problems.

The first of them consists in transition to the new level of technologies and equipment and assumes complex transformation of the DHS in order to increase their reliability, controllability and profitability. The market of the modern energy efficient equipment and technologies, both domestic, and foreign production that was created and continuing to develop, emergence of the service infrastructure providing servicing of innovative level of power stations promote it.

The second task is formation of methodological bases and principles of creation of new modern DHS, the development of modern information and technological platform and computational tools for management of development and operation of DHS. Implementation of new energy-efficient technologies should be carried out in accordance with the methodology of optimal design of DHS, taking into account their existing condition and modern requirements for efficiency and reliability. The application of the scientific bases corresponding to modern requirements for making decisions on the designing and development of the DHS will allow to organize the process of their innovative transformation, that as much as possible use effects of cogeneration, provides an optimum combination of the district and distributed (decentralized) heat supply to consumers.

The paper presents a synthesis of research results on the development of scientific and methodological support for the comprehensive solution of the main technical, economic and organizational problems of designing, functioning and development of modern DHS. These studies were conducted at the Melentiev Energy Systems Institute of SB RAS (Irkutsk city) by the scientific team of the Laboratory of Heat Supply Systems.

The developed approaches, methods, models and algorithms form an unified methodology, which includes the 3 following main sections:

1) determination of the optimal scale of development of the district heat supply sector in DHS;

2) optimal managing of DHS taking into account different forms of heating market in modern conditions of liberalization of heat power industry;

3) comprehensive analysis and optimization of the reliability of DHS taking into account the full technological stages of production and distribution of heat energy.

The following is a thesis description of the main points of these methodological developments and the results of practical research (case studies) carried out using the developed methodological ensuring.

* Corresponding author: postnikov@isem.irk.ru

2 Methodology

2.1 Determination of the optimal scale of development of the district heating sector in DHS

The technique for territory zoning by type of heat supply was developed, which consists in dividing the urban area into zones of district and distributed (decentralized) heating based on the determination of the heat load density (HLD). A mathematical model is proposed for optimizing the levels of centralization of heat supply based on the criterion of linear heat density (LHD). The analysis of the impact of standard LHD values on the optimal levels of centralization of heating and the analysis of separated of technical and economic factors on results of heat and power planning are provided.

Mathematical models and methods have been developed for solving the following problems of determining the optimal scale of new and developing DHS: 1) determination of the optimal coverage areas of existing heat sources (HS) and the rational extent of their pipelines of heat network (HN) based on an indicator of the effective heat supply radius (EHSR); 2) assessment of the appropriateness of enlargement/downsizing of the system; 3) the allocation of consumer zones requiring the construction of new HS; 4) preliminary selection of new HS locations.

To coordinate the proposed methods and models, a combined algorithm has been developed that combines various types of computing process (linear, branched, cyclic, etc.) and allows you to take into account the changing parameters when solving a mathematical model. In the framework this algorithm a method was proposed for substantiating decisions on connecting consumers to DHS based on the connection efficiency coefficient (CEC) of a new consumer.

These methodological developments presented in detail in publications [1–5].

2.2 Optimal managing of DHS taking into account different forms of heating market in modern conditions of liberalization of heat power industry

Organizational, structural and mathematical models have been developed to find the optimal distribution of heat load between district HS taking into account the interests of different market participants in the DHS. For each model appropriate algorithms were developed for the realization of calculations. The obtained results allow us to analyze the impact of various conditions of the model on the main technical and economic indices of DHS (optimal distribution of heat load between sources, optimal flow distribution in the HN, volumes of heat energy consumption and costs for its production and transportation, heat energy prices, etc.). Based on this analysis, decisions on justify the method of tariff regulation for consumers in DHS of any complexity and scale are made. Special attention is paid to the consideration of the actual organizational model “Unified Heat Supply Organization” (UHSO), for which balanced solutions was obtained for each participants of the heating market, which ensure the needed consumer demand.

A comprehensive scientific and methodological ensuring has been obtained for solving the problems of functioning and developing DHS in market conditions, based on a combination of methods and models of the theory of hydraulic circuits (THC), the theory of industry markets, approaches to game theory and engineering fundamentals for the design of pipeline systems. As a result of optimization of the heating market, based on the methodology of redundant design schemes of DHS, optimal levels of production and consumption of heat energy are determined that correspond to market equilibrium (equal supply and demand for heat energy), taking into account benefits of each participants of the heating market in DHS.

These methodological developments presented in detail in publications [6–11].

2.3 Comprehensive analysis and optimization of the reliability of DHS taking into account the full technological stages of production and distribution of heat energy

A methodology has been developed for a comprehensive analysis of DHS reliability taking into account fuel supply to HS, which contains a number of scientific and methodological approaches, methods and models aimed at evaluating reliability taking into account technological connectivity, continuity and mutual influence of internal and external factors of fuel supply processes, production and distribution of heat energy. Developed comprehensive approach provides the maximum level of systematic solution to considered problems of analysis and synthesis of the reliability on each stages of the entire considered technological chain of heat supplying. The algorithm for the comprehensive analysis of the reliability of the DHS taking into account the fuel supply to HS includes the following main steps: 1) imitating modeling of the functioning of the system of fuel supply (SFS) based on the statistical test method (Monte Carlo method); 2) probabilistic modeling of the functioning of DHS based on the apparatus of markov random processes; 3) modeling of post-failure thermo-hydraulic modes in HN based on models of THC; 4) calculation of nodal reliability indices (RI) combining the results of assessing the probabilities of DHS states and levels of heat supply to consumers in these states. As a result, the maximum emergence effect for the considered processes of generation and distribution of thermal energy in the DHS is achieved, which, in combination with the nodal reliability indices provides the DHS reliability evaluation best corresponding to real conditions.

Special methodological approaches to the modeling of non-ordinarity and dependent events in the DHS are proposed, which are considered at the level of probabilistic modeling of functioning of the DHS when solving problems of analysis and synthesis of DHS reliability. A case studies based on calculated experiments for DHS schemes showed the area of required use of modified markov random models taking into account non-ordinarity and dependent events in the DHS.

A technique has been developed to ensure (or increase) the parametric and operational reliability of the DHS, consisting of a number of mathematical models and approaches that can determine such reliability parameters of system components (failure and restoration rates) that provide the required level of reliability of heat supply to consumers at the minimum cost of achieving these parameters and constrains on its technically possible values. In the framework of this technique the formalization of the functions of prosumers with additional heat power and time redundancy due to its own HS was proposed. To account for the functioning of prosumers the corresponding formalized components are integrated in the model for calculating of nodal RI for taking accounting an additional functional and time redundancy.

These methodological developments presented in detail in publications [12–16].

3 Case studies

3.1 Determination of the optimal scale of development of the existing DHS of Irkutsk city based on the optimization of EHSR taking into account the reliability

The developed methodological support for determining the optimal level of district heating was applied for the DHS of Irkutsk city. The general scheme of this system is shown in Fig. 1. The total length of the HN from the district HS (Novo-Irkutskaya Combined Heat & Power Plant or NICHPP) is 474.3 km, including 112.9 km of transmission pipelines (TP).

Fig. 1. General scheme of the DHS of Irkutsk on the city map

A calculated scheme of the considered DHS with decisions on EHSR is presented in the Fig. 2. Its values for the NICHPP disregarding reliability requirements along the TP and their branches are limited by nodes highlighted in red in the Fig. 2. The values of the radius vary from 2 km (the least distance between the consumer and source) to 15.5 km. An reliability analysis of DHS shows that the standard values of nodal RI are not met for some nodes that belong to the zones of EHSR. According to the reliability indices obtained, we adjusted EHSR in the considered system. In the Fig. 2, the boundaries of EHSR, considering reliability, are shown in blue color and dashed lines. Thus, the maximum EHSR for the NICHPP, considering the reliability requirements, will decline from 15.5 km to 14.6 km and the total length of TP in the zone of EHSR will shrink by 4.2 km and make up 67.7 km. According to the obtained results, considering reliability requirements, the zone of EHSR embraces 284.3 km of network out of 474.3 km, i.e. 40% of the networks are beyond EHSR zone. Specific heat cost for the longest branches of TP and average specific heat cost for the system are presented in the Fig. 3. Correlation between the heat load and a material characteristic of the heat network has a significant influence on the specific heat cost for each node. The greater the specific material characteristic of the heat network (per heat load unit), the higher the specific heat cost and vice versa [1–3]. All network sections have different specific material characteristic and EHSR depends on it.

In addition to the proposed method for determining the optimal EHSR, a method has been developed for assessing the effectiveness of connecting a new consumer, which consists in determining the maximum length of HN pipeline from the point of connection of new consumer to the existing DHS. Fig. 4 presents the maximum length of the pipeline from the point of connection to the existing HN to new consumers depending on their heat load and different temperature modes of HN.

So, for example, from Fig. 4, it can be determined that connecting a new consumer is effective if the pipeline is constructed at the basis of 500 m per 12.5 GJ/h at a supply/return temperature of 138/70°C (or at a temperature difference in supply and return pipelines equal to 68°C). A lower temperature difference in supply and return pipelines in the network section is characterized by an uplift in capital and operating costs. Therefore, the maximum length of the heat pipeline declines.

Connection of new consumers within the zones of EHSR, taking into account the requirements for reliability, will decrease the growth of operating costs in DHS, reduce heat losses and provide the required level of system reliability.

Heat supply to consumers outside the EHSR zone, as a rule, requires the construction of a new HS. At the same time, the expansion zone of EHSR (that is, connecting new consumers) cannot be determined by only one it level due to the irregular distribution of heat loads on the system. To solve this problem, it is proposed to use an additional criterion of the local EHSR, which allows one to assess the economically feasible distance between the consumer and the point of connection to the district network.

The obtained values are recommended to be updated annually or when EHSR changes due to a considerable change in the connected heat load of consumers and total length of HN pipelines.

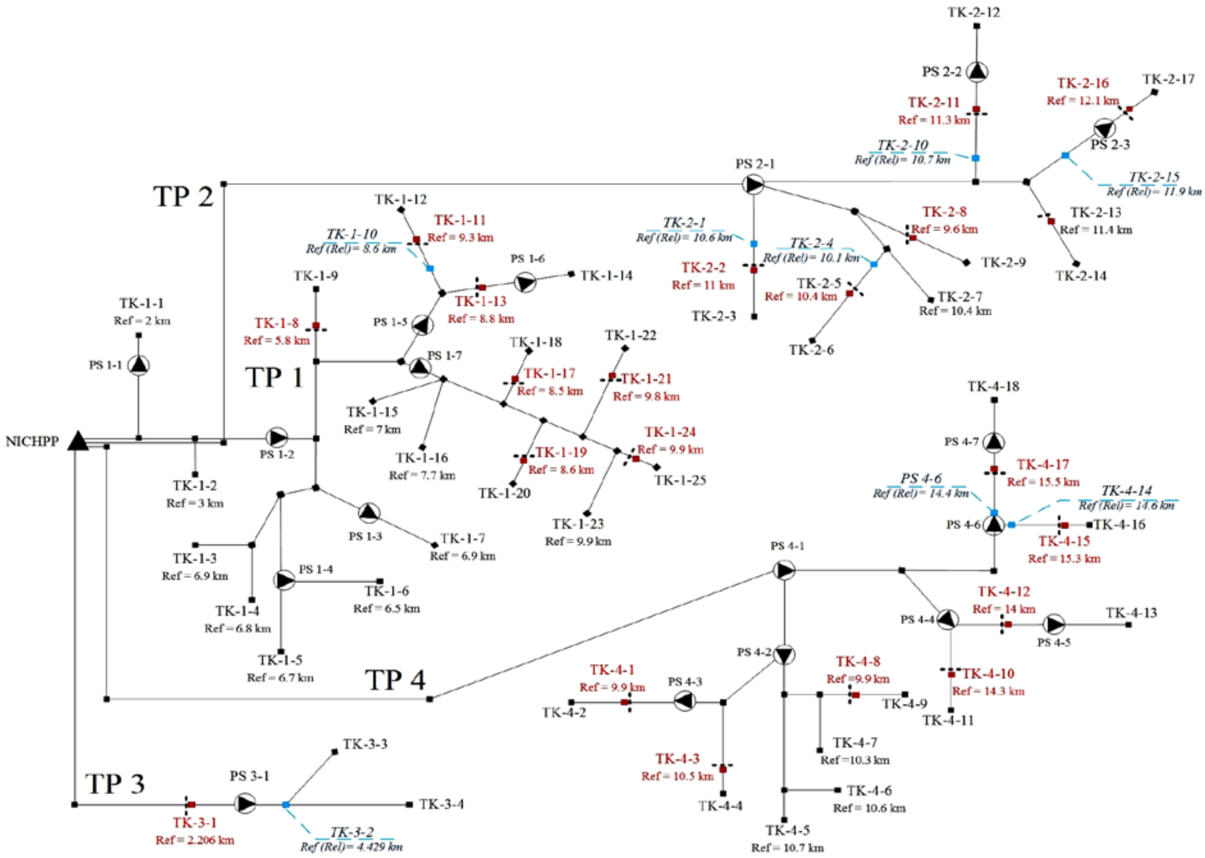

Fig. 2. Calculated scheme of the DHS of Irkutsk with decisions on EHSR: red nodes are corresponded decision without accounting the reliability; blue nodes are corresponded decision with accounting the reliability (TP1–TP4 – transmission pipelines)

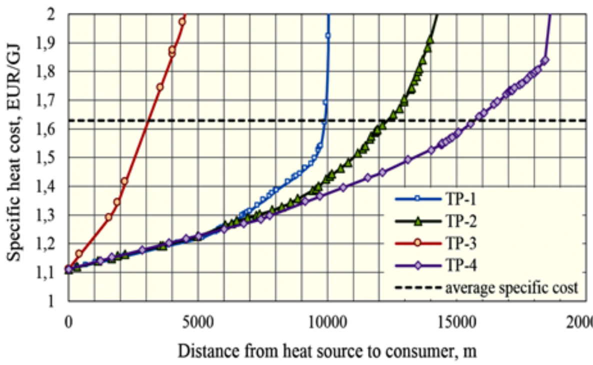

Fig. 3. Specific heat cost for the longest branches of TP of the DHS in Irkutsk city on based NICHPP

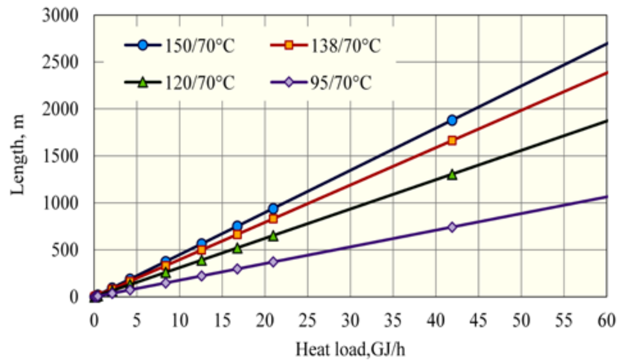

Fig. 4. Maximum length of the pipeline from the point of connection to the existing DHS in Irkutsk to the new consumer

3.2 Optimal management of DHS in Angarsk city (Irkutsk region) taking into account the diverging interests of heating market participants

Practical research has been carried out based on scheme of the existing DHS in Angarsk city using the developed methodological support for optimal managing DHS in the conditions of the market organization of relations between the subjects of the city's heat supply.

A general scheme of the studied system on the plan of Angarsk city is presented Fig. 5. A calculated model of this system is shown in the Fig. 6, which is obtained by aggregating the initial scheme.

The heat loads of the Angarsk is covered by three district HS: CHP-1, CHP-9, and CHP-10 of the energy company "Irkutskenergo". The total heat power of these sources is 4177.8 Gcal/h. The calculated scheme of the DHS of Angarsk consists of 1273 network sections and 1242 nodes, of which 534 are aggregated (jointed) consumers.

The following initial data is used in the practical research: heat loads of consumers, functions of demand for heat energy, cost functions for HS, parameters of HN sections (lengths, diameters, etc.), annual schedule of heat loads (schedule and Rossander equation), climatic parameters (mainly, outside air temperatures); cost indices (electricity tariff, fuel price, etc.), and other data.

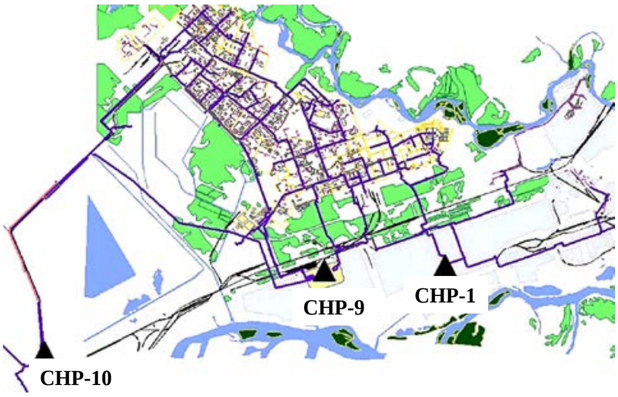

Fig. 5. Scheme of the DHS in Angarsk on the city map

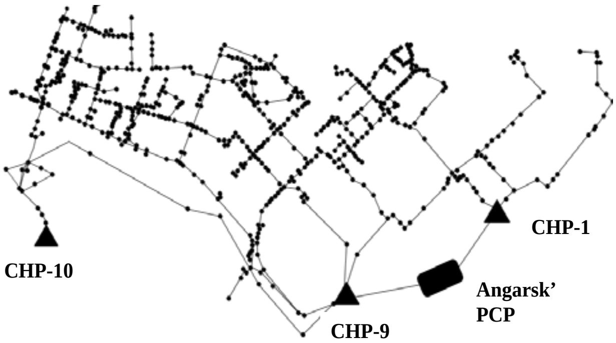

Fig. 6. Calculated scheme of the DHS in Angarsk

The studies of the heat energy market in Angarsk were carried out in order to determine the impact of the form of organizing heating to consumers on the technical and economic indices, including the optimal distribution of heat load between HSs, costs for the production and distribution of heat energy, as well as prices for heat energy for different categories of consumers.

The calculation for considered DHS was carried out for several possible options for organizing heat supply to consumers in Angarsk, including the "Single Buyer" model with a competitive market and a number of models in the form of UHSO with various methods of tariff regulation, including those with free pricing. As a result of calculations, optimal solutions were obtained for the following indicators: HS capacity taking into account their effective participation in covering heat loads, distribution of covering zones for each HS, flow distribution in the HN, costs of operation and development of the system, prices for thermal energy.

The results for the UHSO model with free pricing (liberalized monopoly market) are shown in Fig. 7. For the considered model, CHP-9 covers 57.5% of the total heat load of consumers, the share of CHP-10 is 27.7%, and CHP-1 is 14.8%. At the same time, the average annual equilibrium tariff for household consumers and will be 733.2 rub/Gcal, and for the largest industrial consumer Angarsk petrochemical plant (Angarsk PCP) will be 965.1 rub/Gcal. The total revenue of the UHSO from the sale of heat energy to consumers will amount to 5.63 billion rub; and its profit for under calculated period will be about 1 billion rub or 17.7%.

The results for the model "Single buyer" in the HN (competitive heat market) are shown in Fig. 8. The calculation for this model showed that 28.5% of the heat energy in the system is generated on CHP-1, 44% – on CHP-9 and 27.5% – on CHP-10. The main share of the generated heat energy (76%) falls on household consumers, for which the price of heat energy will be 695.2 rub/Gcal, and for Angarsk PCP the price of heat energy will be set at 859.3 rub/Gcal.

The results obtained make it possible to choose the most effective forms of organizing heat supply (heat energy market), depending on the conditions under consideration DHS. A diagram with a comparative analysis of the main indices of the calculations for various forms of the heat energy market for the DHS in Angarsk is presented in Fig. 9. As seen from this diagram, studies of the DHS showed that the form of organization of heat supply to consumers significantly affects not only the total heat production for HSs and its distribution between them, but also on other technical and economic indices of the system. A comparative analysis of the considered models for optimizing heat supply in Angarsk (heat energy market) revealed that its optimal form of organization is UHSO model when regulating the heat energy tariff for household consumers at the level of average total costs. At the same time, the maximum equilibrium consideration of the interests of each market participant in the system is ensured and optimal technical and economical indices of the system are achieved.

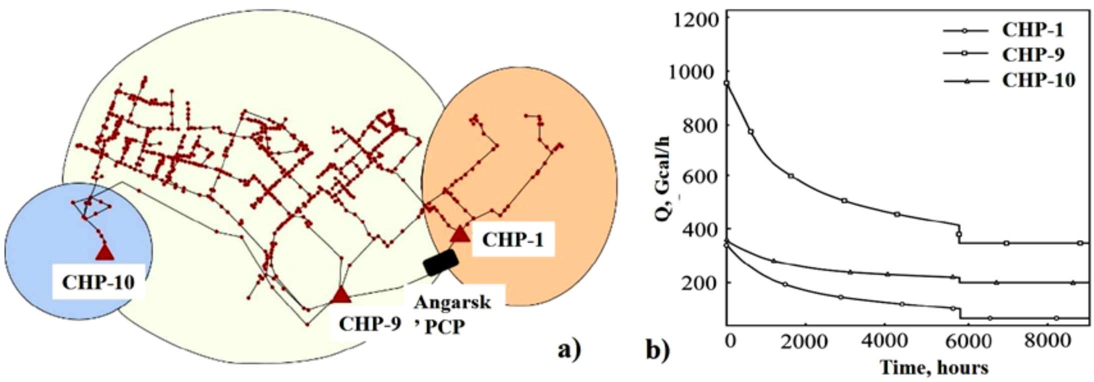

Fig. 7. Distribution of coverage areas (a) and load schedules (b) of district HS in the DHS of Angarsk in the conditions of "Unified heat supply organization" model with free pricing (monopoly market)

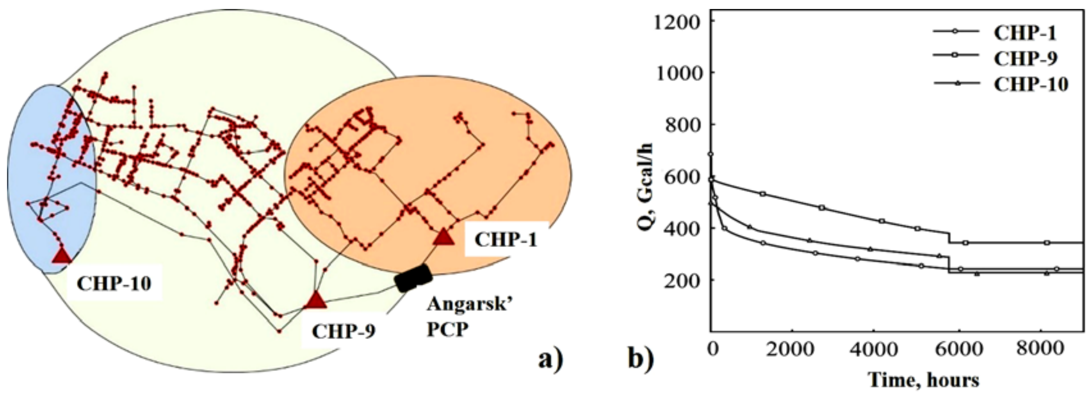

Fig. 8. Distribution of coverage areas (a) and load schedules (b) of district HS in the DHS of Angarsk in the conditions of "Single buyer" model in HN (competition market)

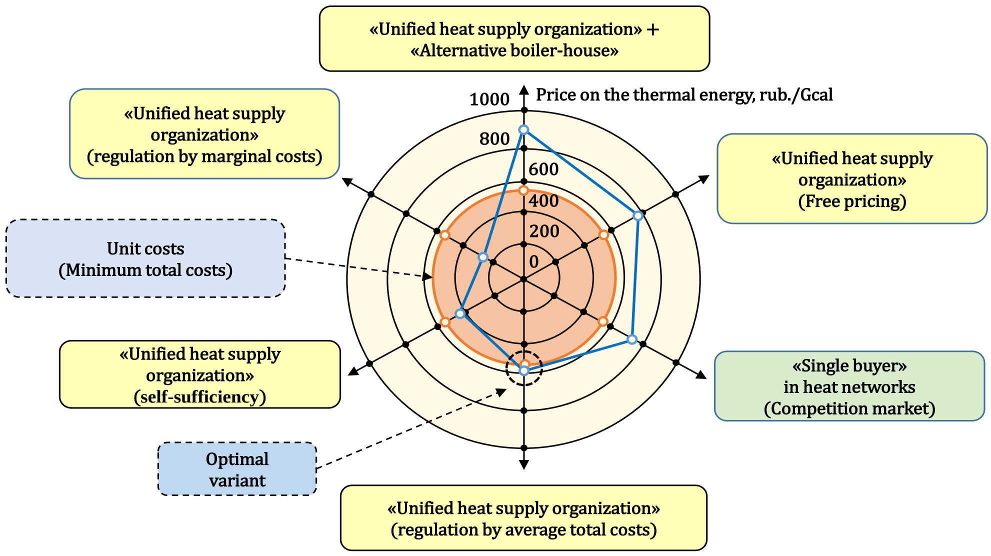

Fig. 9. Results of the comparative analysis of the various forms of the heat energy market for the DHS in Angarsk

3.3 Comprehensive analysis of the reliability of the DHS in Shelekhov (Irkutsk Region) taking into account the fuel supply to HS

The developed methodology for a comprehensive analysis of the reliability of DHS was applied on the scheme of the existing DHS in Shelekhov city (Irkutsk region) with district HS (CHP-5 of the energy company "Irkutskenergo") with a capacity of 1843 GJ/h (440 Gcal/h with peak boiler) and district HN with a total length of transmission part of 15.7 km.

The calculation schemes of the considered DHS are presented in Fig. 10: the initial general scheme on the city map (a) and the calculated scheme (b) obtained by aggregating the system components (network sections and nodes-consumers). According to an comprehensive approach to the analysis of the DHS reliability, the DHS calculated scheme for reliability modeling is formed by combining the HS and HN calculation component schemes [12–15]. The final aggregated calculated scheme of the DHS obtained in this way consists of 89 components, of which 41 components correspond to sections of HN and 48 components correspond to main technological units of HS.

On the basis of the obtained calculated scheme, the graph of DHS states is formed, shown in Fig. 11. The structure of the states and events is formed with the condition of the Poisson stream of events (simplest stream). The element number of the graph corresponds to the number of the failed component of the studied system.

States on the graph are grouped according to combinations: to the left of the fully operational state "0" there is a subset of failure states of HN components (from 1 to 41), to the right is a subset of failure states of HS components (from 42 to 89), their combinations are given below as complex states of simultaneous failures of HN and HS components which are indicated by their numbers with a "+" sign. The event structure also takes into account the interruptions of fuel supply to HS or the functioning of SFS. To take into account possible fuel shortages at HS (STS failures), two additional states with numbers 90 and 91 (Fig. 11) have been added to the general structure of the DHS states, corresponding to the range of fuel shortages (min and max). According to the previously described methodology for a comprehensive analysis of the reliability of DHS, these fuel shortages are determined based on the results of simulation modeling of fuel supply to HS, carried out using the method of

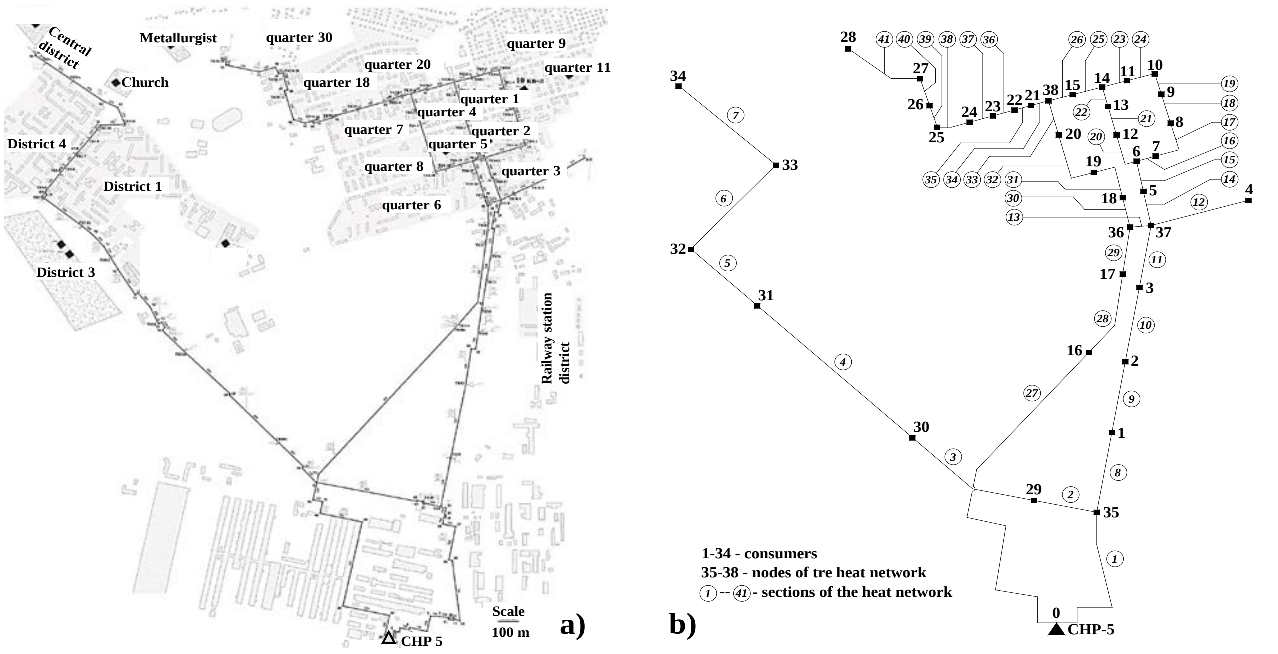

Fig. 10. Schemes of DHS in Shelekhov: a) general scheme on the city map; b) aggregated calculated scheme with unified consumers

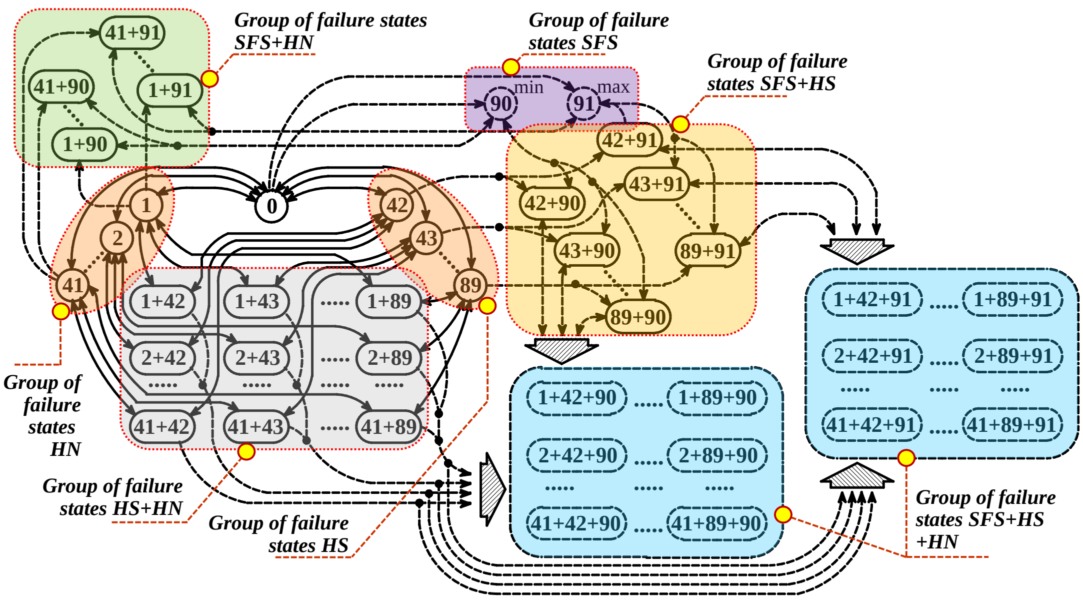

Fig. 11. Graph of the states of DHS in Shelekhov tacking into account the functioning of SFS (i.e. states corresponding to shortages of fuel supply to HS – 90 and 91)

statistical tests (Monte Carlo method) based on actual data on the supply and demand of fuel. These states of possible fuel shortages are combined with HS and HN failures and expand the graph with new groups of corresponding states (Fig. 11).

Probabilistic modeling of the functioning of DHS in Shelekhov to assess its reliability was carried out using the markov stationary model in accordance with the structure of states and events described by the presented graph (Fig. 11). This process is described by the corresponding system of linear stationary Kolmogorov equations containing more than 3000 variables. The result of its solution is probabilities of all considered states, which are then used together with the results of calculations of post-emergency modes to determine the nodal RI.

Determination of the levels of heat supply to consumers in different states of DHS (post-emergency modes of DHS), including taking into account interruptions of the fuel supply to HS, it is carried out on the basis of multivariate calculations of the flow distribution in the network using methods of THC. The results of these calculation for identification of post-emergency modes in DHS contain a significant amount of data. The relation of the levels of heat supply to consumers in different states corresponding to failures of HS and HN components is presented in Fig. 12.

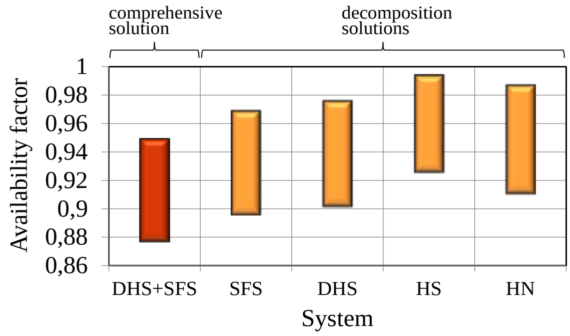

Fig. 13. Ranges of nodal AF for comprehensive and decomposition analysis of the reliability of DHS

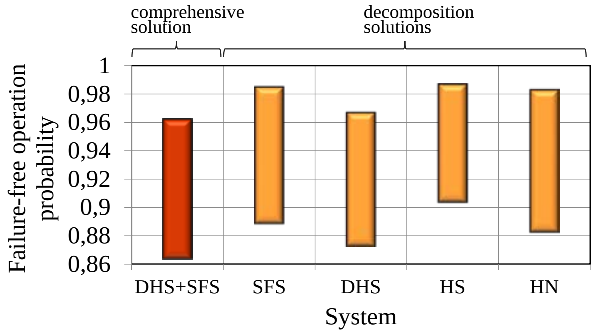

Fig. 14. Ranges of nodal FOP for comprehensive and decomposition analysis of the reliability of DHS

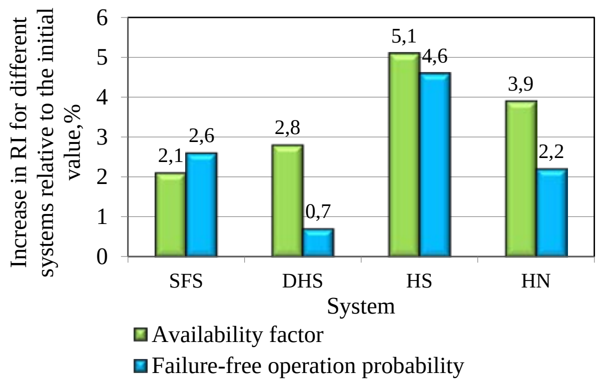

Fig. 15. Changes in nodal RI (AF and FOP) for SFS, DHS and subsystems of DHS in relation to the comprehensive level of this indices (the ratio of indices of decomposition and comprehensive reliability assessment)

Fig. 12. Levels of heat supply to consumers in case of failures of components of DHS subsystems (HS and HN)

The results of the comprehensive and decomposition analysis of the reliability of DHS in Shelekhov are presented in summarized form in Fig. 13 and Fig. 14, where the ranges of values of the availability factor (AF) and the failure-free operation probability (FOP) are given as for a comprehensive solution and for the subsystems under consideration separately. Based on the decomposition of nodal RI (AF and FOP), the degree of impact of each of subsystem on the total level of reliability of heat supply to consumers is determined. Within the limits of the RI ranges presented in the diagrams, their values are contained for all considered consumers of the system. Comparison of the obtained indices with the standard values showed that the requirements for AF are not ensure for all consumers of the system, for FOP – for 32% of consumers. Changes in nodal RI for considered subsystems of DHS in relation to the integrated assessment level are shown in Fig. 15.

Analysis of the presented results allows us to formulate the following conclusions about preliminary general directions for improving the reliability of heat supply to consumers of DHS in Shelekhov.

1. Fuel supply interruptions on HS in the considered system reduce the reliability of designed level of heat supply to consumers to a greater extent than failures of HS and HN components. This is confirmed by lower values of AF for SFS compared with DHS (Fig. 13 and Fig. 15). The range of increase in its values to the standard level is from 1 to 9.3%. Improving the reliability of SFS is achieved by regulating and increasing fuel reserves, providing the system with additional sources of fuel and a more reliable system for its transportation.

2. Index AF, calculated relative to HS, has the highest values, and for some consumers it complies with the standard. For the group of jointed consumers with the highest values of this index, achieving its standard level will require a minimal redundancy in the HS scheme. For other consumers, HS-related AF is low. To increase it, more significant measures for increasing of functional and structural HS redundancy will be required. It is also necessary to take into account that the installed heat capacity of HS (CHP-5) is significantly higher than the required generation for heat supply to house-hold consumers of the city, since most of this power covers technological loads. Therefore, there is an additional reserve for heating during periods of low heat loads.

3. The reliability of the reduced level of heat supply to consumers, characterized by index FOP, is affected to a greater extent by the failures of the DHS components (Fig. 14 and Fig. 15). Decomposition of RI is showed that HN is a less reliable subsystem. In this regard, one of the main directions of increasing the reliability of DHS are related to the implementation of a set of measures for the component and structural redundancy of HN. Such, the additional looped network connections

(bypass) in the network and duplication of some sections will provide the required level of reduced heating to consumers in emergency modes. Replacing the network components with more reliable ones and increasing its restoration rates (incl. due to improvement of emergency and restoration service) will increase the values of both indices (AF and FOP).

4. The presented results of the reliability analysis are aimed at obtaining the basis for making further decisions on searching the optimal ratio of measures to increase the reliability of heat supply to consumers. The rational distribution of reliability both in DHS (i.e. for subsystems – HS and HN) and SFS, and in the ways to ensure it (functional, component, structural redundancy, fuel reserves, energy storages, etc.) are a subject of special research of the problems of reliability synthesis. For example, the methodology for the optimal increase/ensuring the reliability parameters of DHS components as the one of the problem of reliability synthesis is considered in articles [14] and [15]. Some reliability optimization issues for the DHS with prosumers are presented in works [17–19].

4 Conclusion

As a result of the provided researches, scientific and methodological ensuring was developed for the comprehensive solution of a number of key technical, economic and organizational tasks of designing, functioning and developing modern DHS, taking into account their relationship. Within the framework of the developed scientific and methodological support, the following basic problems were solved: optimization of levels of district heating in DHS with feasibility study for connecting new consumers, selection of optimal forms and models of heating market for DHS, comprehensive analysis and ensuring (optimization) reliability of DHS taking into account the fuel supply of HS, and also other additional problems.

The developed scientific and methodological platform makes it possible to solve different problems for the innovative transformation of DHS (designing, management, reliability and others) in a joint complex, taking into account their logical relationship and methodological compatibility, which ultimately provides support for decisions to achieve the maximum efficiency, economy and reliability of heat supply to consumers.

Provided practical studies have confirmed the applicability and efficiency of the methods and models developed in the project, not only for test calculation schemes but also for existing DHS of cities. As results the new characteristics for studied systems were obtained, directions for their effective functioning and development were formulated with the joint solution of the complex of the most key and relevant technical and economic problems for modern DHS. The implementation of provided methodology into the practice of designing and development of DHS will contribute the increasing their efficiency and reliability, and transition the heat supply industry into an effective part of the economy.

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Ontological Engineering for Methodological Support of Research into Energy-related Anthropogenic Impact of the Environment

Tatyana.Vorozhtsova[1] , *Elena* Maysyuk[2], *Irina* Ivanova[2]

[1]Melentiev Energy Systems Institute SB RAS, Department of Artificial Intelligence Systems in Energy, Irkutsk, Russia
[2]Melentiev Energy Systems Institute SB RAS, Laboratory of Energy Supply to Off-grid Consumers, Irkutsk, Russia

Abstract. Ontological engineering is performed for studies on the environmental impact of energy objects. The work was carried out within the framework of the project supported by the Russian Foundation of Basic Research “Methods of building an ontological knowledge space for intelligent decision-making support in the energy sector and environment, in terms of the quality of life”. The study proposes developing a set of interconnected ontologies with the view to harmonizing terminology of different subject domains for research and decision support. The basic terminology used to examine the environmental impact of energy objects and to perform appropriate quantitative assessments is considered. Semantic methods are proposed, in particular, an ontological analysis of the subject domain, to systematize environmental assessments and establish relationships between the main indicators describing the impact of energy sector activity on the components of the environment. The ontological approach allows systematizing and visualizing the relationship between the components of the environment, energy objects and their characteristics, and impact factors. Ontological engineering made it possible to build a sequence of research and systematize the methodology used to assess the energy-related environmental impact.

Keywords. Anthropogenic impact, anthropogenic factor, ontology, energy objects, ontological engineering, ontological approach.

1 Introduction

Assessment of the environmental impact of energy objects is undoubtedly an urgent issue. Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences works on the use of semantic methods, including ontological modeling of this subject domain. Currently, a research team of the Institute, with the support of the Russian Foundation of Basic Research, is implementing the project "Methods of building an ontological knowledge space for the intelligent decision-making support in the energy sector and environmental science with regard to the quality of life". This project suggests a systems analysis of a methodology for the studies of the environmental impact of energy. The first stage of these studies involves an analysis of the existing methods and models for research aimed at harmonizing the sources of information and systematizing the indices used to implement these methods.

In general, the assessment of the impact of the energy sector in this study means a comprehensive investigation of the relationship between the processes that occur at various levels of the phenomena studied: from the impact of energy objects, which subsequently creates anthropogenic pollution, to the consequences in the form of changes in the natural environment components.

Ontological engineering involves the development of ontologies providing analysis and coordination of terminology of subject domains of energy and environment that intersect in our research, the establishment of relationships between the terms used, and structuring of the information necessary for this.

The ontological engineering performed previously in the field of the research into the interaction between energy and geo-environment [1] reflects the diversity of anthropogenic factors at different stages of the heat and electricity production process. Anthropogenic impacts include all effects produced by human activities on the environment.

This paper analyzes the methods applied today to assess the environmental impact of energy objects in order to structure the methodology necessary for this. The main attention is paid to the influence of energy generating facilities [2].

2 The energy-related environmental impact and classification of anthropogenic factors

In recent decades the anthropogenic pollution of the environment has been global in nature [3 - 6]. Today the human impact on nature is associated with changes in:

- landscape and structure of the earth's surface;
- composition of the biosphere;
- thermal balance of the planet or its regions;
- flora and fauna.

Anthropogenic impact leads to a change in the state of the environment, where new components (pollutants) appear. The objects of pollution are the atmosphere, soil, water, plants, animals, and microorganisms. Sources of pollution are industrial facilities, including energy and utility facilities.

The energy sector is one of the most serious sources of pollution. The anthropogenic impact of energy sector on the biosphere is seen in all stages of energy production - in the extraction and transportation of resources, in the production, transmission, and consumption of energy.

The functioning of energy objects affects all components of the environment - the atmosphere, water bodies, flora and fauna, and humans. Energy production is associated with landscape changes, the formation of quarries and dumps. The transportation of coal leads to the spread of harmful substances in the atmosphere and soil. Typical harmful impurities due to the burning of solid fossil fuels are soot, ash, carbon oxides, sulfur, nitrogen, heavy metal compounds, water vapor, and other substances, including carcinogens. The transmission of electric power causes electromagnetic fields near power lines. The operation of power plants is always associated with heat emissions. In addition, large areas of land are withdrawn from economic use.

In general, the harmful effects of energy objects on the environment are assessed based on a systems analysis of all interconnected processes at various stages of electricity and heat production.

In this regard, it is necessary to take into account the types, sources, levels of the influence of various anthropogenic phenomena and factors. In literature, there are many classifications of anthropogenic factors according to different features [5]. For example, according to the general nature of the impact, i.e. a change in landscapes, withdrawal of natural resources, and environmental pollution. The objects of influence are the surface of the earth and mineral resources, soil and vegetation, water bodies and atmosphere, as well as the microclimate of the environment, the animal world, and humans. Quantitative characteristics of the impact include spatial scales (global, regional, local), the severity of impact, the degree of danger, and others.

There is a classification of the anthropogenic factors [6] according to the following features:

- by nature mechanical, physical, chemical, landscape;
- by physical properties - substance, process, phenomenon, object;
- by the persistence of changes that occur in the environment (nature) - temporary reversible changes, relatively irreversible changes, absolutely irreversible changes, anthropogenic stress of ecosystems;
- by the ability to accumulate - only at the time of production, for a long time;
- by frequency - continuously acting factor, periodic factor, sporadic factor;
- by the ability to migrate - non-migratory, migrating with streams of water and air, migrating with sources, migrating independently.

3 Ontological engineering

Ontological engineering is the process of designing and developing ontologies to analyze the domain knowledge, including its extraction, structuring, and formalization.

The ultimate goal of ontological engineering is a formalized representation of the domain knowledge for its further use in the knowledge work and knowledge management system [7 - 9].

In this study, the development of ontologies is necessary to:

- clarify and harmonize terminology of different subject domains – environment and energy;
- define basic concepts in the study of the environmental impact of the energy sector;
- systematize the relationships between the concepts and identify classes and subclasses of ontologies;
- structure the knowledge and information in the context of the ongoing study.

In this stage, a set of ontologies classified as non-formal is developed. They are the result of discussion and clarification of terms and their definitions, identification of basic concepts, and description of the relationship between the concepts. As for the purpose of their development, the proposed ontologies are of applied nature, since they describe a conceptual model of the objective of the study on the environmental impact of the energy sector. For illustration, the ontologies are presented graphically using CmapTools. This provides the possibility of interaction between specialists of different subject domains.

The presentation of the ontologies in the formats necessary for computer processing is provided for further use of the developed system of ontologies.

This study considers the following basic concepts related to the energy-related environmental impact: *energy object*, *energy resource*, and *component of the environment*, which is affected due to the occurrence of an anthropogenic factor. Based on the analysis of methods existing for the assessment of this impact, we propose separate consideration of the concepts of *anthropogenic factor, anthropogenic impact, anthropogenic pollution*, and its *consequences*.

The definitions of these basic concepts are given below.

Energy object is a combination of energy plants and auxiliary devices, which are integrated territorially and technologically, and designed to jointly perform production and engineering tasks.

Energy resource is an energy carrier, which is or can be used in the energy sector at a given level of technology or in the foreseeable future of its development.

Component of the environment is all that helps to ensure and maintain favorable conditions for the preservation of life on Earth. This category includes the earth, mineral resources, soil, flora and fauna, oceans, atmosphere, and near-Earth outer space.

The anthropogenic factor is the cause of the anthropogenic impact on the natural environment, due to the process and operating conditions of the object, and its characteristic features. In terms of energy objects, anthropogenic factors are understood as emissions, waste, radiation, noise, vibration, radiance, etc. The anthropogenic factor depends on the type and kind of energy resource and type of technologies of the energy object.

The anthropogenic impact is a consequence of the anthropogenic factor, the process of the influence of economic or other human activity on the components of the environment. Anthropogenic factors of energy objects have physical, chemical, biological, electromagnetic, noise, and radiation effects on various components of the environment. The level of anthropogenic impact is determined by the anthropogenic load, which depends on the magnitude of the factor, environmental conditions, and duration of exposure.

Anthropogenic pollution is a result of changes in the components of the environment caused by anthropogenic impact. The degree of pollution depends on the anthropogenic load and determines the concentration of harmful substances in the components of the environment. The degree of pollution is determined by the composition of harmful substances, the ability to adapt to anthropogenic impact and its duration.

The consequence is a result of anthropogenic pollution. This may be the withdrawal of land, land depletion, landscape disturbance, destruction of vegetation, acidification of soil, diseases of animals and humans, drying out of water bodies, etc.. Figure 1 shows the basic relationships between the basic concepts.

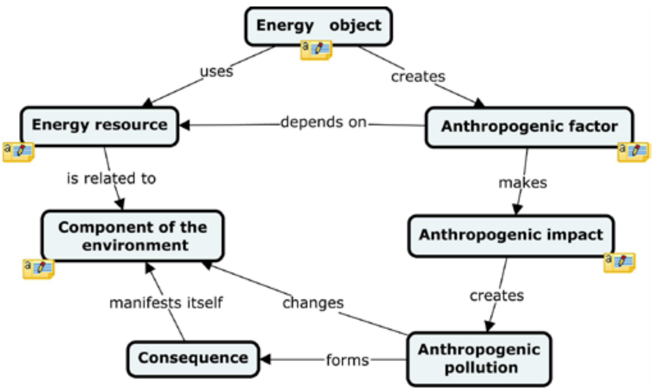

Fig. 1. Metaontology of the environmental impact of energy sector

In the study, these concepts are considered as the base classes of metaontology. The next level of ontologies details the basic concepts, clarifies relationships and reflects the properties of each of them.

The concept of *anthropogenic factor* is the most important in this study. The anthropogenic factor results from the operation of an energy object, depending on the energy resource used. It is characterized by some properties, such as *frequency of exposure*, *ability to migrate*, and has one of the states. Anthropogenic factors include emissions, discharges, waste, noise, and radiation. A detailed definition of the anthropogenic factor concept is shown in Figure 2.

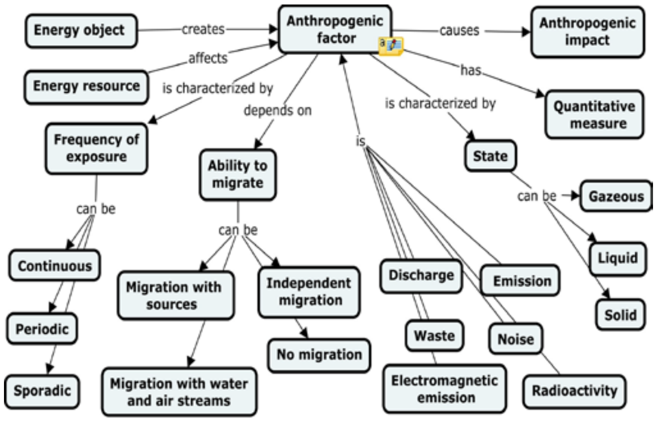

Fig. 2. Ontology of the anthropogenic factor

Each of the concepts used has been detailed similarly. For example, the concept of *anthropogenic pollution*, as noted earlier, is a consequence of *anthropogenic impact*.

Anthropogenic impact forms the consequence of anthropogenic pollution. Its effect on the component of the environment is measured by the level of pollution and depends on the anthropogenic load. It is also necessary to take into account the properties of frequency and the ability to be accumulated, as shown in Figure 3.

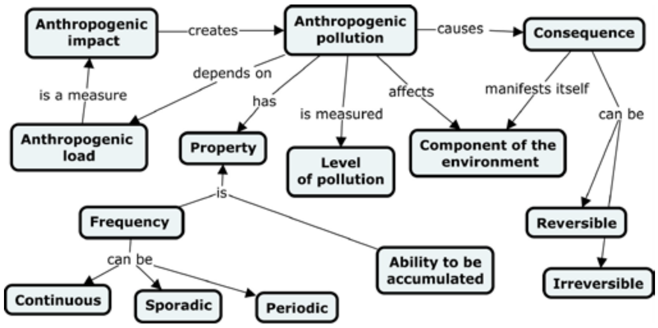

Fig.3. Ontology of anthropogenic pollution

Thus, a thorough examination of each concept makes it possible to factor in all the details in the study of the subject domain, classify terms, and establish relationships to take relevant information.

The next levels of the ontology system deal with the types of energy objects, their technical and production characteristics necessary for the implementation of methods for assessing the energy-related environmental impact.

The developed system of ontologies is the basis for an intelligent system of decision support and the creation of databases and knowledge bases.

4 Methodological support of the studies on the environmental impact of energy objects

The methodological support in this study means a method of quantifying the relationships between the concepts and phenomena that reflect the environmental impact of energy objects.

Considering successively the metaontology in figure 1, it is necessary to clarify that the anthropogenic factor implies the operation of energy objects, which causes changes in the composition, structure, and properties of the environment components: atmosphere, water bodies, soils, and living organisms.

In this regard, the initial disturbance from the operation of energy objects is the appearance of irrelevant impurities and changes in the state of the components of the environment. Accordingly, a quantitative measure of the anthropogenic factor for each component of the environment is a respective set of characteristics/indices with their units of measurement. The existing approved methods for calculating emissions, discharges, waste, etc., can serve as methodological support for the quantitative assessment (Figure 4).

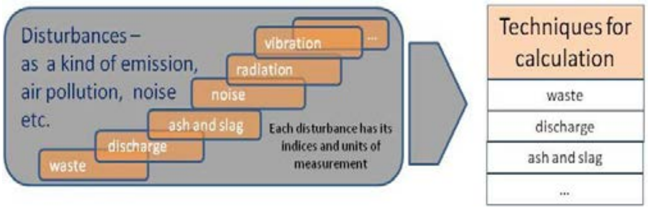

Fig. 4. Methodological support for the quantitative assessment of the anthropogenic factor

In general, the anthropogenic factor of the energy object operation is related to the anthropogenic impact through disturbance. The anthropogenic impact is a change in the natural environment components because of disturbances.

At the same time, quantitative indicators of disturbances in combination with the characteristics of the properties of the environment components make it possible to determine whether or not there is an effect for a particular component of the environment, whether it is high or insignificant.

The properties and state of the environment components are described by climatic models, and the "behavior" of incoming impurities is described by models of their distribution.

A quantitative measure of impact is the anthropogenic load, which is assessed qualitatively as high, medium or low.

The methodological support for the study of anthropogenic impact is associated with the collection and analysis of data on the current state using official reports on the state of the environment. The methodological support also includes certain climatic "behavioral" models that describe physical, thermodynamic, and chemical processes in the natural environment components for a particular territory.

The methodological support contains the methods of:

- assessing the current (background) state of the environment component;
- analyzing and collecting the information about the pollutant, its properties, hazard/ harmfulness;
- assessing the adaptation, self-cleaning and self-healing abilities of the environment components.

The pollution of the environmental components is formed depending on the severity of the impact (anthropogenic load) and duration. The pollution is determined by the composition of harmful substances, their hazard class, and the ability to be accumulated in the component of the natural environment.

Assessment of the extent to which the environment components are polluted due to the impact suggests determining the number of harmful substances, which "falls out" on the surface and forms the levels of pollution.

This stage employs the models of the spread of harmful impurities with the view to determining the quantity of impurities washed out from the atmosphere and then the density of deposition of the pollutants on the surface of soils and water bodies, as well as potential volumes of their penetration into living organisms - plants, animals, humans (Figure 5).

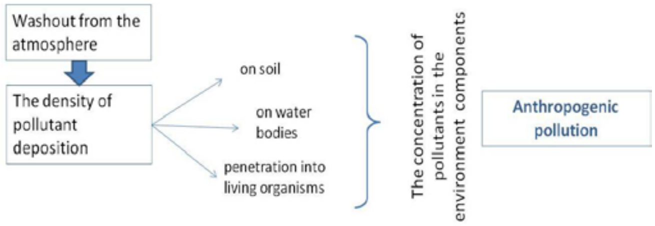

Fig. 5. Scheme of the formation of anthropogenic pollution depending on the density of the deposition of pollutants

Accordingly, a quantitative measure of anthropogenic pollution is the concentration of pollutants in the environment components, given the density of their deposition.

Thus, anthropogenic pollution due to disturbances and the impact of energy objects forms consequences for the environment components. The results of the consequences are the changes that occur: withdrawal, depletion, violation, destruction, acidification, disease, drying, etc.

Methodological support for assessing the consequences is the systematization of existing quality standards for each component of the environment. A comparison of norms and actual pollution levels in the form of concentrations and density of deposition will allow us to assess the environmental impact of energy objects. The quantitative measure of the consequences, which is assumed in this study, is a comparison of concentrations with the existing maximum permissible concentration standards – their exceedance or non-exceedance in the environment components.

Thus, the combination of these four research components makes it possible to build the methodological support for assessing the environmental impact of energy objects (Table 1). In some cases, statistical materials, reporting data on the activities of energy companies and government reports on the state of the environment both nationally and regionally can also serve as methodological support.

5 Conclusion

The paper presents a study on the energy-related environmental impact in the form of ontologies and descriptions of concepts and definitions corresponding to this subject matter. The investigation and assessment of changes in the components of the environment are carried out using the environmental approach, i.e. based on a universal connection of processes that occur at different levels of the phenomena studied.

Table 1. Methodological support

Research component	Quantitative measure	Methodological support
Anthropogenic factor	Emission, discharge, ash and slag waste	Methods for calculating emissions [10 - 12], discharges, and waste from energy facilities [13, 14]
Anthropogenic impact	Anthropogenic load, indicators of the composition of pollutants, their dangers, climatic and orographic characteristics of the territory	Assessment of the background state of the environment components and information on their properties. Systematization of information on properties of energy-related harmful substances [15-17]. Climatic models describing physical, thermodynamic, and chemical processes in the components of the environment [18,19]
Anthropogenic pollution	The concentration of pollutants, the density of deposition.	Models of the spread of pollutants in various components of the environment (taking into account the relief of the underlying surface) [20 - 22]
The effect of anthropogenic pollution	The factor of exceedance of maximum permissible concentrations for various components of the environment, standards for permissible emissions/discharges, etc.	Systematization of existing quality standards for each element of the environment [23-25]

We propose presenting the concepts, definitions and their relationships graphically as an ontology, which provides the visibility and possibility of harmonizing with the appropriate methods of calculating the quantitative measures of the studied components of the environmental impact of the energy sector.

Various methodological approaches and mathematical models have been developed to assess the negative impact of the energy sector. They are used depending on the task.

The formation of methodological support as a way to quantify the relationships between concepts and phenomena requires the collection and processing of a large amount of information and methodological material. The systematization of methods will allow us to build a clear sequence for both quantitative and qualitative assessment of the energy-related environmental impact.

Acknowledgments

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Using intelligent technologies for knowledge formation in research on the impact of power industry on ecology and quality of life

Tatyana Vorozhtsova[1,*], *Dmitry* Pesterev[1], and *Gleb* An[1]

[1]MESI, Department of Intelligent Power Systems in the Energy Sector, Irkutsk, Russia

Abstract. The article discusses the possibilities of using intelligent technologies, namely, ontological and cognitive modeling to represent knowledge in studies of the impact of energy facilities on the environment and the quality of life of the population. The relevance of this work is due to the need to improve research methods. An intelligent information system and an ontological space of knowledge are being developed, integrating tools and an information base to carry out research. It is proposed to use ontologies to identify and organize the basic concepts of different subject areas related to joint research, establish relationships between them, as well as for the structural representation of knowledge. The cognitive modeling methodology is designed to analyze and model situations and make coordinated decisions in the energy industry, taking into account its impact on the environment and quality of life. Cognitive modeling is used to identify causal relationships between concepts, visualize them, describe possible situations and support to decision-making.

Introduction

The Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences (MESI SB RAS) is implementing the project "Methods for constructing an ontological space of knowledge for intellectual support of decision making in energy and ecology, taking into account the quality of life", supported by the RFBR grant No. 20-07-00195. This project envisages the development of an intelligent information system (IIS) that integrates a complex information base for carrying out research, mathematical and semantic methods, tools for assessing the impact of energy on the environment and quality of life. The presence and operation of energy facilities on the territory affects the quality of life of the population, since, on the one hand, it provides the needs for the necessary heat and electric energy, and on the other hand, it is one of the most serious sources of environmental pollution. The relevance of this work is due to the need to support for making agreed decisions in the field of energy research, taking into account its impact on the environment and quality of life. For this purpose, such methods of semantic technologies as, cognitive, and ontological modeling are developed and used. A unified ontological space of knowledge is being developed, which ensures the integration of research in the subject areas of energy and ecology. The developed system of ontologies provides information support for research by integrating the necessary data, designing and developing databases based on the ontological description. The use of ontological and cognitive modeling methods and supporting tools is proposed to assess the impact of energy facilities on the environment. Thus, the formation of an ontological knowledge space for research involves the integration and coordination of all necessary data, information and knowledge for the scientific justification of decision-making in the energy sector, taking into account its impact on the environment and quality of life.

Opportunities and goals of ontological modeling

For intellectual support of data from interdisciplinary research, taking into account the intersection of knowledge from different subject areas, it is proposed to use semantic technologies for describing and modeling knowledge. Domain knowledge modeling is the mainstream and basic paradigm of artificial intelligence. Ontological modeling is one of the leading areas of semantic modeling [1, 2]. Currently, ontologies are the main approach to the development and implementation of knowledge management systems [3 - 5]. The application of ontological modeling in energy research was considered in the works of Massel L. V., Vorozhtsova T. N., Skripkin S. K., Kopaygorodsky A. N. [6, 7]. At the same time, ontological engineering is used as the main method of working with knowledge and a fractal approach is used to knowledge structuring.

Ontological engineering is the process of designing and developing ontologies based on the structural analysis of the subject area [8].

Knowledge about a subject area is a collection of information about the objects of this subject area, the properties of these objects, the relationships between objects, as well as about the processes and situations that occur in this subject area. An ontology is usually constructed as a tree or network consisting of concepts and relationships between them. The ontological engineering process includes the following steps:

- identifying the basic concepts of a given subject area - concepts.
- identifying connections or relationships between concepts
- building a hierarchy of concepts
- description of the properties of the selected concepts.

The main advantage of ontological engineering is:

• systematic - ontology represents a holistic view of the subject area;

• uniformity - material presented in a uniform form is much better perceived and reproduced;

• scientific nature - the construction of an ontology allows you to restore the missing logical connections in their entirety.

The possibilities of applying the fractal approach to structuring knowledge and building an ontological space are described in the work of L. V. Massel [9].The fractal approach assumes that knowledge about the object under study is presented in the form of several layers, each of which characterizes a certain aspect of data, information or knowledge about the object.

Ontological models provide the following opportunities for working with knowledge:

- are a means of representing knowledge
- provide work with meaning of information
- allows automated processing
- provide application integration
- provide inference capability

In this work, the system of ontological models is designed for:

- coordination of research in different subject areas (energy, ecology, quality of life) in accordance with the project goals
- concordance of the concepts of these subject areas
- ensuring the availability and perception of large volumes of complex structured information
- descriptions of the structure and components of the AIS

Components of the ontological knowledge space

The system of ontologies of the developed ontological knowledge space for research includes knowledge representation for interrelated studies of energy, ecology, and quality of life.

The ontological model is based on a fractal approach, which presupposes the inclusion of several layers - meta-levels and their further stratification, which provides for an increasing degree of detail at each next level.

Metaontologies include basic concepts of the subject areas of energy, ecology and quality of life that are relevant to collaborative research. They are used as a basis for describing the components and structure of an intelligent information system, as well as for developing the system interface. The following levels of ontologies include:

- Ontological description of research sections
- Ontologies that describe the data and information used, database ontologies
- An ontological description of knowledge bases that contain descriptions of classes and instances, their properties and relationships, and a set of rules that allow logical inference.

Figure 1 shows metaontology, which combines the basic concepts of subject areas and shows the main research areas – energy, ecology, and quality of life. The presented concepts are the base classes of the ontology system. IIS components correspond to these sections.

The section "Power industry" contains a description of energy objects and their properties, on which the anthropogenic influence on the environment and the quality of life depends. The section "Ecology" describes anthropogenic factors, elements of the natural environment, and methods for assessing anthropogenic impact.

The concept of "Quality of life" is an aggregate characteristic of the living standard and objective and subjective living conditions of the population, which determine the physical, mental, socio-cultural development of a person, group or community of people [10]. According to the World Health Organization (WHO), it is the perception of individuals of their position in life in the context of the culture and value system in which they live, in accordance with goals, expectations, norms and needs. Accordingly, the section "Quality of life" includes a description of indicators of quality of life, factors of influence and methods for analyzing this influence.

Section "Task" contains a description of the tasks to be solved in these studies. Section "Methodology", as a component of IIS, includes a set of methodological approaches in research, methods and algorithms used to assess the impact of energy facilities on the environment and quality of life.

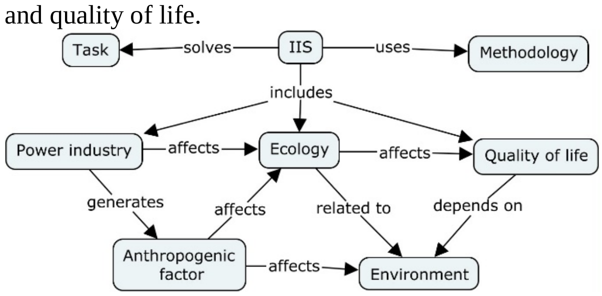

Fig. 1. Metaontology of knowledge of subject areas research

One of the important concepts of the presented metaontology is the "Anthropogenic factor" - the cause of anthropogenic impact on the environment, due to the process and conditions of the object's functioning, its characteristic features. In relation to energy facilities, anthropogenic factors include emissions, waste, radiation, noise, vibration, radiation, etc. The anthropogenic factor depends on the type and type of energy resource and the type of energy facility technologies. Using indicators of anthropogenic impact on the environment and elements of the environment, the degree of negative impact on the quality of life of the population is assessed at the expert level.

Cognitive modeling and its application in these studies

Cognitive analysis and modeling are modern intellectual technologies that are used to study weakly formalized and weakly structured systems, which include economic, social, and environmental systems [11]. Currently, the application of cognitive modeling is developing in the direction of modeling and analysis of situations and support to decision making. Abroad this is reflected in the works of Peter Grumpos and Chrysostomus Stylios [12, 13]. In our country, this is the work of employees of the Institute of management problems of the Russian Academy of Sciences [14, 15], the scientific school of Kulinich [16], etc. At MESI SB RAS it is proposed to use cognitive modeling as a tool for studying the problem of energy security (ES) [17, 18].

Cognitive analysis is based on the cognitive-target (cognitive) structuring of knowledge about an object and its external environment. Cognitive structuring is the identification of the most significant factors that affect the situation and the cause-and-effect relationships between them. The methodology of cognitive modeling is based on modeling the subjective views of experts about the situation. Experts knowledge is presented as a cognitive map.

In this paper, we propose to use cognitive modeling to analyze the mutual influence of energy and ecology factors on the quality of life of the population. The use of ontologies in this case is necessary to identify these factors and formulate concepts. In the ontological space, compiled for the studied interdisciplinary interaction, there are factors from one area, which can both positively and negatively influence factors from another. For example, factors from the field of energy have both a positive effect on the quality of life (use of electricity, use of thermal energy) and a negative one (environmental pollution, noise impact, etc.). Therefore, the main task of cognitive modeling is to determine the final influence of factors on each other in a particular situation. Another task is to visualize the dependencies between the main factors of the study area.

To build a cognitive map, the subject area is analyzed, and the main factors (concepts) that are important for research are identified. If there is already an ontology of the subject area, then concepts are allocated directly on the basis of this ontology. After this stage, connections and their nature are established between the concepts. In the simplest case, the relationships can be either positive or negative. In a more complex case, weight coefficients obtained by expert evaluation are added to the signs of connections. When analyzing a specific situation, the cognitive map is built either anew or selected from among existing ones, provided that it contains the necessary concepts of the subject area.

Figure 2 shows an example of a cognitive map that describes the main factors of the situation "providing the population with heat energy" from the position of the main factor "Quality of life".

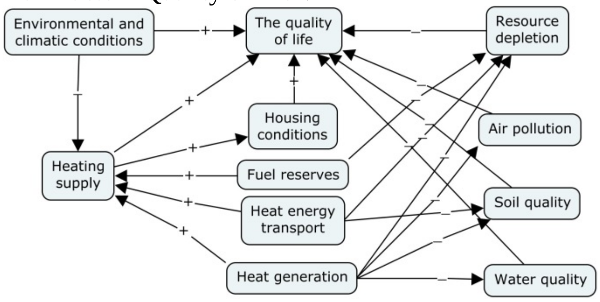

Fig. 2. Cognitive map "providing the population with heat energy".

This map shows the influence of factors on the "Quality of life" target factor. This influence is both positive and negative. To accurately determine the total impact, you will need to introduce weighting coefficients, which are determined by the method of expert assessments. In this case, it is possible to determine the final impact.

Ontologies and data model

Creation of information systems using the ontological approach provides a significant advantage in terms of the correct preparation of information components [19].

As noted, the developed system of domain ontologies for research involves several levels. Ontologies that describe the data and information used are the basis for modeling and developing databases, since the ontology is a convenient basis for developing a data schema [20]. One of the components of the developed intelligent information system is the database development module based on ontologies. As you know, a database consists of tables and data. An ontology is a connected graph from which you can get data, element values, and their generalizing properties. Generalizing properties of items should be interpreted as database tables, and values as data in tables. In Fig. 3, the concept of "Energy source" is presented as generalizing property of the objects "Diesel power station", "Thermal power plant", "Boiler house". In the database, we get the following structure: the table "Energy source" with the data "Diesel power station", "Thermal power station", "Boiler house".

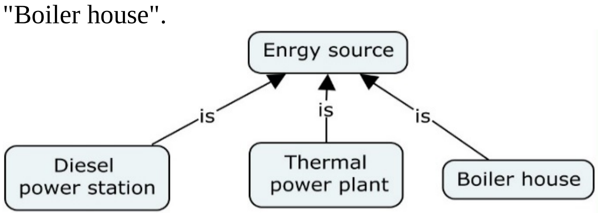

Fig. 3. Ontology "Energy source»

An example of such a table is shown in figure 4.

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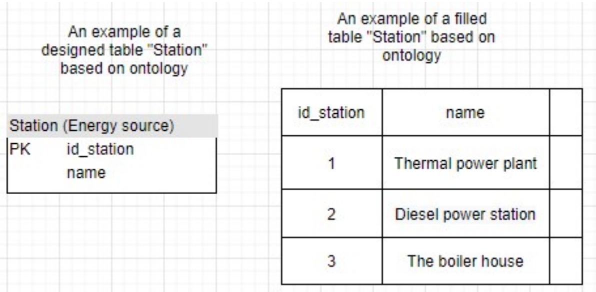

Fig. 4. Table "Energy source" of the designed database

The figure 5 shows a block diagram of the algorithm for converting an ontology into a database schema, and the figure shows a diagram of a database for storing information about an energy facility-a boiler house. Since the ontology uses natural language attributes, to align it with the database schema, it is necessary to limit the set of valid relationships between concepts ("has", "is", "measured in", "can take a value", "consists of").

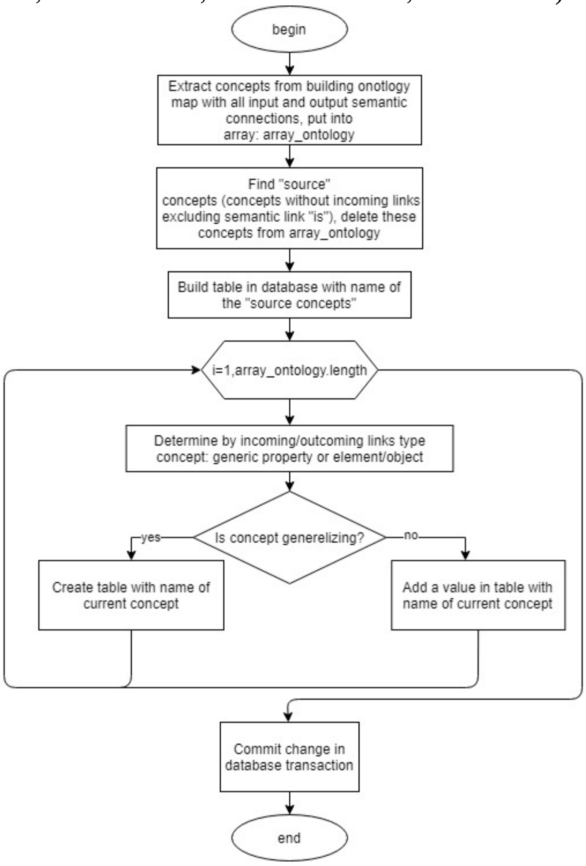

Fig. 5. Algorithm for converting an ontology into a database schema.

In the future, based on the constructed data model, an information system will be formed that will serve as information support for experts in supporting decision-making in the energy and environmental sectors.

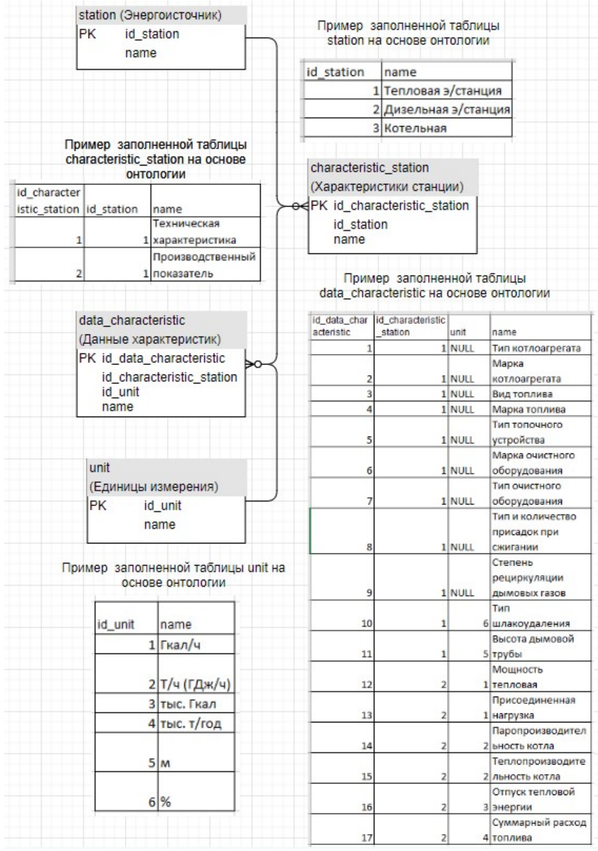

Fig. 6. The database of the boiler

Conclusion

The paper describes examples of using intelligent technologies to perform research on the impact of energy facilities on the environment and the quality of life of the population. For this purpose, an intelligent information system is being developed that integrates a complex information and methodological base of interdisciplinary research. Semantic modelling methods, including ontological and cognitive modelling), are used to support coordinated decision-making in the field of energy, taking into account its impact on the environment. A unified ontological knowledge space is being developed that provides integration of research in the subject areas of energy and ecology.

The developed system of ontologies provides information support for research by integrating the necessary data, designing and developing databases based on the ontological description. Ontologies are used to identify and organize the basic concepts of different subject areas that are relevant to joint research, establish relationships between them, as well as for the structural representation of knowledge.

Cognitive modeling is used to analyze and model situations and make coordinated decisions in the energy industry, taking into account its impact on the environment and quality of life. Cognitive models are used to identify cause-and-effect relationships between concepts, their visual representation in the process of describing possible situations and making decisions.

Acknowledgments

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Matrix structure of unified mathematical model of electric AC machines at control

Rauf Mustafayev[*], *Nurali* Yusifbayli, *Laman* Hasanova

Azerbaijan Scientific–Research and Designed–Prospecting Institute of Energetics, Baku, Azerbaijan

Abstract. The matrix structure of the equations of a generalized electric alternating current machine is proposed, which, based on the Parke equations, is written in the coordinate axes of the machines rotating with the rotor speed. In the matrix structure, the column matrices of the derivatives of the stator, excitation and rotor windings are equal to the product of diagonal matrices consisting of the machine parameters and the column matrices of the flux links themselves and the sum of the matrix columns of the control parameters which are the matrix columns of the stator voltage, excitation voltage, and rotor voltage. It is shown that the matrix structure of a generalized controlled AC machine is transformed into mathematical models of almost all encountered AC electric machines, namely, into a synchronous machine with two excitation windings - a longitudinal and a transverse one; in a synchronous machine with a longitudinal field winding (classic); in an asynchronous machine with a squirrel-cage rotor; into an asynchronous machine with a phase rotor. It has been shown that the matrix structure includes the controls of these machines both from the stator and from the rotor. On the stator side for synchronous machines, it is a frequency control that regulates both the amplitude and frequency of the applied voltage, and on the rotor side, a constant voltage control is supplied to the longitudinal and transverse windings. For asynchronous machines, the stator and rotor are frequency-controlled. The following are examples of frequency control of an asynchronous machine both from the stator and from the rotor.

1 Introduction

When designing complex electromechanical devices for such, for example, systems as “wind-power engineering”, “small hydropower engineering”, etc., which can contain controlled electric machines of different types, it is required not only optimally join electric machine with mechanical one, but in a number of cases to optimize the choice and the type itself of the controlled electric machine.

The equations of a generalized electric machine are well known, which are given, for example, in [1]. It should be noted that these equations more reveal the principle of construction of electromagnetic and electrical connections in electric machine, for practical use they must be transformed taking into account the type of electric machine and the form of writing of their equations.

In addition, the controllability principles and transient processes in individual AC electric machines are studies in papers of famous scientists [2; 3; 4; 5; 6; 7; 8].

2 Materials and methods

The above circumstances predetermine the creation of a universal mathematical model of a controlled alternating current (AC) electric machine, which, remaining structurally unchanged, would allow for studying all modes of operation of AC electric machines used in practice: synchronous machines with electromagnetic excitation and permanent magnets, including frequency-controlled ones; asynchronous machines with short-circuited and phase-wound rotor, including frequency-controlled ones.

Here, Park's equations, written in axes rotating at the rotor speed of ω_r, were taken as the basis of mathematical model of electric AC machines, and the machine has two stator windings and four rotor windings. In contrast with these equations, not angle θ between the rotor axis, rotating at the rotor speed of ω_r, and the synchronous axis, rotating at the synchronous speed of ω_s, but the angle between the rotor axis and fixed axis, hereinafter signed as angle α, is selected as a power angle. Thus, the

[*] Corresponding author: mustafayevri@mail.ru

rotor speed is equal to ω_r, where p – differentiation symbol, τ – synchronous time equal to $\tau=\omega_s \cdot t=314 \cdot t$. In addition, the equations of machines are written in flux linkages.

In this case the equations of controlled electric AC machines can be written in cell wise-matrix form, which is represented in the form.

$$\begin{bmatrix} p\boldsymbol{\Psi}_s \\ p\boldsymbol{\Psi}_f \\ p\boldsymbol{\Psi}_r \end{bmatrix} = \begin{bmatrix} \boldsymbol{A}_{s1} & \boldsymbol{A}_{s2} & \boldsymbol{A}_{s3} \\ \boldsymbol{B}_{f1} & \boldsymbol{B}_{f2} & \boldsymbol{B}_{f3} \\ \boldsymbol{C}_{r1} & \boldsymbol{C}_{r2} & \boldsymbol{C}_{r3} \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{\Psi}_s \\ \boldsymbol{\Psi}_f \\ \boldsymbol{\Psi}_r \end{bmatrix} + \begin{bmatrix} \boldsymbol{U}_s \\ \boldsymbol{U}_f \\ \boldsymbol{U}_r \end{bmatrix} \quad (1)$$

Column matrices are the essence of a vector with projections on d, q axes:

– derivatives of flux linkages of stator, field and rotor windings:

$$p\boldsymbol{\Psi}_s = \begin{bmatrix} p\boldsymbol{\Psi}_{ds} \\ p\boldsymbol{\Psi}_{qs} \end{bmatrix}, \quad p\boldsymbol{\Psi}_f = \begin{bmatrix} p\boldsymbol{\Psi}_{df} \\ p\boldsymbol{\Psi}_{qf} \end{bmatrix}, \quad p\boldsymbol{\Psi}_r = \begin{bmatrix} p\boldsymbol{\Psi}_{dr} \\ p\boldsymbol{\Psi}_{qr} \end{bmatrix}$$

– flux linkages Ψ_s, Ψ_r, Ψ_f themselves :

$$\boldsymbol{\Psi}_s = \begin{bmatrix} \boldsymbol{\Psi}_{ds} \\ \boldsymbol{\Psi}_{qs} \end{bmatrix}, \quad \boldsymbol{\Psi}_f = \begin{bmatrix} \boldsymbol{\Psi}_{df} \\ \boldsymbol{\Psi}_{qf} \end{bmatrix}, \quad \boldsymbol{\Psi}_r = \begin{bmatrix} \boldsymbol{\Psi}_{dr} \\ \boldsymbol{\Psi}_{qr} \end{bmatrix}$$

–voltages of stator, field and rotor windings (control actions):

$$\boldsymbol{U}_s = \begin{bmatrix} U_{ds} \\ U_{qs} \end{bmatrix}, \quad \boldsymbol{U}_f = \begin{bmatrix} U_{df} \\ U_{qf} \end{bmatrix}, \quad \boldsymbol{U}_r = \begin{bmatrix} U_{dr} \\ U_{qr} \end{bmatrix}$$

Matrices $\boldsymbol{A}_{s1}$, $\boldsymbol{A}_{s2}$, $\boldsymbol{A}_{s3}$, $\boldsymbol{B}_{f1}$, $\boldsymbol{B}_{f2}$, $\boldsymbol{B}_{f3}$, as well as $\boldsymbol{C}_{r1}$, $\boldsymbol{C}_{r2}$, $\boldsymbol{C}_{r3}$ are diagonal matrices, which are represented in the form:

$$\left.\begin{aligned}
&\boldsymbol{A}_{s1} = \begin{bmatrix} -r_s \cdot k_{ds} & -\omega_r \\ \omega_r & -r_s \cdot k_{qs} \end{bmatrix}; \boldsymbol{A}_{s2} = \begin{bmatrix} -r_s \cdot k_{dsf} & 0 \\ 0 & -r_s \cdot k_{qsf} \end{bmatrix}; \\
&\boldsymbol{A}_{s3} = \begin{bmatrix} -r_s \cdot k_{dsr} & 0 \\ 0 & -r_s \cdot k_{qsr} \end{bmatrix}. \\
&\boldsymbol{B}_{f1} = \begin{bmatrix} -r_{df} \cdot k_{dsf} & 0 \\ 0 & -r_{qf} \cdot k_{qsf} \end{bmatrix}; \boldsymbol{B}_{f2} = \begin{bmatrix} -r_{df} \cdot k_{df} & 0 \\ 0 & -r_{qf} \cdot k_{qf} \end{bmatrix}; \\
&\boldsymbol{B}_{f3} = \begin{bmatrix} -r_{df} \cdot k_{dfr} & 0 \\ 0 & -r_{qf} \cdot k_{qfr} \end{bmatrix}. \\
&\boldsymbol{C}_{r1} = \begin{bmatrix} -r_{dr} \cdot k_{dsr} & 0 \\ 0 & -r_{qr} \cdot k_{qsr} \end{bmatrix}; \boldsymbol{C}_{r2} = \begin{bmatrix} -r_{dr} \cdot k_{dfr} & 0 \\ 0 & -r_{qr} \cdot k_{qfr} \end{bmatrix}; \\
&\boldsymbol{C}_{r3} = \begin{bmatrix} -r_{dr} \cdot k_{dr} & 0 \\ 0 & -r_{qr} \cdot k_{qr} \end{bmatrix}.
\end{aligned}\right\}$$

First matrix $\boldsymbol{A}_{s1}$ can be represented in the form:

$$\boldsymbol{A}_{s1} = \boldsymbol{A}_{s11} + \boldsymbol{A}_{s1\omega} = \begin{bmatrix} -r_s \cdot k_{ds} & 0 \\ 0 & -r_s \cdot k_{qs} \end{bmatrix} + \begin{bmatrix} 0 & -\omega_r \\ \omega_r & 0 \end{bmatrix}$$

Since ω_r – rotor speed of AC machine is a scalar value, then $\boldsymbol{A}_{s1\omega}$ can be represented in the form:

$$\boldsymbol{A}_{s1\omega} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \cdot \omega_r = -\boldsymbol{J} \cdot \omega_r$$

where $\boldsymbol{J}$–matrix orthogonal to unity matrix $\boldsymbol{E}$, i.e. ($\boldsymbol{J}^2$=–$\boldsymbol{E}$), by analogy with complex unit $j^2=-1$.

Besides equations (1), it is necessary to take into account equations of motion with motive moment m_t and electromagnetic moment m_{em}:

$$\left.\begin{aligned}
&T_j \cdot p\omega_r = m_t - m_{em} \\
&m_{em} = (k_{qs} - k_{ds}) \cdot \Psi_{ds} \cdot \Psi_{qs} + k_{qsf} \cdot \Psi_{ds} \cdot \Psi_{qf} + \\
&+ k_{qsr} \cdot \Psi_{ds} \cdot \Psi_{qr} - k_{dsf} \cdot \Psi_{qs} \cdot \Psi_{df} - k_{dsr} \cdot \Psi_{qs} \cdot \Psi_{dr}
\end{aligned}\right\} \quad (2)$$

Thus, equations (1) and (2) form a universal mathematical model of electric AC machines. In addition to the equation, the definition of active and reactive powers is of interest for m_{em}:

$$\left.\begin{aligned}
p_{em} &= k_{ds} \cdot U_{ds} \cdot \Psi_{ds} + k_{dsf} \cdot U_{ds} \cdot \Psi_{df} + \\
&+ k_{dsr} \cdot U_{ds} \cdot \Psi_{dr} + k_{qs} \cdot U_{qs} \cdot \Psi_{qs} + \\
&+ k_{qsf} \cdot U_{qs} \cdot \Psi_{qf} + k_{qsr} \cdot U_{qs} \cdot \Psi_{qr} \\
q_{em} &= k_{ds} \cdot U_{qs} \cdot \Psi_{ds} + k_{dsf} \cdot U_{qs} \cdot \Psi_{df} + \\
&+ k_{dsr} \cdot U_{qs} \Psi_{dr} - k_{qs} \cdot U_{ds} \cdot \Psi_{qs} - \\
&k_{qsf} \cdot U_{ds} \cdot \Psi_{qf} - k_{qsr} \cdot U_{ds} \cdot \Psi_{qr}
\end{aligned}\right\} \quad (3)$$

It should be noted that the mentioned equations are written in the per unit system, for basic expressions the same units are taken as in the equations, which, for example, are given in [9; 10; 11].

Coefficients k_{ds}, k_{dsf}, k_{dsr}, k_{qs}, k_{qsf}, k_{qsr}, k_{df}, k_{dfr}, k_{qf}, k_{qfr}, k_{dr} and k_{qr} connect the values of currents of stator i_{ds}, i_{qs}, field windings i_{df}, i_{qf} and rotor windings i_{dr}, i_{qr} with appropriate flux linkages.

They are easily defined from the matrix equality (direct and inverse matrices with inductive parameters of machine).

$$\begin{bmatrix} k_{ds} & 0 & k_{dsf} & 0 & k_{dsr} & 0 \\ 0 & k_{qs} & 0 & k_{qsf} & 0 & k_{qsr} \\ k_{dsf} & 0 & k_{df} & 0 & k_{dfr} & 0 \\ 0 & k_{qsf} & 0 & k_{qf} & 0 & k_{qfr} \\ k_{dsr} & 0 & k_{dfr} & 0 & k_{dr} & 0 \\ 0 & k_{qsr} & 0 & k_{qfr} & 0 & k_{qr} \end{bmatrix} = \quad (4)$$

$$= \begin{bmatrix} L_{ds} & 0 & M_{ad} & 0 & M_{ad} & 0 \\ 0 & L_{qs} & 0 & M_{aq} & 0 & M_{aq} \\ M_{ad} & 0 & L_{df} & 0 & M_{ad} & 0 \\ 0 & M_{aq} & 0 & L_{qf} & 0 & M_{aq} \\ M_{ad} & 0 & M_{ad} & 0 & L_{dr} & 0 \\ 0 & M_{aq} & 0 & M_{aq} & 0 & L_{qr} \end{bmatrix}^{-1}$$

where L_{ds}, L_{qs}, L_{df}, L_{qf}, L_{qr}, L_{dr} – full inductances along the d and q axes to the corresponding stator, excitation and rotor windings [relative units]; M_{ad}, M_{aq} – mutual inductances along the d and q axes [relative units].

In expression (4) the right part is a matrix of machine parameters in relative units, but it is necessary to have in mind that they are equal to the inductances of the machine in relative units, i.e. currents and flux linkages are connected by the values of the corresponding inductances, which in relative units are equal to the values of the passport parameters of the machine.

Structure of mathematical model of synchronous machine with excitation along the longitudinal and transverse axes d and q. In this case the matrix form remains unchanged, except for control matrix $\begin{bmatrix} \boldsymbol{U}_s \\ \boldsymbol{U}_f \\ \boldsymbol{U}_r \end{bmatrix}$, which turns into matrix $\begin{bmatrix} \boldsymbol{U}_s \\ \boldsymbol{U}_f \\ 0 \end{bmatrix}$, since for such machines the rotor has damper windings that are short-circuited.

Mathematical model of "classical" synchronous machine (having one field winding, located along the axis *d*), here besides the equality to zero $\boldsymbol{U}_r$=0, the following column-matrices will change:

$$p\Psi_f = \begin{bmatrix} p\Psi_{df} \\ 0 \end{bmatrix}; \quad \Psi_f = \begin{bmatrix} \Psi_{df} \\ 0 \end{bmatrix}; \quad U_f = \begin{bmatrix} U_{df} \\ 0 \end{bmatrix}$$

In addition, also diagonal matrices will change, which will occur in the form:

$$\boldsymbol{B}_{f1} = \begin{bmatrix} -r_{df} \cdot k_{dsf} & 0 \\ 0 & 0 \end{bmatrix}; \quad \boldsymbol{B}_{f2} = \begin{bmatrix} -r_{df} \cdot k_{df} & 0 \\ 0 & 0 \end{bmatrix}; \quad \boldsymbol{B}_{f3} = \begin{bmatrix} -r_{df} \cdot k_{drf} & 0 \\ 0 & 0 \end{bmatrix}$$

As a result of equality k_{qsf}=0 and k_{qfr}=0, $\boldsymbol{A}_{s2}$ and $\boldsymbol{C}_{r2}$, will also be transformed, which will take the form:

$$\boldsymbol{A}_{s2} = \begin{bmatrix} -r_s \cdot k_{dsf} & 0 \\ 0 & 0 \end{bmatrix} \text{ and } \boldsymbol{C}_{r2} = \begin{bmatrix} -r_{ds} \cdot k_{drf} & 0 \\ 0 & 0 \end{bmatrix}$$

If the synchronous machine is made with permanent magnets, i.e. permanent magnets act as the exciter, then additionally the derivative matrix of flux linkages in expression (1) turns into the following matrix: $\begin{bmatrix} p\boldsymbol{\Psi}_s \\ 0 \\ p\boldsymbol{\Psi}_r \end{bmatrix}$. And the voltage $\boldsymbol{U}_{df}$, on which the flux linkage $\boldsymbol{\Psi}_{df}$, depends, should be interpreted as a value that determines the coercive force of permanent magnets, or more exactly the magnetic energy value of permanent magnets, referred to the unit volume of permanent magnets [12].

Expression for the moment of "classical" synchronous machine will take the form:

$$\begin{aligned} m_{em} &= (k_{qs} - k_{ds})\Psi_{ds} \cdot \Psi_{qs} + k_{qsr} \cdot \Psi_{ds} \cdot \Psi_{qr} \\ &- k_{dsf} \cdot \Psi_{qs} \cdot \Psi_{df} - k_{dsr} \cdot \Psi_{qs} \cdot \Psi_{dr} \end{aligned} \quad (5)$$

resistance matrix will appear in the form:

$$\begin{bmatrix} k_{ds} & 0 & k_{dsf} & k_{dsr} & 0 \\ 0 & k_{qs} & 0 & 0 & k_{qsr} \\ k_{dsf} & 0 & k_{df} & k_{dfr} & 0 \\ k_{dsr} & 0 & k_{dfr} & k_{dr} & 0 \\ 0 & k_{qsr} & 0 & 0 & k_{qr} \end{bmatrix} =$$

$$= \begin{bmatrix} L_{ds} & 0 & M_{ad} & M_{ad} & 0 \\ 0 & L_{qs} & 0 & 0 & M_{aq} \\ M_{ad} & 0 & L_{df} & M_{ad} & 0 \\ M_{ad} & 0 & M_{ad} & L_{dr} & 0 \\ 0 & M_{aq} & 0 & 0 & L_{qr} \end{bmatrix}^{-1}$$

The structure of asynchronous machine model in this case: in matrix (1) the 3rd row disappears and in diagonal matrix the 2nd column and equation (1) transform into form:

$$\begin{bmatrix} p\boldsymbol{\Psi}_s \\ p\boldsymbol{\Psi}_r \end{bmatrix} = \begin{bmatrix} \boldsymbol{A}_{s1} & \boldsymbol{A}_{s3} \\ \boldsymbol{C}_{r1} & \boldsymbol{C}_{r3} \end{bmatrix} \begin{bmatrix} \boldsymbol{\Psi}_s \\ \boldsymbol{\Psi}_r \end{bmatrix} + \begin{bmatrix} \boldsymbol{U}_s \\ \boldsymbol{U}_r \end{bmatrix} \quad (6)$$

Since the asynchronous machine is symmetrical in magnetic and electrical relation, then the parameters $k_{ds}=k_{qs}$; $k_{dsr}=k_{qsr}$; $k_{dr}=k_{qr}$ and $r_{dr}=r_{qr}$. Taking this into account, the submatrices are transformed into expressions,

$$\left.\begin{aligned} \boldsymbol{A}_{s1} &= \begin{bmatrix} -r_s \cdot k_{ds} & -\omega_r \\ \omega_r & -r_s \cdot k_{ds} \end{bmatrix} = -r_s \cdot k_{ds} \cdot \boldsymbol{E} - \boldsymbol{J} \cdot \omega_r \\ \boldsymbol{A}_{s3} &= \begin{bmatrix} -r_s \cdot k_{dsr} & 0 \\ 0 & -r_s \cdot k_{dsr} \end{bmatrix} = -r_s \cdot k_{dsr} \cdot \boldsymbol{E} \\ \boldsymbol{C}_{r1} &= \begin{bmatrix} -r_{dr} \cdot k_{dsr} & 0 \\ 0 & -r_{dr} \cdot k_{dsr} \end{bmatrix} = -r_{dr} \cdot k_{dsr} \cdot \boldsymbol{E} \\ \boldsymbol{C}_{r2} &= \begin{bmatrix} -r_{dr} \cdot k_{dr} & 0 \\ 0 & -r_{dr} \cdot k_{dr} \end{bmatrix} = -r_{dr} \cdot k_{dr} \cdot \boldsymbol{E} \end{aligned}\right\} \quad (7)$$

Substituting (7) for (6), one can obtain in expanded vector form an expression for derivative flux linkages of stator and rotor loops $\boldsymbol{\Psi}_s$ and $\boldsymbol{\Psi}_r$:

$$\left.\begin{aligned} & p\boldsymbol{\Psi}_S = \boldsymbol{A}_{s1} \cdot \boldsymbol{\Psi}_S + \boldsymbol{A}_{s3} \cdot \boldsymbol{\Psi}_r + \boldsymbol{U}_S = \\ & -r_s \cdot k_{ds} \cdot \boldsymbol{\Psi}_S - \boldsymbol{J} \cdot \omega_r \cdot \boldsymbol{\Psi}_S - r_s \cdot k_{dsr} \cdot \boldsymbol{\Psi}_r + \boldsymbol{U}_S \\ & p\boldsymbol{\Psi}_r = \boldsymbol{C}_{r1} \cdot \boldsymbol{\Psi}_S + \boldsymbol{C}_{r3} \cdot \boldsymbol{\Psi}_r + \boldsymbol{U}_r = \\ & r_r \cdot k_{dsr} \cdot \boldsymbol{\Psi}_S - r_r \cdot k_{dr} \cdot \boldsymbol{\Psi}_r + \boldsymbol{U}_r \end{aligned}\right\} \quad (8)$$

Coefficients k_{ds}, k_{dr}, k_{dsr} can be determined from the equation:

$$\begin{bmatrix} k_{ds} & 0 & k_{dsr} & 0 \\ 0 & k_{ds} & 0 & k_{dsr} \\ k_{dsr} & 0 & k_{dr} & 0 \\ 0 & k_{dsr} & 0 & k_{dr} \end{bmatrix} = \begin{bmatrix} L_s & 0 & M_m & 0 \\ 0 & L_s & 0 & M_m \\ M_m & 0 & L_r & 0 \\ 0 & M_m & 0 & L_r \end{bmatrix}^{-1} \quad (9)$$

It should be noted that expressions (8) by form coincide with the equations of asynchronous machine mentioned in [13].

Expression for electromagnetic moment of asynchronous machine:

$$m_{em} = k_{dsr}(\Psi_{ds} \cdot \Psi_{qr} - \Psi_{qs} \cdot \Psi_{dr}) \quad (10)$$

As it was already mentioned, in the model structure of AC machines as control parameters can be used $\boldsymbol{U}_s$, f_s – vector and frequency of the rotor winding voltage. Since the structure of the mathematical model of AC machines is based on the writing in the axes *d*, *q* rotating at the rotor speed ω_r, then there are no problems of modeling of voltages of field and rotor windings, as they are directly supplied from regulating devices (e.g., from the output of automatic excitation regulator of synchronous machine, either the output of frequency converter feeding the rotor winding for asynchronous machine).

This problem exists for stator winding. It is necessary to represent a vector of voltages, which supply stator winding of AC machine, whose components $\boldsymbol{U}_{ds}$ and $\boldsymbol{U}_{qs}$ are, naturally, written in axes *d*, *q*, rotating with rotor speed ω_r, in such a form so that to be able to join control system with the electric AC machine (e.g. frequency converter). That is, it is necessary that they reflect the change (regulation) of the amplitude and frequency of the voltage supplying the stator winding. For this purpose the following transformations must be performed [12].

Location of coordinate axes of AC machines is reflected on the diagram (Fig.1). Here α_0, β_0 – coordinate axes fixed in the space; α_s, β_s – coordinate axes rotating synchronously, with electric network frequency ω_s; d, q – coordinate axes rotating at the rotor speed ω_s. Angle between axes α_s, β_s and α_0, β_0 we designate as α_s, which is equal to $\alpha_s=\omega_s\cdot\tau$, where $\tau=\omega_{baz}\cdot t=314\cdot t$ – time in radians, t – time in sec.

Angle between axes d, q and fixed axes α_0, β_0 we designate as α, which is equal to $\alpha=\omega_r\cdot\tau$ and finally, angle $\theta=\alpha+\alpha_s$ – angle between axes d,q and axes α_s, β_s, which is called power angle.

If the stator voltage vector to place in the initial state at an angle π/4 radians to the axes α_s, β_s, then its projections on these axes will naturally be the same and equal to $U_{s\alpha0}=U_{s\beta0}=0.707\cdot U_s$ (in relative units.).

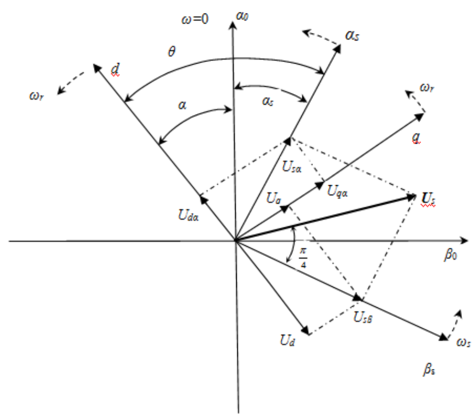

Fig.1. The location diagram of the coordinate axes in the model of electric machines of alternating current.

Projections of vectors $U_{s\alpha}$ and $U_{s\beta}$ on the axes d, q in accordance with Fig.1 can be written in the form:

$$\left.\begin{aligned} U_{d\alpha} &= U_{s\alpha}\cdot\cos\theta = U_{s\alpha}\cdot\cos(\alpha+\omega_s\cdot\tau) \\ U_{q\alpha} &= U_{s\alpha}\cdot\sin\theta = U_{s\alpha}\cdot\sin(\alpha+\omega_s\cdot\tau) \\ U_{d\beta} &= U_{s\beta}\cdot\sin\theta = U_{s\beta}\cdot\sin(\alpha+\omega_s\cdot\tau) \\ U_{q\beta} &= U_{s\beta}\cdot\cos\theta = U_{s\beta}\cdot\cos(\alpha+\omega_s\cdot\tau) \end{aligned}\right\} \quad (11)$$

General projections of these components on the axes d, q according to Fig.1 will be in the form:

$$\left.\begin{aligned} U_{ds} &= U_{d\alpha} - U_{d\beta} \\ U_{qs} &= U_{q\alpha} + U_{q\beta} \end{aligned}\right\} \quad (12)$$

Substituting expressions from (11) for (12) and taking into account that the vector U_s just like the axes α_s, β_s rotates at the speed ω_s, then $U_{s\alpha}=U_{s\beta}=U_{s\alpha0}=U_{s\beta0}=0.707\cdot U_s$. In addition, designating $k_{us}=\dfrac{U_s}{U_{s0}}$ and $k_{fs}=\dfrac{\omega_s}{\omega_{s0}}=\dfrac{f_s}{f_{s0}}$ where $U_{s0}=1$ and $\omega_{s0}=f_{s0}=1$ [r.u.], we'll obtain:

$$\left.\begin{aligned} U_{ds} &= 0.707\cdot k_{us}\left[\cos(\alpha+k_{fs}\cdot\tau)-\sin(\alpha+k_{fs}\cdot\tau)\right] \\ U_{qs} &= 0.707\cdot k_{us}\left[\sin(\alpha+k_{fs}\cdot\tau)+\cos(\alpha+k_{fs}\cdot\tau)\right] \end{aligned}\right\} \quad (13)$$

By means of simple transformations, expression (13) can be represented in a more convenient form:

$$\left.\begin{aligned} U_{ds} &= 0.707\cdot k_{us}\big[\cos(k_{fs}\cdot\tau)\cdot(\cos\alpha-\sin\alpha)- \\ &-\sin(k_{fs}\cdot\tau)\cdot(\cos\alpha+\sin\alpha)\ \big] \\ U_{qs} &= 0.707\cdot k_{us}\big[\cos(k_{fs}\cdot\tau)\cdot(\cos\alpha+\sin\alpha)+ \\ &+\sin(k_{fs}\cdot\tau)\cdot(\cos\alpha-\sin\alpha\ \big] \end{aligned}\right\} \quad (14)$$

The control of the AC electric machine from the stator side is represented in (14). And for synchronous and asynchronous machines, this expression allows for taking into account the change and control of both the amplitude k_{us} of the voltage supplied to the machine and its frequency k_{fs}. Moreover, all other equations of AC machines remain written in the axes rotating at the rotor speed.

It should also be noted that in the absence of frequency converter in the stator circuit of AC electric machine, i.e. when the latter is connected directly to the electrical network $k_{us}=k_{us}=1$.

As it was said, $\boldsymbol{U}_f$ and $\boldsymbol{U}_r$ vectors can also act as control coordinates in the generalized cellular-matrix equations (1). As for the excitation voltage vector $\boldsymbol{U}_f$, in synchronous machine its components $\boldsymbol{U}_{df}$ and $\boldsymbol{U}_{qf}$ along the axes d, q assume the presence of longitudinal and transverse field windings and when presenting the equations written in the axes d, q, rotating at the rotor speed, in the structure of the equations they are constant and, if necessary, controlled values.

Regarding the voltage vector $\boldsymbol{U}_r$. For synchronous and asynchronous machines with short-circuited rotor it is equal to zero $\boldsymbol{U}_r=0$. For double-way feed asynchronous machines: at supply both from the stator side and the rotor side its value, naturally, is not equal to zero and in general case its components are written in the form [12]:

$$\left.\begin{aligned} U_{dr} &= k_{ur}\cdot\sin(k_{fr}\cdot\tau) \\ U_{qr} &= k_{ur}\cdot\cos(k_{fr}\cdot\tau) \end{aligned}\right\} \quad (15)$$

where U_{dr}, U_{qr} – components of rotor winding voltage, which are the output of frequency converter installed in rotor circuit, $k_{ur}=\dfrac{U_r}{U_{r0}}$ – coefficient, taking into account the regulation of voltage amplitude, supplying the rotor winding, $k_{fr}=\dfrac{f_r}{f_{r0}}$ – frequency of current at the output of the mentioned frequency converter, U_{r0} – rotor voltage amplitude in source mode (in relative units $U_{r0}=1$).

Thus, expressions (13) and (15) allow for reproducing frequency control both from the stator side and the rotor side of electromechanical AC converters, i.e. together with equation (1) create a single universal structure of the mathematical model of controlled AC electric machines.

3 Results

The control of a controlled synchronous machine with one field winding along the d axis has been investigated [12]. Just so a frequency-controlled synchronous machine with 2 windings along the axes d, q respectively, can be studied [14].

Here study of controlled asynchronous machine has been conducted. In this case, the structure of the equations in vector form is represented by the expression (6), and the components of the stator voltage are modeled by the expression (14), and the rotary expression (15).

Parameters of machine: x_d=4.878; r_s=0.01; x_m=4.8; r_r=0.31; k_{ds}=5.69; k_{dr}=5.66; k_{dsr}=5.56; $1/T_j$=0.005; x_r=4.9.

Algorithm of solution of equations of asynchronous machine in general form is as follows:

$$D(\tau, Y)=\begin{bmatrix} 0.707 \cdot k_{us} \cdot \cos\left(k_{fs} \cdot \tau\right) \cdot \left(\cos Y_6 - \sin Y_6\right) - 0.707 \cdot k_{us} \cdot \sin\left(k_{fs} \cdot \tau\right)\left(\cos Y_6 + \sin Y_6\right) - Y_5 \cdot Y_2 - 0.01 \cdot \left(5.59 \cdot Y_1 - 5.56 \cdot Y_3\right) \\ 0.707 \cdot k_{us} \cdot \cos\left(k_{fs} \cdot \tau\right) \cdot \left(\cos Y_6 + \sin Y_6\right) + 0.707 \cdot k_{us} \cdot \sin\left(k_{fs} \cdot \tau\right) \cdot \left(\cos Y_6 - \sin Y_6\right) + Y_5 \cdot Y_1 - 0.01 \cdot \left(5.69 \cdot Y_2 - 5.56 \cdot Y_4\right) \\ -k_{ur} \cdot \sin\left(k_{fr} \cdot \tau\right) - 0.031 \cdot \left(5.66 \cdot Y_3 - 5.56 \cdot Y_1\right) \\ k_{ur} \cdot \cos\left(k_{fr} \cdot \tau\right) - 0.031 \cdot \left(5.66 \cdot Y_4 - 5.56 \cdot Y_2\right) \\ 0.005 \cdot \left(m_t\right) - 0.005 \cdot \left[Y_1 \cdot \left(5.69 \cdot Y_2 - 5.56 \cdot Y_4\right) - Y_2 \cdot \left(5.59 \cdot Y_1 - 5.56 \cdot Y_3\right)\right] \\ Y_5 \end{bmatrix}$$

On Fig.2 (a, b, c, d) at k_{us}=k_{fs}=1 (i.e. nominal values of amplitude and frequency of stator voltage) at the first stage at short-circuited rotor $\boldsymbol{U}_r$=0 in the range from 0 to 10^3 radians the starting of generator with the value m_t=–0.3, is implemented and is set in the value ω_r=1.01 (Fig.2,a). At 10^3 radians the voltage is supplied to the rotor winding with steady-state value k_{us}=k_{fs}=–0.15 (asynchronous machine with short-circuited rotor is transformed into double-way feed asynchronous machine). From 10^3 to 2000 radians the rotating frequency becomes equal to ω_r=1.15 (Fig.2,a). Electromagnetic moment is determined by the value m_t and remains constant m_{em}=–0.3 (Fig.2,b) ("minus" sign corresponds to generator mode). Curve of general active power, equal to sum of powers of stator and rotor circuits, is shown in the (Fig.2,c): its steady-state value varies from value p_w=–0.3 at short-circuited loop in the range from 0 to 1000 radians to value p_w=–0.34 at τ>1000 radians, when the rotor speed is increased to ω_r=1.15 by means of regulation of frequency of current in the rotor winding of double-way feed machine. Reactive power (Fig.2,d) varies from value q_w=0.24 (consumes from network) to value q_w=–0.218 (delivers to network). After returning to source mode from 2000 radians to 3000 radians (i.e. when k_{us}=0), is supplied. At control k_{us}=k_{fs}=0.15 at 3000 radians the control equal to ω_r=0.85 (Fig.2,a), the active power decreases from p_w=–0.3 to p_w=–0.25, respectively, and the reactive power, remaining in consumption mode, increases from q_w=0.24 to q_w=0.49, the moment m_{em} is unchanged and equal to m_{em}=–0.3.

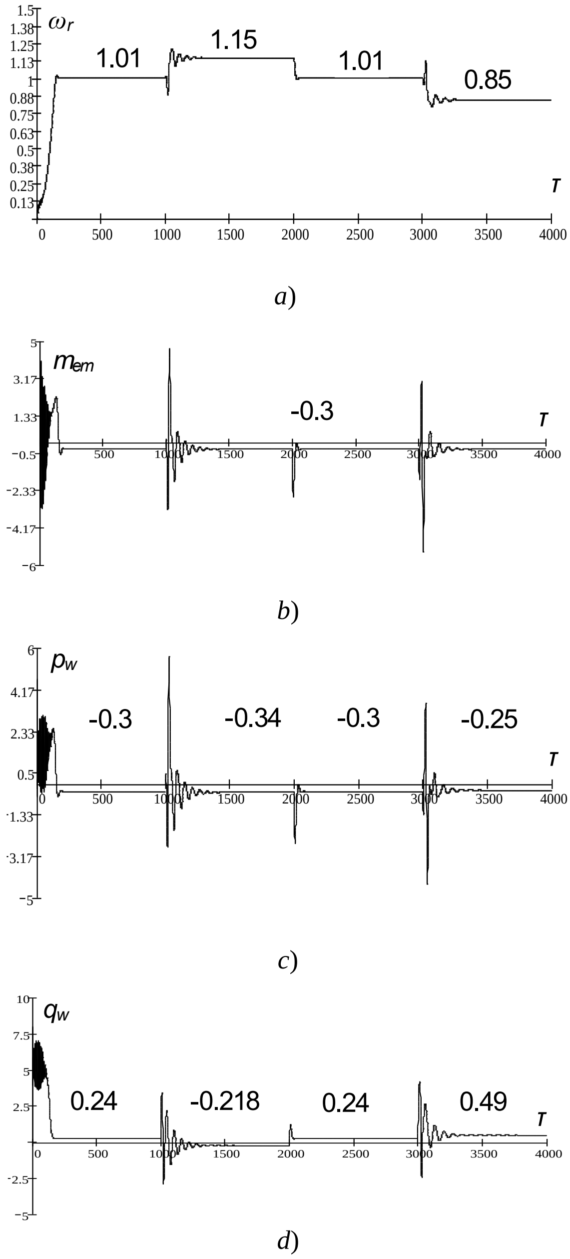

Fig. 2. Fluctograms of change of operating parameters of an double-way feed asynchronous machine when using frequency regulation only from the rotor side with k_{ur}=k_{fr}=–0,15 and k_{ur}=k_{fr}=+0,15 with k_{us}=k_{fs}=1.

Fluctograms of change of regime parameters of double-way feed asynchronous machine at control of voltage and frequency both from the stator side and from the rotor side are represented in Fig.3 (a, b, c, d). Here k_{us}=k_{fs}=0.7, k_{us}=k_{fs}=–0.15 at the first stage and m_t=–0.3. After starting the steady-state value is ω_r=0.7 then at k_{us}=k_{fs}=–0.15 (after 1000 radians) the ω_r becomes equal to ω_r=0.85 (Fig.3,a), the m_{em} remains unchanged and equal to m_{em}=–0.3 (Fig.3,b). The active and reactive powers vary from p_w=–0.21 to p_w=–0.246, respectively, and q_w=0.17 (consumes from network) to q_w=–0.166 (delivers to network) (Fig. 3, c and d).

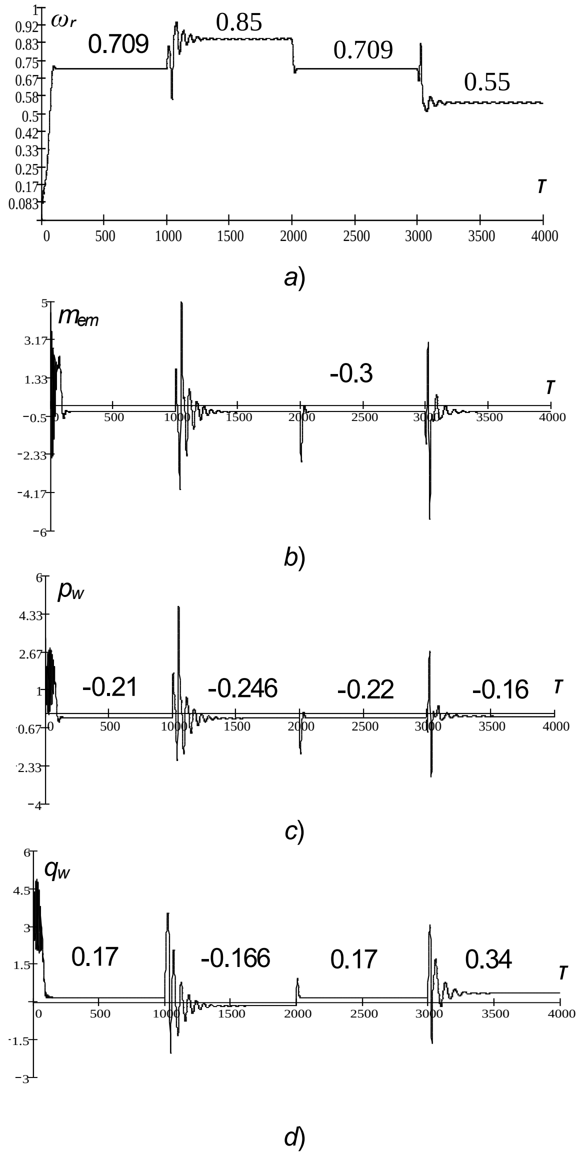

Fig.3. Fluctograms of change of operating parameters of double-way feed asynchronous machine when regulating voltage and frequency both from the stator side k_{us}=k_{fs}=0.7 and from the rotor side with k_{ur}=k_{fr}=–0.15 and k_{ur}=k_{fr}=+0.15.

There after source mode at 3000 radians at unchanged k_{us}=k_{fs}=0.7 the value k_{us}=k_{fs}, is regulated, which was set equal to k_{us}=k_{fs}=–0.15. At that the rotor speed ω_r decreases to ω_r=0.55. The active power accepts value p_{em}=–0.16, and the reactive power in the consumption mode increases almost 2 times (as compared with the source mode) and becomes equal to q=0.34.

The given example of calculation confirms the efficiency of the universal mathematical model structure of controlled electric AC machines. It is known that main power control means for electromechanical AC transformers are frequency converters, which at present are implemented on completely controlled IGBT-transistors or GTO-thyristors with PWM control. The presented structure allows for taking into account in the mathematical model both amplitude and frequency of voltages supplying the stator and rotor circuits of AC machine.

If it is necessary to take into account a saturation, then this can be very simply done by existing methods: to operate by either saturated parameter values, or famous methods of their functional dependence [12]. As regards the consideration of harmonic composition of voltage at the outputs of frequency converters, their consideration also doesn't cause insurmountable difficulties – they can be taken into account in output voltage by means of harmonics factorized to Fourier series.

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Game-theoretic Approach to Electricity Retail Pricing Design for Demand Response Management in Russian Regions

Natalia Aizenberg[1,*], *Elena* Stashkevich[2], and *Nikolai* Voropai[1,2]

[1]Department of Electric Power System, Melentiev Energy Systems Institute SB RAS, Irkutsk, Russia
[2]Department of Power Supply and Electrical Engineering, Irkutsk National Research Technical University, Irkutsk, Russia

Abstract. The paper evaluates present-day retail market electricity rates in Russia from the standpoint of demand response i.e., how they motivate the customers to reduce demand during critical peak periods. For that purpose, the daily payments of different types of customers in RF regions are analyzed. It is shown that not all the retail market rates now in force stimulate the reduction of peak loads. A theoretical game model is proposed for the formation of electrycity rates for different types of consumers that incentivizes the demand response..

Introduction

Such peculiarities of electric power as simultaneous production and consumption, the impossibility of large-scale electricity storage, difficulties of precise planning of electricity generation and consumption necessitate continuous maintenance of production and consumption equilibrium. Power plants traditionally play a major role in maintaining equilibrium. Also electricity markets are designed such that to give incentives to its players to maintain that equilibrium. But in the absence of special measures to manage the demand response, the electricity demand does not depend or to a little extent depends on the market prices as customers do not reduce electricity consumption if prices grow.

At present, with the emergence of smart power meters, advanced high-speed technologies for measurement, transfer, conversion and displaying the information on the current electricity consumption, the problem of demand response is solved based on the corresponding contracts of a load serving entity with individual power consumers; those contracts shall take into account economic benefits of both parties [1-6]. Load serving entities, based on the analysis of different power consumption facilities, identify such utilities that collectively allow almost 25% reduction of peak loads of the entity. Such utilities usually include air conditioners of large dwelling, commercial and administrative buildings, electric boilers, electric drives of pumps of water sprinkling systems in the rural areas, and others. After analysis and optimization of electricity consumption, the companies develop the demand-response electricity program, and set privileged rates for power consumers who agreed to participate in those programs.

RF is currently undertaking efforts to motivate customers to participate in raising the energy efficiency and leveling the load curves e.g., by the introduction of time-of-use (TOU) rates. The paper considers legally grounded rates that are most attractive for customers from the standpoint of their load response, i.e., rates that provide for payment for peak load or peak electricity consumption periods. They include a two-part rate with payment for electricity and capacity at peak loads of the power grid and TOU rate. The paper exploits the applicability of proposed rates for incentivizing the demand response (Section 1). The efficiency of the approach is exemplified by the assessment of daily electricity bills of two consumers of different types in different RF regions. Rates applied abroad [6-9] are considered in parallel, their incentives for demand response are assessed for customers that are similar to those in Russia. It is shown that RF rates, unlike foreign rates, do not always have the required incentives for reducing the peak loads. Studies on the foreign electricity markets that were undertaken recently propose an on-line demand response when a customer is capable to respond to variable power supply almost instantly [10-12]. In our opinion, such approach cannot be implemented in the conditions of the Russian market. We propose a pricing model that takes into account the interests of customers and the costs of a load serving entity for a month's time interval (Section 2).

1 Comparison of the electricity pricing system for different types of customers in different RF regions

Consider the electricity supply system of two customers. The first one includes loads of a student campus (Irkutsk) whose daily curve is typical to that of individuals (Table 1). This customer is assumed to be inactive, i.e., they do

* Corresponding author: zen@isem.irk.ru

Table 1. Daily load curves of two consumers: Campus and TV tower.

Hrs	**0:00**	**1:00**	**2:00**	**3:00**	**4:00**	**5:00**	**6:00**	**7:00**	**8:00**	**9:00**	**10:00**	**11:00**
Campus, kW	51	44	38	35	34	30	32	46	48	49	48	47
TV Tower, kW	166	164	163	163	163	167	167	168	170	169	172	169
Daily zone	night-time	night-time	night-time	night-time	night-time	night-time	night-time	night-time	semi-peak	peak	peak	peak
Hrs	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**	**23:00**
Campus, kW	58	53	55	52	54	62	66	69	76	73	73	63
TV Tower, kW	168	169	170	169	169	166	167	167	168	167	166	165
Daily period	peak	semi-peak	semi-peak	semi-peak	semi-peak	semi-peak	peak	peak	peak	peak	semi-peak	night-time

not change their electricity consumption pattern if saving is not considerable. The second one is a small business customer and its demand is conditioned by a certain production facility. In our case, it is a daily load curve of a TV Tower (Irkutsk), (Table 1). Let us assume that this customer is interested in varying demand response. The second customer is larger than the first one. Both customers belong to a group with a low voltage load below 670 kW. Such customers are legally offered several types of rates. The paper considers the main of them. They are 1PC (price category) rate (flat rate, i.e., the price for any unit of product is the same); 2PC rate (time-of-use (TOU) rate (differentiated by three day periods); and 3PC rate (a two-part rate that includes payment for capacity).

Load serving entity is interested in load response by consumers and, hence, it selects rates motivating the electricity consumption curve optimization. In this case, they are 2PC and 3PC rates. Some authors [3] consider that a two-part rate is most demand-response oriented one as prices within this rate vary from hour to hour, payment for power is related to a peak in the power grid, which creates an additional incentive to shift maximum consumption to other periods of the day. At the same time, the TOU rate is more understandable for a common customer owing to its simplicity. Therefore, both rates shall be well thought over to raise their efficiency and to have a stimulating effect at the retail market.

Further, we will discuss how legally priced rates work at the RF electricity market as regards selected consumers. For that purpose, we will analyze the ratio of electricity payment under all the three rates. It should be noted that the daily load curves of selected customers correspond to their averaged January load; therefore, all the rates we use in the calculation are January 2019 rates. Calculated is the aggregate bill for the month.

All the data on rates were taken from the websites of load serving entity in the corresponding RF regions where electricity is priced on the competitive base, i.e., for two price zones of the wholesale electricity market. As an example, Tables 2 and 3 present the data on rates for 1PC - 3PC for the following price zones: Siberia (Novosibirsk oblast) and European part of Russia (Moscow oblast). Rates are given without VAT.

Table 2. Data on the flat rates (1PC) and TOU rates s (2PC) specified by day periods (nighttime, semi-peak, peak).

RF region	1PC, Rub/MW.h	2PC, Rub/MW.h		
		nighttime	semi-peak	peak
Novosibirsk oblast	3,861	2,922	3,977	7,298
Moscow oblast	5,041	3,669	5,227	8,834

Table 3. Data on two-part rate (3PC).

Capacity rate, Rub/MW per month												
Novosibirsk oblast						656,357.4						
Moscow oblast						735,261.6						
Electricity rates, RUB/MW												
Hours of the day	**0:00-1:00**	**1:00 AM-2:00**	**2:00 AM-3:00**	**3:00 AM-4:00**	**4:00 AM-5:00**	**5:00 AM-6:00**	**6:00 AM-7:00**	**7:00 AM-8:00**	**8:00 AM-9:00**	**9:00 AM-10:00**	**10:00 AM-11:00**	**11:00 AM-12:00**
Novosibirsk oblast	2,973	2,952	2,918	2,886	2,871	2,868	2,877	2,889	2,908	2,952	2,992	3,023
Moscow oblast	3,471	3,385	3,332	3,316	3,339	3,393	3,454	3,604	3,731	3,827	3,884	3,888
Hours of the day	**12:00 PM-13:00**	**1:00 PM-14:00**	**2:00 PM-15:00**	**3:00 PM-16:00**	**4:00 PM-17:00**	**5:00 PM-18:00**	**6:00 PM-19:00**	**7:00 PM-20:00**	**8:00 PM-21:00**	**9:00 PM-22:00**	**10:00 PM-23:00**	**11:00 PM-0:00**
Novosibirsk oblast	3,036	3,053	3,055	3,027	3,028	3,039	3,060	3,060	3,049	3,033	3,029	3,007
Moscow oblast	3,877	3,881	3,881	3,868	3,885	3,947	3,947	3,934	3,896	3,844	3,679	3,524

* Corresponding author: zen@isem.irk.ru

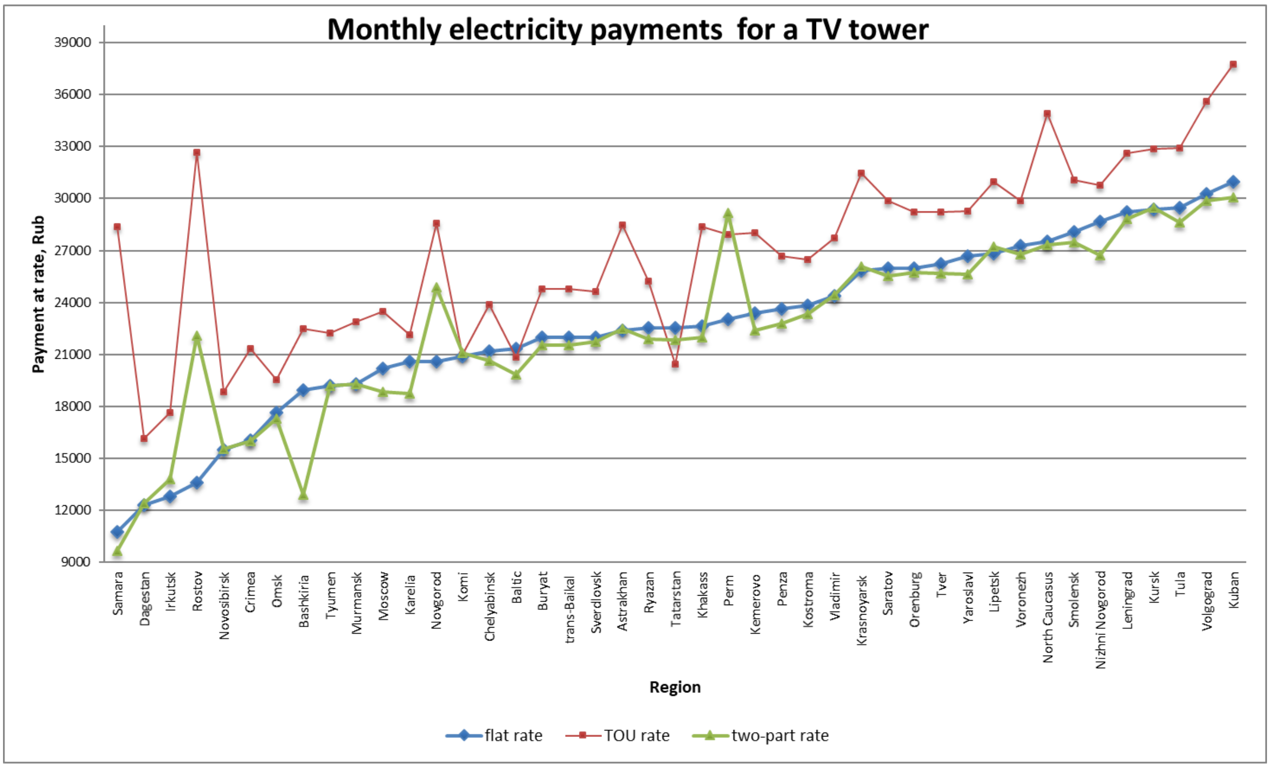

Fig. 1. Monthly electricity payments of TV tower under different rates.

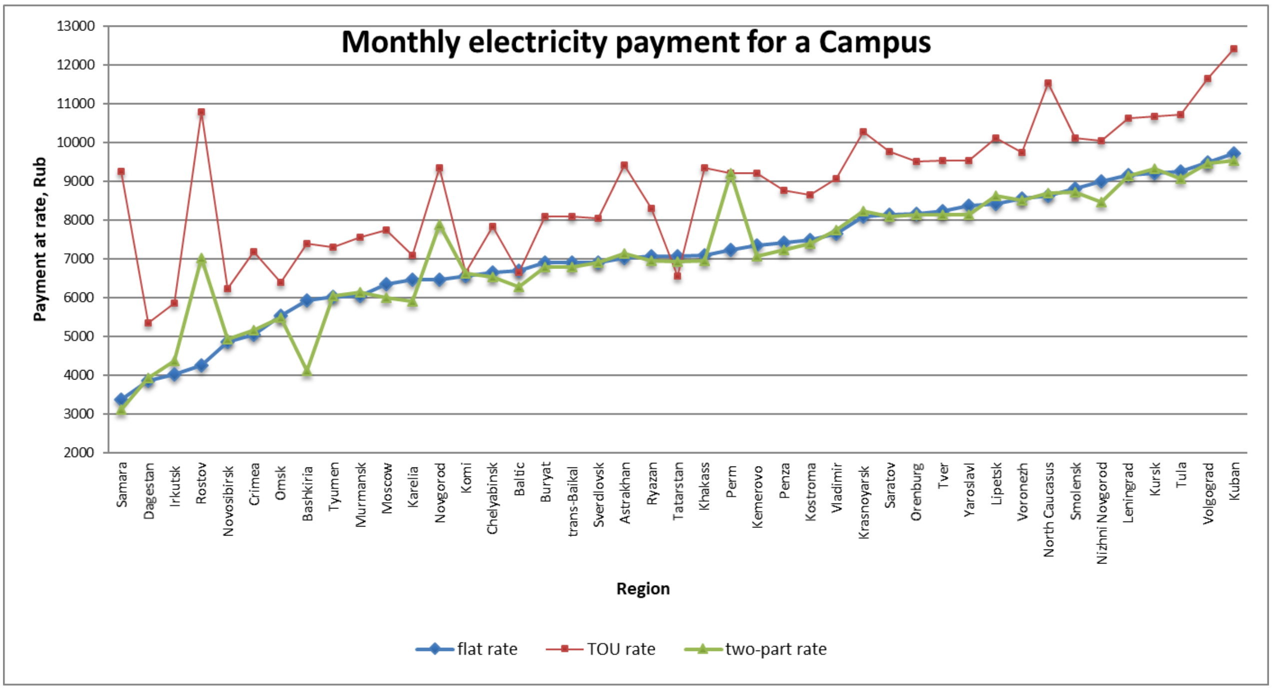

Fig. 2. Monthly electricity payment under different rates for a Campus.

For calculating the payment for electricity in January 2019, we used data on rates for Russian regions located in the price zones of the wholesale market. Figs. 1 and 2 show how changes the payment for the same type of customers in different regions of RF (Campus and TV Tower, respectively). The Figures reflect payment as per the flat rate (1PC) sorted in ascending order.

Figs. 1 and 2 demonstrate that the ratio between payments based on the rates in different RF regions may differ considerably. There are some important peculiarities:

1. We assume that 2PC and 3PC rates stimulate load reduction by a consumer in the peak hours. Therefore, that would be proper for those rates to be lower than rates without incentives (1PC) or to coincide with bills as per

* Corresponding author: zen@isem.irk.ru

1PC. In the latter case, any measures taken to reduce the peak load would reduce payments based on demand-response rates and a customer would prefer those rates as they would be more profitable for him. But, unfortunately, the described logical ratio of rates does not work for the selected customers.

2. TOU (2PC) rate, in our opinion, works poorly in the regions. Payments based on this rate for the selected types of consumers are almost everywhere higher than those based on the flat rate, and the extra charge makes from 13% to 150%. To get benefits from the demand-response rate, the TV tower load shall be about 83% of the total daily load. Such changes in the load do not look realistic and, hence, neither potential consumer of this type would select this ‘stimulating’ rate. The conclusion on the Campus as a consumer is similar.

Table 4 gives data on excess payment under the demand-response rate versus flat rate for a TV Tower consumer in some regions. It also gives estimates of a possible reduction in the peak load against the existing one such that selection of the demand-response rate was attractive. It is obvious that the proposed option does not look realistic.

Table 4. Excess in payment under the demand-response rate (2PC) over the flat one (1PC).

RF region	Daily payment under the rates :		Excess, %
	1PC, Rub/MW.h	2PC, Rub/MW.h	
Irkutsk	12,800	17,627	27
Krasnoyarsk	25,828	31,485	18
Moscow	20,215	23,505	14
Lipetsk	26,841	30,989	13
Sverdlovsk	22,007	24,650	11
Chelyabinsk	21,167	23,904	11.5
Astrakhan	22,390	28490	21
Volgograd	30,267	35,604	15

We assessed the scale of possible peak load shift by customers when selecting the demand-response rate (2PC) in order that it became profitable. Daily payment under the demand-response rate (2PC) in this case shall be less than daily payment under the flat rate (1PC). It turned out that the peak load for the TV Tower shall be changed by 83% and by 76% for the Campus (calculations were rate for Irkutsk and Moscow oblasts at load shift from the peak zone to the daytime zone). Those changes are not realistic. Hence, customers would never choose 2PC rate.

3. The ratios between two-part rate (3PC) and flat (1PC) rates for different regions of Russia are not similar. For example, in Irkutsk, Rostov, Novgorod, and Perm oblasts the payment under the flat rate turns out to be more preferable. In this case it makes no sense to select the stimulating two-part rate and undertake additional measures to respond. There are regions where 3PC rate is beneficial for customers. They are RF regions where payments under both rates coincide or are close, which stimulates energy saving measures for the peak load reduction.

4. Stimulating the 3PC rate is more attractive for TV Tower than for Campus In 11 regions payment at the two-part rate for Tower is lower than at the flat rate .

5. We can conclude that rates in the Russian regions do not always stimulate peak load reduction (it is especially true for TOU (2PC) rate), whereas principles and constraints of rate pricing are the same throughout RF. It is necessary to adjust the system of rates as a whole, and assign rates depending on the rates of other rates. The type of customers prevailing in the region shall be taken into account as well.

If we looked at the foreign practice of pricing at the retail sales market, we would notice that TOU rates prevail [8]. If we carefully investigate their rates, we will get a quite logical picture of rates ratio, and, hence, the working price-based incentives for load curve optimization.

Results for rates for selected by TV Tower and Campus in Ontario (USA) in winter 2019 [9] are given in Table 5. We can see that payments at the flat rate are lower than at TOU rate, which stimulates consumers to select this rate and to take active measures to reduce peak loads.

Table 5. Daily bills of TV Tower and Campus at rates valid in Ontario (Canada) in November, 2019.

Time of Use	Rate, $/kWh	Daily payment, $	
		Campus	TV Tower
Off peak	0.101	1.83	5.77
Mid peak	0.144		
On peak	0.202		
Flat rate	0.155	1.95	6.21

Therefore, the ratio of rates in RF regions requires adjustment. In the third part of the article, we offer a model for rates assignment based on the specific loads of customers and costs of a load serving entity. Rates formed shall motivate consumers to reduce their peak load.

2 A model for assigning the system of demand-response rates by the types of customers prevailing in the region

In the previous section, we proved that rates in RF regions are priced such that one and the same customer might be stimulated to attake different activities. We also know that rates providing for payment for peak capacity or peak-demand time of electricity consumption have an incentivizing effect. At the Russian electricity market, they are 2PC and 3PC rates.

We considered two types of customers. The campus curve corresponds to that of common individuals who are difficult to be motivated to change their behavior. They are not completely rational and poorly respond to financial stimuli at the expense of convenience. Nevertheless, the habits of such customers may be changed with time (in the long-run), therefore, the availability of incentives in rates assigned to them is important. Another group of customers is more rational and will respond to financial incentives more willingly. A

TV Tower is an example of such a customer: it is a small business interested in profit maximization, including owing to using energy saving measures.

Further, we propose a technique aimed at forming the rates that would stimulate customers to optimize their load curves, i.e., those customers that belong to a more rational type would select rates providing for payment for peak capacity or peak-demand time of electricity consumption. Such customers as individuals (households) do not need that, i.e., we assume that they may select a flat rather than the demand-response rate (1PC).

2.1 Mathematical statement of the model

Let the costs of the load serving entity be described by function $C(P)$. They are costs of purchasing electricity at the wholesale market and of its transfer to customers. They are assumed to have a standard form, i.e. constant and variable parts.

For simplification, let us consider the calculation of optimum rates for two different customers that is similar to calculations made in the previous section. The daily load curve of the first consumer corresponds to a standard household with peak loads in the morning and evening. This type of customer has a low total load. Besides, their preferences belong to 'limited rationality', i.e., their behavior is determined more by convenience than by financial incentives. The behavior of the second consumer is assumed to be similar to that of a mid-scale business. The load is higher than in the household, the load curve is determined by the production activity of the company, and a customer is ready to undertake measures to reduce power payments even at the expense of some inconvenience.

A load serving entity is interested in consumption optimization by customers, thus reducing the general costs of the grid, and it offers rates stimulating that. Realizing that large power customers (including production facilities) are easier to be motivated to apply energy saving measures, the rates shall be such that they were those customers who would select demand-response rates. In our case, they are TOU rates. Thus, the problem to be resolved by load serving entity is the maximization of profit provided that TOU rate is selected by a rational (larger) consumer. A flat rate, in this case, is formed based on the load serving entity costs and the permissible sale extra charge.

Let the load of the i-th customer be P_i^t, $i = \{1,2\}$. A vector of loads of customers is $P = (P_1, P_2)$, where $P_i = \sum_t P_i^t$. Time t changes a load of a consumer from hour to hour, but in the model, it is taken account of by time-of-use periods $t \in \{N, H, M\}$: N – nighttime period, H – semi-peak period, and M – peak period. p_L – rate of a flat rate or 1PC rate. p_d^t – rate of TOU rate 2PC depending on the time period t. The main objective of the load serving entity is profit maximization:

$$\pi(p_L, p_d^t, P) \equiv p_L \cdot \sum_t P_1^t + \sum_t p_d^t P_2^t - \sum_t C^t\,(P_1^t + P_2^t) \longrightarrow \max_{P_1^t, P_2^t, p_L, p_d^t, t \in \{N,H,M\}} \quad (1)$$

$$p_L \cdot \sum_t P_2^t \geq \sum_t p_d^t P_2^t, \quad (2)$$

$$P_{i\,min}^t \leq P_i^t \leq P_{i\,max}^t,\ t \in \{N, H, M\}, i = \{1,2\}. \quad (3)$$

A customer in his turn maximizes his practicality. This problem is not discussed here in the explicit form and it is assumed that a customer is interested in cost minimization. So that the load serving entity could not raise prices without control, the level of earnings is controlled by sales extra charge S^t in each price period of the day $t \in \{N, H, M\}$.

$$p_L \cdot P_1^t + p_d^t P_2^t \leq S^t \cdot (P_1^t + P_2^t), t \in \{N, H, M\}. \quad (4)$$

Levels of rates for different types of customers will be separated by constraint (2). From the problem stated we get the following rules for rates assignment with an account of constraints on the sale extra charge:

1. TOU rate (2PC)

$$MC^t \leq p_d^t \leq MC^t \frac{\sum_t P_2^t}{\sum_t P_1^t},\ t \in \{N, H, M\}, \quad (5)$$

where MC^t are marginal costs in the price period *t*.

2. The flat rate is the same for all the time periods (1PC).

$$\frac{\sum_t p_d^t P_2^t}{\sum_t P_2^t} \leq p_L \ \leq S. \quad (6)$$

As is seen from (5), prices within the TOU rate can be rather close to marginal costs. Moreover, if a customer who has chosen that rate lowers the peak hour load, he will impact the level of costs and, hence, will reduce his payments for electricity. Those are stimulating properties of TOU rate in the long run. It is obvious that small customers have no considerable impact on the costs of the load serving entity. For using the above tool one can introduce structures that would aggregate small customers, for them to be able to participate in the demand response policy.

2.2 An illustrative example

Further, we give calculations made using the model for several RF regions. A possible adjustment of TOU rate for two consumers described in Section 2 is given as an example. Problem (1)-(4) was stated and solved for each region separately. It is assumed that only selected consumers (Campus and TV Tower) are in operation at the Russian electricity retail market. Costs taken into account in the model are assumed to be constant. In this particular case, the task is to balance rates such that the TOU rate would stimulate the reduction of peak load. And a customer, both small- and mid-scale one would have incentives to select that rate and to introduce in the long run the energy saving measures to additionally reduce payments under that rate.

Loads of two customers presented in Table 1 were used in the model. It should be mentioned that in those calculations we did not consider load optimization by customers, therefore, variables of consumption volumes $P_1^t, P_2^t, t \in \{N, H, M\}$ for the problem (1)-(4) are assumed to be constant. Costs of a load serving entity are also assumed to be constant. Objective of study has been formulated as follows: how rates for customers shall be adjusted (provided the load curves and load serving entity costs remain unchanged) so that new rates would stimulate peak load optimization and would not reduce the company's profit.

Company costs were calculated based on the average electricity price at the wholesale market for any day within the considered period (January 2019) with an account of the extra charge for electricity transmission services. Several selected regions were analyzed in terms of misbalance between payments at the flat (1PC) and TOU (2PC) rates. Rates of those rates are variables in problem (1)-(4). Constraint (4) was formulated in the following form. The profit of the energy company under load serving entity at new rates must not exceed that at previous rates. It should be kept in mind that a customer selects the rate that gives him more benefits. Under starting conditions as per those described in Section 2, both customers select the flat rate (1PC). Further, we will simulate circumstances when one customer (TV Tower) is interested in the TOU rate (2PC), whereas Campus may adhere to the flat rate (1PC).

Thus we specify new rates under constant load when Campus selects 1PC rate, and TV Tower selects 2PC rate, and profit of the load serving entity is controlled such that to exceed the profit in the initial conditions when TOU rate is specified incorrectly and both customers select the flat rate (1PC). Table 6 gives detailed consideration to characteristics of the initial (described in Section 2) system of rates that is formed after solving the problem (1)-(4) for Moscow oblast. Initial rates are: 1PC – 5.04 Rub/kW; 2PC (nighttime) - 3.67 Rub/kW, semi peak - 5.19 Rub/kW, peak - 8.83 Rub/kW. After solving the problem (1)-(4) the optimum rates were specified as follows: 1PC – 5.17 Rub/kW; 2PC (nighttime) - 3.67 Rub/kW, semi peak - 4.98 Rub/kW, peak - 6.19 Rub/kW. Calculations were made under the assumption that the load serving entity (LSE) costs and a load of customers do not change.

Results of calculation of the load serving entity profit and payments of customers under different rates are given in Table 6. The rate type is given in bold. This was the base for calculating the load serving entity profit.

Table 6. Comparison of payments at the existing rates and rates adjusted based on the model for optimization of motivating properties of different prices for different types of customers (1)-(4). RF region: Moscow oblast.

Customer	Rates in force		Demand-response rates	
	1PC	2PC	1PC	2PC
Campus	**6,344**	6,168	**6,490**	6,525
TV Tower	**20,681**	24,359	20,681	**20,070**
LSE profit	4,049		4,049	

Table 7 presents the results of solving problem (1)-(4) for some RF regions.

Table 7. Payments at selected rates in different regions.

Region	Initial rates		Optimum rates		LSE Profit
	Campus	TV Tower	Campus	TV Tower	
Irkutsk oblast	4,017	12,800	4,122	12,800	822
Krasnoyarsk kray	8,105	25,828	8,209	25,724	2,949
Moscow oblast	6,344	20,215	6,512	20,055	4,049
Lipetsk oblast	8,423	26,841	8,634	26,695	2,869
Volgograd oblast	9,498	30,099	9,666	30,267	4,258
Astrakhan oblast	7,026	22,390	7,177	22,239	2,626
Sverdlovsk oblast	6,906	22,007	7,056	21,857	3,019
Chelyabinsk oblast	6,643	21,167	6,803	21,007	3,208

In our opinion, the implementation of rate rates like this would add 2PC prices stimulating the reduction of peak loads to the system of retail electricity prices. The table shows total payments at the selected rates for the existing system of prices and for the system obtained in the course of optimization and strengthening the demand response properties. In every case, in the course of optimization, the flat rates were growing, and TOU rates decreased. The decrease was mainly observed in the peak period prices. For this reason payment by Campus that selects flat rate in both cases somewhat grows. Payment of TV Tower that initially selects 1PC rate and then 2PC rate reduces. Thus, 2PC rate acquires incentivizing properties. In these circumstances, TV Tower as a customer becomes interested in 2PC rate that would reduce their payment subject to any energy saving activities within the peak zone.

Conclusion

Development of intelligent technologies motivated the active introduction of new methods for demand-response behavior of consumers, including by controlling retail market prices (rates). There are several approaches to that. One of them is the on-line demand response which implies immediate response of a customer to the changing supply. In our opinion, this approach cannot be implemented in the conditions of the Russian market. The level of smart grid introduction in Russia is rather low, the major share of customers has low rationality and they are not ready to spend time and forces to respond to changeable prices. The proposed model allows demand response within a month or a quarter of the year. The time interval used in our study was a month. The efficiency of the approach is represented by calculations using a model for several RF regions for two consumers of different types subject to an unchangeable load curve.

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Determining the Resource of Safe Operation for Objects by Images

Vyacheslav Andreev[1,*], *Olga* Andreeva[1], *Vasiliy* Gai[1], *Maria* Berberova[2,3,4]

[1]Nizhny Novgorod state technical university n. a. R. E. Alekseev, Nizhniy Novgorod, Russia Federation
[2]ANO HE "Russian New University", Moscow, Russia Federation
[3]ANO International Nuclear Safety Center, Moscow, Russia Federation
[4]ANO "Scientific and Research Center for Information in Physics and Technique", Nizhny Novgorod, Russia Federation

Abstract. In this paper, a systematic study of the microstructure damage process of metals and alloys was carried out. The main elements of the microstructure surface image, as well as the rules for the formation and interaction of rough slip traces and cracks to determine the model of damage accumulation on the image of the microstructure surface under cyclic loading are determined. A classifier that allows to determine the number of loading cycles before a sample goes out of service is proposed. A modernized structure of the convolutional neural network was developed to classify images of the damaged microstructure of the metals and alloys surface. The proposed classifier for determining the number of loading cycles made it possible to achieve a classification accuracy of 78.43%.

Keywords. surface images of metals and alloys; accumulation of damage; surface damage; neural networks; classification.

1 Introduction

The complication of technical systems, the transition to higher parameters of technological environments in order to increase the efficiency of production processes leads to an increase in the risk of severe accidents in various industries, transport, energy, oil and gas production, during transportation and processing of energy carriers. The increasingly severe and potentially possible environmental and economic consequences of such accidents lead to an increase in requirements for ensuring high reliability and safety in the operation of such systems. The solution to this complex problem includes, among other things, determining the resource characteristics of the machines and equipment of the systems, including the residual resource, assessing the operating conditions of production facilities, metal structures and equipment, predicting their condition during operation. The growing relevance of these tasks is evident both in the case of combating aging and destruction of structures during their operation, and when creating new materials with desired properties.

One of the perspective areas for solving the problems of operational control and diagnostics of the metal structures state is to use surface images of the microstructures of metals and alloys, the dynamics of which during operation allows an assessment of the resource characteristics of objects. Conducting research in the field of assessing the damage to the microstructures of materials exposed to cyclic influences during their life cycle is an urgent task to determine the resource of safe operation of objects. The problem of safe operation of industrial facilities is devoted to a lot of work and research. A variety of factors make it impossible to solve this problem in a general way. However, a number of specific tasks within the framework of this problem are completely solved.

The results of the study of fatigue processes and damage accumulation are relevant in solving problems of improving the mechanical properties of materials, and can also be used in developing programs for the inspection of metal structures.

Visual control of microstructure images, which allows predicting the fatigue resistance of metals and alloys without damaging effects on the object, is a promising area in the development of automated systems for ensuring the reliability of metal structures, state monitoring and diagnostics in comparison with other approaches.

Accumulation of damage on the surface microstructure during operation leads to the formation of rough slip traces (RST), the development of which leads to the formation of cracks and the destruction of metal structures. An important task is not only monitoring the accumulation of microdamages, but also developing criteria for determining the pre-defective state of the material. In theoretical terms, the task is to develop a model of the process of fatigue failure, taking into account the rotation and deformation of grains, the accumulation of microdamage, the formation of microdefects, their fusion and the formation of a main crack.

* Corresponding author: vyach.andreev@mail.ru

2 Matherials and methods

A significant contribution to the study of images of the surface microstructure of metals and alloys was made by V.S. Ivanova, V.F. Terentyev, J. Carroll, A. Clayton, A. Cherrone, A.L. Zhiznyakov.

Theoretical and experimental studies in the field of loading of materials, leading to the appearance of plastic deformations, the development of which ends with the formation of RST and the subsequent destruction of structures, are reflected in the works of A.V.Guryev, A.A.Weinstein, Yu.V.Sovetova, V.P.Baranova, V.E.Stepanova, D.I.Shetulova, A.V. Gonchar and others.

Assessing the technical condition and quality of the material of structural elements and machine parts in order to ensure their safe operation is an urgent task, for the solution of which non-destructive testing methods are widely used. The stage of accumulation of microdamage during power loading, which begins from the moment the facility is commissioned, requires additional research. Currently, in all industrialized countries, methods and techniques of non-destructive testing of the actual state of the material are one of the most popular developments. At the Institute of Strength Physics and Materials Science of Siberian Branch of Russian Academy of Sciences it is proposed to diagnose the stages of damage accumulation in a material long before the appearance of visible cracks on the basis of the optical-television and acoustic-emission method [1]. The system records strain and acoustic emission signals during material deformation.

At the Baikov Institute of Metallurgy and Materials Science, RAS, studies of the processes of localization of deformation and fracture by replica methods, acoustic emission, magnetic memory of metals, ultrasonic attenuation, micro hardness and electrical resistance are carried out. In particular, the relationship of the estimated physical parameters with the size of the plastic zone and the concentration of micro cracks in it was considered [2]. The mechanical properties of structural steels are studied by acoustic and magnetic methods in the process of stretching flat specimens with a concentrator and the physical parameters characterizing the achievement of the ultimate state corresponding to the yield strength and strength of structural materials are determined [3].

Part of the research devoted to the problem of assessing the actual state of the material relates to the problem of predicting and detecting the moment of crack initiation on the surface of the material using information about the state of the microstructure of the material. As a rule, studies use X-ray diffraction analysis and scanning electron microscopy, which do not allow such "thin" studies at industrial facilities.

In [4], localization of crystallographic slip in slices was studied under uniaxial compression of a single crystal of copper using long-range high-energy diffraction microscopy. During the study, a unique mobile detector step was used, which provided access to many diffraction peaks with high angular resolution. The authors obtained pole figures of different orientations of the single crystal, which made it possible to track the evolution of the distribution of the lattice orientation, which develops as the slip localizes.

In the works of D.I.Shetulov [5, 6] on the basis of images, the complex adverse character of geyser instability, causing heat removal disturbances and additional adverse effects on the structural material of pipelines and the main technological equipment of nuclear power plants, in the form of difficultly predicted cyclic loads, was considered.

3 Estimation of material durability based on microstructure analysis

Obviously, the material used in the structures is subjected to periodic load of the body and gradually destroyed.

It should be noted that the result of fatigue tests also depends on a set of factors - the conditions under which studies were conducted, among which structural, technological, metallurgical, and operational factors are shared (fig. 1).

There are works [7-10], in which a relationship was revealed between the damage to the surface of the microstructure F (between the concentration of rough slip traces) and the number of loading cycles before the appearance of a macrocrack, i.e. the current state of structural elements.

To perform a quantitative assessment, damage F must be represented as a function of many factors, such as n31 - the number of grains on the microstructure, n32 - the number of damaged grains, n33 - the difference in the number of intact and damaged grains over their entire area, n34 - the number of grains damaged by wide slip bands , np1 is the total number of strips in the damaged grains, np2 is the number of wide, tortuous and intermittent slip bands, Fm is the actual area of the microstructure, Fobr is the area of the working surface of the sample:

$$F = f(n_{31}, n_{32}, n_{33}, n_{34}, n_{p1}, n_{p2}, F_m, F_{obr})$$

Theoretical and experimental studies of the relationship between the parameters of a damaged microstructure and the number of loading cycles have been carried out by many researchers.

For example, in [7] it was established that the damage to the surface of microstructures is directly proportional to the following relative values: n32⁄n31, n34⁄n33, np2⁄np1, Fm⁄Fobr, and the revealed dependence has the form:

$$F = \frac{n_{32}}{n_{31}}\frac{n_{34}}{n_{33}}\frac{n_{п2}}{n_{п1}}\frac{F_m}{F_{obr}}$$

It is obvious that with an increase in the number of cycles N, the values n31, Fm and Fobr do not change.

If n32, n33, n34, np1, np2 are absent, then F = 0, which corresponds to the original intact structure.

Thus, using the data obtained by images processing of the microstructure of the surface of metals and alloys, it is possible to determine the number of loading cycles based on experimentally obtained quantitative information.

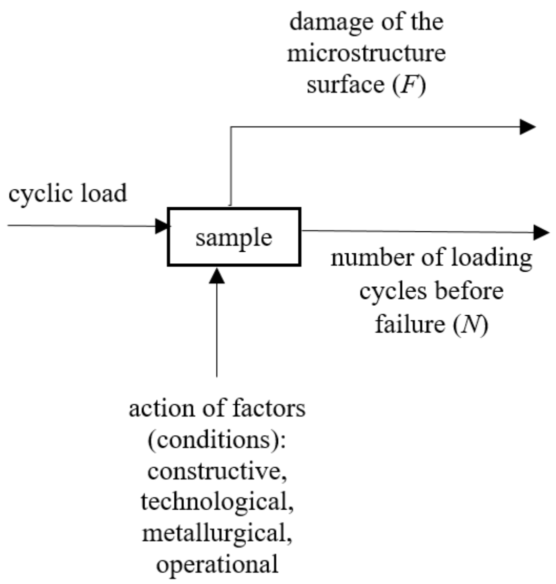

Fig. 1. Fatigue test model

Obviously, the type of dependence of the degree of damage to the surface microstructure on the number of loading cycles is determined by a specific set of acting factors during the operation of metal structures or during their production.

The form of this dependence can be extremely complicated, and its experimental preparation is a long and expensive process.

In this regard, at present, the degree of damage to surface microstructures is assessed by operators based on visual analysis of the microstructure of the surface of the sample.

Obviously, due to the presence of the human factor, such estimates are specific:

- a high degree of subjectivity of the results;
- low accuracy of the results;
- significant time costs for performing image analysis operations on the surface microstructure of metals and alloys.

Due to the need to improve the accuracy of such estimates, it becomes urgent to solve the problems of automating the process of analyzing the image of the surface microstructure and developing a procedure for determining the number of loading cycles based on surface damage.

Experimentally obtained images of microstructures, data on the number of loading cycles and descriptions of the conditions under which cyclic loading was performed, allow us to associate surface damage with a specific number of loading cycles in a certain n-dimensional space of conditions for fatigue tests.

Comparing the degree of damage with the number of loading cycles in a particular test, one can see the relationship connecting F and N for specific combinations of acting factors (fig. 2).

Obviously, knowing the type of such a dependence, we can predict both the state of the structural material under cyclic loading (assess the degree of damage to the microstructure of its surface) and predict the durability characteristics, for example, evaluate the residual life of a part or structure.

Thus, the urgent task of determining the analytical form of this dependence.

Damage to the surface can be considered as the difference between the reference image (the image of the initial surface microstructure) and the image of the surface microstructure after cyclic loading.

The training and test samples for the current task consisted of images that were obtained during fatigue tests described in [13]. An example of such images before and after 2,2·105 cyclic loading is shown in the fig. 3.

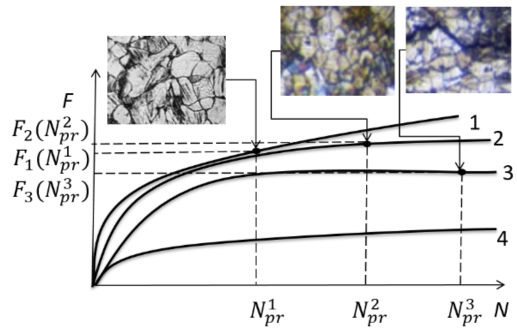

Fig. 2. Dependences *F(N)* for specific combinations of acting factors

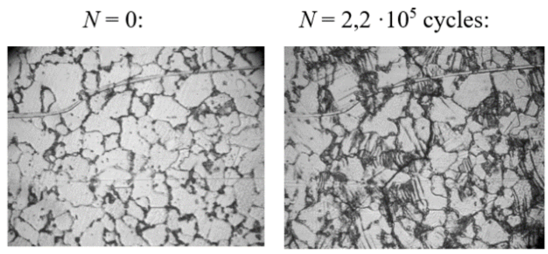

Fig. 3. Example of metal surface images before and after cyclic loading

4 Model

Formally the problem of assessing the degree of damage to the surface microstructure depending on the number of loading cycles can be represented as follows.

A reference image of the surface microstructure si ϵ S is presented, representing its initial state before the test, and for it there is a set of image samples $P_i = \{p_{i1}, p_{i2}, \dots, p_{in}\}$. Each element in the sample set is supplied with a numerical value corresponding to the number of loading cycles N. The set also contains images before and after the formation of a crack.

The task is to build an algorithm that, for each reference image s_i and an image from the set P_i, would determine the number of loading cycles N that led to this result.

$$N = f(s_i, p_i).$$

If we consider images after each loading cycle in the form of elements of one class, then the problem to be solved can be attributed to the image classification problem, where the number of loading cycles characterizes the class number.

In other words, it is necessary to formulate a classifier that allows us to determine whether the image of the damaged surface microstructure belongs to a class that characterizes the number of loading cycles.

Neural networks are used to classify images [11, 12]. In this case, the main task that has to be solved when using artificial neural networks is the process of selecting network characteristics, such as the number of layers, the number of neurons in each layer, as well as the formation of training and test samples for each specific case.

There are deep learning neural networks, which include convolutional neural networks. Work on convolutional neural networks showed quite good results in image processing tasks.

The use of classical neural networks for image processing problems is usually difficult with a large array of input values, since in order to reduce the likelihood of errors of the second type, it is advisable to choose a large number of inputs of the neural network.

The increase in the number of neurons and the connections between them entails a significant increase in the complexity of the learning process, and also requires significant costs for the computational processes used in training the network.

For example, an experimentally obtained image of a metal microstructure has a size of 325 by 255 pixels, that is, an array of values of 82875 in the input layer. Let's say our neural network contains two hidden layers. The number of neurons in the first hidden layer is 4 times the number of input values of the neural network.

Thus, the first hidden layer contains 4 * 82875 = 331500 neurons and accordingly has 82875*331500 connections to the input layer, and the second 165750 neurons and 165750*331500 connections to the first hidden layer.

Since the study uses three groups of images, in the output layer we have 3 neurons and 497,250 connections with the previous layer.

Obviously, in this setting, the task of computing and training the network for classifying images is resource-intensive.

Convolutional neural networks can solve this problem. In addition, they showed quite good results in image processing tasks, since they allow you to take into account information about the relative position of the image pixels.

The main concept in convolutional neural networks is convolutional layers consisting of feature maps that are formed by applying the same weighting factors to a group of neurons.

Thus, each neuron of the feature map associated with a part of the neurons of the previous layer performs a convolution operation.

Also, these types of networks may contain layers of subsampling, which make it possible to achieve partial scale invariance. Such types of layers reduce the spatial dimension of the image, but at the same time retain the features highlighted on previous layers.

In addition to convolutional layers and layers of subsampling, these types of networks contain fully connected layers. The output layer, as a rule, is always fully connected. All three types of layers can alternate, which allows you to create hierarchies of feature maps, and therefore recognize them.

The architecture of the proposed convolutional neural network for classifying images of the microstructure of the surface of metals and alloys to determine the number of loading cycles is shown in fig. 4.

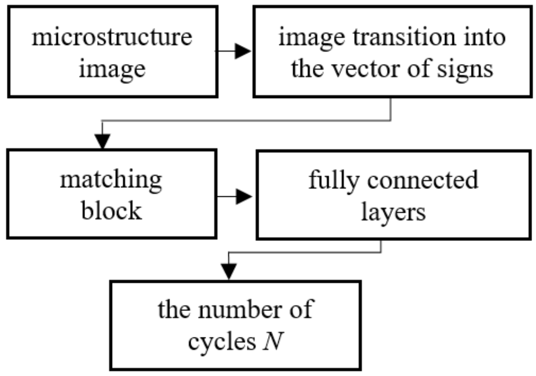

Fig. 4. The architecture of the proposed convolutional neural network for classifying images of the microstructure of the surface of metals and alloys to determine the number of loading cycles

The vector obtained at the output of the “image transition into the vector of signs” unit is used when comparing the reference sample image s and the sample image d after loading. According to the vector space model [14], the similarity between two vectors can be definitely defined as the cosine of the angle between them:

$$\mathrm{sim}(x_s, x_d) = \cos\theta = \frac{x_s * x_d}{\|x_s\|\|x_d\|} \quad (1)$$

Expression (1) can be reduced to the form:

$$\mathrm{sim}(x_s, x_d) = x_s M x_d,$$

where M is the similarity matrix of the reference image s and the sample after loading d. The similarity matrix is a network parameter and is configured during the learning process. The size of the matching layer is 20 + 20 + 1 = 41 neurons and 20 * 20 + 20 * 20 = 800 connections with the previous layer.

Training the model with 250 epochs resulted in the highest test accuracy of more than 86,37%, and the test accuracy was 78.43%.

5 Conclusion

Using a neural network classifier to determine the number of loading cycles, a classification accuracy of 78.43% was achieved. The results of the neural network classifier indicate the possibility of using the developed architecture as an element of an expert decision support system. In the case of assessing the degree of damage to structural elements, increased attention indicates the need to use expert opinion to decide on the possibility of further operation of the facility. The proposed approach will significantly reduce the accident rate at critical facilities.

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NPP Unit Life Management based on Digital Twin Application

Alexander Arzhaev[1,*], *Alexey* Arzhaev[1], *Valentin* Makhanev[1], *Mikhail* Antonov[2], *Anton* Emelianov[2], *Aleksander* Kalyutik[2], *Yury* Karyakin[2], *Maksim* Kurakin[2], *Daniil* Lyashenko[2], *Kirill* Arzhaev[3], *Ilya* Denisov[3]

[1]LLE "SPE "DIAPROK", Moscow, Russia Federation
[2]Peter the Great St. Petersburg Polytechnic University, Sankt-Petersburg, Russia Federation
[3]ANO "International Nuclear Safety Center", Moscow, Russia Federation

Abstract. IAEA activities on ageing management started in 1990 are a part of NPP Units life management or License Renewal as specified in national regulatory documents of member countries. Development of digital technologies makes it possible to manage lifetime NPP Unit issues in effective manner by application of Digital Twin.

Keywords. NPP Life Cycle Management, NPP systems, structures, components, ageing management, NPP Unit Digital Twin, long-term operation, NPP decommissioning.

1 Introduction

Optimization of technical and economic indicators of operation of new NPP units during long-term operation can be achieved on the basis of methodological approaches to Life Time Management (LTM) [1], systematized based on the results of NPP operation feedback in the IAEA member countries [2-3].

The use of Digital twins – DT for the NPP LTM unit is considered as a development of the approaches presented in [4] in relation to long-term operation conditions.

The NPP LTM is inseparably linked to ensuring safe and cost-effective long-term operation for a period of more than 45-60 years for almost all NPP units of the Russian Federation [5]: for new units in accordance with the design documentation, for existing units – in accordance with the procedures of service life extension.

2 LTM and ageing aspects

Correlation between LTM and ageing management is shown schematically on Fig. 1 taking into consideration the key role of systems, structures and components (SSC) integrity [6].

Lifetime management, Fig. 1, means the integration of ageing management and economic planning for NPP in order:

- to optimise the operation, the maintenance and the lifetime of the plant,
- maintain an accepted level of safety and performance,
- maximise return on investment over the lifetime of the plant.

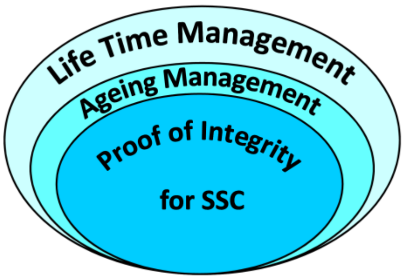

Fig.1. The relationship between the processes of the LTM, ageing management and proof of integrity for SSC

Ageing means the time-dependent gradual change of features and properties related to their function with regard to:

- the conceptual aspects (modification of requirements, modification of safety philosophy),
- the engineering aspects (mechanical SSC, buildings, electrical equipment),
- the systems and control devices relevant to NPP operation (including obsolescence of NPP I&C systems electronic components),
- the technical specifications and the documents,
- requirements and training of NPP personnel.

This also takes into consideration the development of the state-of-the-art of science and technology. It is possible that conceptual design and engineering methods as well as administration rules may become obsolete compared to the state-of-the-art.

Ageing management, Fig. 1, covers all engineering and organisational actions for the utility to guarantee safe operation during the lifetime including control of possible ageing degradation.

Recommendations on modern approaches to accounting for the effects of aging on SSC damage during operation (aging degradation) are contained in the IAEA documents [7-9].

* Corresponding author: arzhaev.alexander@yandex.ru

The issues of ensuring the structural integrity of passive elements – equipment and piping - are considered in the report [10].

3 Possible DT types

Depending on the range of tasks to be solved within the framework of the NPP LTM, it is possible to create and apply DTs at different levels.

One of the integrated DT options for NPPs is an automated enterprise management system of ERP class, the implementation of which is a complex one, taking into account the involvement of economic issues that are extremely sensitive for the NPP and utility management. Within the framework of the task [11], the technical requirements for the development of an automated control system for one of the new NPP unit is presented.

The implementation of Rosatom state Corporation's work on an industry-specific project for managing the NPP construction cost TCM NC (Total Cost Management Nuclear Construction) has prospects of creating a DT of the NPP unit as stated in [12].

The NPP operation Template has the Central place in the General scheme of the DT integration Figure 2 [12].

As can be seen from Fig. 2, the Maintenance automated control system (MACS) is a part of the NPP operation Template.

The possibilities of creating an NPP engineering radiation model are described in [13] and schematically presented in Fig. 3.

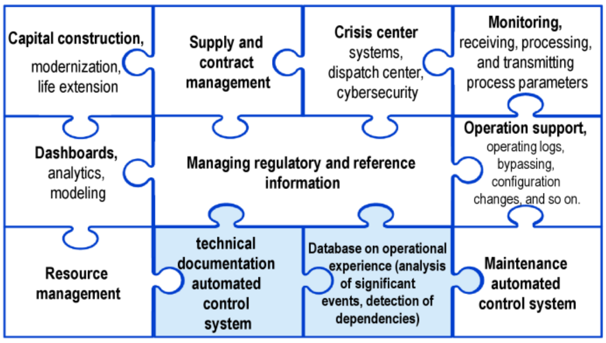

Fig.2. The functional composition of "NPP operation Template" (two areas highlighted in blue present finished product)

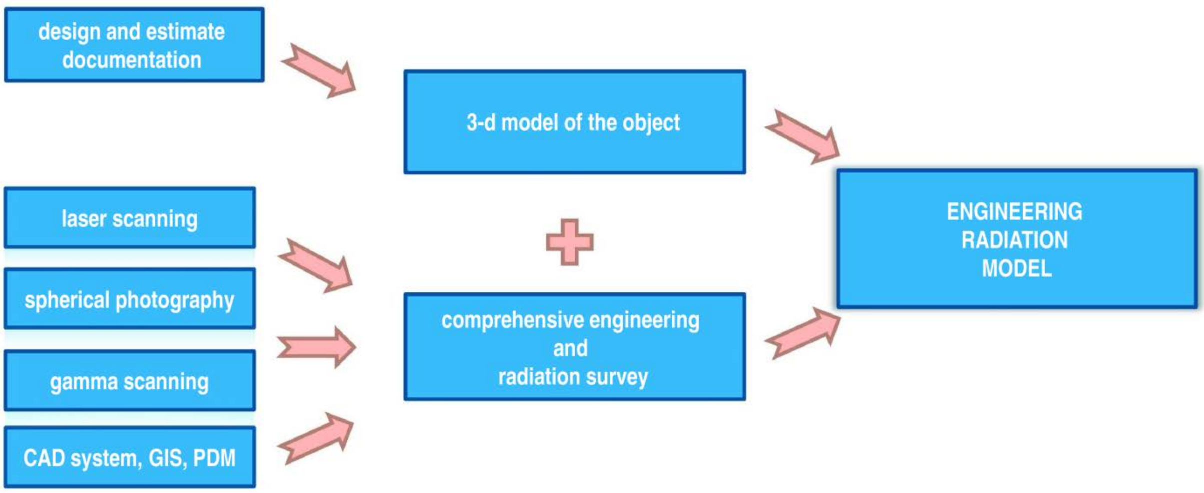

Fig.3. Assembly diagram of an engineering radiation model

The use of similar technologies (as laser scanning, spherical photography, etc.) for forming the "as built" NPP model during construction was proposed in 2014 [14], but had no practical implementation during the construction and commissioning of VVER-1200 units of Novovoronezh NPP-2 and Leningrad NPP-2.

4 Areas for current DT application

Rosatom state Corporation has announced about the start of the design work for two sites: Leningrad-2 (units 3 and 4 with VVER-1200) and Smolensk-2 with VVER-TOI [15]. So it seems valuable to include in design documentation generic DT development for NPP units at sites mentioned above.

Development of engineering model "as built" at constructing stage could be based on technologies described in [13] with further upgrade to engineering radiation model during NPP unit operation.

The technologies tested for decommissioning of the Kozloduy NPP power units [13] are considered relevant for use at unit 1 of the Leningrad NPP with the RBMK-1000 reactor as part of decommissioning operations presented in [16].

According to the concept of decommissioning of units No. 1-4 of the Leningrad NPP [17] optimistic forecasts, the work (including site survey and drawing up a sanitary passport) can last almost until 2060.

So DT development for the unit 1 of the Leningrad NPP decommissioning is an actual and urgent task for effective management of decommissioning process via nearest 40 years and recordkeeping.

Proposed in [4] option for development of a DT for NPP unit based on MACS worth to be effective for application of DT-technology in parallel in both parties: Design company (Party #1) and the Rosenergoatom Utility filial NPP unit (Party #2). Development of Digital passport (DP) as one of the DT basic parts could be started from early design stage with step-by-step adding information gathered via all pre-operation stages as shown on Fig. 4.

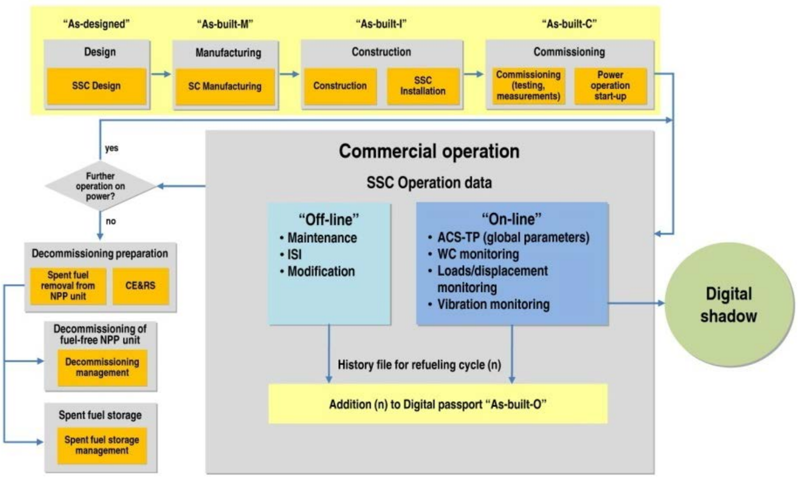

Fig.4. Processes of design, construction and operation of NPP unit related DT technology application

Mutual information exchange between Parties 1 and 2 provides both sides of the interaction with reliable and up-to-date information "as built" at all stages of the NPP life cycle (Fig. 5).

General designer of NPP site is responsible for development of final safety analysis report for "as-built" NPP Unit condition before starting commercial operation. So this company worth to be nominated as Task Leader from Party #1.

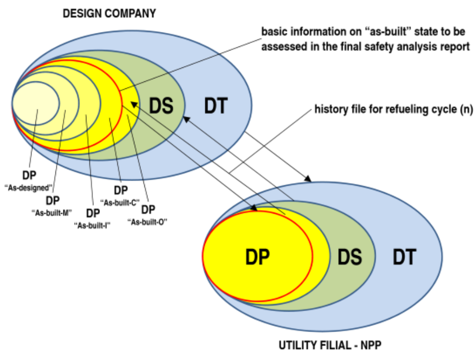

Fig.5. Preliminary scheme of information interaction in parallel application of DT technology by two parties (DP - digital passport; DS - digital shadow)

DT Digital Shadow (DS) gains on-line input information from NPP unit Technologic Process automated control system (ACS-TP) and local monitoring/diagnostic systems as shown on Figure 4.

DS role is to provide actual information for NPP operational personnel about deviations in SSC operation from design parameters and to supply DT prognostic module (implemented into DT shell) by on-line data.

Finally DT prognostic module can be used for different kind of operation trend assessment and NPP staff medium-term predictions for example on remaining life assessment of critical SSC (Fig. 6).

DT gives also possibility to predict obligatory (minimum required) scope of SSC maintenance during upcoming NPP outage within the NPP staff maintenance conception (as for example RCM (Reliability Centered Maintenance) according to [18-19]) taking into account level of specific SSC failure influence on NPP safety [20] and availability [21]. Optimization of periodicity of safety system testing based on procedure [22] could also be a benefit for NPP staff from DT application.

The proposed approach based on DT application can be an effective means of authoring the designer support for NPP staff at all stages of the life cycle, for example, when developing periodic safety reports prescribed in national regulatory documents [23-24].

Early application of DT technology helps to collect to collect comprehensive data on SSC condition which is important for preparation of NPP unit decommissioning stage. Such approach helps to optimise time and labor costs for implementation of final comprehensive engineering and radiation survey (CE&RS) as shown on Fig. 4.

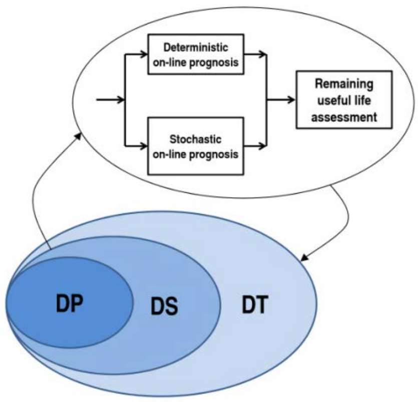

Fig.6. Scheme of interaction between DS and the predictive module in DT-shell for actual SSC remaining life assessment)

5 Conclusion

Finally it could be stated that proposed DT technology is effective for NPP units at all stages of life cycle.

Information exchange interfaces between the DT-prototype (Party #1) and the real DT (Party #2) can provide the most adequate forecasts for the implementation of optimal maintenance strategies.

DT is an effective tool for NPP comprehensive data collection, management and recordkeeping during long-term operation.

DT application is of high importance at unit 1 of Leningrad NPP with RBMK-1000 at early stage of preparation to decommissioning in order exclude any loss of valuable information due to use of obsolete big data handling technology.

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Possible in-service damages of steam generators at VVER-1000 and VVER-1200 NPP units and their impact on long-term operation

Alexander Arzhaev[1,*], *Alexey* Arzhaev[1], *Valentin* Makhanev[1], *Mikhail* Antonov[2], *Anton* Emelianov[2], *Aleksander* Kalyutik[2], *Yury* Karyakin[2], *Maksim* Kurakin[2], *Daniil* Lyashenko[2], *Kirill* Arzhaev[3], *Ilya* Denisov[3]

[1]LLE "SPE "DIAPROK", Moscow, Russia Federation
[2]Peter the Great St. Petersburg Polytechnic University, Sankt-Petersburg, Russia Federation
[3]ANO "International Nuclear Safety Center", Moscow, Russia Federation

Abstract. Specific features of corrosion-mechanical damages of primary circuit header to steam generator vessel branch welds at VVER-1000 NPPs and their impact on safety and economic efficiency during long-term operation are analysed. Measures to avoid the damages for similar zones of VVER-1200 steam generators are discussed.

Keywords. VVER-1000& VVER-1200 reactor facilities, long-term operation, steam generator, weld of primary circuit header to steam generator branch, corrosion-mechanical damage in operation.

1 Introduction

One of serious issues during VVER-1000 NPP operation is damage of primary circuit header (collector) to steam generator (SG) vessel branch welds. The welds under consideration are conventionally indicated as SS-111 for both "hot" and "cold" SG headers.

VVER-1000 NPP Units are significant part of the existing Russian NPP fleet and are also the basis for development of domestic nuclear energy in the future and essential component of nuclear technologies export abroad.

Analysis of the operating experience of the VVER-1000 NPP is important both for long-term operation of existing power units and for future effective operation of new NPPs with VVER-1200 and VVER-TOI reactor facilities with a design life of 60 calendar years.

The analysis is of rather high importance due to lack of clearly established root causes of damages in SS-111 zones. It can be used for the VVER-1200 NPP units under construction and under design to clarify the requirements for diagnostics of technical state parameters of the SS-111 zones both at the stages of commissioning and long-term operation.

2 Operation experience of VVER-1000

The operation of the VVER-1000 NPPs was not perfect, in particular, because of damages revealed on the primary circuit collectors and forced replacement of a significant amount of SGs at NPP Units in Russia and Ukraine [1]. The next problem area turned out to be the SS-111 zone.

Specific design features of SS-111 zones under consideration are shown in Fig.1 [2]. SG branches connected to headers are oblique ones having long and short forming lines. A typical view of the SS-111 zone "pocket" is shown in the right part of Fig.1.

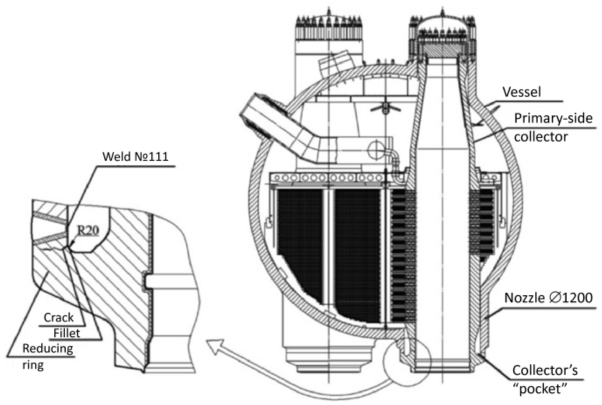

Fig.1. Steam generator PGV-1000M [2]

Damage of SS-111 starts on the inner surface from the "pockets" under corrosion impact of the secondary circuit coolant. Water chemistry parameters inside the "pockets" (Fig.1) may differ for the worse with accumulation of corrosion products and increased content of impurities.

For the first time, SS-111 damage was detected in 1998 at unit No. 5 of Novovoronezh NPP due to a leak. Subsequently, damages of SS-111 welds of "hot" and "cold" SG headers were detected at the Russian NPP units (unit No. 5 of Novovoronezh NPP, units No.No.1, 2 and 4 of the Balakovo NPP), as well as at the

* Corresponding author: arzhaev.alexander@yandex.ru

Ukrainian NPPs (South Ukrainian NPP and Zaporozhye NPP).

3 In-service damage mechanism assessment

Examinations of metal cut from damaged SS-111 zones revealed corrosion-mechanical damage in form of cracks initiating from the inner surface of the "pocket" in contact with secondary side coolant.

Damage in the SS-111 zone of cold SG collector of Kalinin NPP unit No.1 had specific features as long chains of pitting (Fig.2).

Fig.2. Pitting areas in the **SS-111** zone of cold SG collector of Kalinin NPP unit No.1 [3]

Mechanism of crack initiation and growth in the SS-111 zones was defined as delayed deformation corrosion cracking [1,4]. Studies performed in Ukraine have confirmed the same nature of damage of defective SS-111 zones of "hot" and "cold" headers [8]: "comprehensive studies and data obtained earlier suggest that the nature of destruction of welded joints in the steam generators of the South Ukrainian and Zaporozhye NPP is the same, despite the fact that the cracks were formed on the "hot" header in the first case, and on the "cold" – in the second".

In [2] based on results of computational substantiation of strength of the header and its connection zone with the SG branch, using refined three-dimensional finite element models and taking into account the significant factors (pressure environments of the first and second circuits; temperature field during facility operation at nominal parameters, loads from piping of the main circulation circuit (MCC)), it was noted "powerful" impact of MCC on the area of damage in combination with improper work of SG supports PG due to their jamming and additional resistance to SG movement via supports.

In the report of JSC OKB "Gidropress" [6] on the SS-111 zone, it was stated that "the highest level of loading of the zone is realized during hydraulic testing of SG secondary circuit (at yield strength level) and when cooling via blowdown lines, and high loading is also possible during improper operation of the SG supports".

Characteristically, the position of the primary damages in the SS-111 zones of "cold" headers is also close to so-called "MCC line" as for "hot" headers (Fig.3) both on VVER NPP Units of "small" series, and on VVER NPP Units of the project V-320 (according to JSC NPO "CNIITMASH" reports [4, 7]).

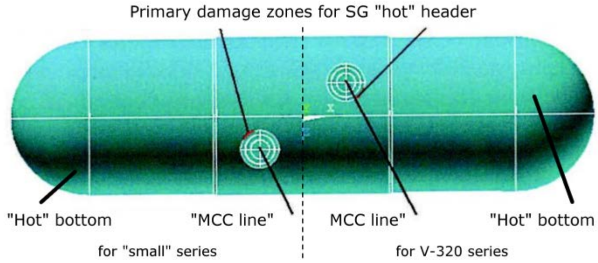

Fig.3. Zones of primary damages for VVER-1000 of "small" series and V-320 series from [8]

The results are consistent with the hypothesis that there is a directed mechanical impact of the MCC piping on the SS-111 zones, which should be considered as the main factor in the formation and growth of primary cracks in the direction of the "MCC line" (Fig.4-6). Fig.4 shows caption comments that are common to Fig.4-6.

Other factors (technology of rolling heat exchange tubes, presence of deposits in the "pockets" of SG, actual parameters of the secondary circuit water chemistry, etc.) should be considered as concomitant, despite their possible influence on crack initiation under delayed deformation corrosion cracking mechanism.

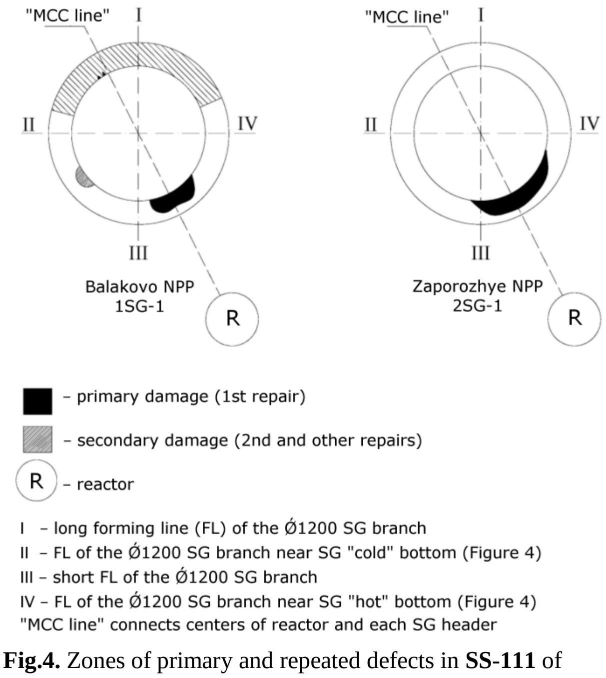

Fig.4. Zones of primary and repeated defects in **SS-111** of VVER NPP Units of the project V-320 ([2])

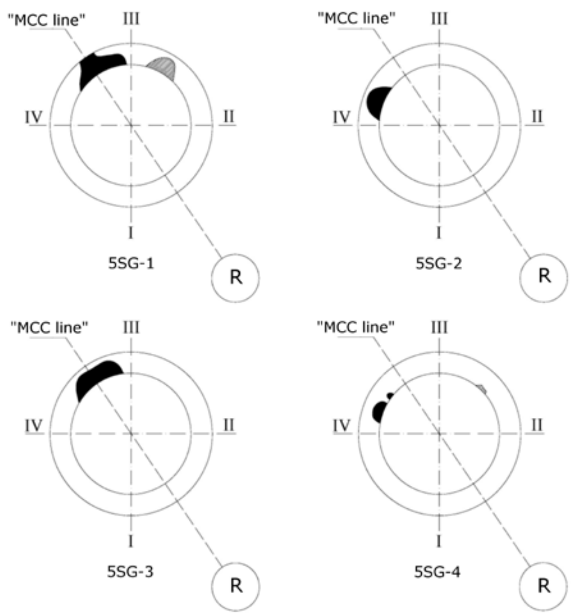

Fig.5. Zones of primary and repeated defects in **SS-111** of the unit No. 5 of Novovoronezh NPP ([2])

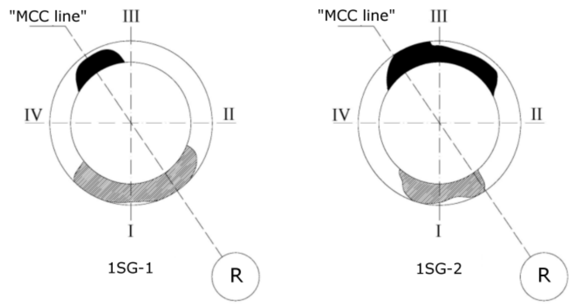

Fig.6. Zones of primary and repeated defects in **SS-111** of the unit No. 1 of South Ukrainian NPP ([2])

Layouts of MCC piping of VVER NPP Units of "small" series and VVER NPP Units of the project V-320 are shown on Fig.7 and 8 from [2].

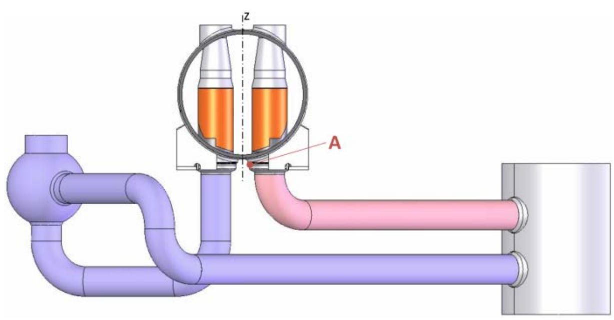

Fig.7. Layout of MCC piping of VVER NPP Units of "small" series ("hot" MCC piping in rose color)

Points A (Fig.7) and B (Fig.8) show maximum loaded zones located near short forming line of SG branches and "MCC line" (Fig.3).

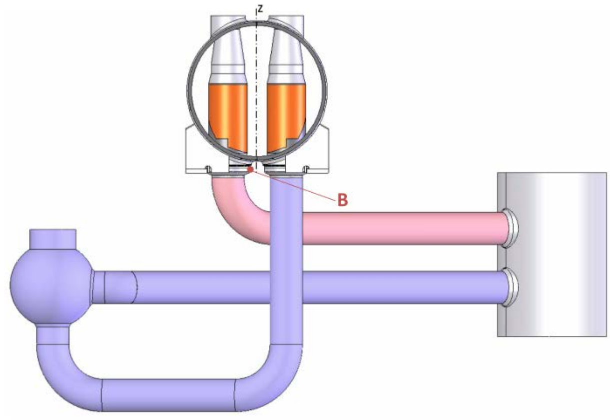

Fig.8. Layout of MCC piping of VVER NPP Units of the project V-320 series ("hot" MCC piping in rose color)

4 Damage cause analysis

Additional resistance to SG movement via supports due to their jamming generates extra loads for the SS-111 zones during start-up and shut-down of NPP unit.

Table 1 provides information on repairs of the SS-111 zones at all NPP units with VVER-1000 reactor facility according to [4, 6, 9]: the intense yellow background highlights the primary damage of the SS-111 zones of the "hot" headers, and the blue background highlights the "cold" headers. The "+" symbols indicate the number of repeated damages in different years. Information on absence of cracking of the SS-111 zones at several VVER-1000 NPPs was confirmed in the speeches of representatives from Ukraine (Rivne and Khmelnitsky NPPs), Bulgaria (Kozloduy NPP) and the Czech Republic (Temelin NPP) at the WANO MC seminar held in Yerevan (Armenia) in May 2015 [10].

Information on repeated damages of the SS-111 zones are shown in Table 2: the intense yellow background highlights the primary damage of the SS-111 zones of the "hot" headers, (the cases of repeated damages are highlighted in light yellow background), and the blue background highlights the "cold" headers. Through-wall damages are marked by "▲" symbols. Negative assessment of the dynamics of damage in 2010-2014 is too pessimistic, since many of these damages are repeated, that is, after the use of repair technology with through-thickness metal removal and subsequent volume filling by welding. However, the repeat leakages in almost the same place (Fig.4) of the 5SG-1 hot collector at unit No. 5 of Novovoronezh NPP, first ~9 years after the replacement of the SG, and then ~15 years after the repair of this defective zone by welding, show that the main factors that led to through-wall damage were not identified and eliminated during the period from 1998 to 2013.

In [11], it is erroneously stated that the time before appearance of through-thickness defect in the metal of the 5SG-1 hot collector at unit No. 5 of Novovoronezh NPP was 24 years.

Table 1. Information on repairs of the **SS-111** zones at all NPP units with VVER-1000

NPP	Unit	SG-1		SG-2		SG-3		SG-4	
		"Hot"	"Cold"	"Hot"	"Cold"	"Hot"	"Cold"	"Hot"	"Cold"
Novovoronezh NPP	5	+++		+		+		++	
Kalinin NPP	1						+		
	2								
	3								
	4								
Balakovo NPP	1	++							+
	2			++					
	3								
	4		+						
Rostov NPP	1								
	2								
	3								
South Ukrainian NPP	1	++		++					
	2								
	3	*	**				**		
Zaporozhye NPP	1								
	2	+	+		+				
	3								
	4					+			
	5								
	6								

Note: at Unit No.3 of South Ukrainian NPP sub-surface flaws were revealed by In-service Inspection [13] and repaired in 2012 (*) and 2014 (**)

Table 2. Information on repeated damages of the **SS-111** zones

NPP	№SG	Replaced	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Novovoronezh NPP	5SG-1	1989[3]	▲															▲		
	5SG-2	1987[3]																		
	5SG-3	1990[3]																		
	5SG-4	1989[3]																		
Kalinin NPP	1SG-3	no																		
Balakovo NPP	1SG-1	1990[3]																		
	1SG-4	1990[3]																		
	2SG-2	2000[3]																		
	4SG-1	no																		
South Ukrainian NPP	1SG-1	1989[3]																		
	1SG-2	1989[33]				▲														
Zaporozhye NPP	2SG-1	1990[3]																		
	2SG-2	1990[3]																		
	4SG-3	no																		

Note: ▲ - damage revealed by leak.

As can be seen from table 1, the damage of the SS-111 zones affects mainly the group of SGs replaced at NPP units due to damage of the headers and/or due to plugging of the heat exchange tubes over the limit. Of the 15 damaged units, only 3 were damaged on SGs operating on the units since installation. Information on SG replacements is provided in the report [12] based on several sources [1, 13-14].

When replacing the SGs on an NPP unit in operation, one of the welded joints SS-111 of “hot” or “cold” header becomes the closing one, whereas when installing SG to MCC at construction stage both welded joints SS-111 of the "hot" and "cold" headers to Dn850 pipelines are never the closing ones.

Thus, it seems acceptable to assume that part of the SGs was installed with the presence of implicit mounting preload during replacement (tables 1 and 2), which was not detected after repair and was not recorded in the reporting documentation. A similar hypothesis assumed presence of implicit mounting preload during the installation of part of the SGs in the MCC on newer blocks also seems realistic, since table 1 shows that the percentage of damaged SGs (from the number of not replaced) is significantly lower than among the sample of replaced SGs.

In the future, implicit mounting preload during the installation/repair could lead to restrictions (jamming) when SG moving via supports, taking into account the specifics of design solutions for MCC of VVER NPP Units of "small" series, and VVER NPP Units of the project V-320.

Therefore, the main cause of primary cracks in the SS-111 zones is the interaction of several factors that were excluded earlier from the analysis of the causes of damage in [15], namely: «4.1 Preload of the Du850 MCC piping during the replacement of the SGs», «4.3. Jammed roller and/or ball bearing supports of SG and/or MCC», «4.4 SG jammed for other reasons», which can be combined into a common cause: "shortness (jamming) of SG displacement on the supports". The crack growth rates depend to a significant extent on water chemistry inside the SG "pockets".

5 Conclusion

So primary damages in the SS-111 zones did not lead to extensive propagation along the circumferential weld perimeter, and the correlation of their location with the "MCC line" indicates the role of mechanical loads in the process of damage that does not pose a threat of complete break. However, for long-term cost-effective operation of the SG, it is necessary to improve load monitoring system for the SS-111 zone (for early detection of prerequisites for cracking initiation) and SG maintenance and repair/replacement technology.

Measures to monitor the thermomechanical loading of the SS-111 zone (especially after weld repair or/ and SG replacement) will allow to get an early warning for NPP personnel about non-project loading and the need for compensative actions in the form of an extraordinary preventive maintenance of SG supports and more frequent ISI of the SS-111 zone.

It should be noted that in-service damages of the SS-111 zone lead to decrease of NPP unit availability rather than safety. Operation experience should be also taken into account for VVER-1200 NPP Unit design to avoid in-service damages of the SS-111 zone during long-term operation.

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Assessment of Personnel Actions in the Most Dangerous Accidents

Maria Berberova [1,2,3,*]

[1]ANO HE “Russian New University”, Moscow, Russia Federation
[2]ANO International Nuclear Safety Center, Moscow, Russia Federation
[3]ANO “Scientific and Research Center for Information in Physics and Technique”, Nizhny Novgorod, Russia Federation

Abstract. The reliability of the human operator is an essential indicator of the safe operation of nuclear power plants. Mistakes can be made during performance checks, maintenance, at the stage of accident management, etc. A number of different factors affect the stability of a nuclear power plant: level of organization of the project, quality of equipment in operation, selection and training of competent personnel, maintaining the qualifications of NPP workers, and etc. In the "man-machine" system, the reliability of the technical component is calculated by known methods and in accordance with established reliability standards. However, the “human” component cannot be technically and accurately determined, therefore, it is necessary to undertake systematic efforts to increase and subsequently maintain the achieved level of reliability of this component. The contribution of the human factor to emergencies at technosphere facilities is significant: 70% of air crashes, 50% of disasters in the fleet occur precisely due to incorrect actions (low reliability) of personnel. According to statistics, the main causes of accidents are improper actions (low reliability) of personnel (60-70%), technical reasons (20-30%), adverse effects of external factors, etc.

Keywords. personnel, the most dangerous (beyond design basis) accidents, personnel reliability, stress, normal operation, emergency.

1 Introduction

Since 1997 (since the approval of OPB88 / 97 (replaced by the Federal Norms and Rules in the Field of Atomic Energy Use “General Provisions for Ensuring the Safety of Nuclear Power Plants” (NP-001-15) [1])), at all Russian NPPs Probabilistic Safety Analysis (PSA) has become mandatory. In November 2004, Order No. 506 [2] was signed at the Russian Emergencies Ministry, according to which a standard safety data sheet for a hazardous facility was further developed. To fill out section II of the safety data sheet [3], it is necessary to carry out a risk assessment of the objects in question. The problem of evaluating the risk indicators of especially dangerous objects (in particular, nuclear power plants) is devoted to the works of both domestic ([4-8 and others]) and foreign scientists ([9-13 and others]). However, the vast majority of studies in this area are devoted to such problems as: physics and kinetics of nuclear reactors; reliability theory; safety analysis; risk assessment. Tasks like assessment of the reliability of personnel under psychological stress in the writings of these authors have not been investigated..

In 2015, the work “Assessment of risk indicators for the second phases of Smolensk and Kursk NPPs” [14] was published. In [14] such methodological approaches like a methodological approach for calculating the doses of external and internal irradiation of the population in the ring segment of the rumba and a methodical approach for assessing damage to the population in the ring segment of the rumba due to exposure to radioactive substances. However, the tasks of estimating the doses of external and internal radiation and the damage to the population (taking into account the age composition of the population) living around nuclear power plants during the most dangerous (beyond design) accidents involving the emission of thermal neutron sources with a low flux density were not studied in this work either.

In mid-2017, work began on the study of the dependence of the results of assessments of the radiation risk of nuclear power plants on the composition of the population living around nuclear power plants [15, 16]. But even these works do not address the issues of personnel reliability under psychological stress.

2 Personnel reliability analysis under psychological stress

According to [17], psychological stress is a reaction to the characteristics of the interaction between a person and the surrounding world. The state of stress is mainly a consequence of personal cognitive processes, a way of thinking and assessing a situation, knowing one's own

* Corresponding author: maria.berberova@gmail.com

abilities (resources), the degree of training in management methods and behavioral strategies in extreme conditions, and their adequate choice.

Factors that determine the stressfulness of an event:

- emotions that are associated with this event;
- the uncertainty of the situation associated with the lack of information for its assessment;
- the significance of the event, reflecting the degree of its danger to a person or others;
- importance to achieve the end result.

Phases of the physiological adaptation process under stress [18]:

1) *Initial adaptation.* This phase develops at the very beginning of the action (physiological or pathogenic factors); consists of two multidirectional complexes of reactions:
   - An indicative reflex (accompanied by inhibition of many types of activities carried out up to this time).
   - Activation of neuro-trophic influence (stores and provides the body with the necessary energy).

   The initial phase of adaptation can be expressed in different ways, depending on the strength of the annoying factors (the stronger they are, the more pronounced this phase). Accordingly, it can be accompanied by a strongly or weakly expressed emotional component.
2) *Transition phase.* During this phase, the adaptive mechanisms of the body gradually switch to a deeper cell level. These shifts provide a new level of homeostasis. The nonspecific resistance of the organism increases, and at the same time, various mechanisms of specific adaptation develop.
3) *Sustainable adaptation.* It is of a long-term nature, the basis of the prerequisites for the development of this phase are memory mechanisms in the central nervous system. Control mechanisms are coordinated. A characteristic feature of life in the phase of sustainable adaptation is the relative profitability ("turning off unnecessary reactions") of energy costs to maintain it. Switching the body's reactivity to a new level is accompanied by both the mobilization of a number of reactions and the return of the activity of auxiliary systems to the initial indicators.
4) *The phase of disadaptation.* This condition can occur as a result of depletion of physiological reserves and a violation of the interaction of regulatory and metabolic adaptation mechanisms. As a result, the body disrupts the balance of consumption and recovery in organs and tissues, as well as the relationship in the work of physiological systems. Once again, auxiliary systems come to a state of increased activity - respiration and blood circulation; energy in the body is not spent economically. Disadaptation occurs most often in cases where the functional activity in the new conditions is excessive or the action of factors that were the main stimulants of adaptive changes in the body increases, and they approach extreme strengths.

3 Comparison and analysis of data obtained under normal use and in an emergency

The study was conducted on the basis of data obtained from the simulator of the Novovoronezh NPP based on a survey of 30 operators [19]. The survey of operators was depersonalized. The tests were carried out in the afternoon and evening shifts. At this time, as a rule, work is carried out on equipment, bypasses of the management personnel, therefore this period can be considered normal loaded.

Operational personnel account for 55% of violations of normal operation.

In case of emergency situations, as a rule, a group reorganization of the control room switchboard occurs. There are the following types of group behavior of operators in case of accidents:

– the main operator (supervisor) takes on a leading role, monitors the situation and makes decisions, and the remaining members of the watch carry out his decision;
– the supervisor and other members of the watch work on an equal footing, so it is difficult to identify the decision maker.

The table 1 shows data on the reliability of tasks by operational personnel on the simulator in normal use.

Table 1. Statistical data and reliability indicators for the performance of tasks by operational personnel on the simulator VVER-440 Novovoronezh training center.

№	Task characteristics and reliability indicators	Operator groups		
		Interns	Experienced operators	Together
1	Number of task types presented	70	37	78
2	The number of completed task implementations	299	85	489
3	Of the total number of tasks:			
	performed unmistakably	217	49	356
	executed with minor errors	43	25	75
	failed (failure to execute)	39	11	58

According to the main indicators presented in table 1, we construct the graph shown in Fig. 1. The graph clearly shows that in normal use, the percentage of error-free operations is high (72.6% error-free operations for trainees, 57.6% - for experienced operators, 72.8% - for joint tasks)

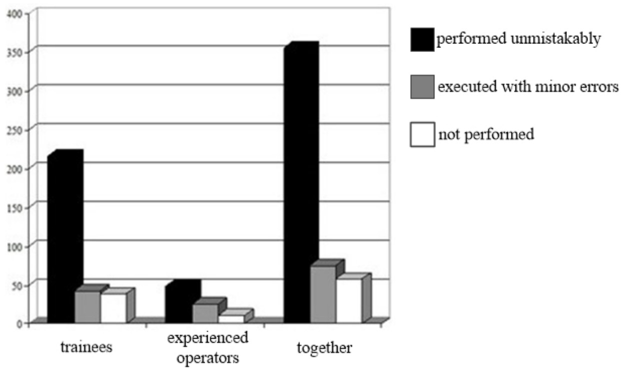

Fig. 1. Schedule of reliability of tasks by operational staff in normal use

When decisive action is required to solve a non-standard task with a shortage of time, the situation becomes stressful. The more controversial the situational and target settings, the higher the level of stress experienced.

For example, there is the desire to remove the controlled unit from a dangerous state and the realization that it is impossible to do this for objective, situational reasons or when the employee does not know how to do this in this situation. This is a typical situation preceding a forced shutdown of a reactor when there is not enough time or information to understand what needs to be done to prevent shutdown.

The opposite picture may also occur - the operator knows what is being done in the specific threat of block exit from the given mode, but in the presence of even the smallest risk, he prefers to provide work to an automatic protection system that will stop the block.

The dependence of the effects of stress on the emotional reaction of a person to a stressor indicates the participation of limbic structures in the higher control of the stress response. The decision is made with the participation of the frontal lobes of the brain, which together with the hippocampus provide a person's response to unlikely events.

It is known that in the early stages of adaptation after exposure to stress (up to 4 days) there is an improvement in memorization of emotional stimuli (by 40-50%) and memory impairment for neutral stimuli.

On the 11-21 day the state of the body returns to normal. Recollection of neutral information rises. At the same time, the accuracy of playback increases significantly (4-5 times).

Adaptive rearrangements affect the most common mechanisms of the central nervous system, controlling the perception and memorization of any emotional stimuli.

During an emergency, memory impairment due to neutral stimuli is expected. The effects of this reaction are more affected by experienced operators. Their emotional response is lower than that of trainees (since they have been repeatedly affected by severe stress, their body has adapted). They are more likely to trust their experience, but the accuracy of reproducing the information they know is lower. This means that the probability of making minor mistakes increases.

The interns will try to remember an instruction, and complete the task in accordance with it.

Table 2. Statistical data and reliability indicators for performing tasks by operational personnel on the vver-440 simulator of the novovoronezh training center in an emergency

№	Task characteristics and reliability indicators	Operator groups		
		Interns	Experienced operators	Together
1	Number of task types presented	28	25	28
2	The number of completed task implementations	271	286	697
3	Of the total number of tasks:			
	performed unmistakably	158	87	336
	executed with minor errors	51	153	242
	failed (failure to execute)	62	46	119

The table 2 shows data on the reliability of tasks by operational personnel on the simulator in an emergency.

According to the main indicators presented in Table 2, we construct the graph shown in Fig. 2. The graph clearly shows that in normal use, the percentage of error-free operations is high (58.3% error-free operations for trainees, 18.8% - for experienced operators, 22.9% - for joint tasks).

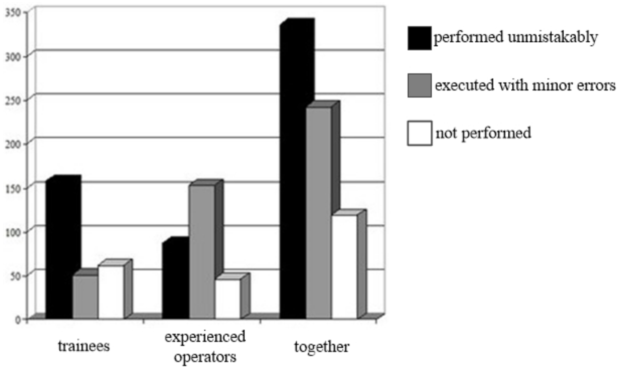

Fig. 2. Schedule of reliability of task performance by operational personnel in an emergency

4 Results

The results of this analysis confirm a significant difference in the mistakes made under normal use and under stressful conditions.

Thus, we see that the stress adaptation system can significantly reduce the emotional response of staff. It is this system that is responsible for the development of experience, which helps to increase the efficiency and correctness of decisions made. At the same time, in an emergency situation, the performance of experienced personnel is deteriorating. This is explained precisely by the system of adaptation of the body to stress, since a reduced emotional reaction reduces attentiveness, which leads to the commission of gross errors by the operator.

5 Conclusion

In the future it is planned:

1) To continue work on the assessment of personnel actions in the most dangerous (beyond design basis) accidents with the emission of thermal neutron sources with a low flux density.
2) To develop a methodological approach to solving the problems of assessing doses of external and internal irradiation and assessing damage to the population (taking into account the age composition of the population) living around nuclear power plants during the most dangerous (beyond design basis) accidents involving the emission of thermal neutron sources with a low flux density.

To develop an atlas of risk indicator estimates; to develop a program for monitoring (control) the safety of nuclear power plants.

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Analysis of the compressorless combined cycle gas turbine unit performance efficiency in district heating systems

Yuriy Borisov [1,3], *Nikolay* Fominykh [1], *Eldar* Ramazanov [2] and *Oleg* Popel [1]

[1] Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya St., Bldg. 13, Block 2, Moscow, Russia
[2] Peoples' Friendship University of Russia (RUDN University), Miklukho-Maklaya str., Bldg. 6, Moscow, Russia
[3] Bauman Moscow State Technical University, 2nd Baumanskaya St., Bldg. 5, Block 1, Moscow, Russia

Abstract. Nowadays, thermodynamic cycles are actively studied, in which pure oxygen and fuel are fed into a combustion chamber, and a temperature of a working fluid is regulated by the supply of carbon dioxide and/or water vapor. These cycles are called “oxygen-fuel”. They allow easy to separate CO2, resulting from a fuel combustion, from the working fluid and remove it from the cycle in its pure form. In addition, it has already been shown that an efficiency of electric power generation of such cycles is approaching the best known technologies. However, the efficiency of cogeneration of electricity and heat is more important for many energy systems, especially for Russian, in comparison with the efficiency of electricity generation. The main goal of the study was to analyze the thermal efficiency for cogeneration of electricity and heat of one of the options for the implementation of oxygen-fuel cycles - compressorless combined cycle gas turbine (CCGT) units. A mathematical model of the compressorless CCGT units was developed, which allows to study the thermal performance in a wide range of operating modes. It is conventionally accepted that the system requires a maximum power for power supply of 300 MW, and a maximum power for heat supply of 600 MW. It is assumed that 300 MW of electricity is constantly supplied to the network. In addition, the heat load is provided according to the standard schedule depending on the ambient temperature, and at the same time an averaged data on the temperature of atmospheric air for central Russia over a ten-year period is accepted. The comparison is made with a steam turbine CHP plant and a CCGT-CHP plant. The results of the comparison showed a significant advantage of the compressorless CCGT unit.

Introduction

The desire to reduce anthropogenic emissions of greenhouse gases, including CO2, initiates the search for new technologies of generating electric and thermal energy. Recently, thermodynamic cycles, in which oxygen is extracted from the air before the combustion process, are actively studied [1-4]. Pure oxygen and fuel are supplied into the combustion chamber, and the temperature of the working fluid is regulated by the supply of carbon dioxide and/or water vapor. Thus, the spent working fluid consists of a mixture of carbon dioxide and water vapor. The phase transition temperatures of these components are very different that allow easy to separate such a mixture. Such cycles are called “oxygen-fuel”. The compressorless CCGT units are one of the most promising options for the implementation of oxygen-fuel cycles for cogeneration of electric and thermal energy [5-7].

The main objective of the research was to study the parameters of the compressorless CCGT unit at various heat loads and to analyze the thermal efficiency of it in the district heating systems.

Description of a compressorless combined cycle gas turbine unit schematic

A compressorless combined cycle gas turbine unit schematic is shown in Fig. 1. The pressure increase of the working fluid is carried out by the feed pumps of liquefied natural gas (LNG) 1, oxygen 2, carbon dioxide 3 and water 4. The LNG pump controls the fuel supply. After the feed pump, LNG is sequentially fed to a cold utilizer of LNG 5 and a LNG heater 6, and then heated fuel enters a primary zone of a combustion chamber 7. The oxygen supply is regulated by the oxygen pump. After the oxygen pump, oxygen first enters an oxygen cold utilizer 8, then into an oxygen heater 9. After which, the heated oxygen enters the primary zone of the combustion chamber.

The carbon dioxide pump controls the flow of CO2. After the carbon dioxide pump, CO2 first enters a heater 10, and then goes to a regenerative heat exchanger 11. Heated CO2 is supplied simultaneously to primary and secondary zones of the combustion chamber so as to ensure an acceptable quality of fuel combustion and the required temperature field at the combustion chamber outlet. A small fraction of CO2 is used to cool hot parts in a flow part of a combined cycle gas turbine 12 (not shown).

The feed water pump 4 supplies water to a recuperative heat exchanger 13, and then, like CO2, H2O enters the primary and secondary zones. Thus, fuel is supplied to the combustion chamber in an amount that provides required thermal and electrical load. The oxygen supply is regulated so that the required combustion efficiency is provided by a minimum excess of oxygen. The supply of CO2 maintains the preset temperature of the working fluid in the turbine depending on the regulation law at the inlet or outlet. The supply of H2O regulates the ratio of generating heat and electric energy.

The mixture of combustion products and recirculating CO2 and H2O with the prescribed temperature, obtained in the combustion chamber, is the working fluid at the inlet of the combined cycle gas turbine 12. The working fluid expands in the turbine, doing work. The work, having performed in the combined cycle gas turbine, is converted into electricity by a generator 14. The working fluid, spent in the turbine, is sent to recuperative heat exchangers 11 and 13, which heat up the recirculating CO2 and H2O. In recuperative heat exchangers, the working fluid is cooled to a temperature as close as possible to the dew temperature when the water vapor, included in the working fluid, begins to condense.

After the recuperative heat exchanger 11, the working fluid is directed to a low pressure contact condenser 15. It has two sections which locates one above the other. Water is supplied into a first section 16 with a temperature slightly higher than the

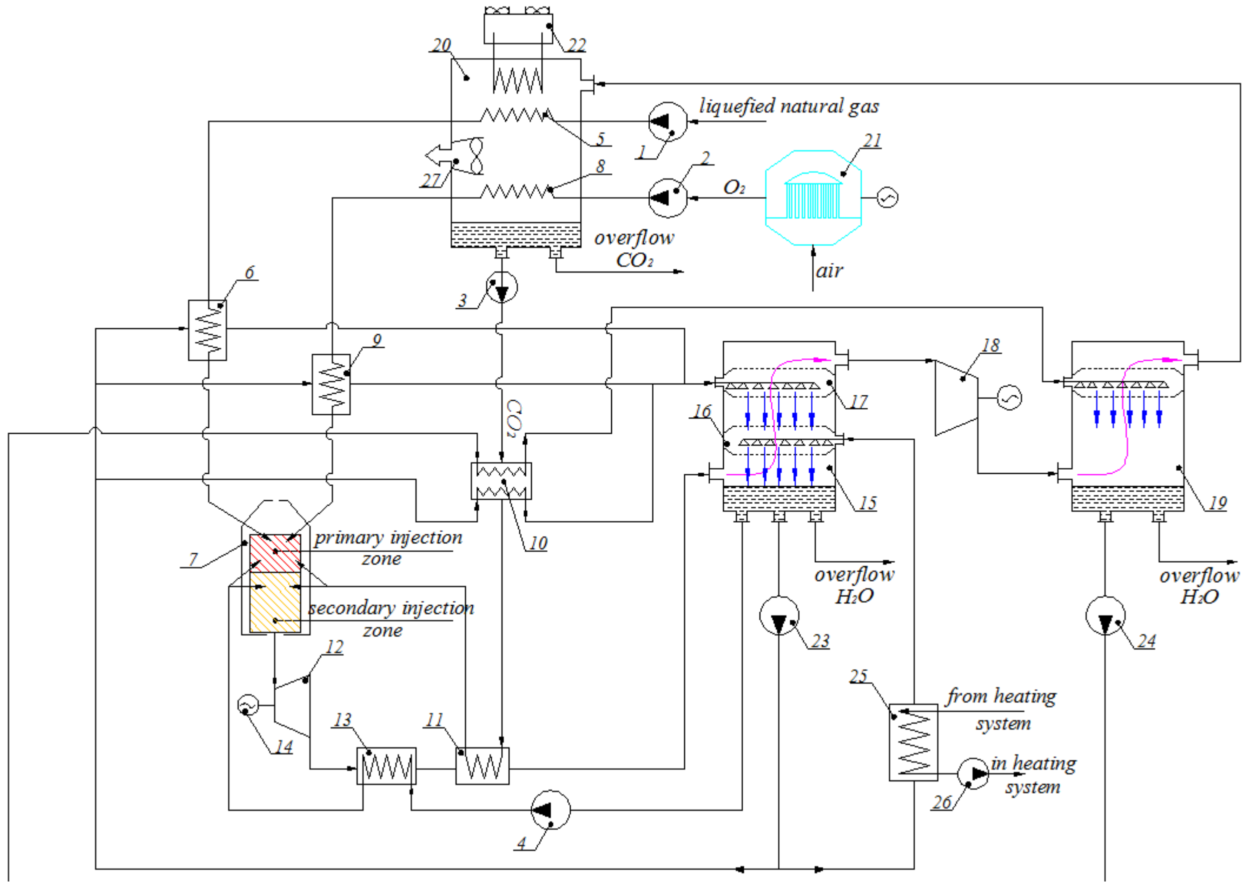

Fig. 1. Compressorless combined cycle gas turbine unit schematic.

temperature of return network water for cooling the working fluid. Cooling water is supplied into a second section 17 with a temperature slightly higher than the temperature of liquid CO_2. At the outlet of the low pressure contact condenser, the working fluid is carbon dioxide with small impurities, including a small amount of H_2O. Therefore, in order to avoid freezing, the pressure of the working fluid is increased by a compressor of CO_2 18 to 3,5 MPa when the condensation temperature of CO_2 is higher than the freezing temperature of H_2O.

After that, the residual of H_2O is condensed in a high pressure contact condenser 19. The working fluid, having cooled in the contact condenser 19, is sent to a liquefier of CO_2 20. Cold of oxygen from an air separation unit (ASU) 21 and LNG cold are used for the liquefaction of CO_2. For this purpose, the liquefier of CO_2 includes the liquid oxygen cold utilizer 8 and the LNG cold utilizer 5.

The entire shortage of cold, which is required to liquefy CO_2, is compensated a refrigeration unit 22. Each contact condenser has its own circulating water circuit. The circulation pumps 23 and 24 take in water from the contact condenser water tanks. Water is divided into several streams in the circulation circuit of the low pressure condenser after the circulation pump 23. Most of the water goes to a network water heater 25 after which it returns to the first section of the low pressure condenser. The remaining water is supplied in parallel streams to the fuel heater 6, the oxygen heater 9 and the CO_2 heater 10.

Having released the heat in the heaters, the cooled water returns to the second section of the low pressure contact condenser. After the pump 24, the circulation water of the high pressure condenser is supplied to the CO_2 heater 10. It is designed so that two heating fluids are used for heating up. After the heater, this water returns to the high pressure contact condenser 19. The return network water is supplied to the network water heater 25. After that, water is heated to the temperature, required by the temperature graph, and returned to the heat network by a network water pump 26.

Liquid oxygen is produced in the cryogenic ASU 21. The liquefier of CO_2 20 is equipped with a system for removing non-condensable gases and collecting an excess of liquid CO_2. In addition, the selection of excess H_2O is provided.

Description of an adopted model of a district heating system

It is assumed that a heat load is heating and a hot water supply. Thermal capacity of 600 MW allows to provide heat to a residential area for 100-130 thousand people. It is accepted that the hot water supply capacity is 20% of the maximum heat output. The schedules of electric power requirement, being very diverse, and the issues of regulating the electric power of the energy system are beyond the scope of this work. Therefore, an option has been adopted in which the compressorless CCGT unit is not involved in the regulation of electric power. Also, it is supposed that a power grid is large enough to accept a nominal 300 MW in all possible situations. A heat load chart was adopted on the basis of averaging data for air temperature of the central part of Russia over a ten-year period. This chart is converted into a dependence of total power on the duration of the days of work (Fig. 2). Total power is related to nominal electrical power

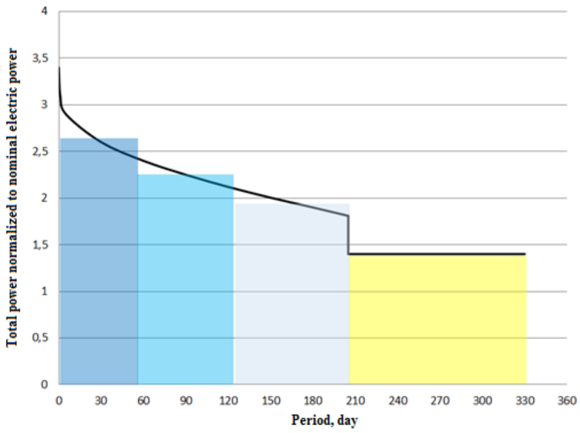

Fig. 2. Adopted annual load schedule.

An area under a line is the energy, generated over the corresponding period of time. The yellow color indicates the energy, generated in the summer, when the heating is not working. During this period of time, with the accepted operational model, approximately a quarter of all annual energy is produced. The heating period can be divided into three equal areas. Such a partition will allow to take into account correctly the change in thermal efficiency with a change in thermal load.

Accepted efficiency criterion for cogeneration of heat and electric energy

The most indicative criterions for the thermal efficiency of energy facilities work are the integral fuel consumptions during a typical period of time. Heat supply systems operate in annual cycles. Therefore, one year is chosen as a characteristic period of time. It is assumed that there are no other sources of energy than fuel. Thus, in the ideal case, the (minimal) annual fuel consumption will be equal to the ratio of total power (thermal and electric), generated per year, to the higher calorific value of fuel. This fuel consumption is taken as a reference point, and the value, which exceeds it, is taken as a criterion of thermal efficiency.

Description of a calculation model for compressorless CCGT unit

At this stage of the research, a relatively low level of detail for a calculation was selected, but it was quite sufficient to solve the tasks. All large parts of the installation are considered as “black boxes” the operation of which is described by universal characteristics and integral equations. Also, an assumption is accepted that the fuel is pure methane CH4. To take into account the thermodynamic properties of the working fluid, the standard tabular values for the properties of pure components (CO2, H2O, O2, and CH4) were transferred to spreadsheets with an interpolation procedure. Before the combustion process, each component of the working fluid is considered separately as a pure substance. The working fluid is a mixture of gases after the combustion process in the combustion chamber. It is supposed that this is a mechanical mixture of individual gases which do not enter into any chemical reactions between themselves, obeying the Dalton law.

A large group of equipment, being a part of the compressorless CCGT unit, affects the operation of the installation only by means of resistance to a movement of the working fluid. This is taken into account in the general model by the total pressure recovery factor. This group includes gas ducts, pipelines, fittings, nozzles, and etc. In a mathematical model, this equipment is taken into account by the total pressure recovery factors (a ratio of total pressure at outlet to total pressure at inlet of related equipment). As an assumption, it is assumed that the recovery factors of total pressure remain constant by the operating mode changes. Their values for the calculations are given in table 1.

Table 1

	Value
Pipelines and fittings for each of the original components in the area from the feed pump to the combustion chamber	0,95
Combustion chamber	0,9
All heaters and utilizers for hot and cold heat transfer fluid	0,95
Recuperators for cold heat transfer fluid	0,95
Recuperators for hot heat transfer fluid	0,97
Contact condensers for cold heat transfer fluid	0,9
Contact condensers for hot heat transfer fluid	0,97

The pressure increase is carried out by pumping equipment. Theoretically, the required pump power is equal to the product of the volumetric flow rate of the pumped liquid and the pressure difference between the inlet and outlet of the pump. The efficiency of the pressure increase is taken into account the efficiency of the pump. Typical characteristics of centrifugal pumps were used to describe the operation of pumping equipment. A view of used characteristics in relative parameters is shown in Fig. 3.

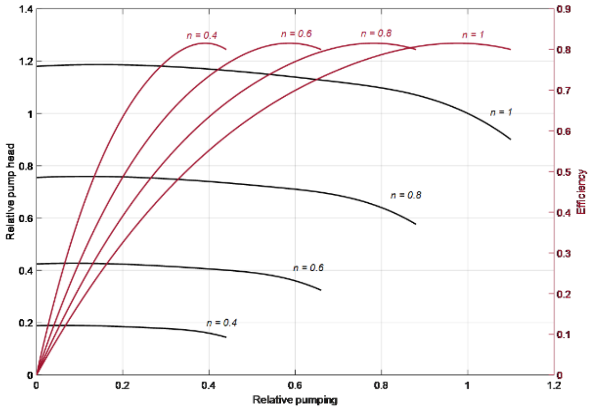

Fig. 3. Typical characteristic of feed pump.

To describe the combined cycle gas turbine, a characteristic in dimensionless coordinates was used, as shown in Fig. 4.

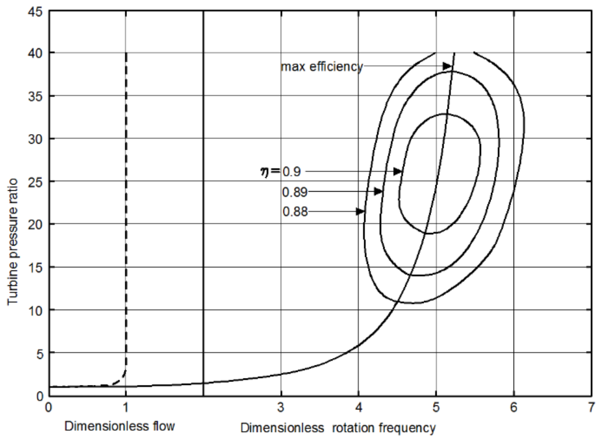

Fig. 4. Characteristic of the combined cycle gas turbine.

The efficiency of heat exchange equipment is taken into account by three factors: thermal efficiency, total pressure recovery factor for a hot heat transfer fluid, and total pressure recovery factor for a cold heat transfer fluid. As an assumption, it is accepted that these coefficients are independent of the installation operating mode. Their values for the calculations are given in table 2.

Table 2. Value of thermal efficiency.

Heat exchanger	Value of thermal efficiency
Cold utilizers	0,95
All heaters	0,9
Recuperators	0,9
Contact condensers	0,95

There are two contact condensers in the scheme of the compressorless CCGT unit in addition to heat exchangers that transfer heat through the wall, separating the heat transfer fluids. In these devices, the heat transfer fluids are not divided. As a result of this, mass transfer processes take place simultaneously with the process of heat transfer. Therefore, the systems of equations are supplemented by equations that take into account mass transfer for these devices. Moreover, a number of assumptions were made, the main of which are as follows.

The device has two heat transfer fluids. The heating heat transfer fluid is in the gaseous phase, the cooling heat transfer fluid is in the liquid phase. Part of the heating heat transfer fluid passes from the gaseous to the liquid phase during the cooling process. It is assumed that the liquid phase completely separates from the heating heat transfer fluid in the contact condenser, and it represents dry gas at the outlet. Also, the all liquid phase passes into the cooling heat transfer fluid. It is neglected (not taken into account in the calculation model) that individual components of the heating heat transfer fluid dissolve in the cooling heat transfer fluid.

In addition, it is considered that the phase transition occurs in equilibrium. At the same time, the partial pressure of water vapor fully corresponds to the saturation temperature.

To describe the CO2 compressor at this stage of research, a compressor characteristic with a thoroughly expanded operating range is conventionally adopted (Fig. 5).

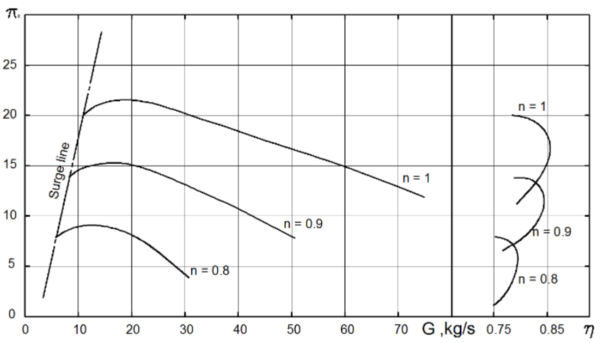

Fig. 5. Compressor characteristic with a thoroughly expanded operating range.

Attention should be paid to the following two parts: a device for producing liquid oxygen - the air separation unit (ASU), and the liquefier for CO2. Despite the fact that these are rather complex objects, they are considered as "black boxes" in this study. Therefore, the purpose of the research was to determine the required ranges of operating modes of these devices, and not to study the operation of these devices at partial loads.

To obtain liquid oxygen in the quantities, required to ensure the operation of a power plant, the most appropriate technology is cryogenic rectification. The energy, consumed by ASU, is spent mainly on the production of cold. The energy consumption for the production of cold can be determined by the following dependence:

$$Q_e = Q_c \times (T_h - T_c)/T_c \times (1/\eta) \quad (1)$$

where Q_e - energy consumption; Q_c - required amount of cold; T_h - temperature of a hot source (in this case, the environment); T_c - required temperature of cold; η - coefficient taking into account the difference between the real process of obtaining cold and the ideal Carnot cycle.

Considering that the required amount of cold is proportional to the required amount of liquid oxygen, then the power of ASU (NASU) can be determined by the following dependence, taking into account (1):

$$N_{ASU} = G_{O2} \times (T_h - T_c)/T_h \times (1/E_{ASU}) \quad (2)$$

where G_{O2} - required oxygen consumption; E_{ASU} - coefficient taking into consideration the production efficiency of liquid oxygen.

The temperature, required for the air separation, is the temperature of it liquefaction. The following assumptions are accepted: temperature, required for air separation - 100 K; coefficient, taking into account the production efficiency of liquid oxygen, does not depend on the operating mode of the compressorless CCGT unit. For the performed calculations, a value of the liquid oxygen production efficiency corresponds to 900 kJ/kg in standard climatic conditions. Such efficiency of modern air separation units is accepted when installations with oxygen fuel combustion are investigated [1].

A liquefaction of CO_2 is also based on a refrigeration cycle. Only in this case, the required temperature is the liquefaction temperature of CO_2. The power N_{lCO2}, spent on liquefying, can be expressed by analogy with (2):

$$N_{lCO2} = G_{CO2} \times (T_h - T_c)/T_c \times (1/E_{lCO2}) \quad (3)$$

where G_{CO2} – consumption of CO_2; E_{lCO2} - coefficient taking into account the efficiency of the refrigeration unit.

The nominal mode is selected as follows: nominal external conditions in accordance with ISO standard; nominal power for the electric supply to the grid was adopted equal to 300 MW; rated capacity for output of heat energy was taken to be equal to 120 MW; maximum power for heat energy output was accepted to be equal to 600 MW; the nominal temperature of the working fluid before the turbine was adopted relatively moderate (1373 K); the nominal pressure of the working fluid before the turbine was taken to be equal to 20 MPa; the expansion ratio of the turbine was accepted equal to 30 (it is kept constant in all modes).

The investigated scheme of the power plant has many degrees of freedom for independent control of parameters. It is necessary to choose the laws of regulation so that the problem has a unique solution (the number of degrees of freedom and the number of regulated parameters coincide). It is possible to independently control the speed of all pumps and the compressor for CO_2. In addition, there is an opportunity to partially bypass the recuperator of H_2O.

At this stage of research, it is not the purpose to find the optimal laws of regulation, because these laws are highly dependent on the engineering solutions, adopted at the later stages of the creation of the compressorless CCGT unit. One of the possible control laws was adopted for the certainty of calculations (without any claims for the best variant). It is assumed that the regulation of the parameters is as follows:

- the network water pump regulates the consumption of water proportional to the square root of power, output to the heating network;
- circulation pumps maintain the ratio of water equivalents for hot and cold heat transfer fluids as close as possible to one;
- the CO_2 compressor keeps constant an expansion ratio of the working fluid in the combined cycle gas turbine at all investigated operating modes;
- the fuel pump regulates the fuel supply so that to provide a predetermined power supply to the grid;
- the CO_2 feed pump maintains a constant temperature of the working fluid at the combined cycle gas turbine inlet at all investigated operating modes;
- the oxygen pump regulates the supply of oxygen so as to provide the minimum necessary excess of oxygen;
- the H_2O feed pump controls the water supply in such a way as to provide the set power for heat supply to the grid;

If the CO_2/H_2O ratio has reached its minimum value, the law of thermal power regulation changes. In this case, keeping the minimum value of CO_2/H_2O, a part of the water is bypassed the H2O recuperator, going directly into the combustion chamber.

Obtained results and their analysis

In accordance with the adopted laws of regulation, calculations were performed that fully cover the power range for electric supply from 120 to 360 MW (For gas turbine units are required to allow exceeding the nominal power by 20% unless the parameters, limiting efficiency or resource of an installation, are not exceeded.) and heat supply from 120 to 600 MW. The dependence of the efficiency of electric supply on the operating mode is shown in Fig. 6. The dependence of the coefficient of fuel utilization (CFU) on the operating mode is presented in Fig. 7. The above dependencies take into account the energy consumption for own needs.

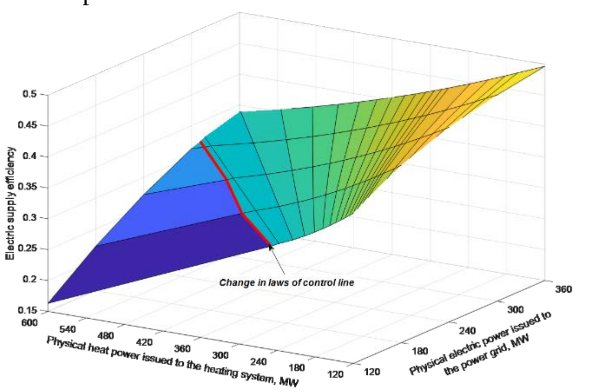

Fig. 6. Dependence of the electric supply efficiency on the operating mode.

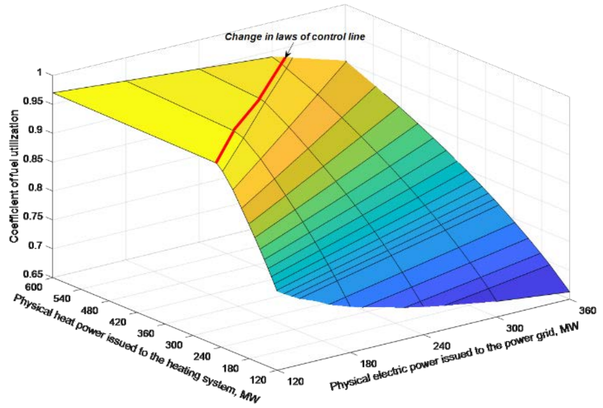

Fig. 7. Dependence of CFU on the operating mode.

It should be noted that the given efficiency and CFU are related to the higher calorific value of the fuel. Natural gas has the higher calorific value approximately 11% more than the lower calorific value. Therefore, this must be taken into account in a comparative analysis with installations in which these indicators are referred to the lower calorific value. Consequently, with minimal heat production (Fig. 6), the efficiency values, achieved in the compressorless CCGT units, for the electric supply at nominal and at maximum operating modes are equal to 46.9% and 48.8%, respectively. These values are very close to the level, having achieved by the best combined cycle plants.

Naturally, with an increase in the heat load, the electric supply efficiency decreases. In addition, at high heat loads, when the heat power is five times higher than the electric power, the efficiency can drop to almost 15% (Fig. 6). Nevertheless, CFU grows (Fig. 7), and it exceeds 95% at high thermal loads. If this value is reduced to the lower calorific value of the fuel, it will exceed 100%. Such high values of CFU are a consequence of the fact that almost all of the water vapor, included into the working fluid, condenses at pressures, corresponding to higher saturation temperatures than the temperature of the return network water.

Therefore, almost all heat of the spent working fluid, including the vaporization heat of water vapor, resulting from the combustion of fuel, is converted into useful heat. In addition, a large amount of heat with the low temperature is utilized in the basic cycle (the liquid components of the working fluid are heated). As a result, only a part of energy, spent for own needs, is lost which cannot be converted into useful heat. The regulation of thermal power is carried out by changing the ratio of consumptions of recirculating CO2 and H2O. The effect of such regulation is associated with the redistribution of heat, removed from the cycle. To illustrate this redistribution, the process of heat removal from the thermodynamic cycle in T-S coordinates is shown in Fig. 8.

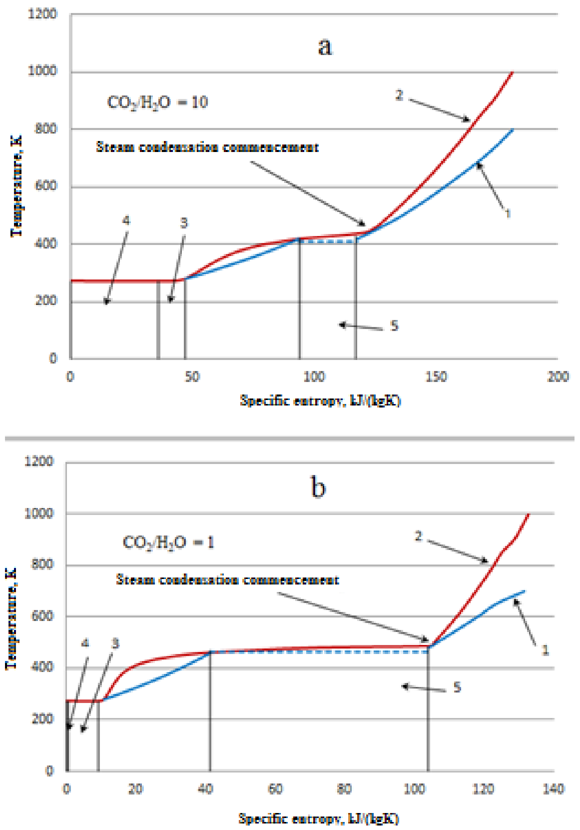

Fig. 8. The cooling process of the spent working fluid in T-S coordinates: 1 - line for heating the components of the working fluid before feeding into the combustion chamber; 2 – line for cooling of the spent working fluid; 3 - heat for warming up fuel and oxygen to the temperature of CO2 condensation; 4 – heat, removed into the environment; 5 – heat, delivered to the heating system.

Entropies S are given in specific units, but all entropies are assigned to one kilogram of fuel for better comparison. The reference points for heating and heated flows are selected so that the minimum temperature head, required to heat transfer, is provided everywhere. If at some point the heat is removed from the cycle, the reference points are adjusted accordingly.

Part of the heat of liquefied CO2 is distributed to fuel and oxygen heating up to the temperature of CO2 condensation (area 3). The rest of the CO2 condensation heat is removed by a refrigeration machine to the environment (area 4). This is the only irrevocably lost fraction of the energy during cooling of the spent working fluid. Part of the heat, removed from the cycle, is sent to the heating system (area 5). The possibility of heat removal to the heating system is connected with the fact that the water equivalent sharply increases at the beginning of water vapor condensation, and part of the heat can be removed from the cycle with a temperature close to the condensation onset temperature of H2O without prejudice to heat recovery in the cycle.

The onset temperature of H2O condensation is higher than 400 K even with the ratio CO2/H2O=10. This heat temperature satisfies the requirements of many heating systems even in the coldest time. The partial pressure of H2O in the spent working fluid increases with a decrease in the CO2/H2O ratio, and, accordingly, the onset temperature of H2O condensation rises. The amount of CO2 decreases. Hence, the amount of heat, removed by the refrigeration machine, declines and the heat removal to the heating system increases.

Already at a ratio of CO2/H2O=1, the heat removal to the environment approaches zero (Fig. 8b). Thus, almost all fuel energy (at the higher calorific value) is useful. Only a part of the energy, spent on the station own needs, and irretrievable losses during mechanical and electrical energy conversions are lost. The amount of energy loss can be 5-10% of the electric power of the station. At the same time, all theoretically possible heat is recovered and the temperature level of the network water, which is typical for the coldest days, is provided. The structure of energy losses for compressorless CCGT unit depending on the heat load is shown in Fig. 9.

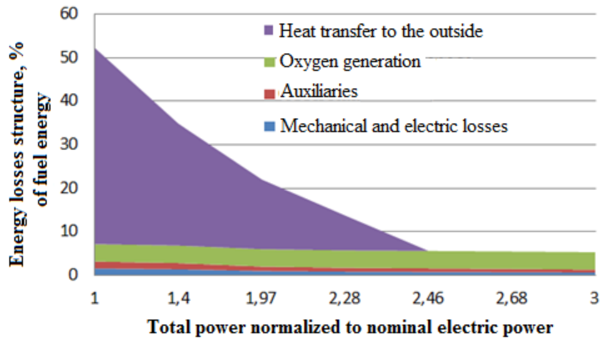

Fig. 9. The structure of energy losses for compressorless CCGT unit.

Energy losses are attributed to fuel energy, determined by the higher calorific value.

Using the dependence of energy losses on the total relative power (the sum of the electric and thermal power referred to the nominal electric power) and the annual load schedule, it is easy to obtain the excessive fuel consumption in the allocated time periods and the total annual excess fuel flow. A bar graph, showing the structure and the magnitude of annual excessive fuel consumption, is presented in Fig. 10.

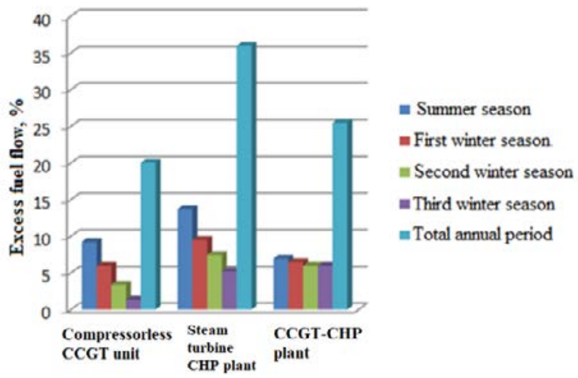

Fig. 10. Structure and magnitude of annual excess fuel flow.

The highest excessive fuel consumption is occurred in the summer when the heat load is minimal. In addition, the more thermal load is observed, the less excess fuel flow will be. The total annual excessive fuel consumption is slightly less than 20%. This value is a fairly good indicator. It can be illustrated by comparison with alternatives. Two of the most effective technologies for cogeneration of heat and electricity are considered for comparison. Several assumptions are made for the correct comparison.

It is assumed that the adopted operational model of the system in each compared variants refers to the rated power of the corresponding installation. The amount of excess fuel flow refers to the theoretically possible annual fuel consumption. It is expected that all compared options have a possibility to maintain a constant electrical load.

The first technology for comparison is the cogeneration steam-turbine plant T-250/300-240. It is currently the most common unit, belonging to the heating combined heat power plants. This plant is used for cogeneration of electricity and heat for the needs of district heating. In condensation mode, this installation has a specific operating fuel consumption of 326 goe/kW*h. This corresponds to an efficiency of 37.7%, if it attributes to the lower calorific value of fuel, and 33.9%, if it relates to the higher calorific value.

Consequently, the excess fuel flow in this mode is equal to 64.1%. Part of this excess is associated with mechanical and electrical losses in the equipment. Another part is connected with the power consumption for own requirements. These losses can be accepted by a constant share of electric power. Additional part of the excessive fuel consumption is related to water vapour, generated during the fuel combustion, which is emitted along with the exhaust gases of the boilers. This value is about 11% of fuel energy.

Supplementary part is the heat of exhaust gases, less the heat of water vapour (The condensation heat of water vapour is artificially moved into a separate component to emphasize the difference between the higher and lower calorific values of the fuel.). When the possibilities of increasing the heat capacity due to the regulation of steam extraction have been depleted, peak boilers are switched on. The exhaust gases heat of the peak boilers is another component of the excessive consumption of fuel. But the largest part of the excess fuel flow in the condensation mode is associated with the removal of heat into the condenser.

In the production of heat, steam extraction is produced and, thus, the heat, removed to the condenser, is transferred to the heating system. Thermal capacity is controlled by steam extraction until all steam is redirected to the heating system. In the real case, it is not possible to redirect all steam to heat production, but these small heat losses can be neglected. The structure of energy losses for a steam turbine CHP plant, depending on the heat load, is shown in Fig. 11.

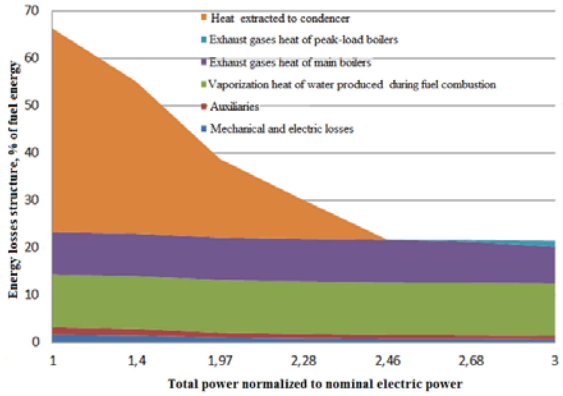

Fig. 11. The structure of energy losses for the steam turbine CHP plant

The total energy losses of the steam turbine CHP plant in the entire range of heat loads are greater than in the compressorless CCGT unit approximately by 15%. The structure and value of the annual excess fuel flow, shown in Fig. 10, show that the steam turbine CHP plant at all time intervals is inferior to the compressorless CCGT unit, and the total annual value of the excessive fuel consumption exceeds more than 15%.

The second technology, adopted for comparison, is a CCGT-CHP plant with cogeneration steam turbines [8]. The initial data for comparison are the following results of thermal tests [8]: efficiency in the condensation mode, referred to the lower calorific value, is equal to 59.8% (this value corresponds to 53.7% for the higher calorific value); guaranteed thermal power in the cogeneration mode is 40% of electric power; CFU in the cogeneration mode equals 80% and 72%, respectively, attributed to the lower and higher calorific values. Based on these data, as well as for the steam turbine CHP plant, the dependence of the energy losses structure on the heat load is plotted (Fig. 12).

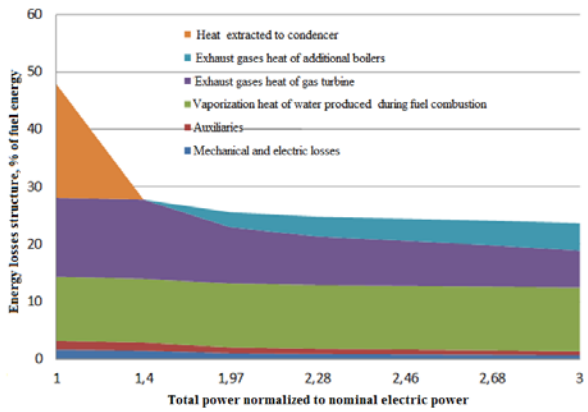

Fig. 12. Energy loss structure of the CCGT-CHP plant with cogeneration steam turbines.

In contrast to STP, heat removal to the condenser is significantly less in the CCGT-CHP plant with cogeneration steam turbines. Consequently, opportunity for heat production is also less. For the adopted operational model of the heat supply system, the heat, generated by the CCGT unit, is sufficient only for hot heating. Additional boilers will be required for heating in winter. It is required 2–3 times more exhaust gases per unit of fuel in the CCGT unit than in STP. In addition, the factors are the same that determine the temperature at the exhaust.

Thus, the component of the excess fuel flow, associated with the exhaust gases in the CCGT unit, is also 2–3 times more. These differences lead to a change in the nature of the structure of annual excessive fuel consumption. The excess fuel flow is approximately the same in all selected time ranges (Fig. 10). In the summer period, the CCGT-CHP plant defeats the compressorless CCGT unit about 5%. However, the CCGT-CHP plant is inferior in all other time periods and loses a little more than 5% in general for the annual period.

Conclusions

A mathematical model for the compressorless CCGT unit has been developed. It allows to study thermal characteristics in a wide range of operating modes at the earliest design stages. Researches have shown that the cycle of compressorless CCGT unit permits to achieve very high rates of thermal efficiency. The efficiency for electricity supply at the nominal mode can reach 46.9% even with a relatively moderate temperature of the working fluid before the turbine (1373 K). In addition, CFU exceeds 95% at high heat loads (referred to the higher calorific value of the fuel).

The obtained design characteristics of the compressorless CCGT unit were used to analyze the thermal efficiency of cogeneration of electricity and heat in district heating systems. The analysis of the efficiency of the compressorless CCGT unit in district heating systems showed their high potential for possible use in such systems. The annual excess fuel flow (exceeding the minimum theoretically possible) is less than 20% with the adopted operational model of the district heating system, while this value reaches 25% for the best CCGT units, and more than 35% for the steam turbine plants.

The high thermal efficiency of the compressorless CCGT unit is achieved by the rational configuration of the heat recovery and utilization system that allows to use all spent working fluid heat, including the heat of water condensation, generated during combustion.

Even without considering the fact that the thermal efficiency of the compressorless CCGT unit is adopted with all the energy costs for removing pure CO_2 from the cycle in the liquid phase state (the most convenient for transportation), there is a significant advantage over the traditional steam turbine plants and CCGT units on this indicator, in which CO_2 is emitted into the atmosphere along with a number of harmful substances in flue gases.

Acknowledgment

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Factor analysis of energy saving in households

Rais Burganov[1,*], *Emina* Altynbaeva[2] and *Ludmila* Maimakova [3]
[1]Kazan State Power Engineering University, Russia
[2]Kazan State Power Engineering University, Russia
[3]Kazan State Power Engineering University, Russia

Abstract. The paper discusses such issues as the role and importance of studying energy-saving behavior of households in the national economy and society, the need for new methodological approaches to their study, neoclassical, institutional, technological approaches to the study of the behavior of households in the energy sector. Also the basics of construction of multi-parameter mathematical models of household behavior are proposed..

1. Introduction

The energy-saving behavior of households as an object of research is constantly in the field of view of researchers from different countries. Among the significant works in recent years, one can single out the study by Mahmoud Salari and Roxana J. Javid on modeling household energy expenditures in the United States [1], Boudet X. and others on clustering energy-saving behavior in the family [2], Ito and Koichiro on the consumption or the average price of electricity [3]. Much attention in scientific works is paid to the study of individual manifestations of the energy-saving process, such as the problem of managing energy conservation in an apartment building, in everyday life. However, in order to solve the problems facing mankind in the field of ensuring the demand of economic entities and society for energy consumption, deeper and more fundamental research is needed, based on the principles of economic theory. It is not just about energy energy, but other types as well [4].

2. Data and Methods

The solution of problems in the field of energy saving of the population is one of the most important tasks of the state economic policy of any country, since the population of the Russian Federation consumes more than 14% of the total amount of electricity. According to statistics, in the structure of consumer spending by households in the Russian Federation, electricity consumption in 2018 amounted to 1.4 percent of the final data. A separate issue is the efficiency of energy use by all types of households. So, according to the researcher Boogen Nina in Switzerland, the average inefficiency of electricity use by Swiss households is about 20-25% [5]. Probably, in Russia, the population spends inefficiently a large share of total energy, including electricity.

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3 Results

A deep study of the energy-saving behavior of households as an object of research and projects should be based on theoretical and methodological approaches, which determine the effectiveness of the measures taken in the field of energy conservation. Depending on these methods, the mechanism for achieving the final goal, namely the optimization of energy consumption at different levels of management, can be predetermined. Thus, the energy-saving behavior of households as an object of study of integral science will receive a more fundamental justification if the methodology of economic theory is used.

Thus, from the point of view of representatives of the neoclassical direction of economic theory, the behavior of households in the use of energy resources is characterized by such concepts as “utility”, “benefit”, “profitability”, “marginal”, etc. Energy elasticity is essential for shaping household behavior. It is known that the most stimulating direction in energy saving is

* Corresponding author: burraabr@gmail.com

getting benefits from energy saving, that is, there is a market model of consumer behavior. The increase in electricity debt is one of the most pressing problems. Turning off the lights on time, good housekeeping and the use of energy-saving lamps in the household can save a lot of energy.

Resh Energy-saving behavior of households in terms of institutional theory is defined by such concepts as "institutions", "rules and regulations", "property", "energy contracts", etc. The institutional behavior of households in the energy sector is also influenced by informal norms. Among the problems is the theft of electricity. If in European countries the volume of theft does not exceed 4%, in the USA - 1-2%, then in many regions of our country it reaches 18-30% of the total electricity consumption. According to experts, half of this figure is the so-called technical losses, the other half is unaccounted electricity consumption, in other words, theft. From the side of the institutional theory, it is also possible to study the influence of the institution of ownership on the energy saving of households. In particular, the principles of using electricity by households in their apartment are different from using electricity in a common space. The lack of incentives for apartment owners to carry out energy saving measures and equipping buildings with general house metering devices makes itself felt. Laws, bylaws and other governing rules of the game in the energy sector are constantly reviewed, supplemented, etc. This is especially noticeable in the field of providing energy services to the population. Each year, households face changes in electricity tariffs, billing, etc.

According to the moral and educational concept as a part of institutionalism, the energy consumption of households is related to such institutions as customs and traditions, a careful attitude to energy - heat resources. Thus, researchers Marlyne Sahakian and Béatrice Bertho have identified the effect of household emotions on both reducing and improving energy use [6].

The technological concept of energy-saving behavior of households involves the use of modern energy-saving technologies. “Smart home”, “smart city”, “smart grids” are already becoming common concepts. Energy efficient technologies hold great promise for reducing the financial costs of households. For example, it is no longer a secret for anyone that LED lamps are more profitable than incandescent lamps of the old type. Technologies do not stand still, therefore there are a huge number of devices and systems for energy saving and energy efficiency. In particular, researchers from the University of Gothenburg have found a way to turn ordinary windows into solar-powered heaters that can significantly increase the temperature of the glass, even in freezing weather. The main functional components of the invention are plasmonic nanoantennas. With the help of plasmons, nanoantennas are capable of intensely absorbing light, which then heats up the entire surface.

In the economic-mathematical model, the process of energy-saving behavior of households can be described by a single or multi-parameter representations.

In a model with one parameter, it is possible to take the growth (or vice versa) of the population's income, which most of all forms the energy-saving behavior of energy users.

The multiparameter mathematical models take into account the influence of external (main and secondary) and internal (main and auxiliary) factors on the energy-saving behavior of households. Each variable can be positively or negatively reflected in the rational or irrational in the behavior of households in energy saving.

So, external factors, that is, influencing the process of energy saving from outside, include:

- the main factor (determining the purpose and meaning of energy saving), for example, a change in energy prices or the introduction of a tax on income received as a result of energy savings in households;
- minor factors (affecting the actions and interrelationships of the elements of the energy saving system), for example, the use of outdated house infrastructure of power grids, an increase in the number of used gadgets.

Internal factors of energy saving in households, that is, influencing the process of energy saving from within the energy saving system, include:

- basic (target settings in energy saving of family members), as using the principle "when leaving, turn off the light";
- auxiliary (for example, the level of equipment with energy-saving devices, the presence of energy receivers in the household with the class "A +++".

4. Discussion and Conclusion

The factorial approach will allow finding more viable models for the development of energy conservation in households.

At the same time, it is necessary to pay attention to the need for government intervention in the process of shaping energy-saving behavior of households. The state should take certain measures to form the optimal energy-saving behavior of households, taking into account their possibilities of using nature-like technologies. For example, in France, the cost of purchasing energy efficient equipment is deducted from the tax base of citizens.

In general, the current state of development of energy-saving and nature-like technologies will transform the behavior of households in the field of consumption of any type of energy.

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Study of the formation and decomposition processes of agglomerates during fixed bed combustion of polymeric materials

Igor Donskoy[1,*], *Aleksandr* Kozlov[1], *Maksim* Penzik[1] and *Denis* Svishchev[1]

[1]Melentiev Energy Systems Institute, SB RAS, 130 Lermontova st., Irkutsk, Russia

Abstract. There are a lot of problems related with thermal utilization of municipal solid waste, including the agglomeration of fuel particles, which occurs during combustion and gasification of waste for energy production. In order to investigate the features of the agglomeration processes, experiments were carried out on melting polyethylene granules in a mixture with ceramic particles. Using a mathematical model, the characteristics of agglomeration in a fixed bed heated with a hot gas are investigated.

1 Introduction

Municipal waste, as a rule, contains a large fraction of combustible components, but their combustion is often difficult due to high moisture content, compositional heterogeneity, and complex thermal behavior. Polymer materials in waste can melt, swell and agglomerate. Agglomeration leads to a decrease in the combustion efficiency, the formation of burnouts and clinkers. In a number of experimental works, the formation of agglomerates during combustion and gasification of biomass and char [1, 2], peat [3], and plastics [4] was investigated. In our works [5, 6], we discussed the limitations on the gasification process efficiency associated with the agglomeration of fuel particles.

In this work, using experimental and theoretical methods, we investigated some features of the formation and decomposition of polyethylene agglomerates in a mixture with inert material.

2 Experimental section

Samples of agglomerates were prepared in a laboratory setup (internal diameter 15 cm, layer height 14 cm). Mixtures of polyethylene granules and expanded clay particles (mass ratio 1:1, batch weight 600 g, particle size about 5 mm) were used. The experimental setup is shown in Fig. 1. The walls of the reactor are electrically heated to a temperature of 350-400°C. To prevent ignition, argon is used as gas medium (flow rate is 2 l/min). In the process of heating, polyethylene melts and fills the porous space, as a result of which the bed shrinks. Fig. 2 shows a typical agglomerate obtained by sintering polyethylene and expanded clay. In the above formulation, the size of the agglomerate is determined by the inner diameter of reactor, although a decrease in the polyethylene content is observed near the walls, which is associated with better conditions for melt flow.

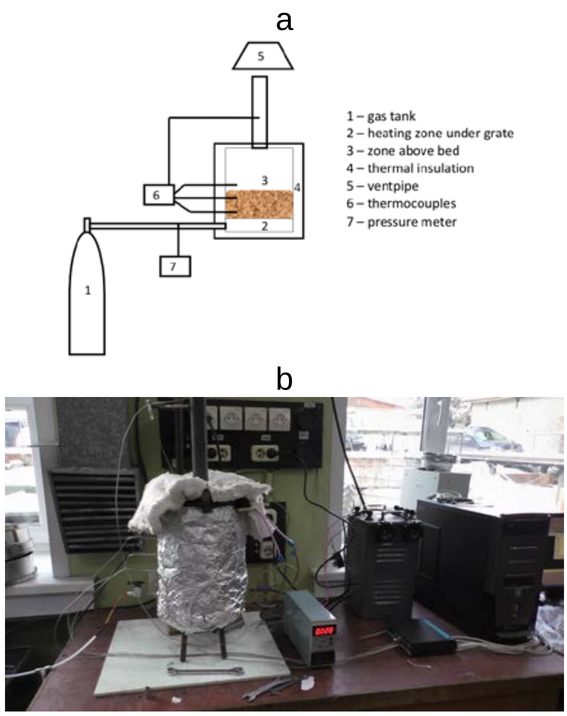

Fig. 1. Experimental setup scheme (a) and its exterior (b).

* Corresponding author: donskoy.chem@mail.ru

Fig. 2. Polyethylene-expanded clay agglomerate.

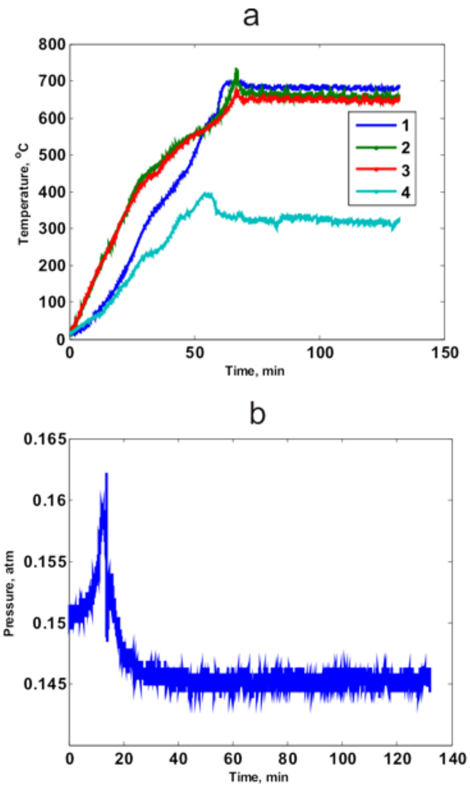

Fig. 3. Experimental results on agglomerate thermal decomposition: temperature in bed (a) and pressure drop between gas feed line and output (b).

After cooling, agglomerate was heated up to 700°C in air flow to clean reactor. The temperature curves are shown in Fig. 3*a*: thermocouples No. 1-3 are located in the bed, thermocouple No. 4 is at the gas outlet from the installation. The decomposition of the agglomerate occurs on its surface, and most of the mass does not participate in the reaction. Combustion occurs extremely slowly due to melting and deformation of the polyethylene surface layer. Therefore, despite the significant external heat input, the decomposition process takes more than hour to complete. Significant oscillations of temperature and pressure are observed during the process (Fig. 3*b*). Active combustion with a temperature rise in the wall temperature layer is observed only at the very late stage of agglomerate burnout. After the temperature and pressure had stabilized, the heating was turned off. Inspection of the contents showed that the decomposition of polyethylene was quite complete: expanded clay completely restored permeability, no polymer or soot residues on the walls and at the bottom were found after removing the material from the reactor.

3 Theoretical section

Numerical calculations of heating modes were carried out under the conditions of an experimental setup using the mathematical model from work [7] (similar models were used in works [8, 9]). The following assumptions are made: the heat and mass transfer equations are two-dimensional; gas filtration occurs according to Darcy's law; the effect of gravitational convection is negligible; uniform initial distribution of the polymer mass over the bed; decomposition of polyethylene is a single stage chemical reaction, the effective kinetic coefficients of the decomposition reaction are taken from [10]. Heating is carried out due to the heated gas, which is supplied to the particle bed at a constant pressure drop (10 kPa). The initial temperature of the bed is 27°C, the heating gas temperature rises from bed temperature to 327°C with different heating rates. When heated to the melting point (200°C), the polyethylene melts and fills the porous space, as a result of which the permeability decreases by several orders of magnitude. The effective cross section of the bed decreases and the gas flow rate decreases sharply. In fig. 3 shows the change in the gas flow rate through the upper boundary of the bed at different heating rates.

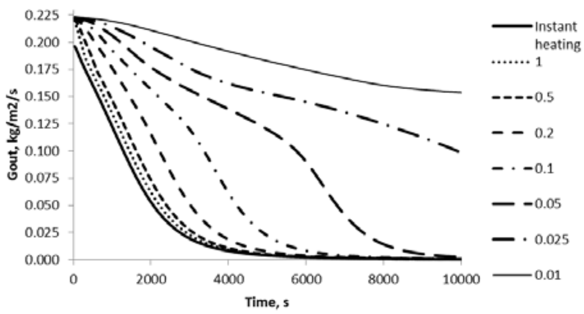

Fig. 3. Change in the mass flow rate of gas through the bed at a constant pressure drop (the numbers in the legend are the values of heating rate, K/s).

It can be seen from fig. 3 that with rapid gas heating (up to 0.5 K/s), the gas flow rate almost linearly decreases with time at the initial stage, after which the decrease in flow rate slows down. In this case, the lower part of the bed heats up quickly, the molten polymer forms a clinker, after which the bed is heated due to the thermal conductivity of the material.

With a further decrease in the heating rate, two stages of gas flow rate change are observed: the first stage with a slow decrease and the second stage, at which the flow rate decrease is close to exponential. The stage of a slow decrease in flow rate is apparently associated with the temperature dependence of the gas viscosity and density on temperature. After reaching the melting point of the polymer, the bed permeability drops sharply. Fig. 4 shows the dependence of the solid polyethylene fraction in the reactor on the heating time. Melting of about 15-20% polyethylene in the lower part of the reactor is sufficient to block the bed. With a decrease in the heating rate, the required fraction of molten polymer decreases: with slow heating, melting occurs in a larger volume of the reaction zone, therefore, the decrease in permeability becomes more uniform.

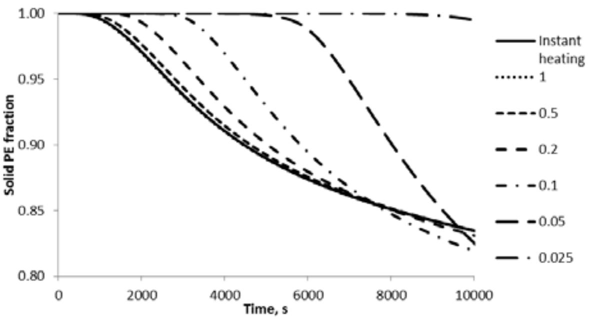

Fig. 4. Overall unmelted polyethylene fraction during bed heating (the numbers in the legend are the values of heating rate, K/s).

4 Conclusion

In this work, a study of the agglomeration of fixed bed consisting of polyethylene granules and inert material particles (expanded clay) was carried out. Samples of agglomerates were obtained, and their oxidative thermal decomposition was carried out. The features of clinker formation during polyethylene melting were investigated using a mathematical model. It is shown that with an increase in the gas heating rate, agglomeration in the lower part of the bed accelerates; therefore, to block the fixed bed, melting of a smaller fraction of the polymer is required.

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Features of formation and reduction of sulfur dioxide emissions when burning brown coal in boilers with liquid slag removal

Vladimir Elsukov[1,*], and *Svetlana* Latushkina [1]

[1]Bratsk State University, 40 Makarenko st., Bratsk, Russia

Abstract. The paper considers the influence of technological factors (design of the boiler-unit, load, air excess, the number of working dust collecting systems) on the formation and reduction of sulfur dioxide emissions in boilers with liquid slag removal. Understanding of this influence can be used both at many operating heat and power sources, and in the development of new combustion technologies. The long-term experience of burning brown coals of the Kansk-Achinsk basin (KAC) at CHPP-6 in Bratsk in boilers of the BKZ-320-140 PT type is studied and analyzed. The analysis uses the results of various thermodynamic and industrial studies of the sulfur dioxide formation during the combustion of KAC, including those carried out by the authors. They identified the temperature and structural zones of the boiler unit, where the resulting reaction of the sulfur dioxide transition to calcium sulfate occurs. It was found that such a zone is the upper part of the cooling chamber, where the indicated transition occurs at temperatures of 1500 ÷ 1400 K. It was found that SO_2 emissions rise with an increase in the boiler load and air excess. They also depend on the number of dust systems and their combination (determining the turbulization of combustion processes). A technological mechanism for the sulfur dioxide transition to calcium sulfate for the operation of boilers with liquid slag removal is proposed. Regime and constructive measures are proposed to reduce emissions of sulfur dioxide.

Keywords. Boilers with liquid slag removal, calcium sulfate, sulfur dioxide, excess air, boiler load, dust-forest systems, pollutant emissions, thermodynamic modeling of combustion processes

1 Introduction

The identification and clarification of factors increasing the efficiency of boilers with liquid slag removal can be in demand both at many operating TPPs and in the development of new combustion technologies. In this paper the authors analyze the long-term experience of burning Kansk-Achinsk coals (KAC) at CHPP-6 in Bratsk in boilers of the BKZ-320-140 PT type. The above experience includes successful upgrades of combustion technologies of the KAU Irsha-Borodinskoye field, as a result of which emissions of nitrogen oxides (NOx) were significantly reduced [1], as well as experimental studies, during which the concentrations of NOx, sulfur dioxide (SO_2), benzo [a] pyrene (BaP) were measured at various points of the boiler , and other technical and economic parameters [1,2].

All values of various parameters presented in these reports and publications [1,2] coincide with the exception of SO_2 concentrations. In the paper [2], the concentration of SO_2 in the effluent gases during the combustion of KAC of the Irsha-Borodinskoye field is ≈ 100–150 mg / m^3, and in publication [1] ≈ 330 mg / m^3. The differences in the presented SO_2 values are explained by the doubts of the authors [1] in the reliability of the SO_2 determination method. Currently, there are repeated measurements of SO_2 carried out at the station by various organizations, in which, when burning Irsha-Borodinsky coal, SO_2 emissions were always recorded less than 200 mg / m^3. Taking these measurements into account, this study gives the SO_2 values from the above work [2] as more representative in comparison with [1].

When analyzing the experimental data, the authors of this paper employed the results of the thermodynamic calculations of the KAC combustion carried out at the Siberian Power Engineering Institute (SEI, now ISEM) [3,4], including by the author [5].

In a number of kinetic studies [6] it was found that with a lack of air, sulfur-containing combustion products of fuel oil consist of H_2S, S, SH, SO, SO_2, and the concentration of sulfur oxides tends to zero. Under stoichiometric conditions, sulfur is mainly represented in the form of SO and SO_2, and traces of sulfuric anhydride

* Corresponding author: elswk@mail.ru

appear in the system. At α> 1, the highest sulfur oxides SO_2 and SO_3 prevail. Both domestic [7,8] and foreign researchers believe that the oxidation of sulfur dioxide to sulfuric anhydride is 0.2-2.5% for boiler units.

When burning solid fuel containing alkali metal oxides, reactions can occur such as:

$$CaO_{(c)} + SO_2 + 0{,}5O_2 = CaSO_{4(c)} - 500 кJ / кmol \quad (1)$$

Note that for the KAC Irsha-Borodinsky deposit, the molar ratio of calcium to sulfur (Ca/S) is approximately equal to three.

Until recently, this reaction has practically not been studied in relation to the combustion of KAC. This can be explained by the fact that during the combustion of KAC in traditional furnaces with the corresponding operating parameters, the formation of condensed gypsum occurred only to an insignificant extent, the equilibrium of reaction (1) was shifted to the left. It is believed that the gypsum formation reaction takes place mainly in the boiler flue pipes at low temperatures. This provision is incorporated into the methodology for determining emissions of sulfur compounds from boilers [9,10].

However, in connection with the recent development of technologies for low-temperature combustion of solid fuel, the above approach can lead to large inaccuracies or errors. Therefore, it becomes necessary to provide accurate information on the conditions of reaction (1) as applied to the combustion of KAC. When conducting thermodynamic studies of the KAC combustion [3,4,5], the authors found that in the state of thermodynamic equilibrium, all sulfur in the fuel is converted to CaSO4 at T <1400 K and the air excess coefficient α = 1.2; the transition begins at T ≈ 1500 K. It can be assumed that, upon combustion of other fuels (with different Ca/S molar ratios), the transition temperatures will change.

The results obtained are important because such combustion conditions are suitable not only for fluidized bed boilers, but also for some solid fuel flaring technologies, which will be discussed below. It follows that, in principle, it is possible to achieve a significant reduction in sulfur emissions from boilers using appropriate combustion technologies without the use of expensive de-sulfurization plants.

The parameters of the transition of gaseous sulphide anhydride to gypsum established during thermodynamic studies require experimental confirmation. It is also important to understand what the thermodynamic limitations of this transition depend on in order to obtain the possibility of increasing the temperature of gypsum formation and expanding the range of corresponding combustion technologies.

2 Combustion technologies implemented in boilers

The boiler is equipped with four individual dust systems with an industrial bunker. Drying and transportation of dust in the pulverization system is carried out by a mixture of "hot" and "cold" flue gases. The boilers are equipped with 16 systems for the supply and combustion of high density dust under vacuum (HDDV), including dust pipes, steam ejectors and burners. Moreover, for each of the 8 primary burners (see Fig. 1), two dust lines are installed. The above papers [1,2] consider experiments carried out on various boilers (boiler units) of the station, including at the boiler units No. 5 and 7. B.u. No. 5 was equipped with two closed (B, C) and two open dust collecting systems (CS), and at b.u. No. 7 (and other boilers) all dust collecting systems were closed (Fig. 2). For our further analysis it is important to note that the discharges of the drying agent from closed dust systems are brought into the upper part of the combustion chamber above the primary burners, and from open dust systems A and D (b.u.No. 5) - into the gas duct in front of the multicyclone collector.

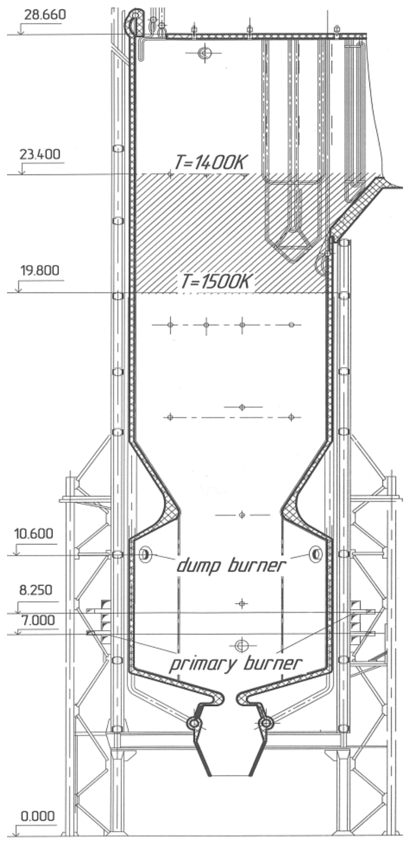

Fig. 1. Boiler furnace BKZ-320-140PT

Furnace b.u. (Fig. 1) is divided by protrusions of the front and rear screens into combustion and cooling chambers with a length of ≈ 6.3 and 19 m, respectively. The cooling chamber has a rectangular section, and the combustion chamber has a section of two communicating octahedrons (Fig. 2.). On the side faces of these octahedrons, two-tier burners are installed, the axes of which are directed tangentially to imaginary circles with a diameter of 0.98 m. Thus, the combustion chamber includes two pre-furnaces, in which "cyclonic" vertical torches are formed.

The concentrations of pollutants were determined according to the methods of the CAB ARRI promgas (the Cental Asian Branch of All-Russian Research Institute promgas).

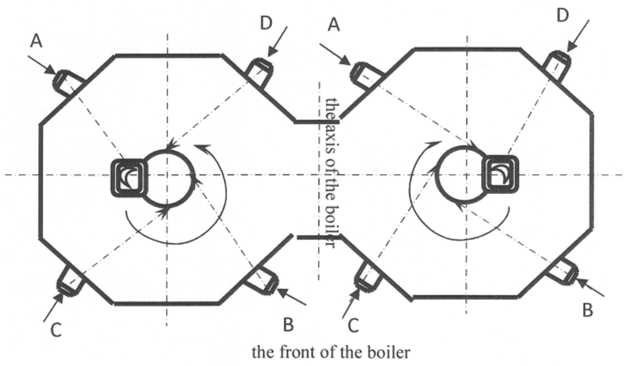

Fig. 2. Diagram of the combustion chamber in plan (A-D - supply of waste gases from the corresponding dust systems)

Since 2005, the plant began to burn KAC of small deposits (Kansky, Irbeysky and others). The use of KAC from these fields has led to a sharp increase in emissions of the main gaseous pollutants: NOx and SO_2. The aim of this paper is to analyze the environmental characteristics of the combustion processes of KAU and identify technical solutions to reduce emissions of all major pollutants, including SO_2.

3 Test results

To identify new patterns in the formation of pollutants, let us consider the results of tests of the b.u. No.5 and 7, stated in the above conclusion, taking into account the aerodynamics correspond to the numbers of the experiments. Numbers consisting of one figure refer to b.u. No.5, and the numbers of two figures, the first of which is 7, - to b.u. No.7.

11 experiments were carried out at the b.u. No.5. During experiments the working dust collecting systems were changed, and α_s (steam superheater) and Gs (steam consumption for ejectors) were varied, all of them are shown in Fig. 3. 18 experiments were carried out at the b.u. No.7. 4 of them are shown in Fig.3 to give an opportunity to compare them with b.u. No.5.

SO_2 concentrations were measured at the output of the furnace. All values have been refined by the authors of the presented work for standard conditions determined with an excess of air in the exhaust gases (α_{exh}) 1.4.

Figure 1 shows the area (shaded) where the flue gases have the above temperatures. The lines of gas temperatures marked in Fig. 1 are constructed according to the literature data [1] and correspond to the boiler load D = 300 t/h and α_s = 1.3. Let us note some provisions of the boiler unit operation that are important for further analysis. When gaseous working bodies (water vapor, air, etc.) are introduced into the combustion chamber, the temperature in the combustion chamber decreases, and at the output of the cooling chamber it rises. This result can be explained by a decrease in the residence time of the combustion products in the cooling chamber and was recorded during tests [1].

Figure 3 shows the results of the SO_2 content measurements in flue gases depending on the load (D), excess air behind the superheater (α_s) and the combination of working dust cjllecting systems. The analysis of the obtained characteristics indicates that SO_2 emissions do not exceed 143 mg/m^3 (it corresponds to the coefficient of binding of sulfur oxides by the mineral part of the fuel ≥75%). The SO_2 value decreases almost 1.5 times with a decrease in load from 297 to 205 t/h. The value of α_{ss} significantly affects SO_2 emissions: with a decrease of α_s, SO_2 emissions also decrease, other parameters remain constant.

4 Technological mechanism of the sulfur dioxide transaction to calcium sulfate

The presented dependencies can be explained by the following circumstances.

The rate of direct reaction (1) will be highest at the maximum temperature, that is, in the range of 1400-1500 K. The longer the flue gases will be at the indicated temperatures, the higher the binding coefficient of sulfur oxides will be.

Flue gases move relatively slowly in the cooling chamber, where reaction (1) predominantly takes place. Then in convective gas ducts the gas velocity increases and the temperature decreases. Accordingly, the reaction rate decreases sharply (1). Consequently, the earlier the flue gases in the cooling chamber cool down to 1500 K, the longer the reaction time (1) and the higher the binding coefficient of sulfur oxides will be .

It is known that with an increase in the boiler load, the temperatures of gases in the entire volume of the combustion chamber increase. This leads to a decrease in the SO_2 binding coefficient. The same happens with an increase in αs in flue gases (an increase in the flow rate of blast air into the combustion chamber and a decrease in the residence time of the combustion products in the cooling chamber).

The influence of the vacuum systems number on the course of reaction (1) is ambiguous. On the one hand, when two vacuum systems are turned on, the rotational component of the gas movement, their turbolization and the reaction rate increase (1). On the other hand, an increase in the consumption of flue gases (with an increase in the number of dust systems) leads to an increase in their temperatures in the cooling chamber, which reduces the reaction time in the cooling chamber. So the SO_2 emissions in experiment 10 (when 1 dust system is in operation) is noticeably lower than in experiments 11 and 2 (with the dust systems turned off). However, switching on two vacuum systems (eg 7.11) again increases SO_2 emissions to the values of tests 11 and 2.

Taking into account the above analysis, the following measures to reduce SO_2 emissions can be proposed. Excess air should be supplied not to the combustion chamber, but to the cooling chamber so that the temperature of the gases after mixing with air is 1500 K. This will increase the reaction time (1) and, accordingly, the SO_2 binding coefficient. The fuel should be burned in the combustion chamber at $\alpha_{c.ch}$ ≈1.015±0.05. The proposed measure is a special case of staged compression technology and, of course, requires additional reconstruction of air ducts. As you know, staged combustion technologies are widely used to reduce NO_x emissions. In this case, they can reduce both NO_x and SO_2.

Another measure to reduce SO_2 emissions can be recirculation of part of the ash from the ash collector to the cooling chamber. It will increase the area of its contact with SO_2 and, accordingly, the formation of gypsum.

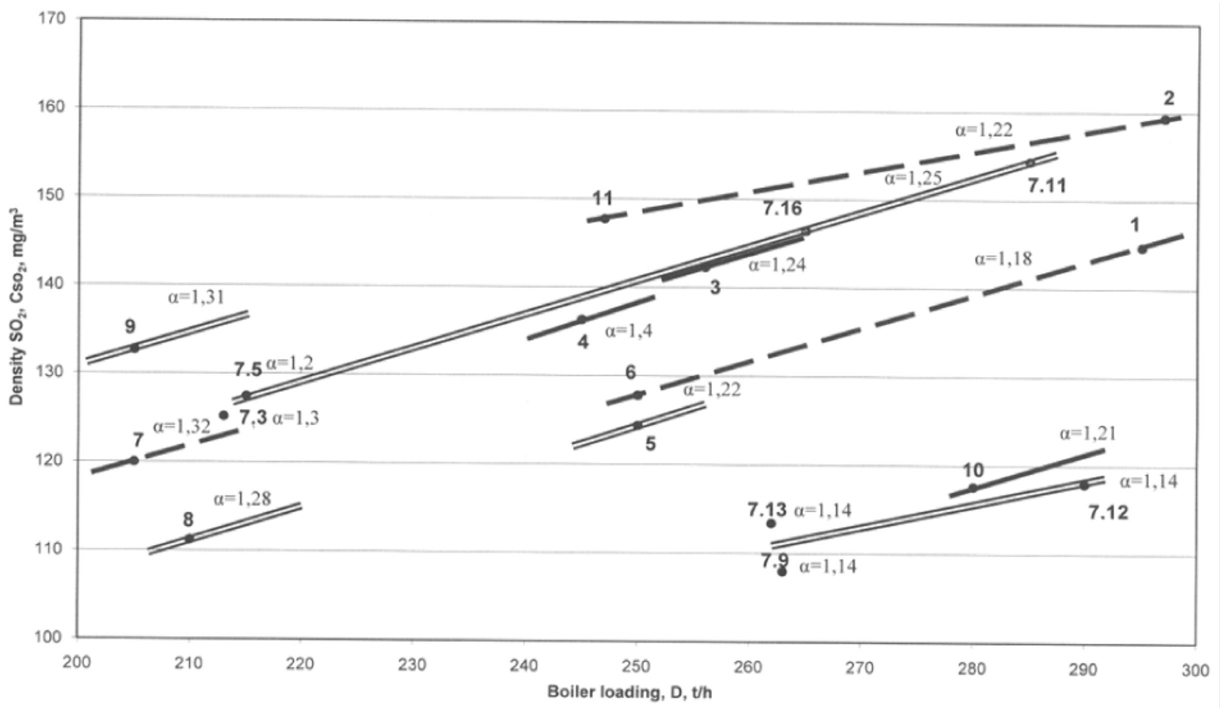

Fig. 3. Dependence of the density of sulfur dioxide on the boiler load, the number of working dust collecting systems and their combination, excess air (=== gases from two dust systems are discharged into the furnace; ─── gases from one dust system are discharged into the furnace; - - - - - no drying agents are discharged into the furnace)

5 Conclusions

1) Based on the analysis of thermodynamic and industrial studies, a mechanism for the transition of sulfur dioxide to calcium sulfate during the combustion of Kansk-Achinsk coals in boilers with liquid slag removal is proposed;
2) It is shown that during the combustion of KAC in boilers with liquid slag removal, most of the fuel sulfur (≥75%) is converted to calcium sulfate in the boiler cooling chamber in accordance with thermodynamic studies;
3) It was revealed that SO_2 emissions increase with an increasing boiler load and air excess;
4) The number of operating dust collecting systems has a complex effect on SO_2 emissions. On the one hand, an increase in this number leads to an increase in the consumption of flue gases and a decrease in the transition time of SO_2 to $CaSO_4$, on the other hand, the turbulization of combustion processes increases, and it accelerates the above transition;
5) Regime and constructive measures are proposed to reduce emissions of sulfur dioxide.

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Application of IDEF0 functional modeling methodology at the initial stage of design the modernization of TPP in ETC

Natalia Fedorova[1,*], *Yuriy* Shcheglov[1], and *Pavel* Kobylyackiy[2]

[1]Platov South-Russian State Polytechnic University (NPI), 346428, Rostov region, Novocherkassk, Prosveshcheniya, 132, Russia
[2]Don State Agrarian University, 346493, Rostov region, Persianovski set., Octyabrski district, Russia

Abstract. The tasks of thermal power plants (TPPs)modernization are to improve technical and environmental indicators, reduce the cost of energy, and take into account the requirements of international and Russian legislation. At the initial stage of modernization design, coordination of TPP indicators with specialists of various profiles and development of a general concept and structure of the station is necessary. In the traditional technical standards of the Russian Federation there are no documents regulating this process. To date, developed and adopted as national standards in a number of countries, including Russia, the IDEF methodology and family of standards, covering all stages and design aspects. This article discusses some aspects of the IDEF0 standard application at the initial stage of designing the TPPs modernization.

1 Introduction

Any technical objects in the process of operation become obsolete physically and mentally. To bring the operated technical facilities in line with modern technical, environmental, legal, social requirements, modernization or reconstruction is required. The purpose of TPPs modernization is to increase work efficiency according to a set of diverse criteria. The tasks of TPPs modernization are to improve technical and environmental indicators, reduce energy production cost, take into account the requirements of international and Russian legislation, increase reliability and reduce the risk of accidents, to improve the social relations in the station located region. Modernization of existing thermal power plants includes a number of stages: determination and analysis of thermal power plant problems, setting goals and tasks of modernization, studying the market of specialized technologies and equipment, preliminary preparation of alternative modernization projects, choosing a priority project [1], pre-project preparation of documentation and object of modernization, design (often understood as exclusively technical), project implementation, testing and commissioning, operation of the upgraded TPP.

Thermal power plants, especially solid fuel ones, have a great negative impact on the environment. As the result of fuel combustion, ash and slag materials are generated and accumulated, harmful oxides and excess steam are released into the atmosphere, soil and water bodies are polluted by heavy metals, and thermal pollution occurs. One of the ways to solve these problems is the transformation of thermal power plant into an energy technology complex (ETC) in the process of modernization. The task of the TPP functioning is the production of energy, electric and, possibly, thermal. The task of the ETC functioning is waste-free energy production; other (material) marketable products are produced from the energy cycle waste. In addition to a power plant as a producer of electric and thermal energy (heat-energy zone), an ETC based on TPPs can include up to 5 additional zones in various configurations (industrial separation, industrial utilization, analytical, service, transport and logistics) [2].

Design and operation of thermal power plants in Russia are standardized by a variety of regulatory and technical documents [3-8, etc.]. However, a number of aspects of the TPP life cycle, which must be agreed upon before the start of the technical design, are not covered by these documents. In some cases, these aspects should be agreed with environmentalists, lawyers, economists and other specialists who do not have technical education and do not have the skills to work with technical documents, drawn up, for example, according to a unified system of design documentation (USDD).

At the end of the 20th century, a methodology and a family of IDEF standards were developed, covering all stages and design aspects [9-12]. IDEF standards are accepted as national standards in a number of countries. The IDEF0 methodology is also adopted in Russia [13-15]. The IDEF methodology has an intuitive graphic language, which makes it possible to use it as a means of interprofessional communication, including when designing the modernization of thermal power plants in ETC [16].

* fedorovanv61@rambler.ru

2 Design standards for thermal power plants

Today, two groups of design standards can be distinguished: traditional technical standards (in Russia these are state standards of the Russian Federation) and standards based on the functional modeling methodology (IDEF).

Design of thermal power plants in Russia is carried out in accordance with national technical standards [3-8]. Separate documents, for example, [17, 18], regulate the procedure for TPPs technical and economic indicators calculating. But many aspects that need to be coordinated with relevant specialists and taken into account during design cannot be fully implemented and described by these means, namely:

– legislative conditions governing the construction and operation of TPPs;

– organizational relationships of TPPs with suppliers of fuel, equipment, consumables, repair organizations, electric grid companies;

– the impact of TPPs on the environment, the amount of waste produced and the possibility of their disposal;

– relationship with the social sphere, the number of jobs created, the need for various qualifications workers, the ability to train the required specialists in the station located region;

– regional conditions, including climatic and infrastructural;

– the need for electrical and thermal energy, including daily, weekly, seasonal, annual load fluctuations;

– risks of various nature, etc.

From the position of technical documentation, TPP is considered in isolation and only from a technical and technological point of view. But to ensure the successful functioning of the station should be considered as a complex system in collaboration with the external environment [19]. To take into account all aspects of the TPP life cycle, technical specialists will have to contact lawyers, economists, ecologists, sociologists, systems analysts, investors who speak other professional languages, which leads to the need to develop means of interprofessional communication.

Requirements for the design documentation (graphic and text documents that fully and unambiguously determine the composition and structure of the product and contain all the necessary data for its development, manufacture, control, operation, repair and disposal), similar to the USDD RF, exist in different countries, have its features and the trend towards world uniformity [20-24]. These requirements, legally documented in national standards, continue to apply along with adopted national standards based on the IDEF methodology (United Kingdom, [25]). The current system of normative and technical documentation of the Russian Federation and the IDEF0 standard do not contradict each other and are not alternative, since they have different fields of application in the process of design and operation of TPPs. In particular, the use of the IDEF0 standard is advisable at the initial stage of design. The IDEF0 standard, and subsequently other IDEF family standards that do not currently have an interpretation in USDD RF, should mutually complement technical standards and regulations. This will speed up the design process and increase the efficiency of TPPs operation.

3 Methodology and family of IDEF standards

3.1 IDEF methodology overview

In the 70s of the XX century, new approaches began to be developed to describe the structure and functions of complex systems, taking into account both the needs of social communication in the projects design and the opportunities provided by modeling and using computer software [26, 27]. One of such approaches was the development of a methodology and family of IDEF (Integrated DEFinition) standards, including 15 standards, covering all stages and design aspects [9-12] (Table 1).

Table 1. Classification of IDEF standards.

Designation	Name
IDEF	Integration Definition Metodology
IDEF0	Function Modeling
IDEF1	Information Modeling
IDEF2	Simulation Model Design
IDEF3	Process Description Capture
IDEF4	Object-Oriented Design
IDEF5	Ontology Description Capture
IDEF6	Design Rationale Capture
IDEF7	Information System Auditing
IDEF8	User Interface Modeling
IDEF9	Business Constraint Discovery method
IDEF10	Implementation Architecture Modeling
IDEF11	Information Artifact Modeling
IDEF12	Organization Modeling
IDEF13	Three Schema Mapping Design
IDEF14	Network Design

3.2 Functional modeling in the IDEF0 standard

Modern functional modeling is defined by the National Institute of Standards and Technology, USA, IDEF0 standard [9], which directly describes the methodology of functional modeling and graphical notation for representing the generated models. This technology is taken as the basis for the development of national standards in a number of countries. So in the UK in 1993, a similar SSADM (Structured Systems Analysis and Design Method) methodology was adopted as a national standard for the information systems development [25]. At the end of the 20th century, the Russian version of the IDEF0 standard was presented [13], later the State Standard of Russia developed, adopted and put into operation functional modeling standards [14-15] recommended for use in government agencies in order to support, in particular, the certification procedure for production activities for compliance with international standards ISO 9000 (9001) for the creation of quality management systems. In recent years, the need to harmonize Russian standards with foreign standards, both in terms of product requirements and documentation, is relevant for organizations that have foreign partners. Thus, the use of the IDEF0 standard is a normatively justified design stage in the Russian Federation.

The IDEF0 standard is the first in the lIDEF standards line. It is based on the concept of system units and the relationships between them. The IDEF0 methodology is based on an approach called SADT (Structured Analysis & Design Technique). The basis of this approach and IDEF0 methodology is the graphic language for the description (modeling) of systems. Each functional block (object, process) within the framework of a single system under consideration must have its own unique identification number (Fig. 1, A0). A block has three inputs: on the left is an input stream, material, informational or other, subjected to processing and transformation in a given functional block, on top is a control action that affects the transformation algorithm of a functional block, on the bottom is a mechanism, means that allow the block to perform functional tasks, convert input stream to output. For the block, the output on the right is the result of the conversion, the output stream. According to the recommendations of [13], an informational output stream at the bottom can be provided – a challenge, feedback. When constructing and analyzing IDEF0 models, the focus is on the relationships between the blocks, rather than their (temporal) sequence.

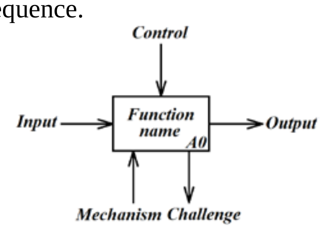

Fig. 1. Functional blok.

The IDEF0 language is standardized in terms of syntax and semantics. Therefore, functional models are clearly defined, well-structured, visual, modifiable and easy to use, and can have any depth of detail defined by the developer. IDEF0 models are three-dimensional, since any two-dimensional IDEF0 diagram can be supplemented by child functions represented on different layers or levels of the model. There are no restrictions on the number of child functional layers in the IDEF0 model. The standard provides for the possibility of developing models of two object states: AS-IS and TO-BE. Changes in the object during the transition from one state to another, new blocks and connections are distinguish visually (Fig. 2-7), in contrast to the schemes made in accordance with the USDD RF (Fig. 8, 9). The IDEF0 standard allows you to simulate both functional (Fig. 2-7) and structural (Fig. 10-13) circuits without overloading the created model with data that is redundant for specific purposes.

4 Energy facilities modeling using the IDEF0 standard

4.1 An example of IDEF0 model constructing and an analysis of TPP ash and slag removal system simulation results

During the modernization of TPP in the ETC, the focus is on the ash and slag materials disposal. In [1], using the Saaty′s Analytic Hierarchy Process, it was shown that this strategy is a priority in a wide range of diverse indicators values compared to strategies of other energy cycle wastes disposal.

The two-level model of ash and slag removal AS-IS-process at TPP is presented in fig. 2-3. The four-level model of ash and slag removal and disposal TO-BE-process at ETC is presented in fig. 4-7. For comparison, in fig. 8-9 shows the flow chart of ash hydro-transportation at TPP / ETC with dry ash collectors, made in accordance with the technical standards of the Russian Federation.

In fig. 8, we can trace the movement of slag and ash, starting from the slag bath of the boiler and ash collectors and ending with the ash and slag dump. A part of the TPP water path related to the ash and slag removal system is shown. The main elements of the equipment are shown, but their relative position is rather arbitrary. The arrows indicate the movement of water, air, ash, slag and ash-and-slag pulp, the medium specific form becomes apparent from the context of the scheme. The dotted line marks the zone related to the main building of the TPP. Instrumentation locations are indicated on special diagrams. The requirements for staff, the procedure for site maintenance, and routine maintenance are reflected in job descriptions. Laws, state standards and technical regulations related to the design and operation of this workshop were taken into account at the initial stage of design. Changes in the legislation, in particular, in the field of coal waste management, may lead to the need of change this scheme. But at the same time, the legislative, environmental, economic, staff and social aspects of the TPP design and operation, affecting the work order and composition of technical documentation, do not themselves relate to technical documentation and are not combined in single document.

According to fig. 2-7, all the components of the input stream «Control» (Laws, State standards, Technical regulations, Standards) and the components of the input stream «Mechanism» (Devices, Staff) are applied to all decomposition blocks without further elaboration. They form the so-called «Ttunnels», therefore, they are shown only in context diagrams. «Equipment», as a compo-nent of the «Mechanism» input stream, also applies to all blocks, but with the details disclosed in the corresponding diagrams.

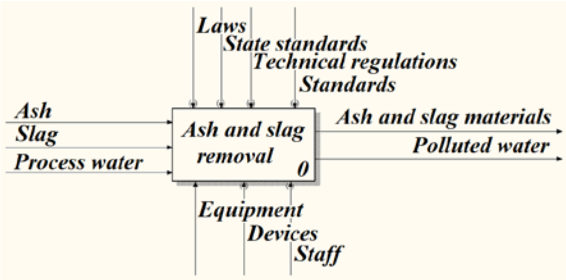

Fig. 2 Context diagram of the AS-IS-process ash-and-slag removal at TPP.

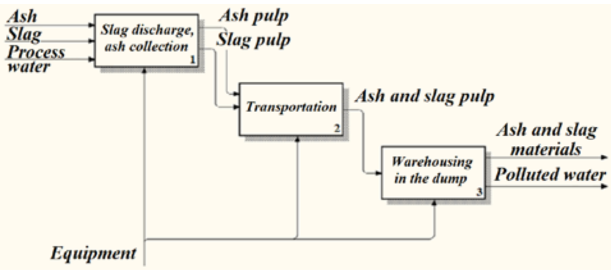

Fig. 3 Decomposition of the AS-IS-process context diagram of the ash-and-slag removal at TPP.

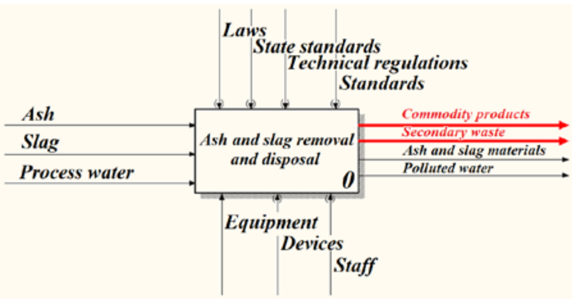

Fig. 4 Context diagram of the TO-BE-process ash-and-slag removal and disposal at ETC

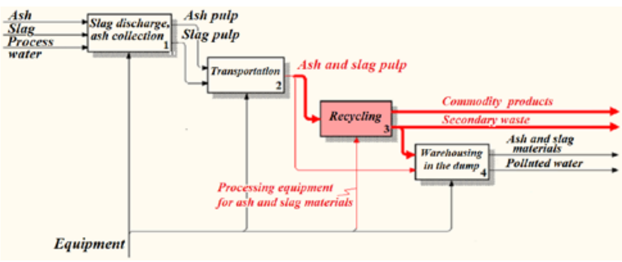

Fig. 5 Context diagram of the TO-BE-process ash-and-slag removal and disposal at ETC

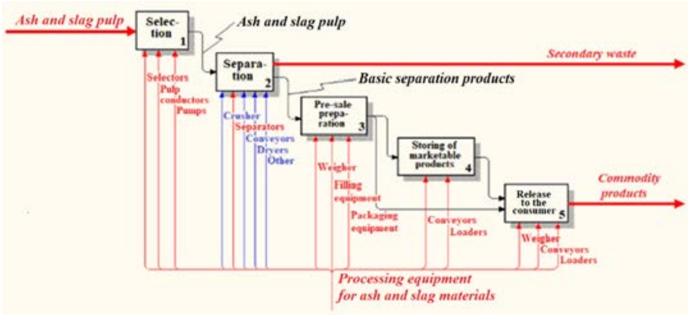

Fig. 6 Decomposition of the TO-BE-process «Recycling» stage of the ash-and-slag removal and disposal at ETC.

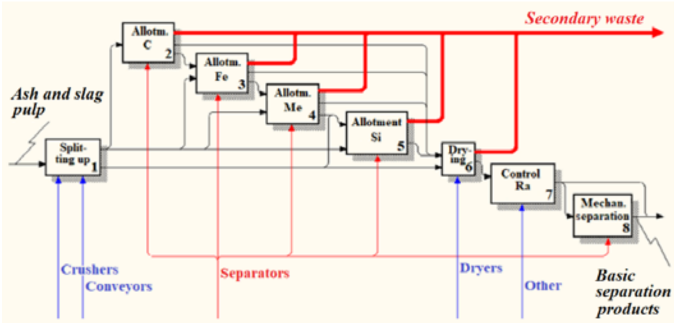

Fig. 7 Decomposition of the TO-BE-process «Separation» stage of the ash-and-slag removal and disposal at ETC.

In fig. 2 in the format of a context diagram, material flows are shown that in the «Ash and slag removal» function block are transformed, as well as the conditions and means of the transforming process. Quantitative characteristics can be indicated, for example, the volume of water con-sumed or the mass of the resulting ash and slag materials over a fixed period of time. If it is necessary to coordinate the positions of the diagram with lawyers, specific regulatory documents of the international, federal or regional levels, for example, dates of adoption and validity of licenses for land use and water use, can be indicated. In fig. 3 the decomposition of the context diagram is shown, the main stages of the ash and slag removal process are highlighted, and the phased conversion of input streams to output is shown. When considering this diagram, it is possible to agree on the complexity of the stages (introducing the Staff characteristics on the field of the diagram, indicating the labor costs, qualifications, and tolerance levels by stages). If necessary, the diagrams (fig. 2, 3) may indicate the marking and tech-nical characteristics of the equipment, in particular, the year of commissioning. This will make it possible to visualize the least reliable sections of the technological scheme that require priority equipment replacement. On technical informativeness the IDEF0 diagrams of the lower decomposition level correspond to the schemes of technical standards (Fig. 8). At the same time, the package of IDEF0 diagrams allows you to structure the process of ash and slag removal and present related information of legal, financial, social content, the coordination of which with relevant specialists is necessary when designing and operating the ash and slag removal system.

In fig. 4-7 shows the TO-BE process of ash and slag removal and disposal at the ETC with the introduction of the ash and slag processing section, in fig. 9 – a modernized ash and slag removal scheme, made in accordance with state technical standards RF.

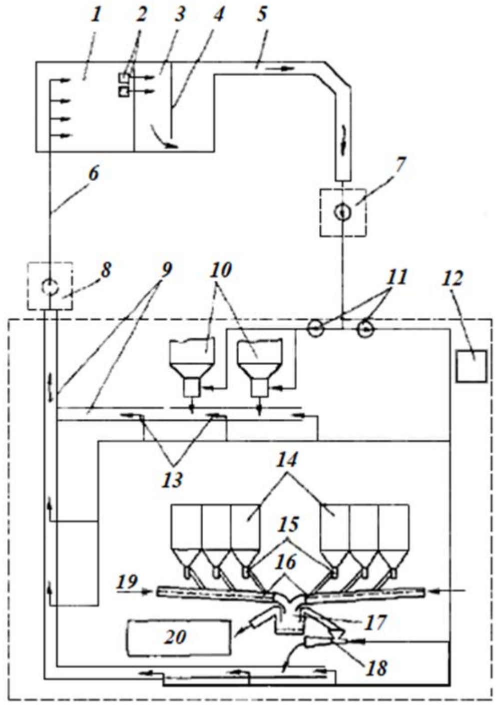

Fig. 8 Scheme of hydraulic ash removal at TPPs with dry ash collectors: 1 – ash and slag dump, 2 – mine wells, 3 – clarified water pool, 4 – separation dam, 5 – open channel, 6 - pulp line, 7 – pumps, 8 – pressure pumps, 9 – gravity channels, 10 – slag bath of the boiler, 11 – flushing pumps, 12 – installation for periodic cleaning of pipelines from carbonate deposits, 13 – incentive nozzles, 14 – ash collectors, 15 – pneumatic sluice gates or flashers, 16 – air chute, 17 – the end pneumatic layer shutter-switch, 18 – the mixing device for reception of an ash pulp, 19 – compressed air, 20 – dry ash.

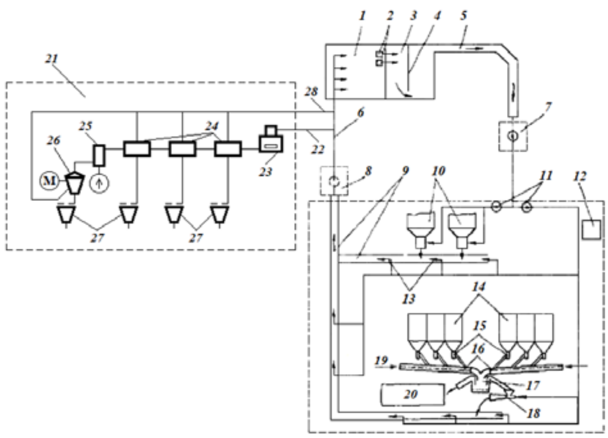

Fig. 9 Scheme of hydraulic ash removal at TPPs with dry ash collectors and the introduced section for processing of ash and slag materials: 1-20 – similarly to Fig. 7, 21 – section for processing ash and slag materials, 22 – selection of ash and slag for processing, 23 – crusher, 24 – devices for the isolation of morphological and chemical components, 25 – dryer, 26 – mechanical separator, 27 – bunkers of finished products, 28 – disposal secondary waste.

The diagram (fig. 9) shows the ash and slag processing section general structure and the specific place of this section introduction. The scheme format does not provide for the indication of measuring instruments on it, in particular, for monitoring the content of radionuclides, the flow of water, air and electricity. The marking and parameters of the input equipment are indicated in the specification or in the text part of the project.

According to fig. 4-7, in the TO-BE process, as compared to the AS-IS process, new components of the output stream are added – «Commodity products» and «Secondary waste». These changes will affect the entire technological cycle: the required amount of process water will change, new laws and regulations, measuring instruments and equipment will be required, the requirements for staff training will change.

The most serious changes will affect the «Equipment»: new devices will be required, such as Separators, Crushers, Dryers, Scales, etc. Moreover, the Separators group combines devices that are different in purpose and principle of action: for the separation of carbon, magnetic separation of iron, mechanical separation by size, etc. To draw attention to this aspect, this equipment group is highlighted. It is planned to store secondary separation waste in the dump, which will affect the composition and properties of the material product located in the dump. The «Slag removal, ash collection» stage has not changed, the changes in the «Transportation» and «Warehousing in the dump» stages are insignificant, therefore, their decomposition is not shown on the TO-BE diagrams. Upon completion of the «Transportation» stage, ash-and-slag pulp is transferred either to «Warehousing in the dump» or to «Processing» – a new stage, which includes, in particular, «Separation», «Pre-sale preparation» and «Release to the consumer» of Commodity products based on ash and slag. Processing of ash and slag materials can be carried out both within the framework of a single energy technological complex on the basis of a coal TPP, and delegated to special structures independent of TPP. Modernization of the TPP ash and slag removal system, presented in Fig. 4-7, the most simple to implement, since it does not connect with the process of ash and slag formation in the TPP boiler and with the subsequent removal of ash and slag from the boiler. But at the same time, it does not take into account some of the features and possibilities provided by the TPP technological cycle, such as liquid slag separation during liquid slag removal, use of flue and mill gases for drying, use of contaminated wet gases which formed in the processing of ash and slag materials in the TPP technological cycle, etc.

4.2 The modernization project of TPP into ETC in the IDEF0 standard

In fig. 10 shows the AS-IS-structural diagram of TPP in the IDEF0 standard, in fig. 11 – decomposition of the context diagram. In fig. 12, 13 – the context TO-BE-structural diagram of ETC based on TPP and its decomposition, respectively. Internal flows that remain unchanged are not shown. In TO-BE diagrams, the color indicates the addition of new or changing process units and flows.

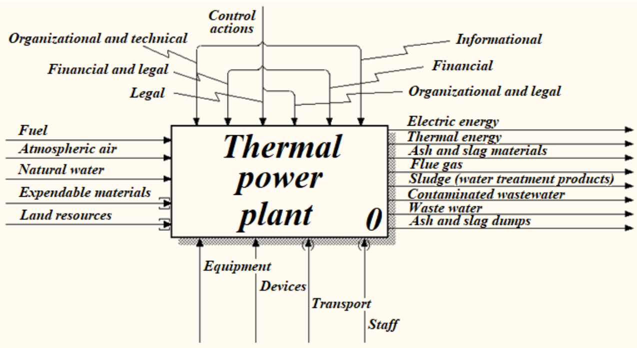

Fig. 10 The TPP structural scheme in the AS-IS IDEF0 context diagram format.

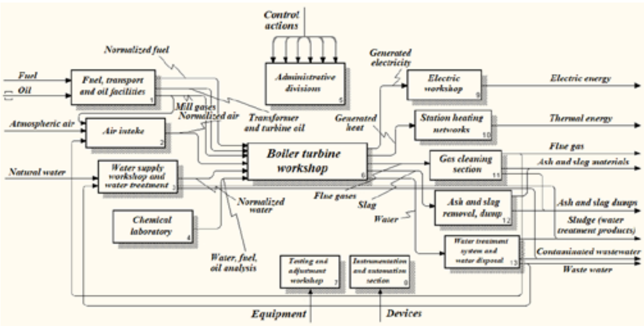

Fig. 11 Decomposition of the context AS-IS diagram IDEF0 of the TPP structural scheme.

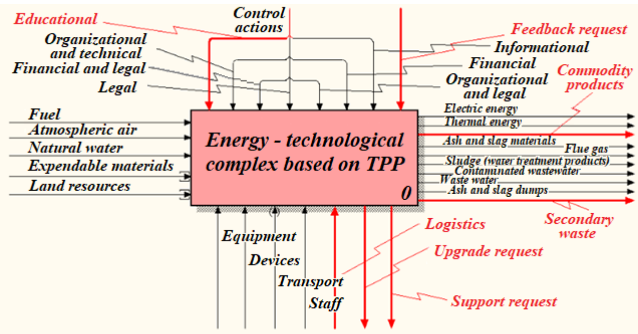

Fig. 12 The ETC structural scheme in the TO-BE IDEF0 context diagram format.

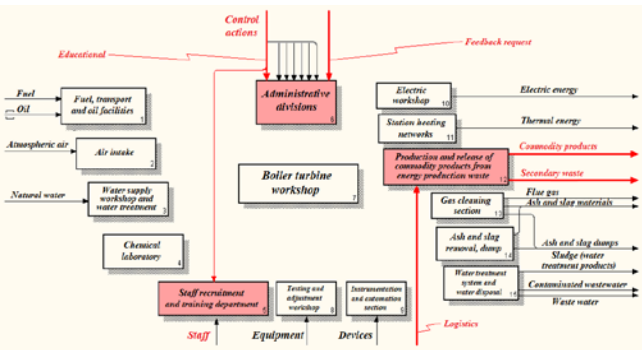

Fig. 13 Decomposition of the context TO-BE diagram IDEF0 of the ETC structural scheme.

The TO-BE context diagram shows that, compared to TPP, new material products are added for the ETC – Commodity products (from waste from the energy cycle) and Secondary waste. To fulfill the function of commodity production, conditions are necessary – the availability of logistics, support for the modernization of TPP and its transformation into an ETC (material, technical, financial, information and legal, organizational). A request for support is formed during the modernization of TPP.

Successful modernization requires changes in legislation, in state standards and norms, in the system of benefits, subsidies and fines, in organizational structures at the state level that oversee the energy facilities modernization. To increase the efficiency and effectiveness of these changes, feed-back of the information-legal environment and the internal material and financial environment of ETC is required, which is reflected in the introduction of the corresponding impact into the TO-BE diagrams. Also added a new control action – Educational. The ETC development, implementation and operation increase the staff qualification requirements.

The ETC functioning financial success depends directly on its adaptability: to the requirements of the consumer market, to the emerging market for innovative technology and equipment, to changing operating conditions.

4.3 Specifics of using the IDEF0 standard for energy facilities

Designing using IDEF standards in comparison with our traditional design technologies, taking into account the Russian Federation state technical standards, has its own capabilities, features, advantages and disadvantages, and the scope of primary applicability (Table 2).

Table 2. Specifics of using the IDEF0 standard for energy facilities.

Charact eristics	State standards of the Russian Federation	IDEF0 standard
Capabilities	Detailed technical project The specification, drawings, conditional graphic designations (CGD) are standardized The feasibility study is performed separately Work schedules are developed separately	A single project includes technical, financial, legal, organizational information A small amount of CGD - named blocks and arrows The ability to not display non-essential items Unlimited decomposition depth The ability to display the sequence, duration and cost of blocks The ability to display various points of view on the project, experts data
Featu res	Strict guidelines for the drawings and text documents design	Design recommendations

Continuation of the table 2.

Advantages		An image of technical objects with a completeness that allows them to be implemented materially (to build, carve, etc.) Unification and standardization of CGD establishes a one-to-one correspondence between circuit elements and equipment State standards fundamentals is taught in educational institutions	Coherence with international standards Simplified CGD Visibility and clarity for specialists in various fields of activity
Disadvantages		This is clear only to technical specialists on the project profile Contain redundant technical information for the initial design phase Do not contain non-technical information required at the initial design stage and during the modernization of the facility	Not applicable for the technical implementation of the project (construction, manufacture of the object) Lack knowledge of various profiles specialists about the capabilities of standard
Application scope	In the design process	At the stage of project implementation When developing technical solutions When calculating the criteria and indicators of technical and economic efficiency When choosing equipment When developing technical documentation for the implementation of the facility	At the stage of development and approval of the project When setting goals and design tasks In the formation (selection) of performance evaluation criteria When forming the technological and organizational structure of an object When coordinating the project with non-technical specialists (lawyers, ecologists, economists, etc.) When developing documentation
	At the enterprise	Chief engineer and organizational structures under his control at the enterprise	Director of the enterprise Legal service Financial service Staff service, etc.

4.4 IDEF0 standard application methodology in the energy facilities design

Designing using the IDEF0 standard (as well as other standards of the IDEF family) is a methodological tool, an approach to the design process. This technique allows you to optimize the design process, but not its result. The design process in the broad sense is not only technical design, but also related issues inseparable from it. Process optimization is the reduction of time for coordination, taking into account various aspects and points of view, the ability to choose the best option based on a set of criteria. It does not explicitly include technical and economic calculations, does not affect the choice of specific technological schemes and brands of equipment (these calculations and decisions remain with specialists – engineers and economists), and does not allow us to say that the efficiency of the system is increased with the use of this technique. But according to the documents [13-15], the use of the IDEF0 standard is a normatively justified design stage in the Russian Federation, as legitimate as the application of state technical standards.

The methodology for applying the IDEF0 standard in the design of energy facilities modernization includes the steps of:

– audit: analysis of design documentation, technical passport and the actual condition of the facility;

– formulation of the goals and tasks of modernization;

– construction and analysis of AS-IS diagrams in the IDEF0 standard;.

– development of alternative modernization projects;

– selection and justification of a priority project (for example, using the Saaty method);

– construction and analysis of TO-BE diagrams in the IDEF0 standard;

– development of design documentation for the project implementation.

5 Conclusions

On the example of a functional diagram of the TPP ash and slag removal system modernization with the introduction of ash and slag processing workshop and a TPP structural diagram, the individual stages of the methodology for developing an energy facility modernization project to by constructing AS-IS and TO-BE models in the IDEF0 standard are shown. The use of functional modeling in the IDEF0 standard is an effective and visual tool for displaying and analyzing the structure and functions of energy production facilities, process business planning and generation of modernization projects for these facilities.

The current system of normative and technical documentation of the Russian Federation and the IDEF0 standard are not alternative, since they have different fields of application. IDEF standards, and in particular, IDEF0, and technical standards should complement each other, which will speed up the design process and increase the efficiency of TPP operation. Models of the IDEF0 standard cannot replace traditional detailed technical plans and schemes, but are convenient and effective at the initial stage of design (planning) and can become the basis for the further development of detailed schemes in accordance with state technical and design standards.

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Accounting for variable operation conditions when optimizing cogeneration GTU and CCGT

Aleksandr M. Kler[1], *Pavel* V. Zharkov[1], *Elena* L. Stepanova[1] and *Yulia* M. Potanina[1,*]

[1] Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, 130 Lermontov str., Irkutsk, Russia

Abstract. The paper deals with a new approach to mathematical modeling and optimization of cogeneration GTU and CCGT, taking into account the variable conditions of their work, developed at the ISEM SB RAS. An analysis was carried out of the features of using this approach in relation to the thermal power plants. According to this approach at mathematical modelling of the plant there are structural optimized parameters (affecting the design of the plant), mode optimized parameters (affecting the operation of the plant in the mode with partial thermal loads) and balancing parameters affecting solution of the system of equations in the nominal mode and in modes at partial loads The connection between the design calculation (at rated loads) and verification calculations (at partial thermal loads) is carried out through the structural characteristics of the plant elements, determined during the design calculation. Taking into account these features, the problem of optimization of continuously changing parameters of cogeneration TPP was formulated, focused on the use of the developed optimization method. New mathematical models of the elements of the thermal power plants have been created. Optimization technical and economic studies of the considered plants were carried out in relation to various climatic conditions.

1 Introduction

A significant part of the world's electrical energy is produced by thermal power plants (TPPs) that burn fossil fuels. A significant number of such plants operate with variable external conditions. This concerns changes in the heat loads of heating units that carry out combined heat and power generation, due to a change in the heating load proportional to the outside temperature. In their mathematical modeling, it is necessary to take into account several characteristic operating modes. In this case, in one typical mode (most often in a mode with rated loads), the so-called design calculation of the plant is carried out. With the given parameters of the thermodynamic cycle and some design parameters of the plant elements, the calculation of all missing design and other parameters is carried out, which makes it possible to determine the investment to the plant, the energy consumption for auxiliary needs, etc. This mode can be named as a design mode, because it defines the design characteristics. In other typical modes, with fully known design parameters of all elements, the so-called verification calculation is carried out, which allows, for given design characteristics of the TPP elements and external conditions, to determine the flow rates of working fluids and coolants and thermodynamic parameters at all points of the TPP technological scheme. It should be noted that we are talking about the calculations of the operating modes established in time. Both of these types of calculations are reduced to solving nonlinear systems of algebraic and transcendental equations.

Optimization of TPP taking into account variable operating modes was considered in several works of ISEM SB RAS [1-4]. Optimization problems were formulated, and optimization calculations were carried out for cogeneration steam turbine, gas turbine and combined cycle plants using gradient methods that allow optimizing a large number of parameters. However, the cumbersomeness of the coordinated calculation of several modes greatly increased the optimization time and significantly worsened the convergence of the optimization process. Significant problems arose when using gradient optimization methods, since the determination of gradients due to the complexity of mathematical models of thermoelectric power plants is possible only by the finite-difference method. When considering several modes of operation, the errors of the verification calculations were superimposed on the errors of the design calculation, which significantly reduced the accuracy of determining the gradients of the objective function and restrictions. This significantly reduced the accuracy of finding the optimal solution and the stability of the optimization process.

The indicated optimization problems, taking into account several characteristic modes of operation of the TPP, are inherent in the traditional approach to mathematical modeling and optimization of the TPP parameters. According to this approach, mathematical models of elements (heat exchangers, turbomachines, combustion chambers, etc.) are developed. With each

* Corresponding author: julia@isem.irk.ru

reference to such a model, a nonlinear system of equations is solved that describes the corresponding element. As a rule, the calculation is performed by the iterative method. The calculation of the plant as a whole is reduced to an iterative process (using the same methods), at each iteration of which the models of the plant elements are sequentially addressed and the systems of equations for these elements are solved.

Since all the indicated systems of equations are nonlinear, their exact solution is impossible, which leads to the previously noted errors. At the same time, an increase in the accuracy of solving systems leads to a significant increase in the time of optimization calculations.

In [5], a new effective approach to mathematical modeling and optimization of TPP was proposed. In accordance with this approach, the process of solving nonlinear systems of equations of elements and the plant as a whole is transferred from the level of mathematical modeling to the level of optimization. In this case, all iterative processes are removed from the models of the plant elements and only the calculations of the residuals of the corresponding equations are left. This gives a dramatic improvement in the speed, convergence and stability of the optimization process, as well as an increase in the accuracy of finding the optimal solution.

In this paper, the features of this approach are considered when taking into account variable operating conditions.

The problem of optimizing the TPP parameters according to the criterion of economic efficiency (electricity price, heat price and internal rate of return on investment), taking into account several operating modes, according to a new approach to mathematical modeling of TPP, can be formulated as follows (problem I).

Find

$$\min_{x^{nm}, y^{pt}, x_1^{pt}, y_1^{pt}, ..., x_{n^x}^{pt}, y_{n^x}^{pt}} C^{el}(IRR, E_{yr}, Q_{yr}, B_{yr}, K, d^{ec}) \quad (1)$$

subject to

$$\theta^{nm} = H^{nm}(x^{nm}, y^{nm}, d^{nm}), \quad (2)$$

$$-z_{TP} \le \frac{\theta_j^{nm}}{\varepsilon_j^{nm}} \le z_{TP},\ j = 1,..., L^{nm} \quad (3)$$

$$G^{nm}(x^{nm}, y^{nm}, d^c) \ge 0, \quad (4)$$

$$\underline{x}^{nm} \le x^{nm} \le \overline{x}^{nm}, \quad (5)$$

$$S^K = \varphi^{nm}(x^{nm}, y^{nm}, d^{nm}), \quad (6)$$

$$K = \psi(S^K, d^{nm}), \quad (7)$$

$$B^{nm} = B^{nm}(x^{nm}, y^{nm}, d^{nm}), \quad (8)$$

$$Q^{nm} = Q^{nm}(x^{nm}, y^{nm}, d^{nm}), \quad (9)$$

$$N^{nm} = N^{nm}(x^{nm}, y^{nm}, d^{nm}), \quad (10)$$

$$\theta_i^{pt} = H^{pt}(x_i^{pt}, y_i^{pt}, S^K, d_i^{pt}), \quad (11)$$

$$-z_{TP} \le \frac{\theta_j^{pt}}{\varepsilon_j^{pt}} \le z_{TP},\ j = 1,..., L^{pt} \quad (12)$$

$$G_i^{pt}(x_i^{pt}, y_i^{pt}, S^K, d_i^{pt}) \ge 0, \quad (13)$$

$$\underline{x}^{pt} \le x_i^{pt} \le \overline{x}^{pt}, \quad (14)$$

$$B_i^{pt} = B^{pt}(x_i^{pt}, y_i^{pt}, S^K, d_i^{pt}), \quad (15)$$

$$N_i^{pt} = N^{pt}(x_i^{pt}, y_i^{pt}, S^K, d_i^{pt}), \quad (16)$$

$$Q_i^{pt} = Q^{pt}(x_i^{pt}, y_i^{pt}, S^K, d_i^{pt}), \quad (17)$$

$$i = 1,...., n^X \quad (18)$$

$$E_{yr} = N^{nm}\tau^{nm} + \sum_{i=1}^{n^X} N_i^{pt}\tau_i^{pt}, \quad (19)$$

$$Q_{yr} = Q^{nm}\tau^{nm} + \sum_{i=1}^{n^X} Q_i^{pt}\tau_i^{pt}, \quad (20)$$

$$B_{yr} = B^{nm}\tau^{nm} + \sum_{i=1}^{n^X} B_i^{pt}\tau_i^{pt}, \quad (21)$$

where C^{el} is the the price of electricity determined at a given internal rate of return on investment and the price of heat supplied from the TPP, E_{yr} is the annual electric power supply, Q_{yr} is the annual heat energy supply, B_{yr} is the annual fuel consumption, K - capital investments into the plant, d^{ec} - initial economic data required to determine C^{el} (heat price, fuel price, share of conditionally fixed costs from capital investments, etc.), H^{nm} - L^{nm}-th dimensional system of nonlinear algebraic and transcendental equations describing design calculations in nominal (design) mode, θ^{nm} - L^{nm}-th dimensional vector of residuals of the system of equations H^{nm}, x^{nm} - n^{nm}-th dimensional vector of optimized parameters in the design mode (flow rate of working fluides, parameters of the thermodynamic cycle, structural parameters of elements), y^{nm} - L^{nm}-dimensional vector of calculated balanced parameters responsible for the solution of the system H^{nm}, d^{nm} - vector of constant parameters used in calculating the design mode, $\underline{x}^{nm}$, $\overline{x}^{nm}$ - vectors whose components define the minimum and maximum bounds for the corresponding component of the vector x^{nm}, G^{nm} - m^{nm}-th dimensional system of inequality constraints, which determines the range of admissible values of parameters in the design mode, S^K is the vector of design parameters of the plant determined at design mode, d^c is the vector of costs of the equipment components, B^{nm}, Q^{nm}, N^{nm} - hourly consumption of equivalent fuel, hourly heat supply to consumers and useful electric power in design mode, respectively, H^{pt}

- L^{pt} -th dimensional system of nonlinear algebraic and transcendental equations describing modes with off-design operating conditions, θ_i^{pt} - L^{pt} -th dimensional vector of H^{pt} -th system residuals in the *i*-th off-design mode at partial loads, x_i^{pt} - n^{pt} - dimensional vector of the optimized parameters in the *i*-th off-design mode at partial loads (fuel consumption, pressure in the regulated steam extraction of a cogeneration steam turbine, etc.), y_i^{pt} - L^{pt} - dimensional vector of calculated balanced parameters responsible for the solution of the system H^{pt} at the *i*-th mode at partial loads, d_i^{pt} - vector of constant parameters used in the *i*-th off-design mode at partial loads, G_i^{pt} - m^{pt} -th dimensional system of constraints - inequalities, which determines the range of admissible values of parameters in the *i*-th off-design mode at partial loads, $\underline{x}^{pt}$, $\overline{x}^{pt}$ - vectors whose components define the minimum and maximum bounds for the corresponding components of the vectors x_i^{pt}, B_i^{pt}, N_i^{pt}, Q_i^{pt} - hourly consumption of equivalent fuel, useful electric power and hourly heat supply in the *i*-th off-design mode at partial loads, n^X - the number of modes at partial loads with carrying out verification calculations, τ^{nm} is the annual duration of the design mode, τ_i^{nm} is the annual duration of the *i*-th off-design mode at partial loads, ε_j^{nm} is the required accuracy of the solution at the *j*-th level of the system H^{nm}, ε_j^{pt} is the required accuracy of solving the *j*-th equation of the system H^{nm}, z_{TP} - constraints on relative residuals modules $\dfrac{\theta_j^{nm}}{\varepsilon_j^{nm}}$ and $\dfrac{\theta_j^{pt}}{\varepsilon_j^{pt}}$.

The approach to optimization of TPP parameters considered in [5] in relation to problem (I) has the following form. In expressions (3) and (12) z_{TP} is replaced by the parameter *z*. Each iteration takes two steps. At the first step, problem (I) is solved (taking into account the indicated changes). Moreover, at the first iteration, *z* takes on a large value $z^0 >> 1$. It should be noted that *z* is fixed at the first step.

At the second step, z is added to the optimized parameters and the problem of minimizing *z* is solved under all conditions (8)-(21) and with an additional condition $z \geq \dfrac{F(x,y)-F^t}{\sigma}$, where σ is the required accuracy of determining the optimal solution, F^t is the value of the objective function at the point of solving problem (I) at the first step. When solving the problem of the first step at the current iteration, the optimal value z^t obtained at the second step of the previous iteration is taken as a fixed value *z*. This process continues until the condition $z^t \leq z^r$ is met, where z^r is the required value of *z*.

Analysis of the structure of relations between the parameters of design and verification calculations shows that a change in any component of vectors x^{nm} and y^{nm}, with constant values of all components of vectors y_i^{nm} and y^{nm}, will affect the result of all verification calculations. This is due to the connection on the vector S^K. Therefore, among partial derivatives of the form $\dfrac{\partial g_{ia}^{pt}}{\partial x_j^{nm}}$, $\dfrac{\partial \theta_{ib}^{pt}}{\partial x_j^{nm}}$, $\dfrac{\partial Q_i^{pt}}{\partial x_j^{nm}}$, $\dfrac{\partial N_i^{pt}}{\partial x_j^{nm}}$, $\dfrac{\partial B_i^{pt}}{\partial x_j^{nm}}$ and $\dfrac{\partial g_{ia}^{pt}}{\partial y_l^{nm}}$, $\dfrac{\partial \theta_{ib}^{pt}}{\partial y_l^{nm}}$, $\dfrac{\partial Q_i^{pt}}{\partial y_l^{nm}}$, $\dfrac{\partial N_i^{pt}}{\partial y_l^{nm}}$, $\dfrac{\partial B_i^{pt}}{\partial y_l^{nm}}$, there will be non-zero elements. This, in turn, requires determining partial derivatives of software and performing both design and all verification calculations. This, in turn, requires the performance of both design and all verification calculations when determining the partial derivatives with respect to x_j^{nm} and y_l^{nm}. On the contrary, changing the components of the vectors x_i^{pt} and y_i^{pt} with the values of x^{nm} and y^{nm} unchanged and the parameters of x_j^{pt} will only change the results of the i-th verification calculation. Therefore, the partial derivatives of all functions, except for the derivatives of vector functions θ_i^{pt}, g_i^{pt}, and scalar functions B_i^{pt}, N_i^{pt}, Q_i^{pt} will be equal to zero. Thus, when determining the partial derivatives with respect to the components of the vectors x_i^{pt} and y_i^{pt}, it is sufficient to carry out a verification calculation of this mode only. This makes it possible to reduce significantly the amount of computations when determining derivatives using the finite-difference method.

An important means of speeding up optimization calculations is the use of parallel calculations. In the optimization algorithm used in this work, there are two stages where such an application can have a significant effect. This primarily refers to the calculation of the objective function gradients and constraint gradients by the finite-difference method. The calculation of the partial derivative of some function *f* with respect to the *i*-th component of some vector x_i is carried out by the expression for the central difference of the form

$$\frac{\partial f}{\partial x_i} \approx \frac{f(x_1^0,...x_{i-1}^0,x_i^0+\Delta x_i,x_{i+1}^0,...x_b^0)-f(x_1^0,...,x_{i-1}^0,x_i^0-\Delta x_i,x_{i+1}^0,...x_n^0)}{2\cdot\Delta x_i}$$

where $x_j^0,...j=1,...,n$ are the values of the j-th component of the vector x at the base point, Δx_i is a trial step along the *i*-th component of the vector x. After the base point x^0 is known, the determination of partial derivatives of an arbitrary function *f* over all components of the vector x can occur independently, and two calculations of the function *f* must be performed to determine one partial derivative. In one calculation, the *i*-th parameter of the vector x takes the value $x_i^0 + \Delta x_i$, and in the other calculation - $x_i^0 - \Delta x_i$. In relation to the considered TPPs optimization, the derivatives are found over the components of independent vectors $x^{nm}, y^{nm}, x_i^{nm}, y_i^{nm}, i = 1,...n_{re}$. Given the dimension of these vectors, the calculation of partial derivatives can be divided into $n^{nm} + L^{nm} + n^X(n^{nm} + L^{nm})$ parallel branches. . At the same time, two calculations must be performed on each branch, including the determination of all residuals and inequality constraints, as well as the objective function. Taking into account the above-mentioned feature of the relationship between the design and verification calculations, both design and verification calculations are performed when determining derivatives from the components of vectors x^{nm} and y^{nm}. When determining derivatives from the components of vectors x_i^{pt} and y_i^{pt}, only the *i*-th verification calculation is performed.

Another stage of the optimization algorithm, which allows organizing parallel computations, is one-dimensional minimization along the chosen direction. It should be noted that the methods of half division, tangents and their combinations often used at this stage do not allow parallel calculations, since the choice of the current point along the direction of descent depends on the choice of the point in the previous step.

In this paper, we use a one-dimensional minimization method that does not have this drawback. After the descent direction *S* is selected from the point x^0, any point x along this direction is determined from the expression $x = x^0 + \lambda \cdot S$, where λ is a positive scalar value (step along the direction *S*). Since the interior point method is used for optimization, the condition $\psi(x^0) > 0$ is always satisfied, where ψ is a vector function of all constraints - inequalities of the problem. By linearizing the vector function ψ at the point x^0, it is easy to determine the maximum step $\lambda^{\max}$ for meeting the condition $\psi(x^0) \geq 0$. The value $\Delta\lambda = \frac{\lambda_{\max}}{n+1}$ is determined and *n*-steps $\lambda_i = \Delta\lambda \cdot i$, $i = 1,...,n$ are found. The coordinates of the points $x = x^0 + \lambda \cdot S$, $i = 1,...,n$ are determined. At all points x_i, design and verification calculations of the plant are carried out. The search is performed for a valid point where all constraints are met as strict inequalities, and the objective function reaches the lowest value among *n* points. Calculations of all *n* points are independent and can be performed on parallel branches.

It should be noted that in order to transfer the solution of systems of equations from the level of mathematical models, it is necessary to remove from them all computational cycles used to organize iterative processes. In the element model, only the residuals of its system of equations are calculated, which are the information-output parameters of the model. The variables that, in the traditional construction of the model, were determined as a result of solving the system of equations (balancing variables) are the information-input parameters of the model. Changing these variables allows you to reduce the values of the residuals modules to the required level. As already noted, according to the developed optimization method, the balancing variables act as additional optimized parameters. On the basis of these principles, mathematical models of the elements of technological schemes presented below were developed.

2 Optimization of operating modes of cogeneration gas turbine and combined cycle power plants

2.1 Optimization studies of the cogeneration gas turbine unit

Optimization studies of a cogeneration gas turbine unit (GTU) (Fig. 1) were carried out for two variants of climatic conditions. One nominal mode (design calculation), three modes at partial heat loads and one mode at a load on hot water supply only (non-heating period) were considered, in which verification calculations were carried out.

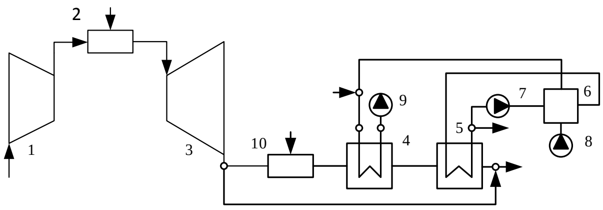

Fig: 1. Design flow diagram of the cogeneration gas turbine unit.
1 – air compressor, 2 – combustion chamber, 3 – gas turbine, 4 – waste heat boiler, 5 – contact heat exchanger, 6 – water heater, 7-9 – pumps, 10 – additional combustion chamber.

As an optimization criterion when conducting optimization studies, the price of electricity was taken at a given price of supplied heat and an internal rate of return on investment, which determines the level of economic efficiency of the investment project, and also the optimized parameters of the cycle in the nominal mode, design and mode optimized parameters, the number of which for each gas turbine had 11, 12 and 25 parameters, respectively. In the design mode, the list of parameters to be optimized included: the calculated heat load of the consumer; fuel consumption; internal, external diameters and pipe pitches of the heating surfaces of the waste heat boiler and heat exchangers; mass water velocities; gas pressure at the outlet of the air compressor; gas temperature at the gas turbine inlet; the share of the flow rate of exhaust gases from their total flow after the gas turbine going to the waste heat boiler. As regime optimized parameters in characteristic modes (verification calculations) were taken: fuel consumption; heating water consumption of the heating water make-up heater; gas temperature at the gas turbine inlet; the share of the flow rate of exhaust gases from their total flow after the gas turbine going to the waste heat boiler. Restrictions were imposed on the maximum permissible gas temperature at the gas turbine inlet, the non-negativity of the temperature head in the waste heat boiler, and on the mechanical stresses of the metal of the heat exchanger pipes. The number of imposed restrictions for power plants in each of the regions under consideration is 268 parameters.

Optimization calculations were carried out under the following conditions. The range of variation of the electrical power of the gas turbine was taken equal to 50-60 MW. The design outdoor temperature for the heating system for option 1 was taken as -25 °C, for option 2 it was -55 °C, the temperature chart of the heating network for option 1 was taken as 120/70 °C, for option 2 it was 150/70 °C. The heating period was divided into three intervals. For option 1, the duration of heating periods was 418 hours, 1316 hours, 3176 hours, the design outdoor temperature during these periods: 20 °C, -10 °C, 1.5 °C, respectively. For option 2, the duration of the heating periods was 1617 hours, 2262 hours, 2217 hours, the design outdoor temperature during these periods: -40 °C, -20 °C, 2 °C, respectively. The durations of non-heating periods were taken as 3850 hours and 2664 hours. The maximum permissible value of the gas temperature in front of the gas turbine is 1450^0C. When calculating the capital investments of the GTU, the following initial information was taken. Specific costs: gas turbine – 70 dollars/kW (per unit of maximum full power of the gas turbine), air compressor – 50 dollars/kW, turbine electric generator, pumps – 60 dollars/kW, heat exchangers made of carbon steel – 7000 dollars/ton, from steel 20000 - 21000 dollars/ton, electrical equipment 192 dollars/kW, systems depending on fuel consumption 240000 dollars/(ton/h). The internal rate of return on capital investments is 0.15, the coefficient of accounting for construction costs is 1.6; coefficient taking into account unforeseen costs – 1.03; coefficient taking into account other costs – 1.3; the coefficient of price adjustment for equipment – 1.65; coefficient taking into account the cost of unaccounted equipment – 1.1. The coefficient of the increase in the cost of construction in the climatic conditions of option 2 is taken equal to 1.52. The studies were carried out at fuel prices: for option 1 – 100 dollars/tce, for option 2 - 175 dollars/tce.

The main annual indicators for calculating the modes of the cogeneration gas turbine plant are given in table 1.

Table 1. The main annual indicators of the GTU

Main indicators	Options	
	1	2
Price for heat energy, dollars/Gcal	20,0	30, 0
Price for electricity, cents/kW	3,05	5,44
Specific investments, dollars/kW	537,8	774,2
Annual fuel consumption, thousands ton ce	187,7	183,5
Annual power consumption, thousands MWh	468,18	480,2
Annual heat consumption, thousands Gcal	608,1	590,0
Utilization ratio of heat fuel	0,77	0,78
Specific consumption of conventional fuel for heat release, kg ce/ Gcal	153,6	153,6
Specific consumption of conventional fuel for electricity supply, g ce/kWh	201,4	193,6
Annual fuel consumption of the 1st combustion chamber of the gas turbine, thousands ton ce	166,3	167,4
Annual fuel consumption of the 2nd combustion chamber of the gas turbine, thousands ton ce	21,4	16,1

Analysis of the results of optimization studies of GTU operating modes in both regions showed the following. The heat load of power plants is covered by heating the network water in the heat recovery boiler without attracting a peak source. With the fuel and heat prices taken into account, the electricity price was: for option 1 – 3.05 cents/kWh, for option 2 – 5.44 cents/ kWh, respectively. The coefficient of fuel heat utilization is equal to: for option 1 – 0.77, for option 2 – 0.78; the specific investment for option 1 – 537.8 dollars/kW, option 2 – 774.2 dollars/kW. The cost of conventional fuel for electricity supply: for option 1 – 201.4 g ce/kWh, for option 2 – 193.6 g ce/kWh. The maximum useful electrical power from both the gas turbine in design operating mode reaches 60 MW.

2.2 Optimization studies of cogeneration combined cycle power plant

The application of the new approach to the modeling of power plants is presented by the example of optimization of the parameters of the cogeneration combined cycle power plant, the diagram of which is shown in Fig. 2.

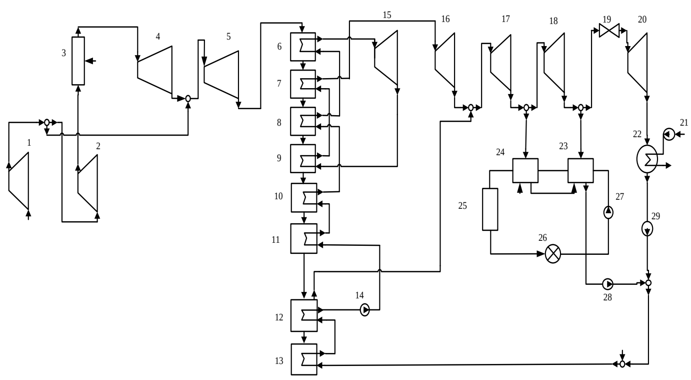

Fig: 2. Design flow diagram of the cogeneration CCGT.
1, 2 – air compressors, 3 – combustion chamber of a gas turbine, 4, 5 – sections of a gas turbine, 6, 8 – stages of a convective steam reheater, 7,9 – stages of an intermediate

steam reheater, 10, 12 – high and low pressure evaporators, 11, 13 – water economizer stages, 14 – feed water pump, 15-18, 20 – steam turbine compartments, 19 – regulating diaphragm, 21 – circulation pump, 22 – condenser, 23.24 – network heaters, 25 – peaking water boilers, 26 – heat consumer, 27,28,29 – pumps.

The plant includes a gas turbine unit with air extraction from the compressor for cooling the nozzle and rotor blades of the GT, a waste-heat boiler using combustion products, a cogeneration steam turbine, and a peak hot water boiler.

The mathematical model of the plant as a whole includes new mathematical models (without iterative cycles) of its elements - gas turbines, air compressors, convective gas-water heat exchangers on combustion products, sections of a steam turbine, and a condenser. The following parameters were optimized: heat load of the consumer in the design mode, fuel consumption into the combustion chamber, diameters, pipe pitches of heat exchangers of the waste heat boiler, mass velocities of water (steam) in them, enthalpy of water (steam) at the outlet, width and depth of the flue, pressure and enthalpy of live steam, circulation ratio in circuits with drums - separators, etc. The limitations that determine the area of physically and technically permissible operation of the plant: on mechanical stresses and the limiting temperature of the metal of heat exchanger pipes, non-negativity of temperature head at the gas inlet and outlet, flow rates of working fluids etc. were taken into account. The general calculation model contains 487 optimized and balancing parameters (131 in the design calculation and 89 in each verification calculation) and 589 inequality constraints (112 in the design calculation and 118 in each verification calculation).

As an efficiency criterion for optimization, the price of electricity was used at a given internal rate of return on investment. The design outdoor temperatures and the duration of the heating periods are taken the same as in the optimization calculations of the GTU. The results of optimization calculations are presented in Table 2 (flow rates, pressures and temperatures at various points of the flowchart are given for the mode with the rated load).

Table 2. Technical and economic indicators of TPP

Main indicators	Value	
	Option 1	Option 2
Gas temperature at the exit of the combustion chamber, °C	1300	1300
Gas temperature at the inlet of the heat recovery boiler, °C	693	689
Temperature of live steam, °C	488	504
Pressure of live steam, MPa	13,0	13,8
Consumption of live steam, kg/s	80,4	90,5
Temperature of reheat steam, °C	472	490
Pressure of reheat steam, MPa	3,5	3,6
Consumption of reheat steam, kg/s	80,4	90,5
Annual fuel consumption, thousands ton ce	450,6	557,6
Steam pressure in the 2nd heater, MPa	0,09	0,11
Steam pressure in the 1st heater, MPa	0,06	0,078
Steam pressure in the condenser, MPa	0,0038	0,0037
Calculated heat load, Gcal/h	376,2	351,7
Capacity, MW	353	364,4
Price for electricity, cents/kWh	8,09	8,64
Specific investments, dollars/kW	1596	1603
Extraction factor	0,62	0,73

Conclusions

Application of a new effective approach to optimization of parameters of thermal power plants operating with variable external conditions is presented. In accordance with this approach, the process of solving nonlinear systems of equations of elements and the plant as a whole is transferred from the level of mathematical modeling to the level of optimization. New mathematical models of the elements of the thermal power plants have been created, focused on performing design and verification calculations. Optimization technical and economic studies of the considered thermal power plants in various climatic conditions were carried out.

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Natural Language Processing for Forecasting Innovative Development of the Energy Infrastructure

Alex Kopaygorodsky[1,2,*]

[1]Melentiev Energy Systems Institute SB RAS, Irkutsk, Russia Federation
[2]Irkutsk National Research Technical University, Irkutsk, Russia Federation

Abstract. The article deals with the application of natural language processing methods to support research and forecasting the innovative development of energy infrastructure. The main methods of NLP, which are used to build an intelligent system to support scientific research, are considered. Methods of building infrastructure for processing Open Linked Data and Big Data are described. Semantic analysis and knowledge integration are based on ontology system. Applying suggested methods allow increasing quality of scientific research in this area and make it more effectively

Keywords. natural language processing, knowledge management, ontology, forecasting innovative development.

1 Introduction

In recent years, methods of natural language processing and semantic analysis have been actively developing, which makes it possible to use them to solve problems of scientific and technological forecasting. These methods are also applied in the energy technology research area. The use of Data Science methods in high-tech industries can significantly increase the efficiency of management decisions. Such an approach to the management of individual organizations at various levels are called “data-driven management”. When implementing this approach, specialized information and analytical departments are created in organizations under the leadership of CDO (Chief Digital Officer / Chief Data Officer). The opinion of CDO is key in matters of company development, identification of new business opportunities, ensuring entry into new market segments, bringing fundamentally new products, services and services to the market, etc. The main source for making management decisions is the results of the analysis of information and data collected from various sources. These are analysed to identify existing and emerging trends and shorten the response time to them, which reduces material losses, increases profits and ensures the sustainable development of the company. Ignoring technical and economic trends can be fatal or cause significant financial damage, examples of such companies are Polaroid, Kodak, Motorola, 3Com, Sun Microsystems.

The application of the described approach is relevant when solving forecasting problems and organizing monitoring of innovative technological solutions in any sector of the national economy, and especially for the development of the energy infrastructure of Russia. The energy infrastructure is the basis for the functioning of other industries, the results of which are ultimately aimed at improving the quality of life of the population. Predictive methods for the development of the energy industry, based on traditional mathematical models and software systems, are not always effective in conditions of uncertainty and lack of the necessary reliable information for the available models. The involvement of intelligent methods of semantic analysis, machine learning and Big Data technology to create tools that facilitate the work of experts and tools that perform preliminary processing of information analysed by experts is relevant.

2 Related Works

Forecasting as a method of research is used in the domain of Energy Infrastructure to study the development and functioning. In [1], authors considered the technological prospects of various directions of decisions of the problem of resource restrictions of the development of wind and solar energy. From that were drawn conclusions on the prospects of development of the Russian high-tech sectors of the Energy Industry and Economy. In addition, there is the problem of comparatively low installed capacity utilization of wind turbines in Russia [2]. Unfortunately, in view of the peculiarities of Russia's energy sector, the use of biofuel does not have any significant distribution. However, the use of biofuels is being actively studied in other countries of Europe and Asia [3, 4].

In [5] authors propose a language-independent semantic method for implementing an extractive multi-document summarizer system by using a combination of statistical, machine learning based, and graph-based methods. The author tool set learns the semantic representation of words from a set of given documents via word2vec method.

* Corresponding author: kopaygorodsky@isem.irk.ru

Also, Artificial Intelligence techniques successfully for forecasting the conduct of separate energy technologies. In [6], authors use patent indicators to predict the technological advances in Hydrogen Storage Materials (HSM). The patent analysis was carried out using bibliometrics and Text Mining approaches in order to forecast the future trend of development. Authors evaluated the technological life cycle stage, HSM class prominence, and the role of different countries in HSM patenting. They suggested that the life cycle stage of HSM is near market deployment.

The importance of knowledge sharing and the impact of this process on innovation are reviewed in [7]. Authors note that dialogue is the main tool for turning knowledge into innovation. This knowledge is also shared to stimulate innovation. Authors determined from the key topic analysis that the most established topics are open innovation, knowledge transfer, and absorptive capacity. This last concept facilitates that organizations identify and interiorize external knowledge that contributes to the achievement of institutional goals.

Employees of the Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences (ESI SB RAS) are engaged in the development of intelligent methods and tools to support decision-making in the field of energy research as well. Researchers use methods based on intelligent semantic technologies for searching, extracting and analysing heterogeneous data from electronic sources of information in accordance with the Big Data concept. [8-10]

3 Approaches for Natural language processing

There are many natural language processing methods used in information systems. All methods can be roughly divided into two large groups: statistical and linguistic methods. [11]

Statistical methods are based on the analysis of the frequency of occurrence of words: counting the number of occurrences of words in various fragments, the distribution of frequency across documents, etc. Linguistic analysis, on the other hand, is based on identifying individual words, analysing their morphological features, syntactic and semantic analysis of text fragments.

Stemming technology plays an important role in improving the analysis results and reducing the search area. Stemming allows you to identify the basis of a word, to associate many forms of the same word with each other, which makes it much easier to process text arrays. An important feature of stemming is its dependence on the language, since the word formation rules for each natural language are usually specific. The best results are obtained with stemming based on pre-calculated tables and dictionaries. However, this approach also has some difficulties: it is impossible to determine the stem of a new word that has not been previously processed.

One of the most common statistical measures is TF-IDF. TF is Term Frequency. IDF stands for Inverse Document Frequency. The TF-IDF measure allows you to assess the importance of a word in the context of a document, which is included in a collection of documents (corpus). TF-IDF of a word is proportional to the frequency of the word in the document and inversely proportional to the frequency of the word in all documents in the corpus. The TF-IDF measure makes it quite easy to separate words from general vocabulary from specific terms. However, an improperly selected corpus greatly affects the TF-IDF gauge. One of the main uses of TF-IDF is the vector representation of documents in a collection.

Another statistical analysis method is word2vec. This algorithm allows you to represent words as a multicomponent vector. Word2vec was developed by Google in 2013 and has been reflected in commercial projects of many companies. Word2vec is based on a collection of artificial neural network models designed to generate vector representations of words in natural language. Word2vec uses a large collection of text documents as input and maps each word to an N-vector. The resulting vectors allow calculating the semantic proximity of words.

The most common in the field of data analysis are two languages - Python and R.

Python's popularity is driven by a large number of libraries. One of the more interesting libraries for linguistic analysis of Python texts is the Natural Language Toolkit (NLTK). The NLTK library includes many tools for corpus management and analysis.

To solve the problem of supporting the forecasting of the innovative development of the energy infrastructure, both statistical and linguistic methods of text processing were used. After the construction of the terminological dictionary of the subject area, vector representations were calculated for its elements. When processing arrays of textual data, at the first stage, filtering and separation from frequently used words and other similar language elements were performed. Then the classification and semantic comparison with the elements of ontologies was performed. Further, the obtained characteristics of each document were processed statistically in order to identify general trends and patterns.

4 Semantic analysis of Big Data

Linked Open Data from state information systems, as well as from some commercial systems, are used as sources of information to predict the innovative development of energy infrastructure. All of these sources can contain potentially interesting information, but there can also be information noise. Examples of such sources are databases of scientific publications, conducted research, the results of intellectual activity, etc. Such sources, as a rule, adhere to a certain structure of the published data, and therefore can be processed using software adapters. In addition, Internet search engines can be used to search for unstructured but potentially interesting information for researchers. After the automatic acquisition of information, the results are analysed, classified and subsequently evaluated.

Scanning information sources regularly allows not only filling the knowledge store but also tracking the dynamics of changes in qualitative and quantitative indicators based on cognitive models. Analysis of the results of the issuance of Internet search engines allows you to assess information interest and track trends in technology development since the order and search results depend on the interest of many users. The technology for organisation monitoring of open and big data is based on the use of a pool of crawlers (software robots) specific to certain types of information resources. The main task of search robots is to extract and unify information about resources. It is necessary to perform some stages to analyse information posted on various sites. The first step is to get links to such sites. Today there are well-known information retrieval systems that are widespread on the Internet and have indexed information resources. The work of crawlers is based on extracting primary information from the databases of such search engines: at this stage, you can get the resource address, title and description. Then a detailed analysis of the content of the resource obtained from the found address is performed.

In the structure of the subsystem for information retrieval and analysis of open sources, two types of nodes can be distinguished: operational and control. The main task of operational nodes is to ensure the work of crawlers and data adapters. Control nodes are responsible for setting tasks for operational nodes, overall coordination and agreement of results. Due to its specifics, the task of information retrieval and analysis can be divided into many parallel processes, while the number of operational nodes can be large enough, which will increase the power of the information retrieval and analysis subsystem. Thus, it is advisable to locate some components for search in data centres (as close as possible to the backbone communication channels). In data centres on rented computing resources, clusters of data adapters that process structured sources of open data on demand and crawler farms that scan the Internet space are deployed. When testing data collection, the control node locate in Eastern Siberia, where connection to large trunk communication channels is difficult, operational nodes were located at traffic exchange points and were geographically locate in Central Europe.

5 Knowledge integration based on ontologies

When justifying decision-making on the paths of innovative development, due to the complexity and multifactorial nature of the estimates and options obtained, a rational approach is a combination of formalized methods and the informal experience of experts. The results obtained at each stage should be presented in a comfortable and easily perceived form both for experts and, as a result, for a decision-maker. This feature is very important. Using the visual analytics apparatus allows you to get such an idea. Visual analytics tools make it possible to evaluate in detail the main data sets for substantiating the innovative development of the energy sector: by research and development in the field of energy technologies, by the composition and topology of connections, by intensity and significance, by activity centres and other parameters presented in various analytical sections. Also, researchers perform visualization of solutions to multi-criteria problems on a variety of predefined scenarios. The scenario approach reduces the uncertainty factors of external and internal conditions at the stages of choosing a solution.

The integration of information and knowledge obtained from various sources is carried out based on a system of ontologies. Semantic integration uses a common conceptual framework for mapping (linking) individual elements based on it. An ontological space that includes a collection of ontologies does this. The system of ontologies consists of the ontologies of the fuel and energy complex, energy industries and individual energy technologies, energy research. The ontology system is the main component of the search engine, based on which the domain setting and allow to make a knowledge integration.

The ontology of energy technologies describes a hierarchical end-to-end conceptual model of the subject area that describes the object of research, specifies the structure of energy technologies, levels and slices of their consideration. The ontology of energy technology indicators describes the classification of technical, economic, environmental and social indicators of energy technologies, contains a description of the models of aggregation, generalization, comparison and use of technology indicators.

The main indicators include the level of technology maturity, the intensity of R&D in the main and related areas, the growth of application potential, key countries and organizations, technical barriers, and trends. The ontology defines the current forecast and limit values of indicators. Indicators are used in the selection of promising technologies for subsequent systemic consideration.

Ontologies describe the hierarchy of energy technologies with sufficient detailing of their components and interrelationships at different levels (resources, functions, types of energy conversion, consumer services, infrastructure, management, etc.); specifications of technologies or their characteristics for technical and economic efficiency; specifications of the full life cycle of energy technology (Life Cycle Assessment); specifications of socio-economic factors; specifications of indicators of innovative technology development; define a conceptual basis with bilingual reference and synonyms for concepts of all levels.

A fragment of a bilingual ontology is shown in Figure 1.

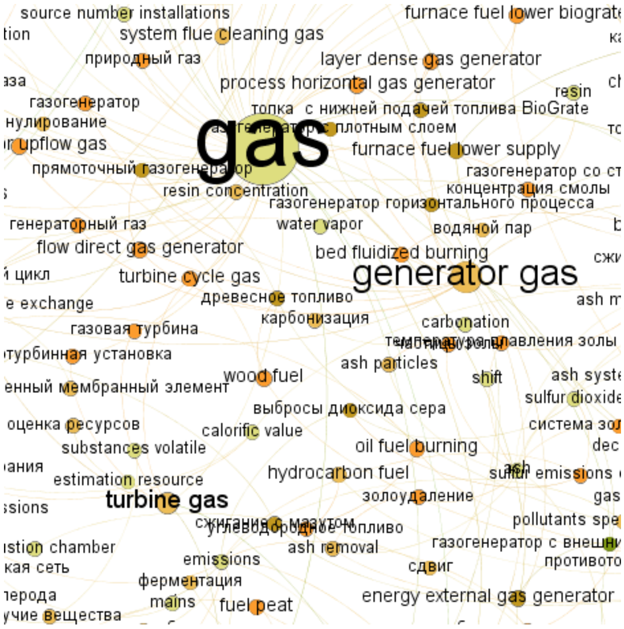

Fig. 1. Fragment of the bilinguistical ontology of energy technologies.

During the data collection process, more than 2 million primary documents were obtained from various open sources, more than 450 thousand documents were identified and classified based on the built ontology system. The knowledge portal organises access to information on 135 thousand scientific articles on energy systems published in 2009-2019. And about 213 thousand valid patents issued in different countries in 2009-2019, the application of which is possible in the field of energy.

The author analysed information on advanced research in the field of energy. A sharp increase in China's work in the field of energy and related engineering and materials science over the past 5 years has been revealed. Such an increase in scientific interest and the number of patents indicates improvements in existing and the creation of new mobile sources of electricity (high-capacity batteries) and, possibly, superconductors. Practical results will allow China to make a significant contribution to the development of the global electric car market in the next 5-7 years.

6. Conclusion

Natural language processing and semantic analysis of Big Data can be successfully applied to predict the innovative development of energy infrastructure. Also, these methods can be applied in solving scientific and practical problems of a similar class in other subject areas. Application of these methods and tools will facilitate preparation and increase the validity of advanced recommendations and decisions in the field of strategic energy development. These methods provide the organization of monitoring of innovative scientific and technical solutions and technologies in the energy sector, including their assessment of their effectiveness and feasibility, taking into account the characteristics and needs of the economy.

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Energy and economic analysis of thermoelectric generator on wood fuel

Oleg Marchenko

Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

Abstract. The advantages of thermoelectric generator (TEG) are the absence of moving parts, reliability, long service life, the possibility of fully automatic operation without maintenance. At the same time, TEGs also have disadvantages - low efficiency and high cost. In this regard, it is advisable to use them in autonomous installations of small power, as well as in devices intended mainly for heat supply, when the low efficiency of thermal energy conversion into electrical energy does not play a role. It is the latter case that is realized in furnaces that burn biomass. In this paper, we consider the main physical effects due to which the direct conversion of thermal energy into electrical energy occurs in semiconductor thermoelements. The conjugate problem of heat and electric charge transfer with temperature-dependent properties of a semiconductor is reduced to a problem with constant properties. Based on the literature data, the boundary conditions for the TEG were selected, its sizes were optimized, current-voltage characteristics were constructed, and the maximum power and efficiency were determined. Estimates of the cost and economic efficiency of using TEG are made.

1 Introduction

Most technologies for using wood biomass for power supply to consumers include the stages of thermal and then mechanical energy production. Mechanical energy is converted into electrical energy in electromechanical generators.

There are technologies that make it possible to obtain electrical energy without preliminary production mechanical energy. One of these technologies is the direct conversion of thermal energy into electrical energy in thermoelectric generators (TEG) [1, 2]. It uses thermoelectric effects: *a*) the temperature gradient in a solid causes diffusion of the electric charge carriers (in a semiconductor – electrons and holes), i.e. electric current; *b*) electric current is accompanied by heat generation or absorption.

The main thermoelectric effects – Seebeck, Peltier and Thomson – were discovered in the XIX century. Subsequently, it turned out that TEG of metal thermocouples have too low efficiency. At the same time, the use of semiconductor materials, including those with a variable doping profile or composed of separate segments, each optimized for the corresponding temperature range, made it possible to achieve an efficiency of up to 12-15% [3].

TEGs do not have moving parts, can operate without maintenance for a long time, they are compact, reliable, noiseless and environmentally-friendly power sources. At the same time, TEGs have disadvantages - high cost and low efficiency. These features have identified the application areas of TEG: space and ground power plants of low power, including those with nuclear heat sources (reactors and radioisotope sources). Such installations are designed for long-term operation without maintenance and therefore more important characteristics than efficiency are reliability, weight, specific energy content, specific power, etc.

Other options for using low-efficiency power sources are for electrochemical protection of gas pipelines against corrosion when fuel is available in excess [3, 4], or for heat recovery, which is normally lost in the surrounding space [5]. For example, TEG designs have been developed for utilizing heat from exhaust gases from cars [6, 7] or heat that is lost during combustion or gasification of biomass [8, 9].

Thermoelectric generators make it possible to create new commercially attractive systems that use waste heat and renewable energy resources [10, 11]. Wood biomass is an important source of renewable energy, the use of which in the global energy sector is increasing. Utilization of waste from industrial timber harvesting and its processing through energy use has a positive effect on the environmental situation and in some cases allows increasing the reliability and efficiency of heat and power supply to consumers. Combining the TEG with biomass stoves allows the generation of electrical energy using waste heat.

The systems proposed for this in the literature [12-14] are designed mainly for the use of standard thermoelectric modules with a fixed design. It is of interest to evaluate the ultimate characteristics of such devices that can be achieved by optimizing their design. The purpose of this work is the formation of a mathematical model of TEG

E-mail address: marchenko@isem.irk.ru

that recovers heat generated during the combustion of biomass, the choice of boundary conditions for the equations of heat and electric charge transfer, the calculation of energy and economic characteristics, and the optimization of the TEG design.

2 Design of semiconductor power sources

A thermoelectric generator is a solid state heat engine that uses electrons and holes as a working fluid to directly convert thermal energy into electrical energy. Thermoelectric generators consist of p- and n-types semiconductor legs joined into thermoelements (thermocouples) by metal plates (Fig. 1). The thermoelements are thermally and electrically insulated from their surroundings. The heat flux passes through the thermoelements from the hot junction to the cold one. The electrical energy generated from the thermal energy does work on an external load; the remainder of the thermal energy is rejected from the cold junction.

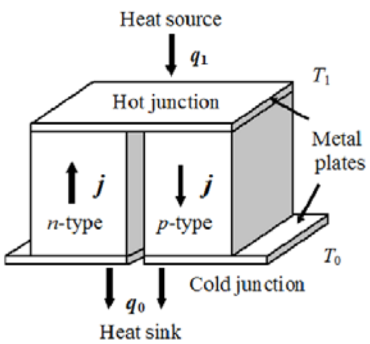


Fig. 1. Thermoelement consisting of two semiconductor legs (p- and n-type): $\boldsymbol{q}$ is the heat flux density, T is the temperature, $\boldsymbol{j}$ is the electric current density; subscripts: 0 – cold junction, 1 – hot junction.

Several thermoelements form thermoelectric batteries which can be used both separately and be connected with one another in series-parallel electrical and thermal circuits (Fig 2). Heat conductors simultaneously serve as electrical insulators, preventing the short circuit through the framework. Thermal insulation reduces parasitic heat transfer between the heat source and the heat sink, and also protects the semiconductor alloy from evaporation and chemical interactions at high temperatures.

A thermoelectric generator consists of a set of thermoelectric batteries, a heat source and a cooling system. The manufacturing of the TEG from separate interchangeable batteries makes it possible to simplify assembly, control the generator quality and increase its reliability.

Liquids or gases can be used to transfer heat to TEG hot junctions and to remove heat from cold junctions. Fig. 3 represents one of the variants of a space power plant with a TEG [2].

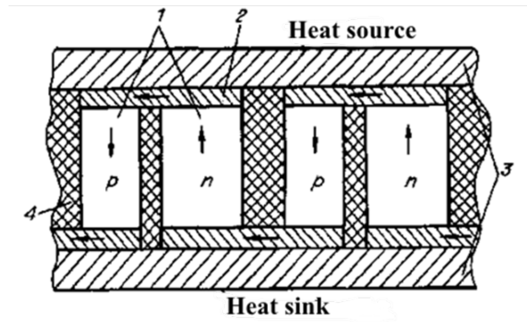


Fig. 2. Thermoelectric battery: 1 – semiconductor legs, 2 – metal buses, 3 – heat conductor, 4 – heat insulation.

3 Thermoelectric phenomena

In an unevenly heated continuous medium, in addition to heat flux the temperature difference causes diffusion of the electric charge carriers, i.e. electric current. Electric current in turn is accompanied by heat generation or absorption.

The dependences of the electric current density $\boldsymbol{j}$ and heat flux density $\boldsymbol{q}$ on the temperature gradients T and potential φ have the following form [15]:

$$\boldsymbol{j} = -(1/\rho)(\alpha\nabla T + \nabla\varphi) \tag{1}$$

$$\boldsymbol{q} = -\kappa\nabla \mathrm{T} + \alpha T\boldsymbol{j} \tag{2}$$

where α is the thermoelectric power (Seebeck coefficient), κ is the thermal conductivity and ρ is the electrical resistivity. Thermoelectric material properties α, κ and ρ depend on temperature and coordinate.

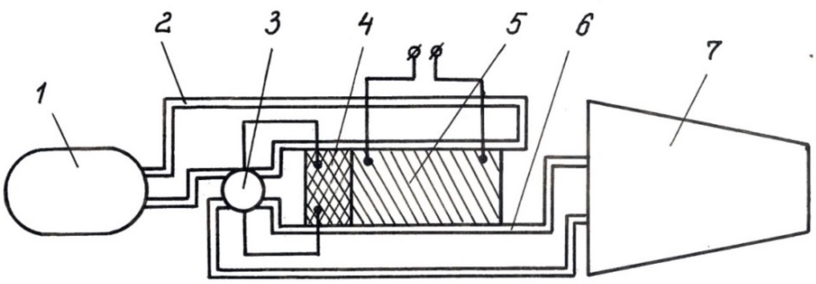


Fig. 3. Diagram of a power plant with a thermoelectric generator: 1 – heat source (nuclear reactor), 2 – hot fluid, 3 – pump, 4 – TEG pumping section, 5 – TEG main section, 6 – cold fluid, 7 – radiator.

In steady state conditions, the governing equations result from the principles of conservation of charge and energy [15]

$$\nabla \boldsymbol{j} = 0 \quad (3)$$

$$\nabla(\boldsymbol{q} + \varphi \boldsymbol{j}) = 0 \quad (4)$$

Solving differential equations (3) and (4) with the appropriate boundary conditions, one can find the temperature and potential distributions, and then determine the heat flux through the considered surface S

$$Q = \int_S (\boldsymbol{qn}) dS \quad (5)$$

electric current

$$J = \int_S (\boldsymbol{jn}) dS \quad (6)$$

and other characteristics. Here $\boldsymbol{n}$ is the outward normal.

4 Energy characteristics of thermocouple legs

Let us assume that *a*) the semiconductor leg is homogeneous and isotropic, *b*) the problem is static and one-dimensional and *c*) thermoelectric material properties α, κ and ρ are constant (independent of temperature).

With constant material properties, the one-dimensional conjugate problem of heat and electric charge transfer has an exact analytical solution. From system (1) - (4) with boundary conditions

$$\begin{cases} T(0) = T_0, & T(l) = T_1, \\ \varphi(0) = \varphi_0, & \varphi(l) = \varphi_1 \end{cases} \quad (7)$$

where l is the length of the thermoelement leg, there follow the dependence of the temperature on the coordinate x ($0 \leq x \leq l$)

$$T(x) = T_0 + (T_1 - T_0)(x/l) + \\ +(1/2)(j^2\rho/\kappa)(l - x)x \quad (8)$$

heat flux density at the boundaries $x = 0$ and $x = l$ (heat balance equations)

$$q_0 \equiv q(0) = [\kappa dT/dx + j\alpha T]_{x=0} = \\ = \kappa(T_1 - T_0)/l + j\alpha T_0 + (1/2)j^2\rho l \quad (9)$$

$$q_1 \equiv q(l) = [\kappa dT/dx + j\alpha T]_{x=l} = \\ = \kappa(T_1 - T_0)/l + j\alpha T_1 - (1/2)j^2\rho l \quad (10)$$

dependence of the potential difference (voltage) V on the current density j, i.e. volt-ampere characteristic

$$\varphi_0 - \varphi_1 \equiv V = \alpha(T_1 - T_0) - j\rho l \quad (11)$$

electric power

$$w = jV = q_1 - q_0 \quad (12)$$

and efficiency

$$\eta = w/q_1 \quad (13)$$

Multiplying the specific values q_0 and q_1 by the cross-sectional area of the leg S, summing the heat fluxes and voltages, one can obtain a system of equations for an arbitrary TEG design, consisting of sequentially and parallel connected thermoelements legs, metal buses and heat conductors [3].

At constant junction temperatures T_0 and T_1, the specific power reaches the maximum value

$$w_{max} = \alpha^2(T_1 - T_0)^2/4\rho l \quad (14)$$

at current

$$j_{opt} = \alpha(T_1 - T_0)/2\rho l \quad (15)$$

Efficiency reaches its maximum value

$$\eta_{max} = [(T_1 - T_0)/T_1][(M - 1)/(M + T_0/T_1)] \quad (16)$$

at current

$$j_{opt} = \alpha(T_1 - T_0)/(M + 1)\rho l \quad (17)$$

where

$$M = \sqrt{1 + Z(T_1 + T_0)/2} \quad (18)$$

and

$$Z = \alpha^2/\rho\kappa \quad (19)$$

is figure of merit of thermoelectric material [1].

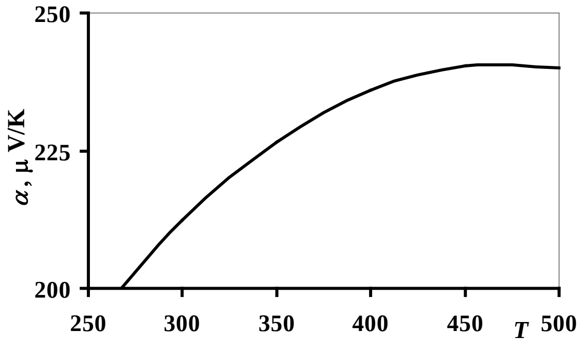
5 Method of average parameters

The properties of almost all thermoelectric materials change in the temperature range from T_0 to T_1 so much that it is impossible to neglect their temperature dependence. For an example Fig. 4 presents the characteristics of the widely-spread bismuth telluride (Bi_2Te_3) [16, 17].

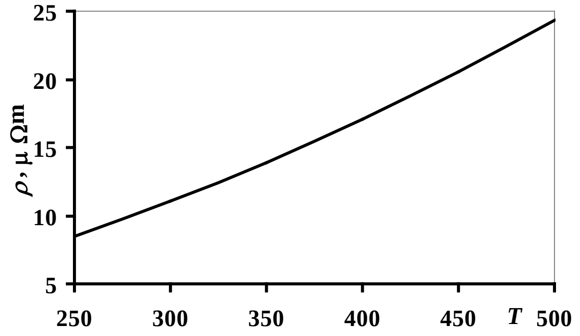
With variable properties of materials, the small value of thermoelectric effects in comparison with the heat transferred by thermal conductivity makes it possible to find a solution to the problem by the method of perturbation. The perturbation method already in the first approximation provides an accuracy acceptable for practice: the error does not exceed 1%. In this case, it turns out that the solution for variable properties of materials practically coincides with the solution given above for constant properties with their replacement by properties averaged over the temperature range by integration [18]

$$\begin{cases} \overline{\alpha} = \frac{1}{T_1 - T_0}\int_{T_0}^{T_1} \alpha(T)\,dT \\ \overline{\kappa} = \frac{1}{T_1 - T_0}\int_{T_0}^{T_1} \kappa(T)\,dT \\ \overline{\rho} = \overline{\rho\kappa}/\overline{\kappa} \end{cases} \quad (20)$$

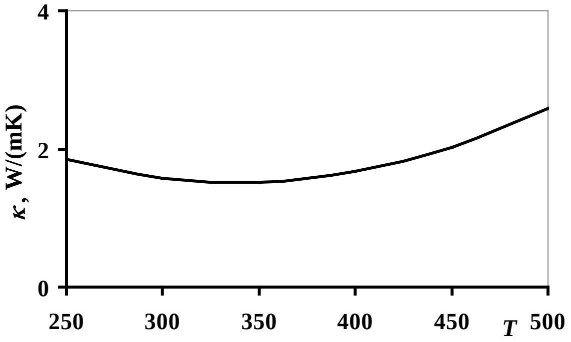
(***a***)



(*b*)



(*c*)



(*d*)

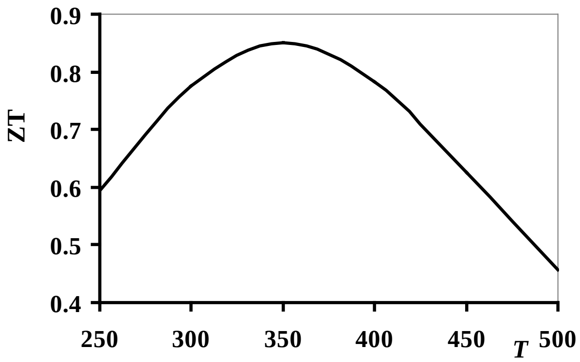


Fig. 4. Temperature dependence of Bi_2Te_3 properties: Seebeck coefficient (*a*), electrical resistivity (*b*), thermal conductivity (*c*) and dimensionless figure of merit $ZT = (\alpha^2/\rho\kappa)T$ (*d*), T is temperature in K.

6 Mathematical model

To simulate a TEG on wood fuel, we assume that its junctions exchange heat with a heat source and a cooling system, having temperatures T_H and T_C (Fig. 5) according to Newton's law (heat flux is proportional to the temperature difference). In this case, the junction temperatures do not remain constant and depend on the current. The system of equations for determining the temperatures of junctions and heat fluxes is:

$$q_1 = (T_H - T_1)/\xi_1 \qquad (21)$$

$$q_1 = \kappa^*(T_1 - T_0)/l + j\alpha T_1 - (1/2)j^2\rho^* l \qquad (22)$$

$$q_0 = \kappa^*(T_1 - T_0)/l + j\alpha T_0 + (1/2)j^2\rho^* l \qquad (23)$$

$$q_0 = (T_0 - T_C)/\xi_0 \qquad (24)$$

where ξ_1 and ξ_0 are thermal resistances,

$$\kappa^* = \kappa(1 + \varepsilon_\kappa) \qquad (25)$$

$$\rho^* = \rho(1 + \varepsilon_\rho l_0/l) \qquad (26)$$

and constants ε_κ and ε_ρ take into account heat leakage through thermal insulation and additional resistances of metal buses and contact electrical resistances (l_0 is reference length) [3].

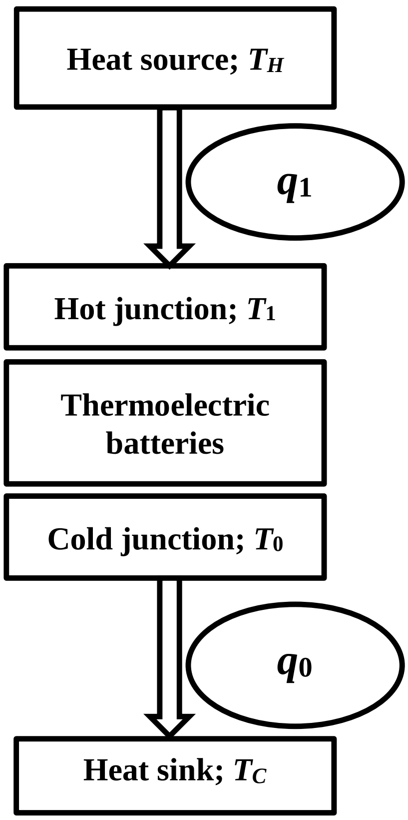


Fig. 5. TEG scheme.

An important characteristic of a TEG is its cost. For subsequent optimization of the TEG design, the dependence of the cost on the legs length can be approximated as follows:

$$p = p_0(1 + \varepsilon_p(l/l_0 - 1)) \quad (26)$$

This shows that $p = p_0$ for $l = l_0$ and $p = p_0(1-\varepsilon_p)$ for $l = 0$. Thus, p_0 is reference cost and ε_p is the share of semiconductor material in the total cost.

7 Initial data

Calculations were carried out for TEG made of thermoelectric alloy bismuth telluride (Bi_2Te_3) [19]. The main data for the mathematical model were selected on the basis of analysis and generalization of experimental and theoretical studies of similar devices [12-14, 20-22] (Table 1). Energy and cost characteristics are related to the unit of the TEG area.

Table 1. TEG model characteristics.

Characteristics	Value	Characteristics	Value
T_H, K	750	ε_ρ	0.06
T_C, K	300	ε_p	0.5
ξ_0, cm^2K/W	10	l_0, cm	0.5
ξ_1, cm^2K/W	25	p_0, \$/cm^2	2.5
ε_κ	0.05		

8 Calculation results and their analysis

The calculations were carried out for two variants.

In the first variant, with a constant length of thermoelement legs $l = 0.5$ cm, the current j was varied (Fig. 5). With increasing current, the hot junction temperature T_1 decreases, the cold junction temperature T_0 increases and the temperature difference across the semiconductor $\Delta T = T_1 - T_0$ decreases from 202 to 135 K (see Fig. 5*a*). This is due to an increase in heat fluxes q_1 and q_0 and an increase in temperature drop across thermal resistances ξ_1 and ξ_0. The voltage decreases from the maximum value at $j = 0$ to zero at a short-circuit current of 36.5 A/cm^2 due to a decrease in the EMF and a voltage drop across the internal resistance of thermoelements (see Fig. 5*b*). Efficiency peaks at 17.1 A/cm^2, power at 18.1 A/cm^2 (see Fig. 5*c*). The difference in energy characteristics between these modes is negligible: the efficiency in the maximum power mode and the power in the maximum efficiency mode deviate from their maximum values of 5.3% and 4.3 W/cm^2 by no more than 0.5% (Table 2).

Table 2. Optimal solutions.

Variant	l, cm	j, A/cm^2	w, W/cm^2	η, %	p/w, \$/W
		l = const			
w = max	0.5	18.1	0.428	5.26	5.85
η = max	0.5	17.1	0.426	5.28	5.87
		l = var			
w = max	0.86	15.0	0.459	7.03	7.40
p/w = min	0.36	20.0	0.382	4.23	5.62

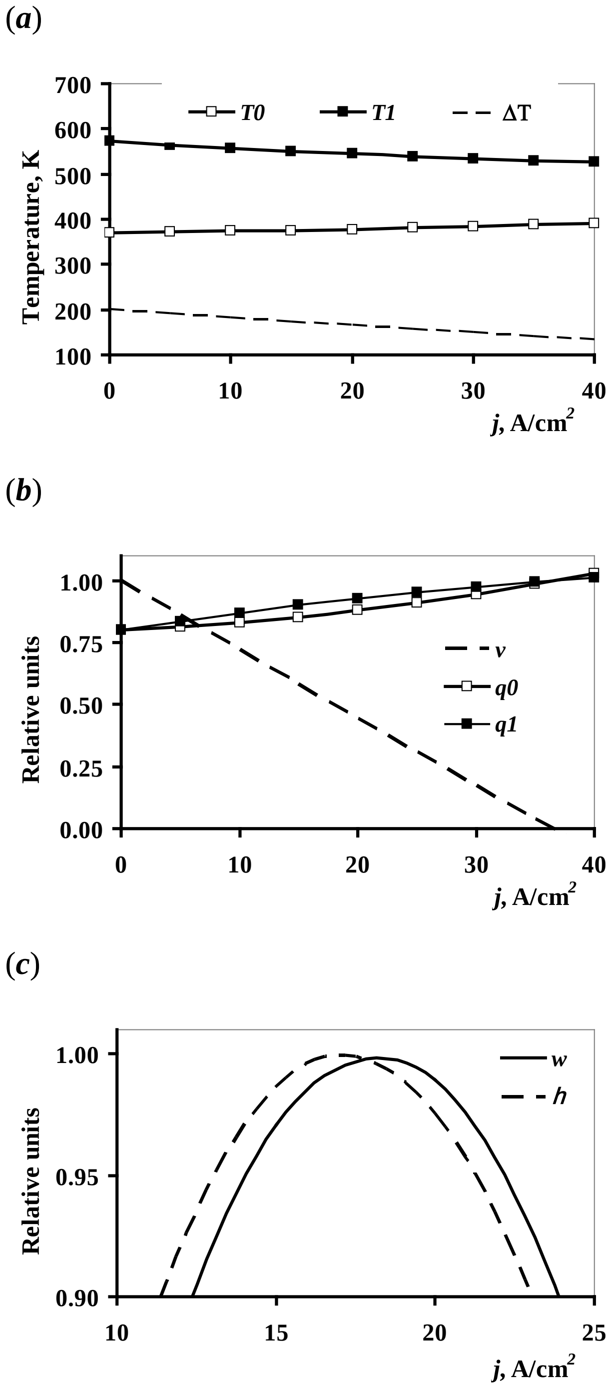
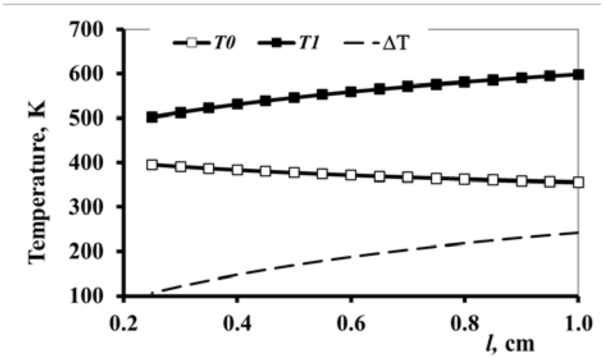


Fig. 5. Characteristics dependencies on current density: temperatures and temperature difference $\Delta T = T_1 - T_0$ (*a*), voltage and heat flux density (*b*), power density and efficiency (*c*).

In the second variant, the legs length l was varied, and the current j was chosen from the requirement of the maximum power w (Fig. 6). With increasing legs length, the hot junction temperature T_1 increases, the cold junction temperature T_0 decreases, and the temperature difference across the semiconductor increases (see Fig. 6*a*). This is due to a decrease in heat fluxes q_1 and q_0 and a decrease in temperature drop across thermal resistances ξ_1 and ξ_0. The voltage increases due to the increase in temperature difference (see Fig. 6*b*). With an increase in l, the efficiency monotonically increases, the cost per unit of power reaches a minimum at l = 0.36 cm, and the power reaches a maximum at l = 0.86 cm (see Fig. 6*c*). In this case, the difference between the modes w = max and p/w = min is significant: the deviation of characteristics at the transition from one mode to another is 20 - 30%.

In the considered variants, the TEG on wood fuel provides a specific power up to 0.46 W/cm^2, an efficiency up to 7% and a specific cost of about $ 5.6/W.

(***a***)



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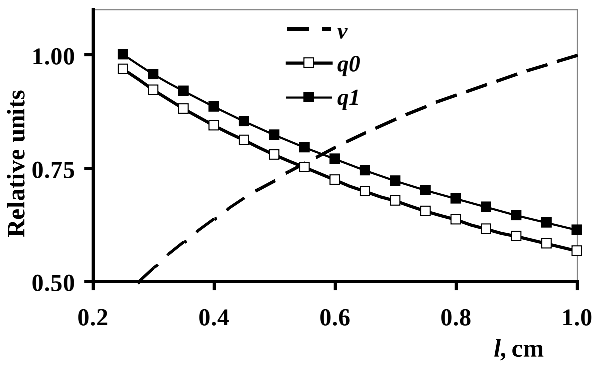

(c)

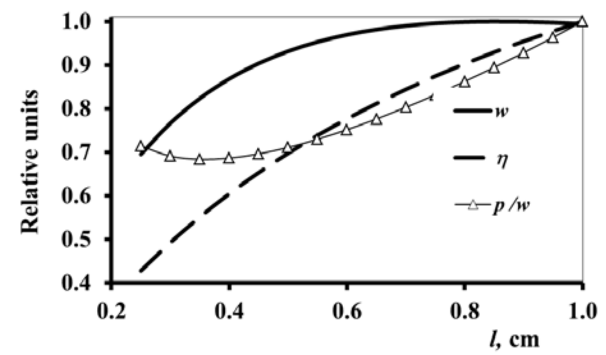

Fig. 6. Characteristics dependencies on thermocouple legs length: temperatures and temperature difference $\Delta T = T_1 - T_0$ (*a*), voltage and heat flux density (*b*), power density, efficiency and unit power cost p/w (*c*).

9 Conclusion

To assess the characteristics of TEG on woody biomass, a mathematical model was used in the form of a conjugate problem of heat and electric charge transfer in the thermoelement legs and a system of equations describing the heat exchange of TEG with the environment according to Newton's law.

With constant material properties, the one-dimensional stationary problem for the thermoelement leg has an exact analytical solution. It is shown that, for temperature-dependent properties, the small value of thermoelectric effects in comparison with the heat transferred by thermal conductivity makes it possible to find a solution to the problem by the perturbation method. Already in the first approximation, the perturbation method provides an accuracy acceptable for practice: the error does not exceed 1%. It turns out that this approximation is equivalent to using an analytical solution with constant properties, replacing them with properties averaged over the temperature range by integration.

Based on the analysis and generalization of experimental and theoretical studies of similar devices, the initial data for the mathematical model are selected - the temperature of the heat source, the environment, as well as thermal resistance and other parameters.

Calculations were performed for two variants: *a*) with a constant length of the thermoelement legs and varying the current from zero to the short-circuit current and *b*) with varying the legs length choosing the current from the requirement of maximum power. The regularities of changes in temperatures, energy and cost characteristics are investigated. It is shown that at a constant length of the thermoelement legs, the modes of maximum power and maximum efficiency differ insignificantly. With an increase in the length of the legs, the cost per unit of power first reaches a minimum, then the power reaches a maximum, and the efficiency increases monotonically.

Under the considered conditions, the TEG on wood fuel provides a specific power up to 0.46 W/cm^2, an efficiency up to 7% and a specific cost of about $ 5.6/W.

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An experimental study of combined operation of energy storage system and gas engine power plant in off-grid power system

Gleb Nesterenko[1,2*], *Gleb* Prankevich[1], *Aleksey* Savitskiy[1], *Dmitriy* Gladkov[2], *Vyacheslav* Zyryanov[2], *Sergey* Kuchak[2], and *Julia* Mokrousova[2]

[1]Energy Storage Systems LLC, Novosibirsk, Russia
[2]Novosibirsk State Technical University, Novosibirsk, Russia

Abstract. Test results of the main industrial prototype of energy storage system (ESS-10-1200-400) of nominal power 1200 kVA, energy capacity 400 kWh and voltage 10 kV based on lithium-ion batteries when operating in combination with gas engine generators (GEG) as a part of experimental power system with active abrupt variable load are given. Its structure, components and parameters, as well as the components and parameters of ESS are described. Tests have shown high operation capacity of the prototype tested, high efficiency of the implemented algorithms and confirmed the expediency of the use of ESS for smoothing power surges/sheddings in the GEG, thus preventing their emergency shutdown resulted from the power surge.

1 Background

At present the technologies of energy storage in Russia have reached the level of common practical application in the electrical power systems. Implementation of the energy storage systems (ESS) in the electric power systems of all types is one of the most important tendencies in the Russian power industry development. High-rate ESS allow solving a range of complex problems much more efficiently than traditional methods [1-5]. ESS is a multifunctional device capable of regulating active and reactive power, frequency, performing the functions of active filtering higher harmonics and compensation of three-phase voltage asymmetry.

Nowadays, the greatest technical and economic effect from the application of ESS can be obtained, first of all, at the objects of distributed generation, in Smart and Microgrids (including those operating on renewable energy), at off-grid power plants in oil and gas sector. The predominant part of the power generation at the mentioned above objects is generated mainly by diesel, gas turbine and gas engine units.

Gas engine generators (GEG), as well as diesel generator units (DGU), have high reliability in terms of structure, which makes it possible to work on inexpensive gaseous fuel (natural gas, propane, butane, associated petroleum gas, etc.), which, as a rule, is in abundance in places of oil and gas production.

At the same time the GEG, unlike the DGU, has a number of characteristic features [6]:

- in abrupt surges/sheddings of 10-20 % of the rated power the GEG is shut down by technological protection system;

- surge/shedding rate should not exceed 1% per second of rated power of the GEG;

- during continuous operation, the load of the GEG must be at least 35-40 % of the rated power.

The necessary consideration of these features in the process of GEG operation is especially important, because gas engine generators are widely used at off-grid power plants of oil and gas producing enterprises, the load of which has a pronounced abruptly variable stochastic character. This kind of the load, in addition to other negative effects, leads to increased wear of the equipment and, consequently, to increased costs for repair and maintenance of gas engine units.

This article describes the results of experimental tests and studies of energy storage system conducted by LLC "Energy Storage Systems", LLC "DC Systems" and NSTU on May 24, 2019 in Novosibirsk. The tests were carried out on the main industrial prototype ESS-10-1200-400 with nominal power of 1200 kVA, energy capacity of 400 kWh, nominal voltage of 10 kV produced by LLC "Energy Storage Systems", designed to work as part of an off-grid power supply system based on GEG (Figure 1).

The aim of the tests is to verify that the main ESS prototype, the parameters of the system as a whole and each of its subsystems satisfy the requirements of the technical specification, to confirm the efficiency of ESS to ensure the smoothing mode of the load power surge/drop (limiting rate of increase/decrease of the power of the power consumed from the GEG).

* Corresponding author: nesterenkogb@yandex.ru

Fig. 1. Experimental power system for testing the combined work of ESS-10-1200-400 and GEG.

2 Description of the experimental power system

The circuit diagram of the experimental power system for testing ESS is shown in Figure 2. The experimental unit consists of two GEGs, power transformers, sectionalized active load, whose value is discretely changed by switching devices, energy storage system, control and recording equipment, control system.

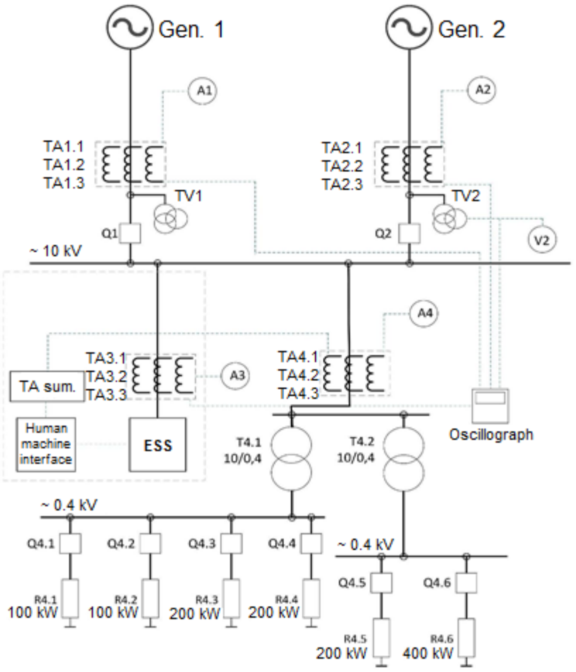


Fig. 2. The principal scheme of the test experimental installation (ESS - energy storage system, Gen.1, Gen.2 - gas engine generators, T4.1, T4.2 - power transformers, R4.1-R4.6 - active load resistance, Q1, Q2, Q4. 1 - Q4.6 - circuit breakers, TV1 and TV2 - measuring voltage transformers, TA1.1 - TA4.3 - measuring current transformers, HMI - human-machine interface of a control subsystem, TA sum. – summing current transformer).

3 Equipment components of the experimental power system

Two gas engine generators GmbH MWM TCG 2020 V12K with generators AvK DIG 120 i/4 working on natural gas are used in the experimental installation. Technical specifications of the GEG are given in Table 1 [7].

To simulate the active abruptly variable load, a load switching module was used, which allows to connect and disconnect the active load unit on a periodic predetermined base:

- 2 load blocks (modules) of IC-400-100, each of 100 kW active load;
- 2 loading blocks (LOAD BANKS), each of 400 kW active load (power of one of the blocks is artificially limited to 200 kW);
- 2 load blocks (electric heaters) KEV-60, each of 200 kW active load.

Table 1. Technical characteristics of gas engine generators for frequency of 50 Hz.

Electric power, kW	1125
Thermal power, kW	1253
Electrical efficiency, %	40,9
Thermal efficiency, %	45,6
Total efficiency, %	86,5
Overhaul when operating on natural gas, through, h	64000
Speed of rotation, min^{-1}	1500
Average piston speed, m/s.	9,8
Dry unit weight, kg	11700

ESS-10-1200-400 was used as a test energy storage system. During testing, the ESS was used to provide a smoothing mode for the load power surges/sheddings in an experimental off-grid system. The connection between lithium-ion batteries and the power system was provided by a power transformer and a bidirectional transistor converter assembled in a classical three-phase bridge scheme.

The storage subsystem (SS) uses GBS-LFP100AH accumulators with the technical characteristics given in Table 2 [8]. The main SS element is the storage module MA6x200.600, which is a unit of six storage cells with a capacity of 200 Ah, serially connected, elements of the storage battery control system and a casing. Two modifications of the modules are used in ESS - positive and negative electrodes. Technical characteristics of the module are presented in Table 3.

Table 2. Technical characteristics of the GBS-LFP100AH.

Capacity, Ah	100
Material of positive electrode	lithium ferrum phosphate
Nominal voltage, V	3,2
Standard charge current, C_{rate}	0,25
Standard discharge current, C_{rate}	0,5
Maximum continuous discharge current, C_{rate}	3
Peak discharge current, C_{rate}	10
Internal resistance, Ohm, max	0,6
Self-discharge per month, %, max	1

Table 2 extension. Technical characteristics of the GBS-LFP100AH.

Number of charging cycles, once, min	2000
Weight, kg	2,8
Overall dimensions, LxWxAl, mm	126x65x253
Operating temperature, °C	-20…+65

Note. The current value is indicated in C-rate (relative units / hour), where C=100 Ah. For example, at C_{rate}=1 current is 100 A.

The modules are placed in six rows on racks. Each battery (of three) consists of two racks: in the first, besides 15 modules, there are switching power equipment and secondary circuits, and in the second there are 18 battery modules.

Table 3. Technical specifications of the MA6x200.600 battery module.

Battery type	GBS-LFP100AH
Number of batteries	12
Number of battery cells	6
Nominal voltage, V	19,2

The electrical energy conversion subsystem is based on three three-phase power converters each of 400 kVA and performs the following functions:

- transformation of three-phase voltage of alternating current of industrial frequency into voltage of direct current and charging of SS batteries;

- maintenance of SS accumulators in a mode providing their operability and the maximum resource;

- conversion of DC voltage into AC voltage of industrial frequency and power output to the load or to the grid.

In the converter control system the elements of the theory of instantaneous power and the block of phase locked loop [9,10] are used.

4 Test program

GEG have serious limitations in terms of the allowable dynamic of load changes, making their application in power systems with abruptly variable load more difficult. Therefore, the main attention during the tests was paid to checking the efficiency and debugging of the ESS control algorithms to decrease the rate of the rate of power change of the GEG at abrupt load surges. The analysis of transient processes is of special interest, because the main specific features of changes in the operating parameters of off-grid power systems with GEG at oil and gas production enterprises are abrupt and deep sheddings and surges of frequency and voltage, accompanied by increased fuel and motor resource consumption, and at surges (more than 10 - 20% of the load capacity) - GEG shutdown by technological protection system.

Two algorithms were tested as possible ESS control algorithms for combined application with GEG in off-grid systems.

The first algorithm is designed for limiting the rate of change in generator power at abrupt changes of load (further - "dP/dt compensation mode "). When dumping or shedding the load ESS provides a smooth change in the generated power, significantly reducing the drops and outs of voltage, frequency, as well as excluding the possibility of shutdown of the GEG by the technological protection system.

The second algorithm is intended for limiting the maximum and minimum power generated by the GEG ("power limitation mode"). At peaks of consumption ESS outputs power equal to the difference between the load power and the power limit set by the GEG (upper set point), and at low load it loads it to the minimum set point (lower set point), while storing energy. In this way, the GEG load graph is smoothed, which allows to operate the generator unit in a more beneficial mode, minimizing fuel and motor resource consumption. Smoothing the load graph makes it possible to select the installed GEG power significantly less than the maximum load.

The test program included the following experiments:

1. Verification of ESS operability during the implementation of the first algorithm in the mode of limiting the rate of change in the GEG power during the increased and decreased load power at different work cycles of the load with different settings for the rate of change of power.
2. Verification of ESS operability during implementation of the second algorithm in the mode of limiting maximum and minimum GEG power for different load cycles with different setpoints.

4.1 Results of the first algorithm – "dP/dt compensation mode"

In testing, the rate of change in the summing power generated by the GEG 1 and 2 was limited to 22.5 kW/s - 1% of the summing power (2250 kW) of the two GEGs. The exponential change of the power was realized in the ESS control algorithm.

In the experiments the modes of ESS operation were explored for the compensation of surges and sheddings of different loads power - 100, 200, 400, 600, 800, 1200 kW.

The test scheme is shown in Figure 2.

The initial state of the scheme:

- switches Q4.1-Q4.3 are off;
- switches Q1, Q2, Q4.4-Q4.6 are on;
- the load is 800 kW;
- ESS is in standby mode.

Different operating cycles of load changes were simulated by switching the active load resistances. The basic, unplugged load was 35-40 kW (power supply to the load fans, lighting and appliancies).

Instantaneous values of GEG1, GEG2, ESS currents and 10 kV bus voltages were recorded by a digital oscilloscope with a sampling rate of 25 kHz. All other instantaneous values of the mode parameters were calculated on their basis.

A fragment of an oscillogram obtained during the implementation of the first operating cycle is shown in Figure 3. Without implementation of the ESS, it would be impossible to have such a load graph - the technological protection system of the GEG would shut it down at the first power surge. At the initial moment, the ESS fully "takes over" the load surge or drop and smoothly " passes" it to the GEG according to the exponential law.

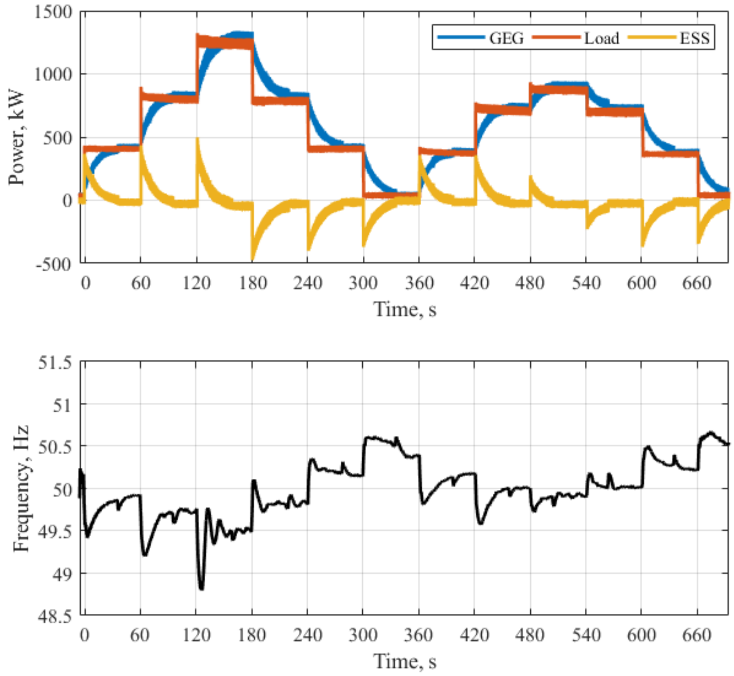


Fig. 3. Oscillogram of load power, ESS power, GEG power and frequency at permissible power change rate (setpoint) 22.5 kW/s.

A fragment of an oscillogram obtained by implementing the second operating cycle is shown in Figure 4. The experiment has shown high efficiency of ESS for limiting the rate of power change in the GEG at surges/sheddings in the range much larger than in the previous case - 800 and 1200 kW. Without ESS, such power surges may lead to the emergency triggering of the protection system and shutdown of the GEG.

Figure 5 shows the oscillograms obtained during the third operating cycle, performed at a higher load change frequency. The load varied on a large scale every 10 seconds and since the permissible power change rate of the GEG was assumed to be the same as in the experiments described above, so the GEG failed to achieve full load coverage. Due to this fact, with a high frequency of abrupt load changes, a much larger part of its variable component of the load is provided by ESS.

In all the experiments described above, the ESS switched to the mode of power output at each load surge, and at sheddings to the mode of excess consumption of power from the GEG, acting as a damper.

Figures 6 and 7 show oscillograms of frequency, ESS, GEG power and load at the critical value of load shedding from 1200 to 1000 kW with and without ESS. In these experiments, the same control algorithm as described above was implemented. Transient processes with the ESS run with significantly lower deviations of mode parameters, first of all, frequency, than without ESS, which positively affects the operating conditions of the GEG and confirms the efficiency of the implemented control algorithm.

During the implementation of the first algorithm, in all the experiments carried out there were no shutdowns of the GEG by the technological protection system caused by surges and sheddings in the load power. The reaction time of the ESS to the load power surge/drop was not more than 10 ms. The quality of transition processes has significantly improved. The improved operability of ESS has been confirmed and the efficiency of the control algorithm for smoothing load power surges has been shown.

4.2 Implementation of the second algorithm – "power limitation mode"

During this test, the ESS with pre-charged SS batteries worked on limiting the summing maximum and minimum power of the two GEGs (the lower set point is 900 kW, the upper set point is 1100 kW). When the load power went beyond the set-point values, the difference between the set-point and actual load was compensated by the ESS. The experimental scheme and initial test conditions were the same as in the previous case.

In the tests, abruptly variable graph of the load power variation from 800 kW to 1200 kW was set. The reaction time of the ESS to changes in the load power did not exceed the set limit of 20 ms, and the power generated by the GEG 1 and 2 did not exceed the set limits of 900 and 1100 kW (Figure 8).

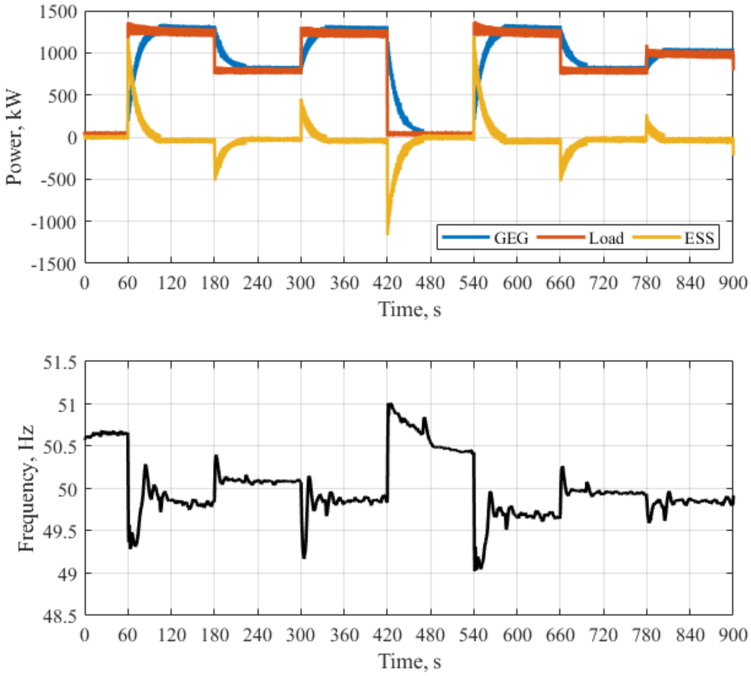
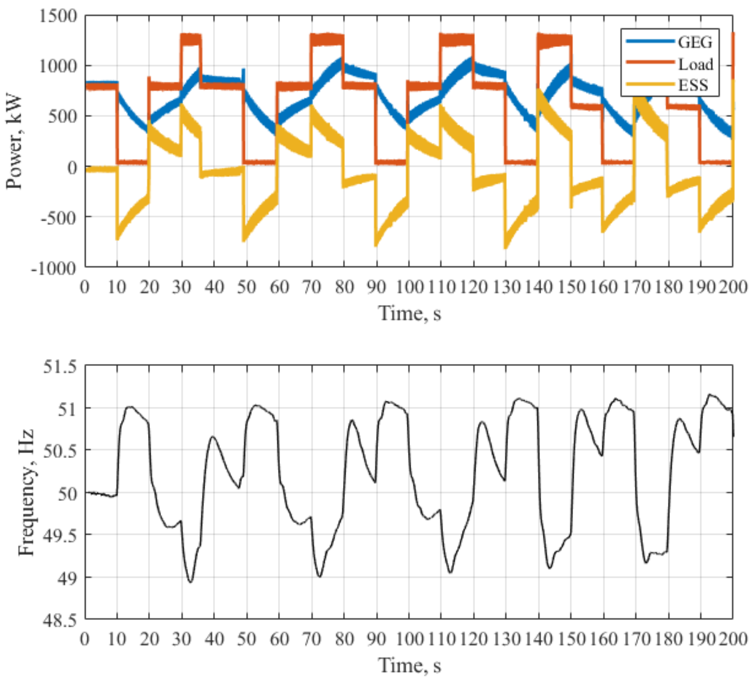


Fig. 4. Oscillograms of load power, ESS power, GEG power and instantaneous frequency value on GEG buses at permissible power change rate (setpoint) 22.5 kW/s.

Fig. 5. Oscillograms of load power, ESS power, GEG power and instantaneous frequency value on GEG buses at permissible power change rate (setpoint) 22.5 kW/s.



* Corresponding author: nesterenkogb@yandex.ru

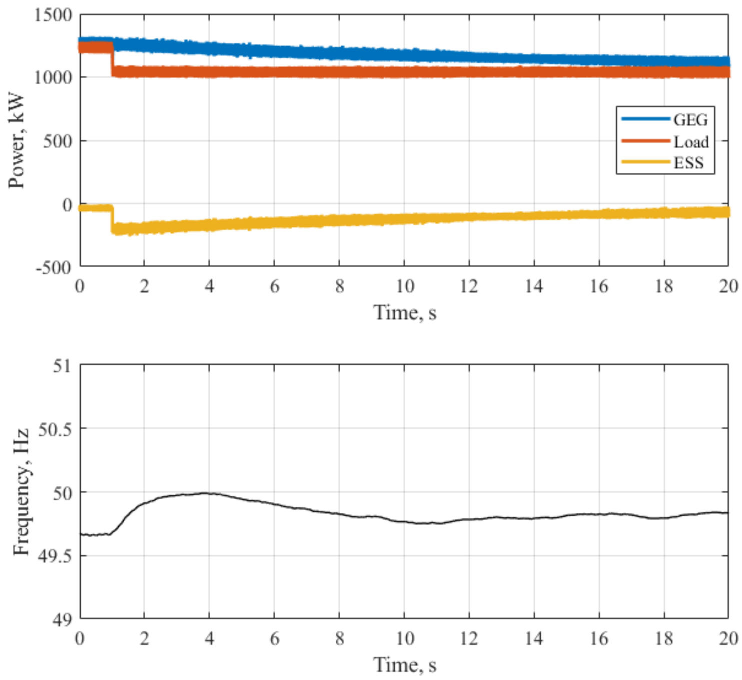


Fig. 6. Oscillograms of load power, ESS power, GEG power and instantaneous frequency value on GEG buses without ESS when resetting load power from 1200 kW to 1000 kW.

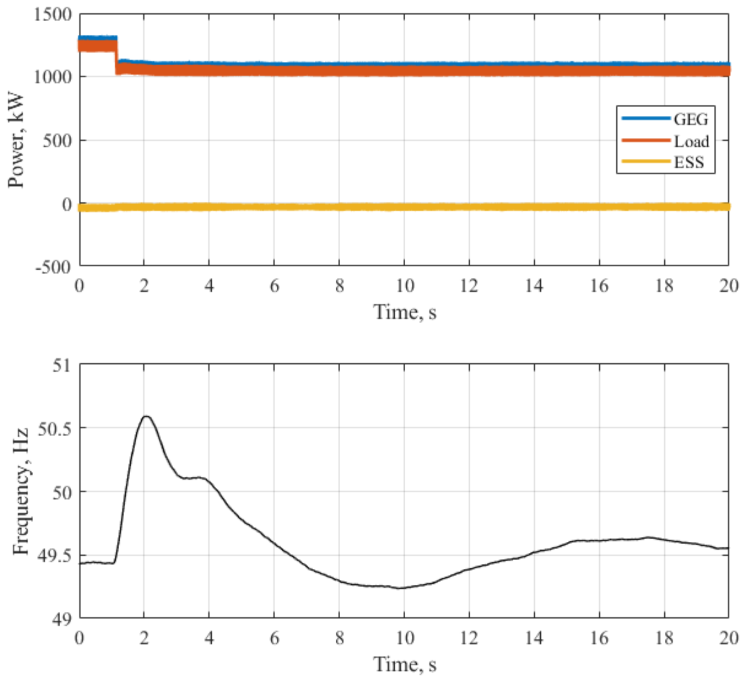


Fig. 7. Oscillograms of load power, ESS power, GEG power and instantaneous frequency value on GEG buses with ESS when the load power is reset from 1200 kW to 1000 kW.

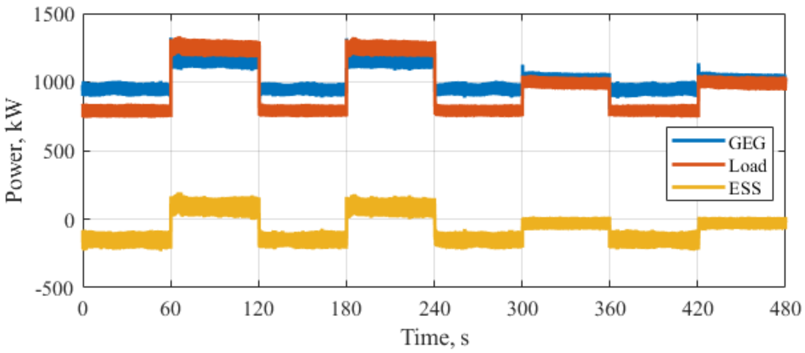


Fig. 8. Oscillograms of load power, ESS power, GEG power with minimum and maximum GEG power limitation.

Based on the same graphs, but with different power range limitations, a number of experiments were carried out, confirming the high efficiency of ESS to solve the problem. When the upper and lower setting values converge, it results in more smoothing of the GEG power graph and its approximation to the average value of the load power graph allows the GEG to work in a more economical mode with less specific fuel consumption. In addition, it is possible to replace the "standard" generator unit with a unit of smaller capacity that is close to the average capacity value of the load graph. Regulation of the variable part of the load graph is fully due to the ESS in this case. In this process, a complex effect is achieved: the minimal specific fuel consumption, the minimal cost of the unit, the minimal cost of its maintenance, increased motor resource of the drive engine, reduced losses in the generator from transients caused by abruptly variable load.

The response time of the ESS on change of load power during the experiments was not more than 10 ms, and the summing output power GEG1 and GEG2 did not go beyond the predetermined limits - lower and upper power setpoint.

5 Conclusion

The tests conducted in the Russian Federation for the first time on the industrial sample of energy storage system ESS-10-1200-400 (power 1200 kVA and energy capacity 400 kWh) in combination with GEGs on the abruptly variable load as part of the experimental unit confirmed the operability of all subsystems of ESS and high efficiency of the proposed algorithms. Implemented algorithms of ESS control have significantly improved the operating conditions of the GEG by a significant reduction in the intensity of transient processes, which resulted in improved technical and economic characteristics of the GEG. Application of ESS together with the GEG operating on an abruptly variable load allows limiting the rate of power change of generator to permissible values. This significantly reduces the requirements to the type of generator unit operating on an abruptly variable load, which is especially important for off-grid power systems using GEGs. In addition, when limiting the rate of power change of the generator, which working on an abruptly variable load greatly reduces the amplitude of torque moments on the shaft of the generator, provides a more beneficial mode of its operation, reduces fuel consumption, saving the motor resource of the GEG.

The use of ESS in the mode of limiting the maximum and minimum load on the GEG allows to operate the GEG without the risk of shutdown by technological protection system at the abruptly variable graph of load and in low load modes. Also, a significant economic effect can be achieved by selecting a generator unit not by the maximum load capacity, but by limiting its peaks. Due to this, capital expenditures on the main equipment, spare parts and operating costs are reduced and specific fuel consumption is reduced [5]. The greatest effect from replacement of a powerful GEG with a unit of lower power in terms of fuel consumption is achieved at low values of the coefficient of the rated power of the unit which is replaced.

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Potential advantages of using compressorless combined cycles in power engineering

Mikhail Sinkevich [1,2], *Yuriy* Borisov [1,3], *Anatoliy* Kosoy [1,4], *and Eldar* Ramazanov [2]

[1] Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya St., Bldg. 13, Block 2, Moscow, Russia
[2] Peoples' Friendship University of Russia (RUDN University), Miklukho-Maklaya str., Bldg. 6, Moscow, Russia
[3] Bauman Moscow State Technical University, 2nd Baumanskaya St., Bldg. 5, Block 1, Moscow, Russia
[4] Moscow Power Engineering Institute, Krasnokazarmennaya str., Bldg. 14, Moscow, Russia

Abstract. Attention of humanity is being increasingly focused on prevention of anthropogenic emissions of greenhouse gases, including CO2 [1]. One of the main contributions to CO2 emissions is associated with the production of electric and thermal energy. Despite great efforts, aimed at developing renewable energy technologies, fossil fuels will dominate in this area of human activity for a very long time. Therefore, the capture of CO2, formed during the combustion of fossil fuels, is of particular importance. If air is used as a fuel oxidizer, the combustion products consist of more than 70% nitrogen. It is very difficult and expensive to separate carbon dioxide from this nitrogen. Promising solutions for carbon capture are associated with air separation and fuel combustion in pure oxygen. Recently, considerable attention has been paid to such cycles [2-4]. The gases temperature of a combustor chamber exit is regulated by the supply of CO2 and H2O to a combustion zone. In this case, a spent working fluid is almost entirely composed of a mixture of carbon dioxide and water vapor, which is easily divided into water and pure carbon dioxide. One of the options for such solutions involves a pressure increase for all components of the working fluid before injection them into a combustion chamber in a liquid phase by pumping equipment [5]. Thermodynamic cycles, in which a pressure of the working fluid is increased in the liquid phase by pumping equipment (without a compressor), can be called compressorless.

Introduction

Compressorless cycles have a number of significant advantages that will serve as prerequisites for the implementation of such cycles in the nearest future.

The main motivation for the implementation of compressorless cycles will be their environmental friendliness. Harmful emissions will be virtually eliminated. Combustion products (CO2 and H2O) will be removed from the cycle in the liquid state, for instance, water of sufficient quality to feed heating networks when water treatment is minimal, and carbon dioxide in the most convenient form for transportation.

There exist various air separation technologies, but a cryogenic rectification is most widely used. This is a sufficiently energy-intensive technological process. In addition, the main energy inputs are spent on the cold production. This cold can be utilized in the compressorless combined cycle. Such cycle suggests an increase in the pressure of all components of the working fluid in a liquid phase. If the temperature of the H2O phase transition at the initial pressure substantially exceeds the ambient temperature, then the remaining components (CO2, fuel gas and O2) at the initial pressure have the phase transition temperature significantly lower than the ambient temperature. Condensation of these components requires cold. A significant part of the cold for these purposes can be obtained by utilizing the cold of the air separation unit. Such utilization provides a significant increase in fuel economy of the production of electric and thermal energy. Estimated evaluations showed that a power plant based on the compressorless cycle can provide an electrical efficiency of 40%, taking into account energy consumption for the plant own needs. Also, 1.46 kW of thermal power being produced for every 1 kW of electric power [5]. This corresponds to a fuel utilization rate (at the lowest heat-producing capacity) of 98%. Compressorless cycles promise to achieve the efficiency of electricity production no worse than the best modern combined-cycle gas turbine units (CCGT Units). In addition, when heat and electricity are produced simultaneously, not only all the heat from the lower calorific value of the fuel, but also a significant part of the heat of vaporization of the water, generated by combustion, can be used beneficially. Therefore, the coefficient of fuel utilization, referred to the lowest calorific value, may approach and even exceed the value of one. If the coefficient of fuel utilization is less than the ratio of the highest calorific value to the lowest one, the law of conservation of energy is not violated.

Compressorless cycles are semiclosed. The main advantage of open cycles is combustion inside the cycle and, as a consequence, the absence of large losses of exergy when heat is supplied from a hot source through the heat exchange surface. While this advantage is maintained the semiclosed cycles have almost all the advantages of closed cycles. The main of these advantages is the ability to effectively control the power of CCGT Units. The power can be changed practically without changing the efficiency of the thermodynamic cycle by preserving the determining thermodynamic parameters (ratio of expansion in the turbine, temperature of hot and cold sources) and changing the pressure in the circuit due to changes of the working fluid flow rate. Additionally, another very important advantage, associated with the ability to vary the pressure in the circuit, is the pressure increase in the circuit can significantly reduce the weight and dimensions of CCGT unit, thereby decreasing the capital costs of building the entire power plant as a whole.

Combined cycle gas turbine units, based on compressorless thermodynamic cycles, have more degrees of freedom when it is necessary to regulate the operating modes. Four components of the working fluid (fuel gas, O2, CO2 and H2O) are fed into the combustion chamber. Their regulation can be carried out independently. The logic of regulation of these components can fit into the following scheme:

- the fuel gas flow rate provides the required amount of generated electricity (feedback works using the following procedure: if consumers do not have enough electricity, fuel consumption increases; if there is an excess of electricity, fuel consumption decreases);
- O2 flow rate maintains the required combustion efficiency (transmitters feedback, controlling the composition of the working fluid at the combustion chamber outlet, allows to increase or decrease oxygen flow rate depending on the presence of unburned hydrocarbons or free oxygen);
- CO2 flow rate provides the required temperature of the working fluid at the turbine inlet (the working fluid temperature monitoring system feedback works as follows: if the temperature is high, the carbon dioxide flow rate increases; if the temperature is low, the flow rate decreases);
- H2O flow rate keeps up the amount of generated thermal energy (feedback works in the following ways: if consumers lack thermal energy, H2O consumption increases; if there is an excess of thermal energy, consumption decreases).

In addition to the opportunity to provide required flow rates of the certain components of the working fluid, it is possible to control the pressure at the turbine outlet. For instance, the pressure of the working fluid at the turbine outlet can be increased or decreased by changing the condensation modes of H2O and CO2. At the same time, the expansion efficiency of the turbine will remain constant or change in the optimal range. Thus, all parameters, determining the fuel efficiency of the thermodynamic cycle, can be kept in the optimal range in almost all operating modes and to provide as high efficiency as possible regardless of the operating mode. In this case, the temperature regime of operation of almost all parts of the CCGT Unit, which implements the compressorless cycle, will be constant. The constancy of the temperature regime solves a number of very important problems associated with thermal expansions, causing the thermal stresses in the structural elements.

Analysis of parameters for compressorless cycles

The ratio of heat and electricity production in the compressorless thermodynamic cycle is mainly determined by the ratio of CO2 and H2O, supplied to the combustion chamber. The estimation calculations with different ratios of CO2 and H2O were conducted for the same conceptual scheme and basic parameters where an electrical efficiency of 40% was shown in the production of 1.46 kW of thermal power for every 1 kW of electric power [5]. The dependence of electric efficiency, coefficient of fuel utilization (CFU) and the ratio of total power output (the sum of thermal and electric power) to electric power, supplied to the network, from the flow rate ratio of CO2 to H2O (logarithmic scale) is shown on Fig. 1.

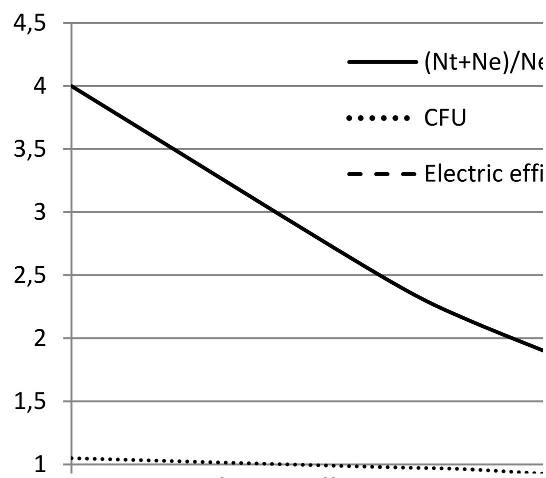

Fig. 1. The dependence of electric efficiency, CFU and the ratio of total power output to electric power from the flow rate ratio of CO2 to H2O (logarithmic scale).

The coefficient of fuel utilization and electric efficiency are related to the lower calorific value. The total amount of energy generation is four times greater than the amount of electric energy with minimal flow rate ratio of CO2 to H2O. This ratio is very close to the ratio of the installed heat and electric power of most thermal power plants. Usually, this ratio of installed capacities is achieved due to peak-load boiler houses. These boiler houses operate a few hours a year, but they require significant capital expenditures during the construction, and constant expenses for their maintenance. Such a wide range of regulation of the ratio of generated capacities in CCGT unit, based on compressorless cycles, allows to eliminate the peak-load boiler houses.

The electric efficiency of the compressorless CCGT unit decreases with an increase in the production of thermal energy. Nevertheless, this decrease does not indicate a reduction in profitability. The main criterion of profitability is coefficient of fuel utilization since it is close to one with almost all ratios of thermal and electrical loads (almost all of the fuel energy, traditionally considered available, is converted into a useful product). CFU even exceeds a value of one at maximum thermal loads. This is due to the part of water condensation heat, formed as a result of fuel combustion, which is traditionally not referred to available energy, in this case turns into useful heat. If the heat demand is small, for example, only hot water supply in the summertime, then it is advisable to increase the flow rate ratio of CO2 to H2O to the maximum. In this case, heat generation is minimized (thermal power is half of electric power), CFU is slightly reduced (approximately to 0.87), but the electric efficiency, taking into account the own needs of the thermal power plant, rises to 0.56.

When heat is not required and only electricity is generated, electric efficiency becomes a measure of efficient performance. In such modes it is also advisable to increase the flow rate ratio of CO2 to H2O to the maximum. If heat is not produced, then the coefficient of fuel utilization coincides in meaning and size with electric efficiency. Given the fact that in the absence of a heat load, there is no energy consumption for providing heat to the consumer (transportation of heat transfer fluids), which is part of the own needs of the thermal power plant. Therefore, the electric efficiency is slightly higher in the production of only electricity than in the joint production.

The analysis of the compressorless thermodynamic cycles advantages is evaluative. The performed benefit assessment of compressorless combined cycles has shown a real prospect for their practical implementation. In order to create a scientific basis for the design of installations, based on compressorless combined cycles, it is planned to continue work in the following areas: development of program codes for research and optimization of compressorless combined cycles; search for optimal circuit designs for power plants that implement work on the basis of compressorless combined cycle; optimization of compressorless combined cycles parameters.

Conclusion

Current trends to reduce CO2 emissions, associated with climate change, bring to one of the first places technologies with air separation and using pure oxygen as a fuel oxidizing agent, since these technologies make it possible to completely capture CO2 from combustion products. Compressorless combined cycles are one of the perspective directions of such technologies. There are a number of prerequisites that allow to talk about the practical implementation of such cycles in the near future.

Air separation is a fairly energy-intensive process. The main energy costs for air separation are associated with the production of cold when using the cryogenic rectification process. This cold is utilized in the compressorless combined cycle in condensation processes of other components of the working fluid, thereby significantly increasing fuel efficiency. Estimated calculations show that CFU is close to value of one in the combined production of heat and electricity, taking into account energy consumption for own needs. When producing only electricity, electric efficiency, taking into consideration own needs, can reach 58%.

The main advantage of open cycles is maintenance of the high temperature of the hot source that compressorless cycles also have along with almost all the advantages of closed cycles. The main of these advantages is the ability to effectively control the power of CCGT unit. Therefore, while maintaining the determining thermodynamic parameters and varying the pressure in the circuit, the power of this unit is changed almost without varying the electric efficiency of the thermodynamic cycle due to a change in the flow rate of the working fluid.

Another very important positive quality of compressorless thermodynamic cycles is a possibility to independently control the production of thermal and electric energy in a CCGT unit, implemented by such cycles. By changing the ratio of the working fluid components, supplied to the combustion chamber, it is possible with constant electric power to change the thermal power. In that case, the maximum thermal power will exceed the minimum one more than six times and CFU will be close enough to the value of one in the full range. This range of the thermal loads regulation provides the possibility of year-round supply of heat without additional peak-load boiler houses. In addition, it allows to work effectively in the summer, providing only a hot water supply, and in the winter, covering all the needs of heat on the coldest days. The rejection of additional peak-load boiler houses will reduce both capital expenditures to build and operating costs.

Conducted analysis of compressorless combined cycle is evaluative, but even such rough estimates indicate the actuality of work in this direction. In order to create a scientific basis for the design of installations, based on compressorless combined cycles, it is planned to continue work in the following areas: development of program codes for research and optimization of compressorless combined cycles; search for optimal circuit designs for power plants that implement work on the basis of compressorless combined cycle; optimization of compressorless combined cycles parameters.

Acknowledgment

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Comparative analysis of the Allam cycle and the cycle of compressorless combined cycle gas turbine unit

Mikhail Sinkevich [1,2], *Anatoliy* Kosoy [1,3] *and Oleg* Popel [1]

[1] Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya St., Bldg. 13, Block 2, Moscow, Russia
[2] Peoples' Friendship University of Russia (RUDN University), Miklukho-Maklaya str., Bldg. 6, Moscow, Russia
[3] Moscow Power Engineering Institute, Krasnokazarmennaya str., Bldg. 14, Moscow, Russia

Abstract. Nowadays, alternative thermodynamic cycles are actively studied. They allow to remove CO2, formed as a result of fuel combustion, from a cycle without significant energy costs. Calculations have shown that such cycles may meet or exceed the most advanced power plants in terms of heat efficiency. The Allam cycle is recognized as one of the best alternative cycles for the production of electricity. Nevertheless, a cycle of compressorless combined cycle gas turbine (CCGT) unit is seemed more promising for cogeneration of electricity and heat. A comparative analysis of the thermal efficiency of these two cycles was performed. Particular attention was paid to ensuring equal conditions for comparison. The cycle of compressorless CCGT unit was as close as possible to the Allam cycle due to the choice of parameters. The processes, in which the difference remained, were analysed. Thereafter, an analysis of how close the parameters, adopted for comparison, to optimal for the compressorless CCGT unit cycle was made. This analysis showed that these two cycles are quite close only for the production of electricity. The Allam cycle has some superiority but not indisputable. However, if cogeneration of electricity and heat is considered, the thermal efficiency of the cycle of compressorless CCGT unit will be significantly higher. Since it allows to independently regulate a number of parameters, on which the electric power, the ratio of electric and thermal power, the temperature of a working fluid at the turbine inlet depend. Thus, the optimal parameters of the thermodynamic cycle can be obtained in a wide range of operating modes of the unit with different ratios of thermal and eclectic powers. Therefore, the compressorless CCGT unit can significantly surpass the best steam turbine and combined cycle gas turbine plants in district heating system in terms of thermal efficiency.

Introduction

Recently, alternative thermodynamic cycles are actively investigated, permitting, without significant energy costs, to remove CO_2, formed as a result of fuel combustion [1-4], from the cycle. Calculations have shown that such cycles may not be inferior to the most advanced power plants with regard to thermal efficiency [4]. The Allam cycle is considered as one of the best for the production of electricity [5]. The construction of power development plant with a capacity of 50 MW is already underway with using this cycle [4]. However, the cycle of compressorless combined cycle gas turbine (CCGT) unit is seemed more promising for cogeneration of electricity and heat [6-8].

When new cycles are studied, researchers have to make many assumptions, accepted based on existing experience. However, they need to be verified experimentally. Such assumptions include the attainable standard of efficiency for individual parts of a power plant, implementing a cycle, and an achievable temperature level.

In various studies, these accepted assumptions may differ significantly. So, in some studies, for example, the turbine inlet temperature is taken to be very moderate, up to 1200 K [1], in other works, it is considered the temperature almost equal to 1700 K [2]. The most realistic temperature is 1400 K [4]. The effectiveness of individual parts of the researched cycles can also differ considerably. If the different cycles are compared by the resulting indicators, obtained in different studies, the problem of separation causes of the variance in the compared indicators arises. This difference is either a consequence of the advantages and disadvantages of the compared cycles, or it is a reflection of the optimism or pessimism of researchers, performed a work.

The Aim of Research

The main goal of the study is an objective comparative assessment of the thermal efficiency of two new promising thermodynamic cycles, which have a rather important advantage - removing CO_2, resulting from the combustion of fuel, from the cycle in the form of a pure substance.

Description of the compared cycles

A compressorless combined cycle gas turbine unit schematic is shown in Fig. 1. Conventionally, the beginning of a thermodynamic cycle may be associated with a moment when all components of a working fluid are being in a liquid phase. Feeding pumps for fuel 1, oxygen 2, carbon dioxide 3, and water 4 are used to increase their pressure. The fuel pump controls the fuel supply. After the fuel pump, the fuel is fed sequentially to a cold utilizer of liquefied natural gas (LNG) 5 (it is supposed to use LNG as the fuel) and a fuel heater 6. And after that, the heated fuel enters the primary zone of a combustion chamber 7. The oxygen supply is regulated by the oxygen pump. Thereafter, oxygen first enters an oxygen cold utilizer 8. Then it goes into an oxygen heater 9, after which the heated oxygen enters the primary zone of the combustion chamber. The carbon dioxide pump controls CO_2 supply. After the carbon dioxide pump, CO_2 first enters a heater 10, and then goes to a recuperative heat exchanger 11. Heated CO_2 is supplied to the primary and secondary zones of the combustion chamber simultaneously so as to ensure an acceptable quality of fuel combustion and the required temperature field at the combustion chamber outlet. A small fraction of CO_2 is used to cool the hot parts in a combined cycle gas turbine flow part 12. The feedwater pump supplies water to a recuperative heat exchanger 13, and then, as well as CO_2, H_2O enters the primary and secondary zones of the combustion chamber. Thus, fuel is supplied to the combustion chamber in an amount that provides thermal and electrical load coverage. The oxygen supply is regulated so that there is a minimum excess of oxygen, providing the required combustion efficiency. The CO_2 supply maintains a predetermined temperature of the working fluid in the turbine (depending on the control mode at the inlet or outlet). The supply of H_2O regulates the ratio of the generated heat and electric energy. A mixture of combustion products and ballasting components with a predetermined temperature, obtained in the combustion chamber, represents the working fluid at the combined cycle gas turbine inlet 12. The working fluid expands in the combined cycle turbine, doing work. The performed work is converted into electricity by a generator 14. The working fluid, having spent in the turbine, is sent to the recuperative heat exchangers 11 and 13 which heat up the ballasting components H_2O and CO_2. In recuperative heat exchangers, the working fluid is cooled to a temperature as close as possible to the dew point temperature when H_2O, being part of the working fluid mixture, begins to condense. Thereafter, the working fluid is directed to a low pressure contact condenser 15 which has two sections, located one above the other. Water is supplied in a first section 16 for cooling the working fluid with a temperature slightly higher than the temperature of return system water. Cooling water, with a temperature slightly higher than the temperature of liquid CO_2, is supplied

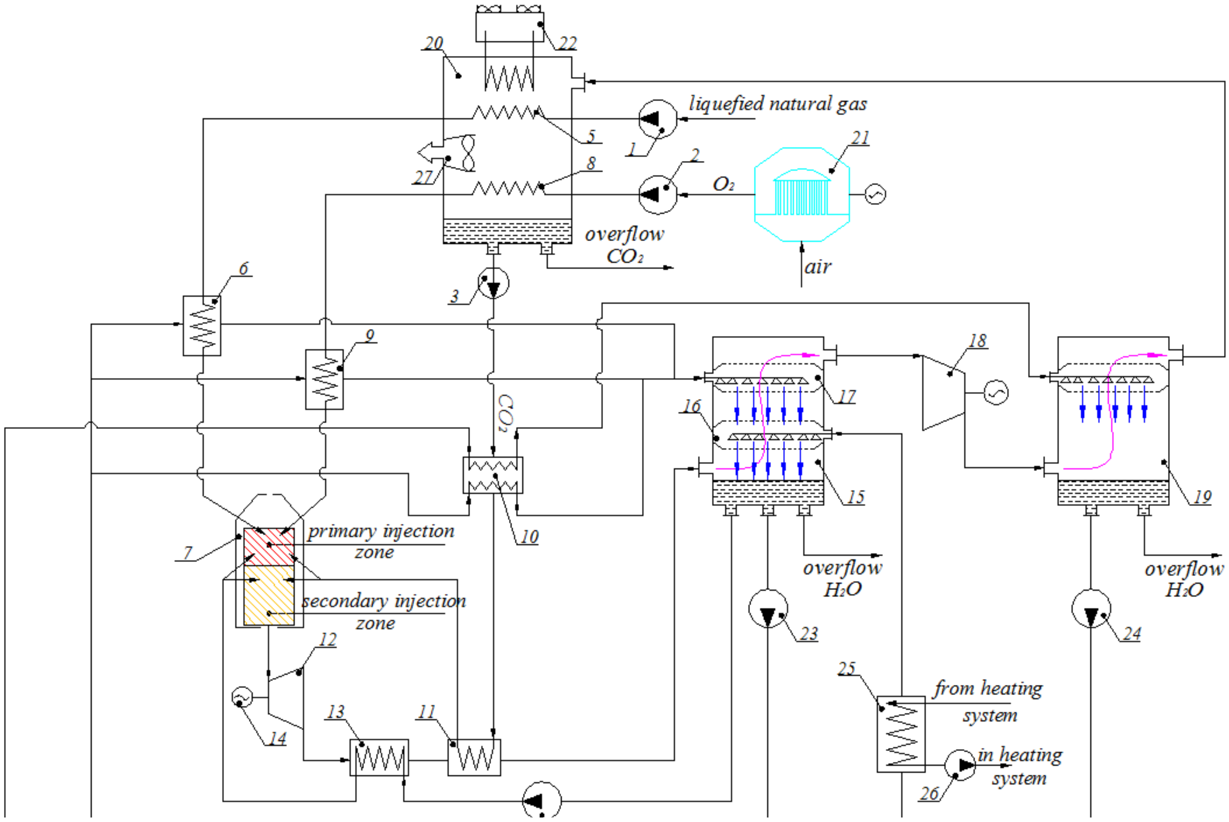

Fig. 1. Compressorless combined cycle gas turbine unit schematic.

in a second section 17. At the low pressure contact condenser outlet, the working fluid is carbon dioxide with small contaminants, including a small amount of remained H_2O. Therefore, the pressure of the working fluid is increased by a CO_2 compressor 18 to 3,5 MPa in order to avoid freezing (the pressure at which the condensation temperature of CO_2 is higher than the freezing temperature of H_2O). After that, the H_2O residues are condensed in a high pressure contact condenser 19. The working fluid, cooled in this contact condenser, is sent to a liquefier of CO_2 20. The cold of liquid oxygen from an air separation unit (ASU) 21 and cold of liquid oil are used to liquefy the CO_2. The liquefier of CO_2 includes the utilizer of liquid oxygen cold 8 and the CNG cold utilizer 5 for this purpose. The entire shortage of cold, required to liquefy CO_2, is compensated by a refrigeration unit 22. Each contact condenser has its own circuit of circulating water. Circulation pumps 23 and 24 take in water from the contact condenser water tanks. The water is divided into several streams after the circulation pump 23 in the circulation circuit of the low pressure condenser. Most of the water goes to a heater of network water 25 after which it returns to the first section of the low pressure condenser. The remaining water is supplied in parallel streams to the fuel heater 6, the oxygen heater 9 and the CO_2 heater 10. Having released the heat in the heaters, the cooled water returns to the second section of the low pressure contact condenser. After the pump 24, the circulation water of the high pressure condenser is supplied to the CO_2 heater 10. It is designed so that two heating fluids are used for heating up. After the heater, this water returns to the high pressure contact condenser 19. The return network water is supplied to the network water heater 25. After that, water is heated to the temperature, required by a temperature graph, and returned to the heat network by a network water pump 26. Liquid oxygen is produced in the cryogenic air separation unit 21. The liquefier of CO_2 20 is equipped with a system for removing non-condensable gases and collecting an excess of liquid CO_2. In addition, the selection of excess H_2O is provided.

A detailed description of the Allam cycle is given in [4]. A diagram in pressure – enthalpy coordinates, conventionally assigned to pure carbon dioxide (Fig.2.), is also shows there.

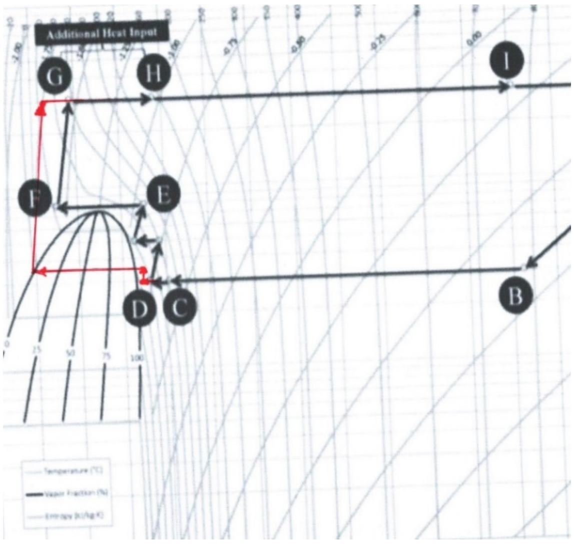

Fig. 2. Image of the Allam cycle in diagram P-I for carbon dioxide [4].

The working fluid is fed into a turbine (at point A) with a pressure of 30 MPa (300 bar) and a temperature of 1323 K (1150 °C). The expansion process in the turbine is shown by line A-B. A pressure is equal to 3 MPa (30 bar) and a temperature is 1000 K (727 °C) at the turbine outlet. After expansion in the turbine, the working fluid is sent to a recuperator where it is cooled, heating the recirculating flow of supercritical CO2 (line B-C). The working fluid is cooled to 333 K (60 °C) in the recuperator. Further cooling of the working fluid is carried out by removing heat into the environment (line C-D). The pressure increase of the working fluid (recirculating gas) is performed in several stages with intermediate cooling between them (line D-E-F-G). The working fluid has a pressure of 30 MPa (300 bar) and a temperature of 333 K (60 °C) at the end of the pressure increase process (at point I). The working fluid is heated (line G-H-I) to 990 K (717 °C) before feeding into a combustion chamber. Most of the heat (equivalent length H-I) occurs due to the heat, transferred in a heat exchanger. Gases have very high heat capacity in the supercritical state at temperatures close to critical. Thus, there is not enough recuperative heat and a deficit of low temperature heat is formed. It is proposed to compensate for this deficit by external sources of low temperature heat (equivalent segment G-H). As an example, heat recovery of ASU is considered.

Results of comparison

The supply of H_2O to the combustion chamber in the cycle of compressorless CCGT unit is regulated and can be equal to zero in the limit. If the same parameters as in the Allam cycle at the turbine inlet are taken, for example, the degree of expansion in the turbine, the adiabatic efficiency of the turbine, hydraulic losses along the path, and the efficiency of the recuperator, then the series of reference points of these two cycles will coincide (Fig. 2). A part of a diagram at an enlarged scale, where these cycles differ, is shown in Fig. 3.

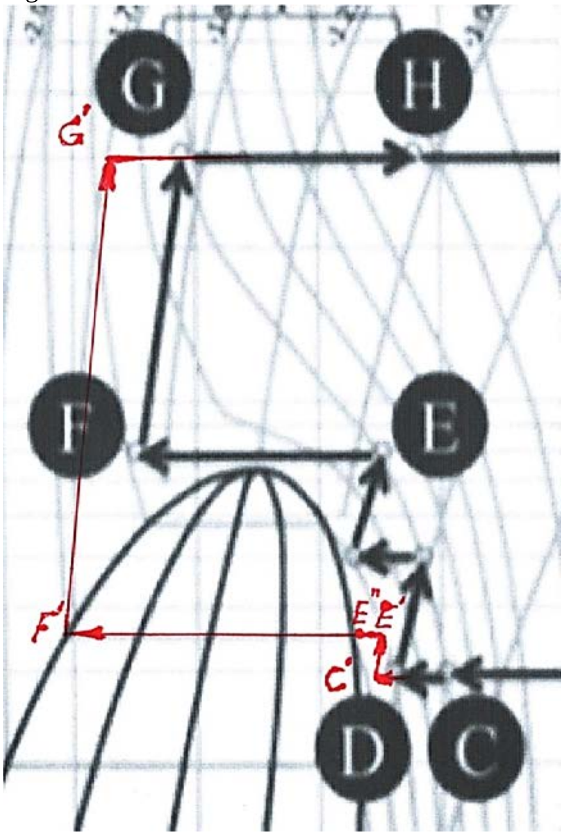

Fig. 3. Comparison of the Allam cycle with the cycle of compressorless CCGT unit for carbon dioxide in the P-I diagram.

In the cycle of compressorless CCGT unit, the spent working fluid is cooled in the recuperator and then in the contact condenser to a temperature slightly lower than at point D (point C'). At the same time, part of the heat is transferred to the heating system if there is a need for it. The all rest heat is returned to the cycle. After that, the compressor of CO_2 raises the pressure to 3,5 MPa (35 bar) so that the condensation temperature of CO_2 is slightly higher than 273 K (0 °C) and there is no frosting of the heat exchange surfaces (point E'). After that, another part of the heat is returned to the cycle in the high pressure contact condenser (line E'-E"). The liquefaction of CO_2 (line E''-F') is carried out at the temperature slightly higher than 273 K (0 °C). The heat of condensation is partially utilized for heating up the fuel and oxygen. The remaining share of the condensation heat of CO_2 is removed to the atmosphere. If the conditions for comparison with the ambient temperature equal to 288 K (15 °C) are accepted, then an additional refrigeration cycle will be required to remove heat. The pressure of liquid CO_2 is increased by the pump (line F'-G'). The temperature at point G' is almost lower than 40 K at point G. However, heating from point G' to point G is produced by cooling of the spent working fluid (lines C-C' and E'-E''). Thus, two analysed cycles are completely identical at the region G-H-I-A-B-C.

For comparison the thermodynamic efficiency of processes it is more evident to present diagrams in the coordinates of temperature-entropy. The compared processes in the temperature – entropy coordinates is shown in Fig. 4.

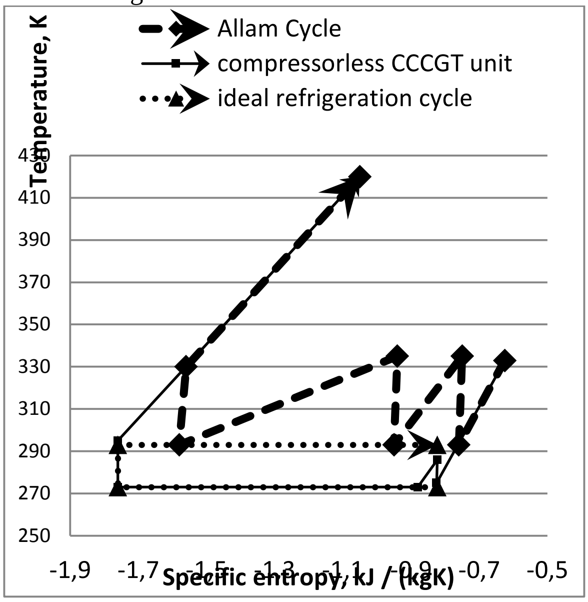

Fig. 4. Comparison of the Allam cycle with the cycle of compressorless CCGT unit in the T-S coordinates.

In the Allam cycle the average temperature of heat dissipation is approximately 313 K (40 °C). The average temperature of heat removal can be somewhat lower due to the choice of an effective working fluid for the refrigeration cycle. In addition, if the processes are idealized (for example, it is assumed that the refrigeration cycle is the ideal Carnot cycle, and the temperature head of heat transfer to the refrigeration cycle is equal to zero), then the cycle of compressorless CCGT unit will be somewhat more efficient than the Allam cycle. However, the Allam cycle can slightly exceed the cycle of compressorless CCGT unit in real thermodynamic processes. All depend on how effective the refrigeration cycle will be and what temperature head will be when removing heat to the refrigeration cycle. The temperature of heat removal from the cycle determines the work that will be spent on increasing the pressure of the working fluid (the work, having spent on the drive of the refrigeration machine, is one of the components of the work, spent on increasing the pressure of the working fluid). Calculations show that the work, spent on increasing the pressure of the working fluid, is 10,5% of the higher calorific value of the fuel [4]. Consequently, a ten percent difference in the efficiency of the cooling and pressure increase processes will lead to a difference in the efficiency of the cycles as a whole by only one percent.

With the small and not indisputable advantages of the Allam cycle for producing only electricity, this cycle is not suitable for cogeneration of electricity and heat. This cycle is characterized by a deficit of low temperature heat. For covering of which, it is still necessary to find a source of such heat. Thus, there is no need to talk about the release of low temperature thermal energy as a commercial product. In the cycle of compressorless CCGT unit, it is possible to adjust the ratio of recirculating CO_2/H_2O. An increase in the amount of H_2O, supplied to the combustion chamber, negatively affects the efficiency of electric power generation. This occurs for two reasons in terms of a thermodynamic point of view. Firstly, the average temperature of heat input in the combustion chamber decreases (the temperature of the working component decreases before the supply to the combustion chamber). Secondly, the average temperature of heat removal from the cycle increases. However, the average temperature of heat removal is part of the removed heat. In addition, all the removed heat is transferred to the heating system in the form of commodity output when a ratio $CO_2/H_2O<1$. The cooling process of the spent working fluid and heating of the working components before feeding into the combustion chamber at various ratios of recirculating CO_2/H_2O is shown in Fig. 5 in T-S coordinates.

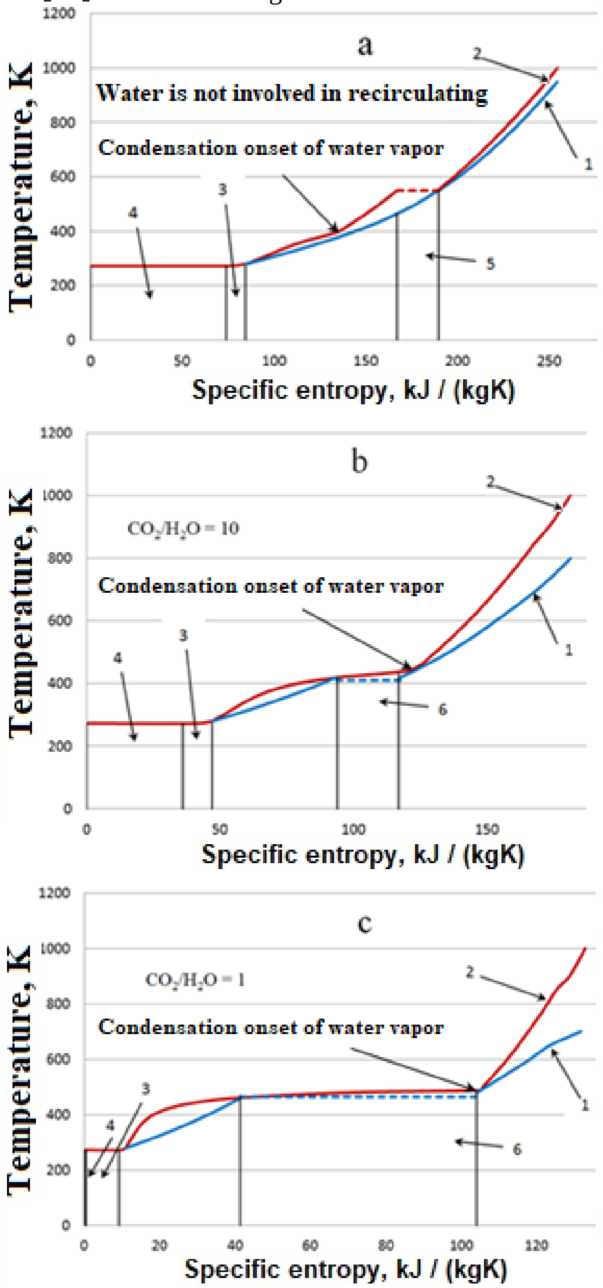

Fig. 5. The cooling process of the spent working fluid in T-S coordinates: 1 – heating line of the working fluid components before feeding into the combustion chamber; 2 – cooling line of the spent working fluid; 3 – heat for heating fuel and oxygen to a temperature of CO_2 condensation; 4 – heat transfer into the environment; 5 – heat, supplied from an external low temperature heat source; 6 – heat, given off to the heating system.

Entropies in specific units are given. However, considering the composition and quantity of the working fluid differ at various points of the cycle, all entropies are assigned to one kilogram of fuel. The reference points for heating and heated flows were selected so that the minimum temperature head, which is necessary for heat transfer, is provided everywhere. If the heat is removed from the cycle somewhere, the reference points are adjusted accordingly. When only CO_2 is used for recycling (Fig. 5a), in order to ensure the maximum temperature of the working fluid components before feeding into the combustion chamber and at the same time not violate the second law of thermodynamics, a certain amount of heat must be supplied to the components of the working fluid in the temperature range of 400-550 K (area 5) from an external low temperature source. ASU can be such source as an option. Part of the spent working fluid heat is diverted to the fuel and oxygen heating to a temperature of CO_2 condensation (area 3). In the Allam cycle, the ability to utilize the cold of liquid oxygen and fuel is not mentioned, but for the cycle of compressorless CCGT unit is an essential point. Heat is generally removed from the cycle of compressorless CCGT unit to the environment at a temperature lower than the ambient temperature (area 4). A refrigeration machine is used for this purpose. In addition, the operation of this machine can be reduced because liquid oxygen and LNG have some stock of cold (heat is necessary for heating to the environment), which can be used to liquefy CO_2 (area 3). The need for heat supply from an external source (area 5) is due to the fact that the total water equivalent of the working fluid components at high pressures in the range of low temperatures significantly higher than the water equivalent of the spent working fluid at these temperatures. And even a small increase in the water equivalent of the spent working fluid, owing to the condensation of water vapor, resulting from the combustion of fuel, cannot compensate for the shortage of low temperature heat. Thus, it is necessary to look for an external source, or all this heat will be compensated by additional fuel. The picture changes significantly when H_2O is connected to recirculation. Already at a ratio of $CO_2/H_2O=10$, condensing water vapor increases the water equivalent of the spent working fluid so that a heat surplus with a temperature of 400-450 K instead of a deficit is obtained (Fig. 5 b). This heat can be released into the heat network in the form of commodity output (area 6). At the same time, heat removal to the environment is almost halved. The needs for hot water supply in summertime can be covered with small amounts of recycle H_2O. The heat removal to the environment approaches to the value of zero with the ratio CO_2/H_2O=1 (Fig. 5c). The heat network is the cold source for the thermodynamic cycle. Thus, almost all fuel energy (at the higher calorific value) is useful. Only a part of the energy, spent on the station own needs and irretrievable losses during mechanical and electrical energy conversions, is lost. The amount of energy loss can be 5-10% of the electric power of the station. Such losses correspond to the coefficient of fuel usage, related to the higher calorific value of fuel, equal to 0,94-0,97. The value will be 1,045-1,08 if it relates to the lower calorific value it. Calculations showed that 1,46 kW of heat can be produced at CO2/H2O=1 per 1 kW of useful electric power, with an efficiency referred to the higher calorific value equal to 0,356 (0,396 attributed to the lower calorific value). Heat efficiency with such indicators at cogeneration of electric and thermal energy will be 10-15% better than a typical steam turbine CHP plant and 5-10% better than CCGT-CHP plant [8].

Conclusions

The analysis showed that the compared cycles have a good potential to achieve high thermal efficiency for the production of electricity, not being inferior to the most advanced technologies. In addition, these two cycles are fairly close for producing only electricity. Some superiority of the Allam cycle can be recognized, but it is not indisputable.

The cycle of compressorless CCGT unit significantly exceeds the Allam cycle for cogeneration of electricity and heat. The compressorless CCGT unit allows to regulate a number of parameters independently, on which the electric power, the ratio of electric and thermal power, the temperature of the working fluid at the turbine inlet depend. Thus, the optimal parameters of the thermodynamic cycle can be obtained in a wide range of operating modes of the installation with different ratios of thermal and eclectic powers. Due to this the compressorless CCGT unit can significantly surpass the best technical steam turbine and combined cycle gas turbine plants in district heating systems in terms of thermal efficiency.

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RESEARCH OF A MULTIAGENT MODEL OF AN INTEGRATED ENERGY SUPPLY SYSTEM DEVELOPED IN THE ANYLOGIC SOFTWARE ENVIRONMENT

Valery Stennikov[1], and *Gleb* Mayorov[1]

[1]Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Pipeline Systems Department of Energy No. 50, 664033, Irkutsk Region, Irkutsk, Lermontov St., 130, Russia.

Abstract. The main goal of the paper is to develop and study an integrated energy supply system model in the AnyLogic software environment using a multiagent approach. Creating a single integrated system will allow: to implement new functionalities; increase reliability by improving redundancy and faster decision making in normal and emergency situations; determine the most profitable supply route individually for each consumer, based on cost and design features; participate consumers with their own energy sources in the process of energy supply of the system. The multiagent model of the integrated energy supply system was created in the AnyLogic software environment, which uses advanced technologies for modeling complex systems that will allow the most visual and detailed display of the interaction mechanisms of objects in the system and analyze the results. This study describes in detail the resulting multiagent model, its main agents, and their state diagrams. A description and analysis of an experiment conducted using this model is also provided. The results show that the multiagent model of the integrated energy supply system works correctly and performs all the specified functions.

1 Introduction

Currently, energy worldwide is undergoing a technological paradigm shift, the focus of which is associated with the transition to the implementation of intelligent integrated energy supply systems (IES**S**). Their creation provides a reduction in operating costs, expanding the scope of services provided, increasing reliability, controllability, security and ensuring the possibility of the participation of an active consumer in the energy supply process [1-3]. Such IESS metasystems have already been developed in other countries [4-5]. For their study, it was proposed to apply a multiagent approach. The model developed on its basis allows one to study the mechanisms of functioning and interaction of agents [6–9]. The principles of building integrated systems and the features of applying the multiagent approach for their study were considered previously [10]. This article presents a multiagent model of an integrated energy supply system developed in the AnyLogic software environment, and also describes an experiment with this model.

2 AnyLogic software environment features

The AnyLogic software environment is a professional tool of a new generation, which is designed for the development and study of simulation models [11-12]. AnyLogic was developed on the basis of new ideas in the field of information technology, the theory of parallel interacting processes and the theory of hybrid systems [13]. Thanks to these ideas, it is simplified to build complex simulation models, for example, to control systems such as IES**S**.

The software modeling environment supports the design, development, documentation of the model being developed, computer experiments, optimization of parameters with respect to a certain criterion, which makes it possible to visualize the mechanisms of interaction and communication between agents [14].

When developing a model, elements of visual graphics can be used: state diagrams, signals, events, ports, etc.; synchronous and asynchronous event planning; libraries of active objects [15-16].

When developing a model using the AnyLogic software environment, one can apply concepts and tools from several classical areas of simulation: discrete event simulation, system dynamics, agent modeling [17-18]. In addition, with the further development and complication of the multiagent model of an integrated energy supply system, the AnyLogic software environment will allow you to integrate various approaches in order to obtain an even more complete representation of the interaction of complex technological processes. Therefore, to create a multiagent model of an integrated energy supply system, this software environment was chosen as the most

* Corresponding authors: sva@isem.irk.ru , mayorovgs@isem.irk.ru

suitable tool for modeling a complex system with many interacting elements.

3 Development of a multiagent model

Based on the structure of a multiagent integrated energy supply system described in [10], its model was developed in the AnyLogic software environment. The basis of this model is the interaction of agents of two systems (electrical and heating) in order to study the mechanisms of functioning of agents and their coordination.

In Figure 1 shows an enlarged scheme of an integrated energy supply system consisting of two consumers, two power stations, two boiler plants, four power lines and four heat mains, the second consumer has an electric boiler. This scheme allows us to study the behavior patterns of agents and the interaction between them.

The following types of agents were distinguished:

- Consumer-agent;
- Agent network;
- Source-agent;
- Networks-agent.

According to the developed structure of the multiagent integrated energy supply system (Fig. 2), the consumer-agent forms a load request and sends it to the agent network, in turn, the agent network sends this request to source-agents and networks-agents. Source-agents and networks-agents interact with each other and with an agent network, and as a result, a solution is formed to fulfill the request.

Next, each agent and their state diagrams are examined in more detail. If an agent can distinguish several states or behaviors that perform various actions when certain events occur, then the behavior of such an object can be described in terms of a state diagram. A state diagram is a state connected by transitions. Transitions can work as a result of its event specified as a condition, for example, it can be the expiration of a given time, receipt of a message according to the state diagram, fulfillment of a given logical condition, etc. [19-20].

The state diagram of the agent of the second consumer, which has an electric boiler, is more complex than that of the agent of the first consumer. This follows from the state diagram shown in Fig. 3.

The consumer-agent forms a request for heating energy (1) and sends it to the agent network (2). A request is sent from it to the consumer's electric boiler about the possibility of generating a given amount of heat or about the absence of heat (3). Based on this request, the data request is compared with the generated heat of the electric boiler (4) and a response is sent to the agent network. If the production of a given amount of heat is possible (5), then the agent of the second consumer receives a price request from the agent network and sends information about the price of heat (6). After this, a response will be received from the agent network with the most suitable supply option for the consumer (7), and there can be two options, either the supply will be from the heating system (boiler plants), or from the electric boiler installed by the consumer. Depending on where the consumer will be supplied with heat, a request for electrical energy will be generated. So, if it will be supplied from boiler plants, the electric load parameter will not change, but if it is supplied from an electric boiler, then the electric load of the boiler will be added to the initial electric load of the consumer.

Having formed a request for electric energy (8), the agent of the second consumer sends it to the agent network (9). After that, it is waiting a response from the agent network, and it can receive one of two messages “Consent” or “Failure”. Accordingly, if it receives the first message, it goes into the “Energy_received” state (10) (see Fig. 3), i.e. the request for energy is completed, and then it goes into a waiting state (11). If it receives a second message, then it enters the state “Energy_not_received” (12) (see Fig. 3), i.e. the request

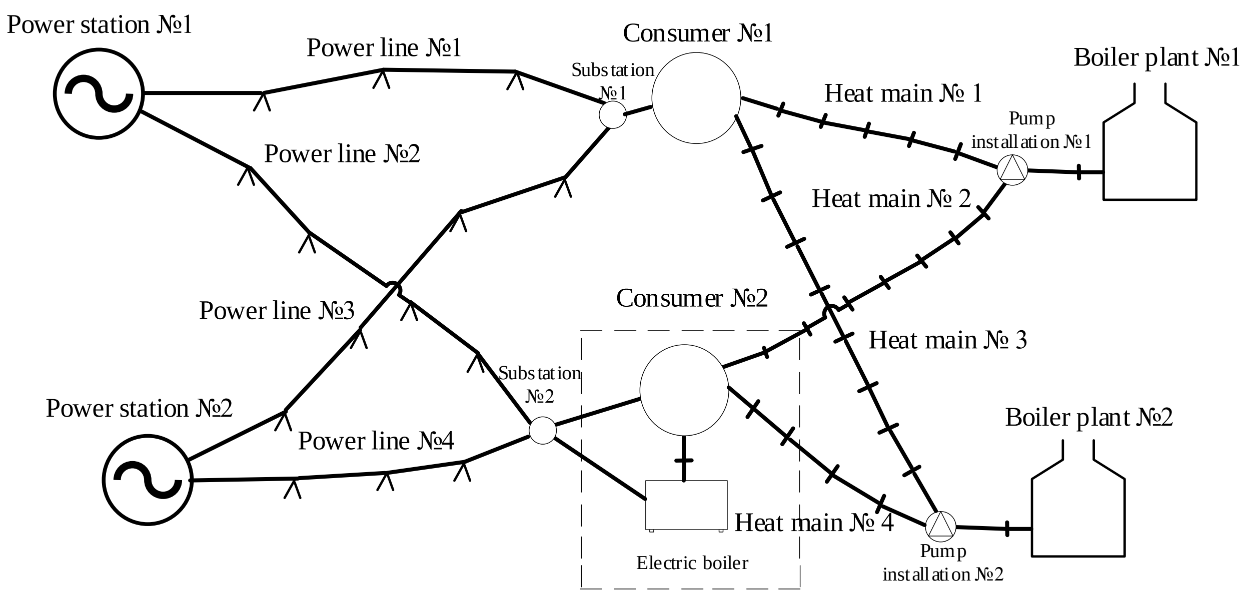

Fig. 1. Scheme of an integrated energy supply system

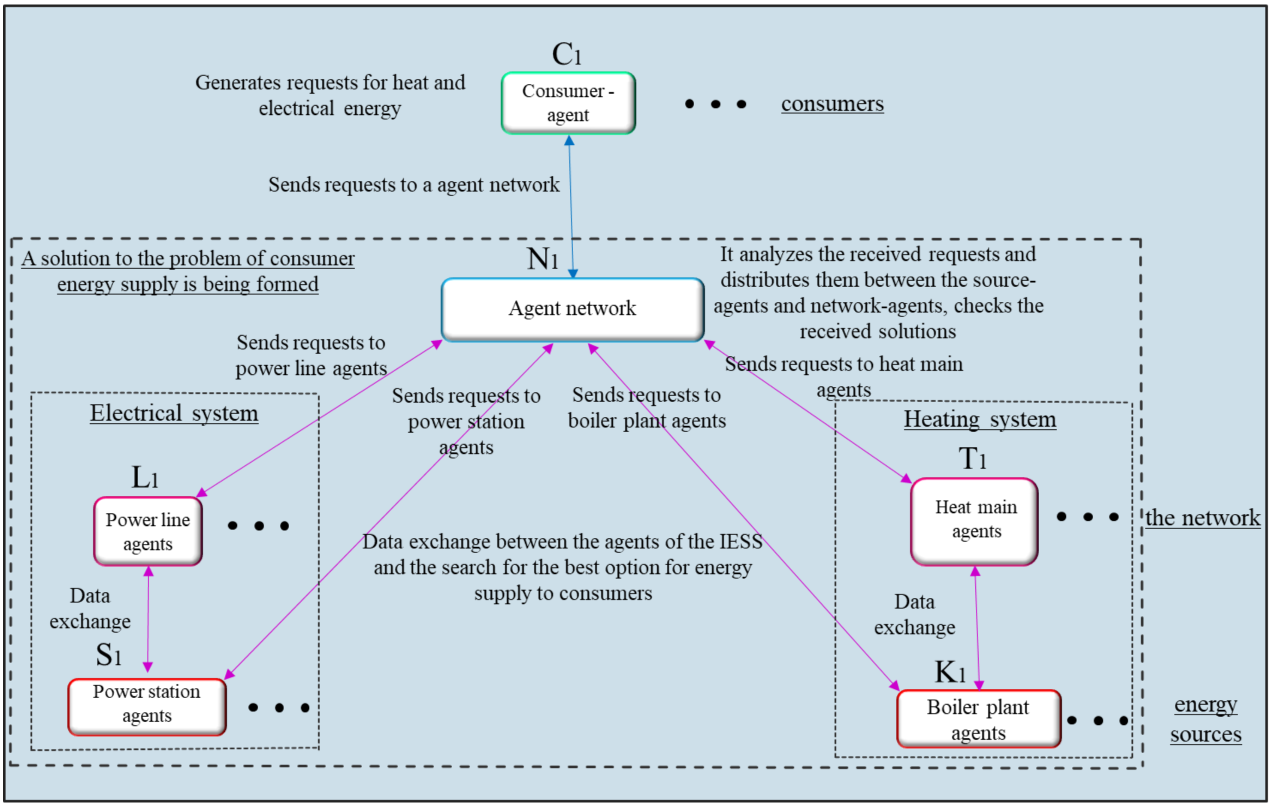

Fig. 2. Structure of a multiagent integrated energy supply system

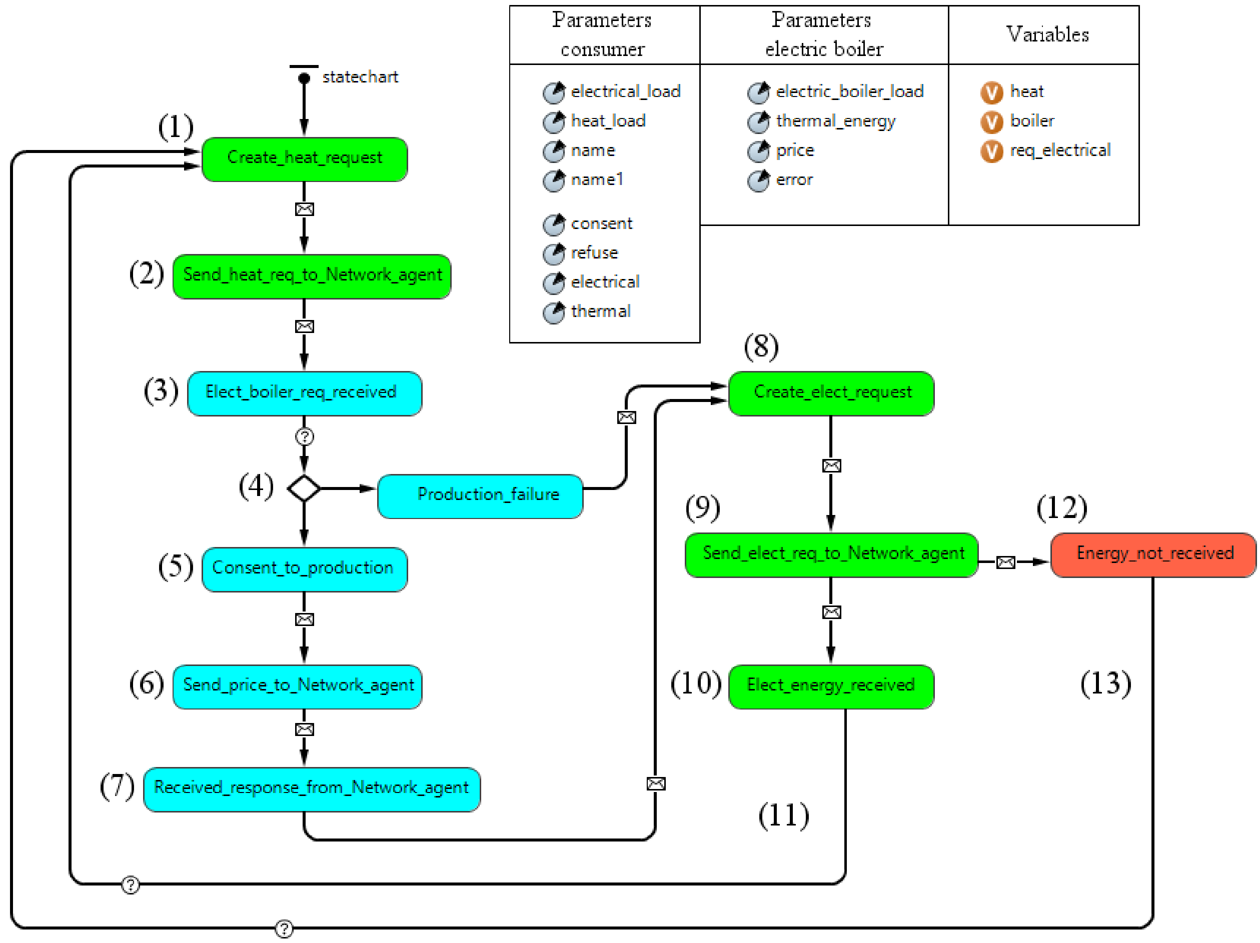

Fig. 3. Second consumer agent state diagram

for energy has not been completed, and then it goes into a waiting state (13).

The agent of the first consumer has a similar state diagram, only there are no diagram blocks associated with an electric boiler.

The agent network state diagram is shown in fig. 4. After receiving a request from a consumer for energy (1), the network agent sends it to source agents and network agents (2), which are associated with this consumer and can supply him with energy. In turn, the source-agents and network-agents, having received the request, check the necessary conditions and send a response to the agent network about the possibility of their participation in the supply of the consumer. After receiving responses from source-agents and network-agents (3), the agent network checks the necessary restrictions and determines whether the supply to the consumer is possible or not (4). If the supply of the consumer is possible (5), the agent network generates a request for the cost of energy to the source-agents (6), then compares the prices received and selects the most profitable option (7). After that, it sends it consent to the necessary energy sources for energy supply, and the rest refuses and notifies the consumer that his request for energy has been completed (8). After sending a message to the consumer-agent, the agent network goes into the waiting state of requests (9). If supplying the consumer is not possible, then the agent network enters the rejection state of the request (10) and sends a refusal to the consumer (11). And after sending a message to the consumer, it goes into a waiting state of requests (12).

Let us analyze the state diagram of network-agents (power lines and heat mains) (Fig. 5). Consider the first power line as an example. Other network-agents have similar state diagrams; they can vary in throughput, type of energy, and consumer connections with corresponding energy sources.

The power line agent receives a request from the agent network (1) and compares the received parameter (required power) with power line throughput (2), while there can be two options for the development of events.

In the first case, if the power line can pass the specified power, the agent goes into a consent state and sends a message with the “Consent” parameter (3) to the agent network.

After that, the power line agent is waiting a response from the power station agent associated with it. Having received a message (4), it sends back to the power station agent a message with the “Yes” parameter (5), which means that it is ready to deliver energy. At the end, the power line agent can receive one of two messages from the power station agent, if the message “Failure” (6) arrives, then it goes to the waiting state of the request, and energy is not delivered through this power line if the message “Delivery” (7), then it goes into the “Delivery” state (8) (see Fig. 5) and delivers

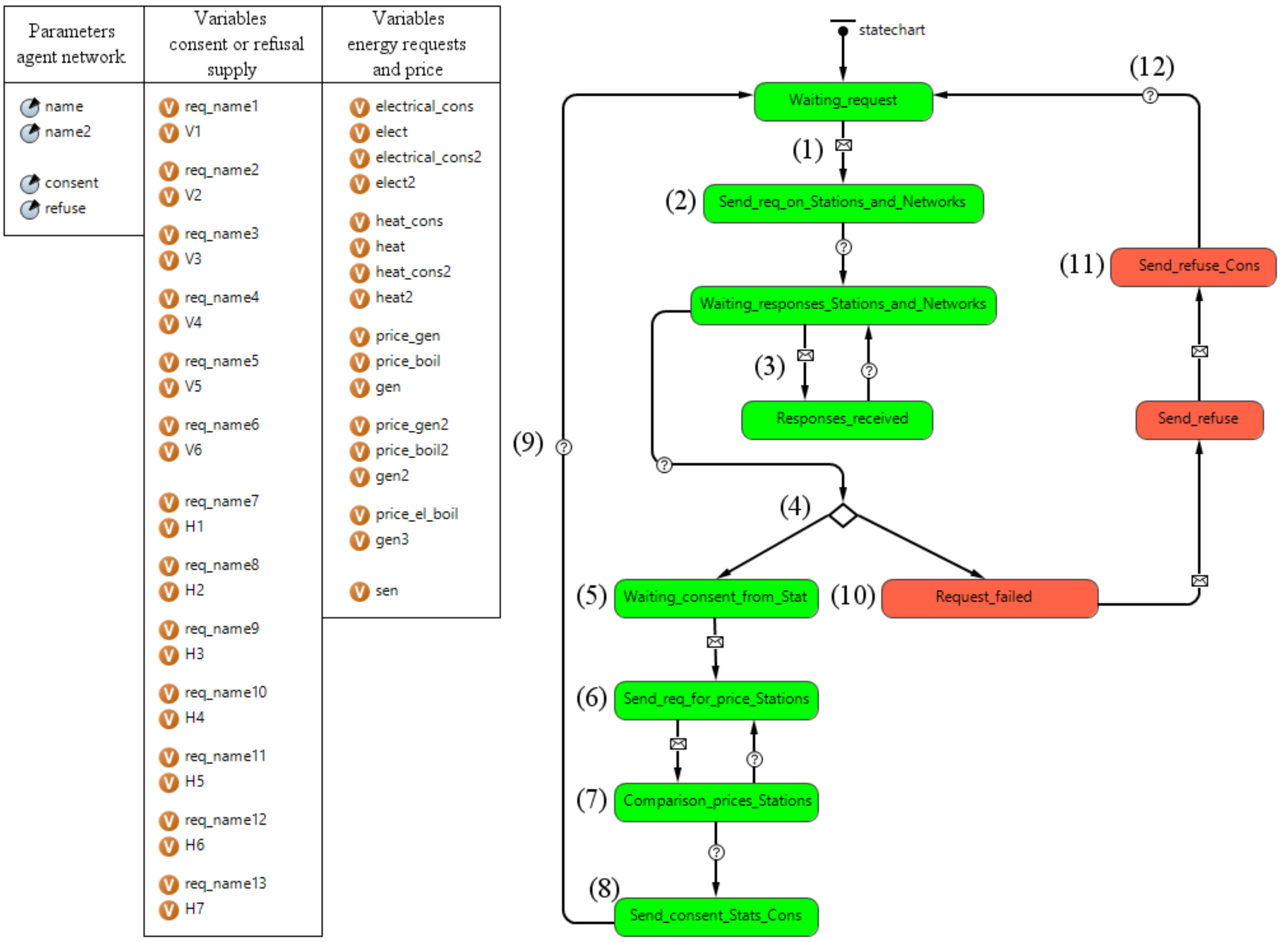

Fig. 4. Network agent state diagram.

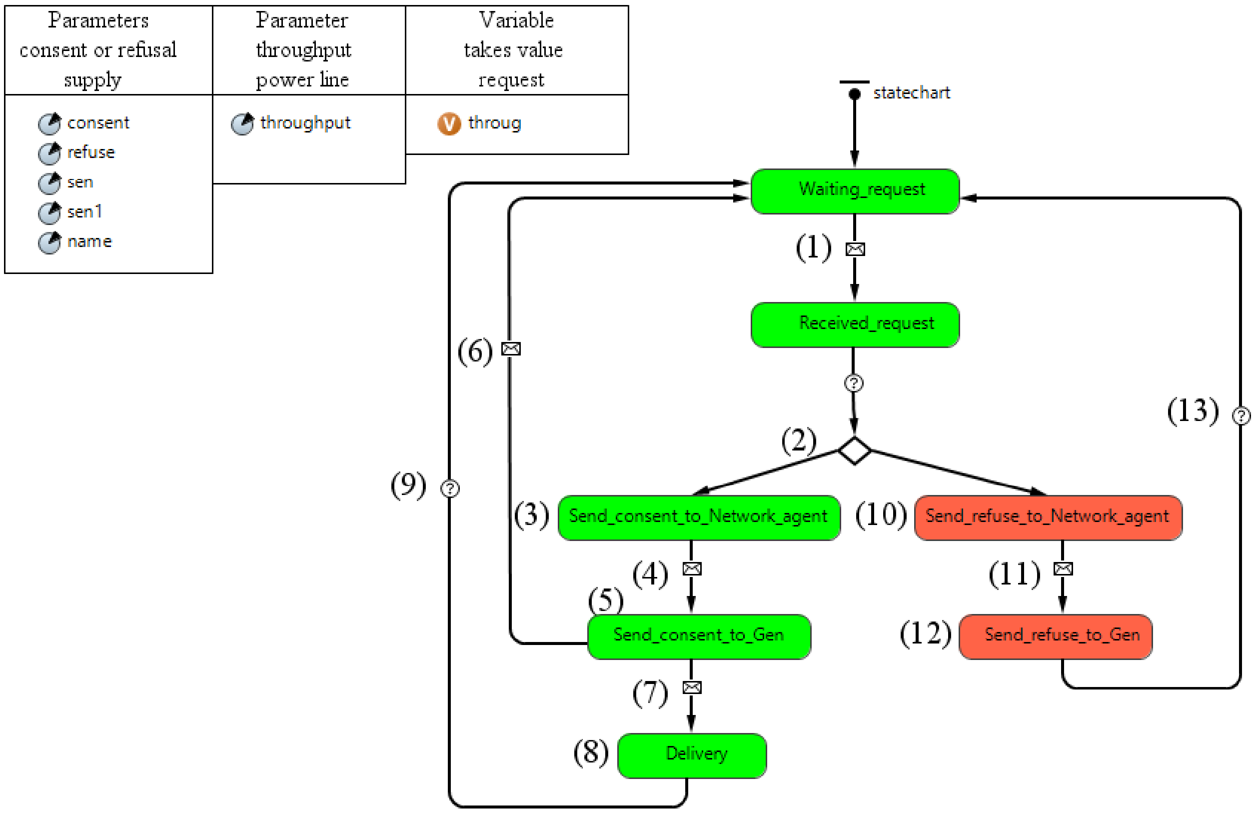

Fig. 5. Power line agent state diagram.

energy to the consumer, then it goes to the waiting state of the request (9).

In the second case, if the power line cannot miss the specified power, the power line agent goes into a failure state and sends a message to the agent network with the "Refusal" parameter (10). After that, the power line agent is waiting a response from the power station agent associated with it. Having received the message (11), it sends back to the power station agent a message with the parameter "No" (12), which means that power cannot be delivered, and then it goes to the waiting state of the request (13).

The state diagram of source-agents (power stations and boiler plants) is presented in Fig. 6. As an example, take the first power station. The second power station and boiler plants have similar state diagrams, while the type and amount of energy, as well as connections with network-agents, may be different.

Having received a request for electricity (1) redirected by an agent network, the power station agent compares this parameter with its available capacity (2), and two cases of events may occur.

In the first case, the available capacity of the power station is less than declared by the consumer, therefore the power station agent goes into the "Generation_failure" state (3) (see Fig. 6). It sends a message with the "Refusal" parameter to the agent network (4), and also sends a "Failure" message to the power line agents with which it is associated (5). In addition, the power station agent goes into a state of waiting for requests (6).

In the second case, the available capacity of the power station is sufficient to fulfill the request, therefore the power station agent goes into the "Consent_to_generation" state (7) (see Fig. 6) and sends a message with the parameter "Consent" to the agent network and the message "Generation" to the power lines agents with which it is associated. After that, it expects a response from power line agents in the form of one of the following two messages. The first message with the parameter "No" means that power lines cannot miss the required power, then the power station agent goes into the state "Line_failure_received" (8) (see Fig. 6). And it sends a message to the agent network with the "Refusal" parameter (9), and then goes back to the waiting state of requests (10). At the same time, the consumer is not supplied from this power station. The second message with the "Yes" parameter means that the power lines can transmit the necessary power, then the power station agent goes into the "Line_consent_received" state (11) (see Fig. 6) and, after requesting the price of energy from the agent network, sends a corresponding message with the parameter "Price" (12). After that, it expects a response from the agent network, if the power station agent receives a "Failure" response (13), it sends a "Failure" message to the power line agents (14) and goes back to the waiting state of requests (15), while the consumer is not supplied.

Upon receipt of the "Consent" message (16), it goes into the "Generation_consent_received" state (17) (see Fig. 6), sends a "Delivery" message to power line agents, and supplies the consumer with energy. After that, the power station agent goes back to the state of waiting for the requests (18).

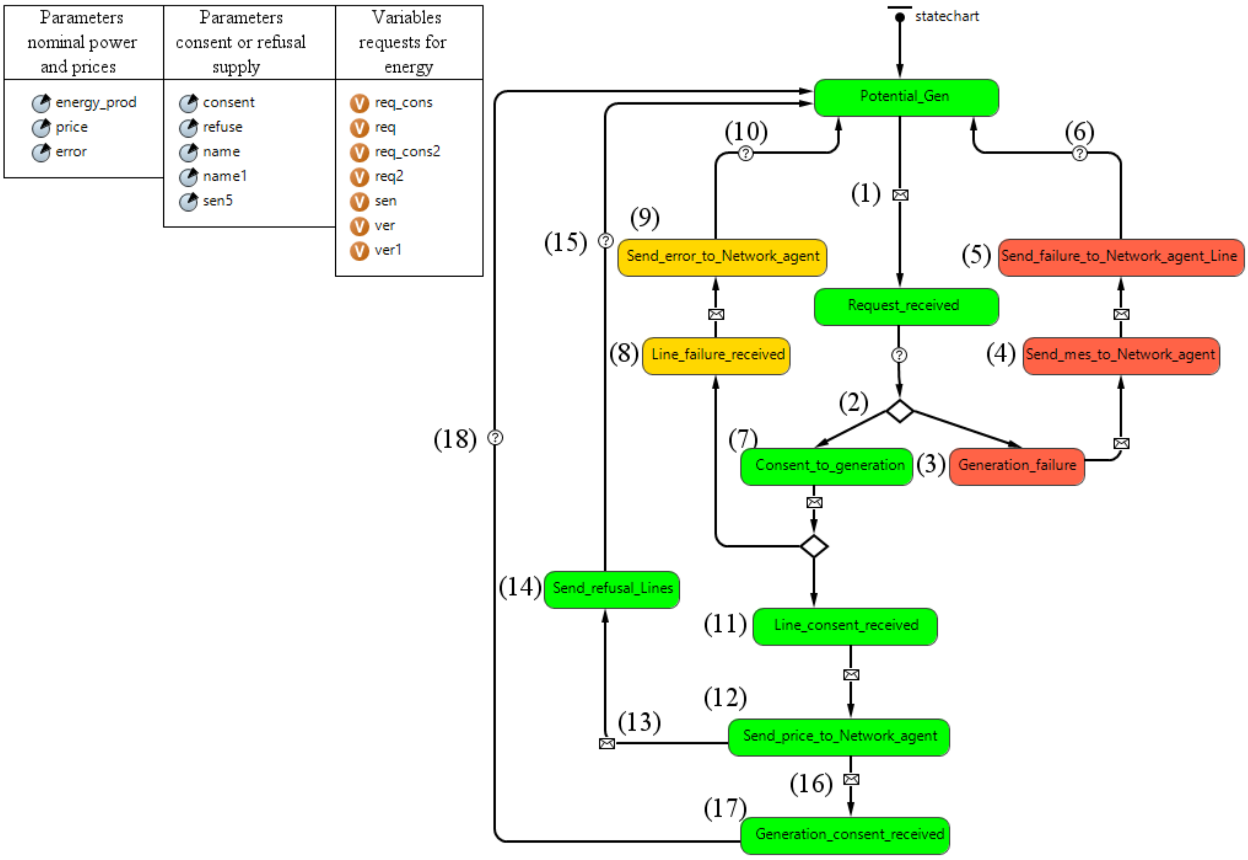

Fig. 6. State diagram of the first power station agent.

4 Experiment with the multiagent model

The generalized scheme of the IESS is shown in Fig. 1. Both power stations are in good condition and can provide the delivery of available capacity. Electric networks are also in working condition and can pass the necessary electric power, except for the power line No. 1, which is under repair. The first boiler plant is already loaded and will not be able to participate in the energy supply process, and the heat of the second boiler plant is sufficient to fulfill the request only from the first consumer. Heating networks are in working condition and can pass the necessary thermal power.

Initial data:

P_{ps1} = 320 MW - nominal power of power station No. 1;

P_{ps2} = 290 MW - nominal power of power station No. 2;

Q_{bp1} = 0 Gcal/h - nominal power of boiler plant No. 1;

Q_{bp2} = 200 Gcal/h - nominal power of boiler plant No. 2;

$Q_{el.b}$ = 100 Gcal/h - nominal power of the electric boiler;

C_{ps1} = 1100 rubles/MW · h - the cost of electricity at power station No. 1;

C_{ps2} = 1300 rubles/MW · h - the cost of electricity at power station No. 2;

C_{bp1} = 1200 rubles/Gcal - the cost of heat of boiler plant No. 1;

C_{bp2} = 1400 rubles/Gcal - the cost of heat of boiler plant No. 2;

$C_{el.b}$ = 1600 rubles/Gcal - the cost of the heat of an electric boiler;

P_{el1} = 100 MW - electrical load of consumer No. 1;

Q_{tl1} = 200 Gcal/h - heat load of consumer No. 1;

P_{el2} = 70 MW - electric load of consumer No. 2;

Q_{tl2} = 100 Gcal/h - heat load of consumer No. 2;

$P_{el.b}$ = 116 MW - load of the electric boiler;

Th_{pl1} = 0 MW - throughput of power line No. 1;

Th_{pl2} = 200 MW - throughput of power line No. 2;

Th_{pl3} = 110 MW - throughput of power line No. 3;

Th_{pl4} = 210 MW - throughput of power line No. 4;

Th_{hm1} = 230 Gcal/h - throughput of heat main No. 1;

Th_{hm2} = 140 Gcal/h - throughput of heat main No. 2;

Th_{hm3} = 250 Gcal/h - throughput of heat main No. 3;

Th_{hm4} = 120 Gcal/h - throughput of heat main No. 4.

In accordance with the given conditions, we will examine in more detail the entire process of energy supply to consumers (Fig. 7). Consumer-agents forms requests for energy a day in advance, and first, requests for heat were formed: the first consumer forms a request for 200 Gcal/h, the second consumer - 100 Gcal/h. Then these requests are sent to the agent network, and it, in turn, redirects the request data to boiler plants, an electric boiler located at the second consumer, and heating networks. Next, a solution is sought through the interaction of heat network agents and heat sources between themselves. As a result of this search, the multiagent model of the integrated system obtained a solution according to which boiler plant No. 2 and heat main No. 3 can provide heat only to the first consumer, and the second consumer will be supplied with heat by an electric boiler located at it, since boiler plant No. 1 does not have necessary heat.

After calculating the heat supply of consumers, the formation of requests for electricity occurs: the first consumer forms a request for 100 MW, and the second consumer forms 186 MW, taking into account the additional load of the electric boiler. Then, the formed requests are sent to the agent network, and it, in turn, redirects them to the agents of two power stations and electric networks. A search for a solution was also carried out through the interaction of agents of electrical networks and power plants. As a result, the multiagent model has received a solution for an integrated system, according to which power supply of the first consumer with electric energy will be provided from power station No. 2 by power line No. 3, since power line No. 1 has been taken out for repairs, as a result of which, power station No. 1 will not be able to participate in power supply to the first consumer, and the power supply of the second consumer will be provided from the power station No. 1 by power line No. 2, as it has a lower cost for electricity than power station No. 2. The total cost of the received option for supplying energy to the first consumer per day amounted to 9840000 rubles, including 3120000 rubles for electricity, 6720000 rubles for heat. The total cost of the received option for power supply of the second consumer per day amounted to 5688000, including 1848000 rubles for electricity. (excluding the cost of energy supply of an electric boiler, which are included in the cost of the heat energy generated by it), heat energy 3840000 rubles.

The experiment shows that all the necessary computational and logical operations have been performed in the model. The power supply of consumers was organized according to the most optimal option, therefore, the logical chains worked out correctly, and the data transmission through the system was carried out correctly, all agents performed the functions assigned to them, and the consumers received the required amount of energy with the given parameters.

5 Results

To implement a multiagent model of an integrated energy supply system, the AnyLogic software environment is proposed as the most adequate tool using advanced technologies for modeling complex systems. In the AnyLogic software environment, a multiagent model of IESS has been developed. For its implementation, the types of agents are determined and their state diagrams are formed, reflecting the behavior and interaction of the agents among themselves, aimed at energy supply to consumers. The experiment showed that the multiagent model works correctly and all specified conditions are fulfilled, system agents correctly perform the functions assigned to them. Further development and improvement of the model will allow us to simulate real energy supply systems and explore complex technological processes occurring in them.

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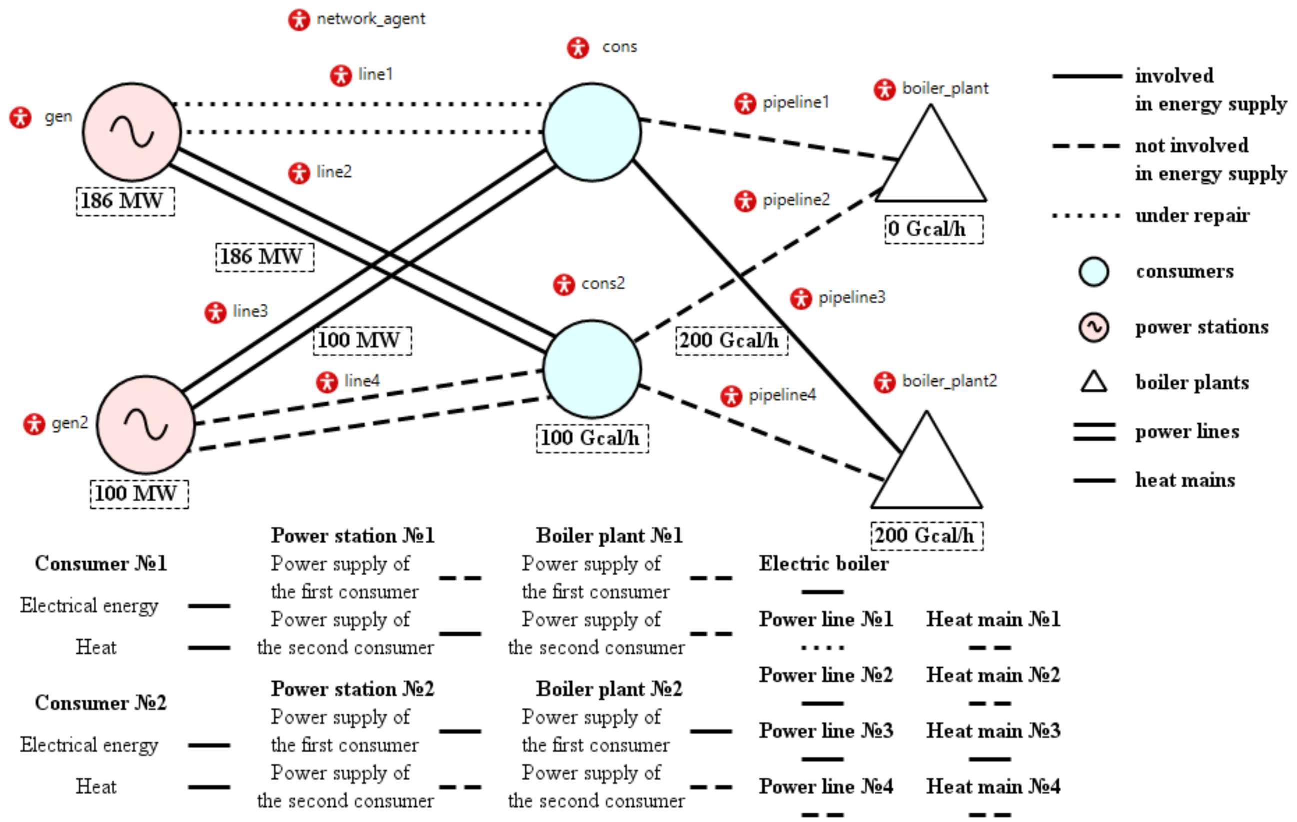

Fig. 7. Scheme of multiagent model of IESS in AnyLogic software

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A technique for determining a relationship between the prices of heat and electricity generated by CHP

Elena Stepanova[1,*], and *Pavel* Zharkov [1]

[1] Department of Thermal Power Systems Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, ESI SB RAS, Irkutsk, Russia

Abstract. A technique was developed to optimize operations of a combined heat and power (CHP) plant taking into account changes in thermal loads. The technique is based on determining the relationship between changes in the price of electricity and changes in the price of heat. The price range is determined, on the basis of which the Pareto-optimal set of decisions is built. This set of solutions helps to find options for technical solutions that ensure the competitiveness of CHP plant relative to single-product heat and power generating plants and the most effective option to choose. It is required to solve three optimization problems to construct a Pareto-optimal set of solutions: the problem of minimizing the price of electricity for a given heat price and the rate of return on investment, the problem of minimizing the energy price to determine the maximum heat price, and the problem of minimizing the exergy price to find the minimum boundary of the heat price range. The technique was tested on the example of a cogeneration gas turbine plant. The cogeneration gas turbine plant has a waste-heat boiler and a contact heat exchanger for heating the make-up network water. The heat price range for the investigated a cogeneration gas turbine plant has been determined. Optimization studies of the operating modes of a cogeneration gas turbine plant were carried out in this range with a certain step. The results obtained can be used to select the optimal technical solutions, select the optimal combination of circuit-parametric solutions that ensure the competitiveness of the products of a cogeneration gas turbine plant.

1 Introduction

The share of CHP plants (CHPP) for energy generation has some growth in the Russian Federation (RF) and some countries. CHPPs that work by burning fossil fuels retain their competitiveness, despite the development of alternative energy. The development of optimal technological schemes, including the use of waste gas heat recovery technologies, the operation of units in the cogeneration mode, which, as a rule, provides the highest energy and economic efficiency, increase the competitiveness of CHPPs [1-5]. Many countries have market conditions for pricing energy products. Energy producers need to know the price range of energy products at which their sale will be profitable, taking into account all the rules and restrictions on the operation of equipment. The heat load of cogeneration CHPPs depends on the climatic characteristics of the region of operation and the prices for the types of energy produced are interrelated. Determination of the dependence of the change in the price of one type of energy on the possible change in the price of another type of energy, taking into account changes in heat loads, is an urgent topic. The choice of optimal technical solutions, the selection of the optimal combination of circuit-parametric solutions for CHPP can be done using modern means of mathematical modeling and optimization. This will ensure the competitiveness of cogeneration CHPP products. The software system for building programs has been developed by the Melentiev Energy Systems Institute (ISEM) SB RAS [6-8]. The use of mathematical models of CHPP, created with its help, makes it possible to perform design, verification calculations and carry out optimization studies of CHPP.

2 Problem statement

RF and many other countries have regions where consumers need electricity and heat due to climatic conditions. Heat consumption for heating and ventilation of buildings for various purposes is proportional to the difference in air temperatures inside the heated premises and outside air. Therefore, the total heat load of cogeneration CHPPs changes with a change in the outside air temperature, since heating and ventilation loads account for a significant proportion. Therefore, the characteristic types of operating modes of such CHPPs must be taken into account in the circuit-parametric optimization. Characteristic operating modes can have heating and ventilation nominal heat loads and heat partial loads corresponding to different outdoor

* Corresponding author: step@isem.irk.ru

temperatures. The annual duration of the CHPP operation in these modes is determined on the basis of the graphs of the duration of the standing outside air temperatures in the area in which the CHPP will operate [9]. The methodological approach was developed by ISEM SB RAS for single-product CHPPs that produce only electricity. According to the approach, the maximum economic efficiency is obtained by combining circuit-parametric solutions that provide a minimum price for electricity at a given value of the internal rate of return on investment [10, 11]. The cogeneration CHPP produces two types of products - electrical and thermal energy [12, 13]. For two-product cogeneration CHPP, a modification of this approach consists in setting the price of one product (heat) and minimizing the price of another product (electricity), at a given value of the internal rate of return on investment [14, 15]. The limitation is imposed on the maximum electric power of the CHPP, and the nominal heat load of the installation is included in the optimized parameters. The mathematical formulation of the problem of minimizing the price of electricity for a given heat price and a given rate of return on investment (Problem I) has the following form.

$$\min_{Q^d, x_s, B_s, x_i, B_i} \left[\frac{(K_t L + B_{year} C^f + K_t(\alpha_{asfoc} + \alpha_{adc}) - Q_{year} C^h)}{W_{year}} \right], \quad (1)$$

under the conditions

$$S_s = f(x_s, B_s, \gamma_s, Q^d), \quad (2)$$

$$G_s(x_s, B_s, \gamma_s, Q^d) \ge 0, \quad x_s^{\min} \le x_s \le x_s^{\max}, \quad (3)$$

$$N_s = f(Q^d, B_s, x_s, \gamma_s), \quad N^{\min} \le N_s \le N^{\max}, \quad (4)$$

$$G_i(x_i, B_i, \gamma_i, S_k, Q_i) \ge 0, \quad x_i^{\min} \le x_i \le x_i^{\max}, \; i = 1, ..., n, \quad (5)$$

$$K_{eq} = f(S_s, d_{uc}), K_t = K_{eq} + K_{bc}, \quad (6)$$

$$Q_i = f(Q^d, \gamma_i), \; N_i = f(Q_i, B_i, x_k, x_i, \gamma_i), \quad (7)$$

$$Q_{year} = Q^d T_s + \sum_{i=1}^{n} Q_i T_i, \quad (8)$$

$$W_{year} = N_s T_s + \sum_{i=1}^{n} N_i T_i, \quad (9)$$

$$B_{year} = B_s T_s + \sum_{i=1}^{n} B_i T_i, \quad (10)$$

where $L = \sum_{i=0}^{N_{con}-1} \frac{1}{(1+CRF)^i} \Big/ N_{con} \cdot \sum_{j=N_{con}}^{i=N_{con}+N_{op}} \frac{1}{(1+CRF)^j}$;

N_{con}, N_{op} – construction and operation periods, respectively; CRF – capital recovery factor; K_t – total capital investment; x_s – the vector of independent optimized parameters determining the structural characteristics of the plant (the cycle parameters, design parameters of elements and operating parameters in nominal mode); x_i – the vector of optimized operating parameters in the i-th mode (the index *i* refers to parameters related to characteristic modes with recalculations); B_s – fuel consumption (per hour) in nominal mode; B_i – fuel consumption (per hour) in the *i*-th mode; B_{year} – the annual fuel consumption; C^f – fuel cost; K_{bc} – capital investments that take into account unforeseen costs and construction costs; α_{asfoc}, α_{adc} – shares of annual costs on semi-fixed operating costs and depreciation charges, respectively; Q^d – the design heat load; Q_{year} – annual heat supply; C^h – cost of heat energy; W_{year} – annual electricity supply; S_s – vector of design characteristics of the CHPP; γ_s – vector of initial data that determines the external conditions of the CHPP in the nominal mode; G_s – l_s -dimensional vector function of constraints-inequalities in the nominal mode; N_s – electric power of the CHPP in nominal mode; $N^{\min}$, $N^{\max}$ – the minimum and maximum values of electric power of the CHPP; G_i – l_i -dimensional vector function of constraints-inequalities in the *i*-th mode; γ_i – the vector of initial data that determines the external conditions of operation in the *i*-th mode; K_{eq} – equipment investment; d_{uc} – the vector of specific costs of equipment elements; T_s – the duration of the nominal mode; T_i – the duration of the *i*-th mode; Q_i – the heat supply in the *i*-th mode; N_i – electric power in the *i*-th mode; N_i^{pn} – electricity consumption for proper needs in the *i*-th mode; $x_s^{\min}$, $x_s^{\max}$, $x_i^{\min}$, $x_i^{\max}$ – the vectors of minimum and maximum values of x_s and x_i respectively; *n* – number of modes.

The task is to select a combination of circuit-parametric solutions for CHPP, which can ensure the competitiveness of the products of cogeneration CHPP relative to single-product power generating plants and relative to single-product heat generating plants, which can be used in the corresponding systems of electricity and heat supply. To search for such a combination of solutions (in accordance with the technique proposed in this work), a series of optimization calculations is carried out according to the criterion of the minimum price of electricity for different given values of the heat price. At the same time, the price of heat varies within a certain range. The set of solutions obtained as a result of a series of optimization calculations is the Pareto optimal set. For any element (solution) of a given set, there is no other solution that would have a lower price of heat and not a higher price of electricity for a given value of the internal rate of return on investment, or a lower price of electricity and not a higher price of heat. The problem of choosing the boundaries of the range (in which the price of heat should change) arises when using this approach. The heat price of an alternative boiler house is used as the upper limit of the range in article [16]. The value of the lower limit of the range is determined on the basis of expert analysis, as a fraction of its upper limit. A number of conditions must be observed when determining the price of heat:

- the price of heat of the alternative boiler house and the price of electricity from the CHP are determined at the same value of the internal rate of return on investment;
- the price of the same elements of equipment, construction and installation work must be the same for the calculations of the CHPP and the alternative boiler house;
- if the CHPP and the boiler house use the same type of fuel, the price for them must be the same;
- the same climatic characteristics should be used when calculating the CHPP and the boiler room (design temperature of the outside air, graphs of the duration of the standing temperatures of the outside air, etc.);
- optimization of the design and operating parameters of the boiler room should be carried out, taking into account changes in heat loads.

It is difficult to ensure compliance with these conditions, especially if one uses the heat price of an alternative boiler house or its individual characteristics (specific capital investments, specific fuel consumption per unit of heat supplied, electricity consumption for auxiliary needs, etc.) obtained by other authors. Taking this into account, the heat price at the boundaries of the range is proposed to be determined in this work as a result of solving two optimization problems based on calculations of only the investigated CHPP. The maximum heat price is determined by the criterion of the minimum price of the supplied energy for the optimization of the CHPP. The annual energy supply is obtained by summing the annual electricity supply and the annual heat supply, reduced to one system of units (MWh). As a result, the price of a unit of thermal energy is equal to the price of a unit of electricity. The price of heat (resulting from the solution of the specified problem) will be higher than the price of heat of any single-product heat generating installation, as calculations show. Because the cost of producing a unit of electricity is much higher than the cost of producing a unit of thermal energy. The mathematical formulation of the energy cost minimization problem (Problem II) is as follows.

$$\min_{Q^d, x_s, B_s, x_i, B_i} \left[\frac{(K_t L + B_{year} C^f + K_t(\alpha_{asfoc} + \alpha_{adc}) - Q_{year} C^h)}{(W_{year} + Q_{year})} \right], \quad (8)$$

under the conditions (2)-(10).

The minimum boundary of the heat price range is determined when optimizing the power plant according to the criterion of the minimum price of supplied exergy. The annual exergy release is obtained by summing the exergy contained in the annual electricity supply and the exergy contained in the annual heat supply. Since a unit of electrical energy contains a unit of exergy, and a unit of thermal energy supplied in the form of hot water contains about 1/4 of a unit of exergy, then the price of a unit of heat, when solving this optimization problem, will be about 4 times less than the price of electricity, and as calculations show, will be significantly lower than the price of any single-product heat generating installation. The mathematical statement of the problem of minimizing the cost of exergy (Problem III) is given below.

$$\min_{Q^d, x_s, B_s, x_i, B_i} \left[\frac{(K_t L + B_{year} C^f + K_t(\alpha_{asfoc} + \alpha_{adc}))}{(W_{year} + E^h_{year})} \right], \quad (9)$$

under the conditions (2)-(10), where E^h_{year} .– the amount of exergy in the annual heat release.

The range of heat prices (obtained as a result of solving the two specified optimization problems) will cover the heat prices of all competitive single-product CHPPs. The Pareto-optimal set of solutions built on the basis of this range will make it possible to determine the options for technical solutions that ensure the competitiveness of CHPPs relative to single-product heat and power generating plants and choose the most effective from these options.

In this work, the method for determining the relationship between the change in the price of electricity and the change in the price of heat for a CHPP is applied to a cogeneration gas turbine unit (GTU). The GTU has a waste-heat boiler and a contact heat exchanger for heating the make-up network water. Heat energy is supplied to consumers in the form of hot water for heating and hot water supply (DHW). The cogeneration GTU has an air compressor, two fuel combustion chambers, a gas turbine, a waste heat boiler, a contact heat exchanger, a water-to-water heater, and pumping units (Fig. 1). The GTU circuit does not have a peak heat source. The heat load is regulated by bypassing a certain part of the flue gas flow rate bypassing the waste heat boiler and the contact heat exchanger. The gas turbine exhaust gases have a high temperature and the volumetric concentration of the O2 oxidizer is 13-16%. Therefore, afterburning of a certain amount of fuel is carried out in the exhaust gas environment of the GTU in the second combustion chamber. This makes it possible to increase the thermal power of the gas turbine unit and stabilize the parameters of the network water heated in the waste heat boiler.

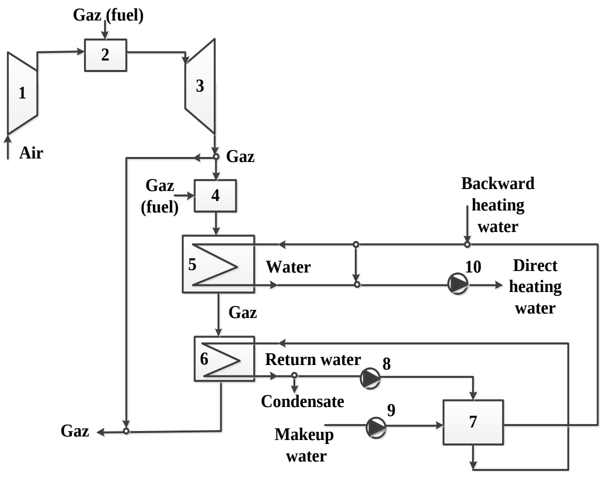

Fig. 1. The basic technological scheme of the cogeneration gas turbine unit (1 - air compressor; 2 - first combustion chamber; 3 - gas turbine; 4 - second combustion chamber; 5 - waste heat boiler; 6 - contact heat exchanger; 7 - water/water heater; 8-10 – pumps).

The design and verification mathematical model of the GTU consists of different element models. Design part - models of all elements are based on design calculations with the determination of the geometric dimensions of heat exchangers and nominal flow rates, gas pressures at the inlet and outlet of the gas turbine. Verification part - models of all elements are based on verification calculations, which are carried out for given design characteristics (obtained as a result of calculations of a design model) and determine the parameters of heat carriers (gas, air and water). The design and verification mathematical model of the GTU carries out one design and several verification calculations at various thermal loads (characteristic modes). The design calculation is carried out at maximum thermal loads (nominal mode).

3 Results of optimization studies

The modes of operation of the cogeneration GTU under study were considered: one nominal mode at a temperature of -25^{0}C (the estimated outdoor air temperature) and the duration of 106 hours; four modes with different thermal loads at average outdoor air temperatures -20^{0}C, -10^{0}C, +1.5 ^{0}C, +18^{0}C (non-heating period) and durations 310 hours, 1084 hours, 2650 hours, 2850 hours. The range of changes in the electrical power of the gas turbine unit in the studied modes was taken equal to 50-60 MW. The temperature schedule of the heat network is adopted equal to120/70^{0}C. The determination of the annual fuel consumption and the annual supply of electric and heat energy is carried out taking into account the duration of the modes. The internal relative efficiency of the air compressor and gas turbine is taken as 0.85 and 0.89, respectively. The maximum permissible value of the gas temperature in front of the gas turbine is assumed to be 1500^{0}C. In the calculation of capital investment, the following source information was adopted [9, 16]. Specific costs: gas turbine – 70 USD/kW (per unit of maximum total power of a gas turbine), air compressor – 50 USD/kW, turbine generator set, pumps – 60 USD/kW, heat exchanger pipes made of carbon steel – 7 thous. USD/t, of steel 20 – 21 thous. USD/t, that of electrical equipment was 0.192 thous. USD/kW, and fuel consumption dependent systems – 240 thous. USD/(t/h). The internal rate of return on investment is 0.15, coefficient considering assembly costs is 1.6, coefficient that takes into account unforeseen costs is 1.03, coefficient that takes into account other costs is 1.3, coefficient of equipment price adjustment to current prices is 1.65, coefficient that takes into account the value of unconsidered equipment is 1.1.

The lower and upper boundaries of the range of changes in the heat price were determined as a result of solving problems (Problem II) and (Problem III): 9 USD/Gcal and 25 USD/Gcal. Optimization calculations were performed with a step of two units. The main indicators of the operating modes of the cogeneration GTU are presented at different heat prices (Table 1, 2, 3). Accepted designations in tables 1-3: outer/inner diameters of pipes of waste heat boiler are indicated d1/d2; transverse/longitudinal pipe spacing of waste heat boiler – s1/s2; heat exchange surface area of waste heat boiler – F1; outer/inner diameters of pipes of heating system water make-up heater are indicated d3/d4; transverse/longitudinal pipe spacing of heating system water make-up heater – s3/s4; heat exchange surface area of heating system water make-up heater – F2; The graph of the dependence of the price of electricity on the price of heat is shown in Fig. 2.

Table 1. The main indicators of GTU (cost of heat energy 9, 11, 13 USD/Gcal).

Main indicators	Cost of heat energy, USD/Gcal		
	9	11	13
Cost of electricity, cent/kW	4,72	4,52	4,31
GTU heat load in nominal mode, Gcal/h	125,4	129,8	136,2
Maximum useful electric power of GTU in nominal mode, MW	59,7	59,6	59,6
Annual heat supply, thous. Gcal	415,0	429,4	450,7
Annual electricity supply, thous. MWh	392,0	391,5	391,2
Annual fuel consumption, thous. t.f.e./year	135,9	136,0	138,7
Annual fuel consumption (the first combustion chamber), thous. t.f.e./year	126,9	126,3	127,8
Annual fuel consumption (the second combustion chamber), thous. t.f.e./year	9,0	9,7	10,9
Relative capital investments, USD/kW	558,0	558,8	563,4
Fuel heat utilization coefficient	0,78	0,80	0,81
Specific fuel consumption for heat supply, kg.f.e./Gcal	153,6		
Specific fuel consumption for electricity supply, g.f.e./kWh	184,4	178,7	177,5
- d1 / d2, mm - s1 / s2, mm - F1, m2	50/47 104/64 2789	50/47 104/64 2892	50/47 104/64 2902
- d3 / d4, mm - s3 / s4, mm - F2, m2	16/14,5 23/20 602	16/14,5 23/20 609	16/14,5 23/20 676

Table 2. The main indicators of GTU (cost of heat energy 15, 17, 19 USD/Gcal).

Main indicators	Cost of heat energy, USD/Gcal		
	15	17	19
Cost of electricity, cent/kW	4,10	3,80	3,54
GTU heat load in nominal mode, Gcal/h	156,3	175,3	179,6
Maximum useful electric power of GTU in nominal mode, MW	59,3	58,9	58,8
Annual heat supply, thous. Gcal	517,2	579,9	594,1

Annual electricity supply, thous. MWh	389,8	387,3	386,3
Annual fuel consumption, thous. t.f.e./year	147,7	156,0	159,9
Annual fuel consumption (the first combustion chamber), thous. t.f.e./year	128,0	129,2	129,8
Annual fuel consumption (the second combustion chamber), thous. t.f.e./year	19,7	26,8	30,1
Relative capital investments, USD/kW	577,5	581,1	585,3
Fuel heat utilization coefficient	0,82	0,83	0,83
Specific fuel consumption for heat supply, kg.f.e./Gcal	153,6		
Specific fuel consumption for electricity supply, g.f.e./kWh	175,3	173,1	172,4
- d1 / d2, mm - s1 / s2, mm - F1, m2	50/47 104/64 3044	50/47 103/63 3305	50/47 103/63 3354
- d3 / d4, mm - s3 / s4, mm - F2, m2	16/14,5 23/20 762	16/14,5 22/19 769	16/14,5 22/19 774

Table 3. The main indicators of GTU (cost of heat energy 21, 23, 25 USD/Gcal).

Main indicators	Cost of heat energy, USD/Gcal		
	21	23	25
Cost of electricity, cent/kW	3,28	2,84	2,22
GTU heat load in nominal mode, Gcal/h	212,7	261,1	277,6
Maximum useful electric power of GTU in nominal mode, MW	58,5	57,5	55,2
Annual heat supply, thous. Gcal	703,6	863,7	918,5
Annual electricity supply, thous. MWh	385,0	373,7	362,7
Annual fuel consumption, thous. t.f.e./year	174,3	196,7	202,1
Annual fuel consumption (the first combustion chamber), thous. t.f.e./year	133,7	134,4	135,4
Annual fuel consumption (the second combustion chamber), thous. t.f.e./year	42,3	62,3	66,7
Relative capital investments, USD/kW	629,1	711,3	745,8
Fuel heat utilization coefficient	0,84	0,86	0,87
Specific fuel consumption for heat supply, kg.f.e./Gcal	153,6		
Specific fuel consumption for electricity supply, g.f.e./kWh	171,9	171,5	168,5
- d1 / d2, mm - s1 / s2, mm - F1, m2	50/47 103/63 3749	50/47 102/62 4284	50/47 102/62 4740
- d3 / d4, mm - s3 / s4, mm - F2, m2	16/14,5 22/19 817	16/14,5 22/19 1024	16/14,5 22/19 1173

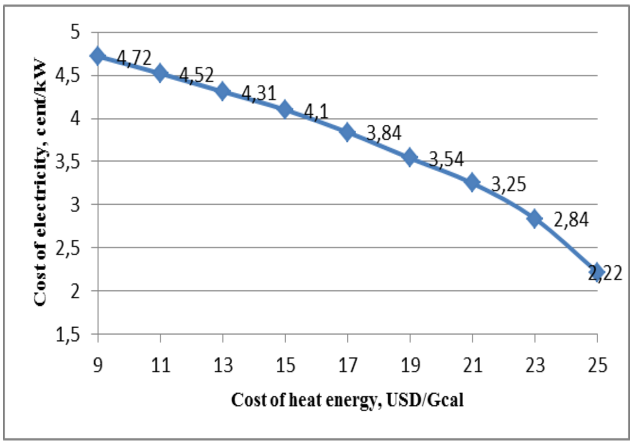

Fig. 2. Dependence of the price of electricity on the price of heat

Analysis of the results of optimization calculations (Table 1 and Fig. 2) shows.

- The change in the price of electricity ranges from 4,72 cents/kW (heat price of 9 USD/Gcal) to 2,22 cents/kW (heat price of 25 USD/Gcal). The heat load increases in the design (nominal) operating mode of the GTU with an increase in the heat price and a decrease in the price of electricity, from a value equal to 125,4 Gcal/h to 277,6 Gcal/h. The useful electrical power of the GTU in the design mode is reduced from 59,7 MW to 55,2 MW.
- Annual supply of heat energy increases from 415,0 thous. Gcal to 918,5 thous. Gcal over the range of price changes for energy products; annual supply of electricity decreases from 392,0 thous. MWh to 362,7 thous. MWh.
- The technological scheme of the investigated GTU has two combustion chambers and the fuel consumption (for afterburning in the second combustion chamber) increases when the heat load increases, as can be seen from Table. 1-3.
- Relative capital investments per unit of useful electric power are in the range of 558,0 USD/kW – 745,8 USD/kW. Relative capital investments are increasing mainly due to the increase in the heat exchange surface of the waste heat boiler and the heating water make-up heater. Their area is determined during the design calculation of the GTU.
- Fuel heat utilization coefficient increases from 0,78 to 0,87 when the heat load increases. Specific fuel consumption for electricity supply varies in the range from 184,4 g.f.e./kWh to 168,5 g.f.e./kWh.

4 Conclusion

The technique for determining the relationship between the change in the price of electricity of a cogeneration CHPP from the change in the price of heat was developed taking into account changes in heat loads. Price ranges are determined using this technique. The Pareto-optimal solution set is based on the price range.

The Pareto-optimal set of solutions helps to determine the options for technical solutions to ensure the competitiveness of CHPPs relative to single-product heat and power generating CHPPs and to choose the most efficient option. The technique has been tested on the example of a cogeneration gas GTU with a waste-heat boiler and a contact heat exchanger for heating the make-up network water. The heat price range is determined for the investigated installation (9-25 USD/Gcal). Optimization calculations of its operating modes were carried out on this range with a step of two units. The main parameters are determined for a specific point in the heat price range: electricity price, calculated heat and electrical loads, annual supplies of heat and electrical energy, annual fuel consumption in general and by combustion chambers, relative capital investments per unit of useful electric power, fuel heat utilization coefficient, specific fuel consumption for heat supply, specific fuel consumption for electricity supply, design characteristics of gas turbine unit equipment. The data obtained can be used to select the optimal technical solutions, select the optimal combination of circuit-parametric solutions that ensure the competitiveness of the products of this cogeneration GTU.

Acknowledgments

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Synthetic liquid fuels: prospects for innovative technologies based on underground coal gasification

E. A. Tyurina[*], *P. Yu.* Elsukov and *A.S.* Mednikov

Melentiev Energy Systems Institute SB RAS Irkutsk, Russia

Abstract. The growing demand for energy, the depletion of oil and gas reserves, and the threat of global climate change have led to an increase in interest in underground coal gasification technologies (UCG) around the world. The potential for using underground gasification of low-grade coal resources with complex mining and geological conditions is huge. The main challenge is the development of competitive technologies for the production of synthesis gas and production of electricity, heat, and synthetic liquid fuels on its basis.

The paper presents a study of one of the promising areas of the use of UCG gas for the combined production of synthetic liquid fuel (methanol) and electricity. A mathematical model of the installation for combined production of methanol and electricity (ICPME) was developed. Based on this mathematical model, a technical and economic optimization of the parameters was carried out to assess the prospects of the scale of application of this coal processing method.

The purpose of research conducted using the mathematical models of the ICPME is to determine the optimal parameters of the installation and the sensitivity of its economic performance indicators to changes in external conditions.

Introduction

The growing demand for energy, the depletion of oil and gas reserves, and the threat of global climate change leads to an increase in interest in underground coal gasification technologies (UCG) around the world. The potential for using underground gasification of low-grade coal resources with complex mining and geological conditions is huge. The main challenge is the development of competitive technologies for the production of synthesis gas and production of electricity, heat, and synthetic liquid fuels on its basis.

The paper considers an upcoming trend in processing of UCG gas enriched with hydrogen and carbon oxides. Pre-purified gas can be considered as synthesis gas for production of valuable synthetic liquid fuels (SLF). Of SLFs, we consider, first of all, methyl alcohol, an environmentally friendly energy carrier that can be used not only as a power-generating fuel but also as a motor fuel [1-7].

Methanol has been one of the most widely used industrial chemicals in the world since the 1800s. It is a key component of hundreds of chemicals. The most large-scale applications in terms of volume are its processing into formaldehyde, which is additionally processed to form resins, adhesives, and various plastics, as well as to produce acetic acid (Fig. 1). Worldwide, one-third of the methanol demand is for formaldehyde production. This accounts for about 10 million metric tons, which is the largest methanol market. One of the newest and fastest growing markets for methanol is the production of light olefins. Olefins, i.e. ethylene and propylene, serve as the backbone of the plastics industry and are usually produced by steam cracking of hydrocarbons such as ethane and naphtha.

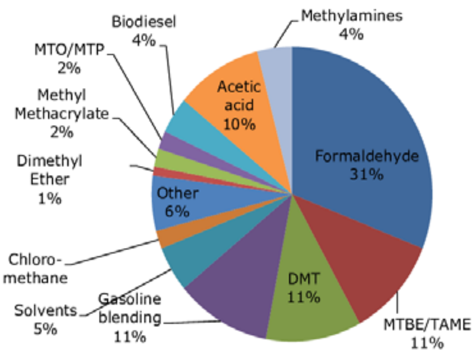


Fig. 1. The uses of methanol (https://www.methanol.org).

A new trend, that of the use of methanol as an environmentally friendly fuel for electricity generation, is gaining momentum. There are several projects worldwide to incorporate methanol into existing gas dual-fueled turbines using. Methanol's low calorific value, low lubricity, and low flash point make it an excellent turbine fuel compared to natural gas and distillate, which can lead to lower emissions, improved heat rate, and higher

[*] Corresponding author: tyurina@isem.irk.ru

power output. A recent methanol-to-power demonstration project by General Electric has shown the viability of this technology, especially for areas not close to gas pipelines.

In the present study, the synthesis gas of UCG of the Rakovsky lignite deposit of the Far East is used for methanol production. The Rakovskoe lignite deposit is located in an area reclaimed by the coal industry with a developed infrastructure and energy consumers available.

According to studies performed by the A. A. Skochinsky Institute of Mining, established reserves of coal by various formations deposited below the strip-mining line and suitable for underground gasification, are 69.2 million tons of category C and 17.6 million tons of category C2, which ensures the operation of the station "Podzemgaz" for its service life at any capacity**.** Novel designs of underground gas generators and technological solutions allow to enhance the characteristics of produced gas and the efficiency of the gasification process [8-11].

Compared to conventional mining and surface gasification, UCG promises lower capital/operating costs as well as other benefits such as no human labor underground. In addition, UCG can potentially be associated with carbon dioxide capture and absorption [12, 13].

The paper presents a study of one of the promising areas of the use of UCG gas for the combined production of SLF (methanol) and electricity.

The processing of UCG gas into methanol is characterized by the release of large amounts of heat and carbon oxides. Combination of chemical processes with power generation increases efficiency of UCG gases utilization. The analytical study of technologies for processing various organic raw materials, performed at the Melentiev Energy Systems Institute Siberian Branch of the Russian Academy of Sciences (ESI SB RAS), revealed the expediency of combining chemical processing technology with power generation in installations for combined production of methanol and electricity (ICPME). The energy and economic efficiency of such an integrated process is much higher than that of separate production processes [7, 14, 15].

A mathematical model of the installation for combined production of methanol and electricity (ICPME) was developed. Based on this mathematical model, a technical and economic optimization of the parameters was carried out to assess the prospects of the scale of application of this method of utilizing UCG gas.

It proves feasible to build small power engineering units for processing of UCG gas. In this case, the power of the ICPME can be increased by units connected in series as needed.

Below is presented a study of the ICPME operating on the products of underground coal gasification under the conditions specific to Far East. The performed research focused on optimizing the operation of the synthesis unit and power generation unit. The data on the method of gasification, composition, and specification of UCG gas of the Rakovsky deposit were obtained from the Far Eastern State Technical University through the courtesy of the team of researchers under the supervision of Professor B.I. Kondyrev [16, 17].

1 The current state of research in the field

As was noted, at present in Russia and abroad there are ongoing studies on deep processing of solid fuels by the underground gasification method, which is one of the key directions of the introduction of additional volumes of energy resources into fuel and energy balances [18].

The analysis of the activity of domestic industrial UCG enterprises with respect to the production of the gaseous energy carrier of low heat of combustion (up to 4 MJ/m^3) attests to their technical and economic feasibility if compared to shaft mining of coal **[**19**].**

In articles [8-9, 16, 17] the authors analyzed the development of technologies for underground gasification of coal and presented the prospects of development of coal deposits in the Far East.

Studies [11, 20**]** demonstrated that the attained technological level of development of the UCG process allows producing gas with sufficiently stable qualitative and quantitative parameters depending on the applied process tools and requirements on the part of consumers.

The study **[**17**]** traced the history of development of the technology of underground coal gasification in Russia and abroad. The authors covered the key strands of UCG technology improvement that are undergoing development at the Far Eastern State Technical University, where the center for deep processing of coal is being established. The important role of the described technology was emphasized, and information on UCG plants under construction in the Far East region was presented.

Studies [21-24] analyzed the energy efficiency of the complete process cycle from coal mining to coal use at combined heat and power plants. Innovative solutions for increasing energy efficiency and energy saving of hydrocarbon resources, based on building local coal and gas energy complexes, were proposed. The estimates of the degree of an increase in combustion heat of the generating mixture so as to achieve the level required for gas-turbine generating units was provided.

Articles [25-28] reported on research on UCG with the main emphasis on chemical and physical characteristics of feedstock, process chemistry, gasifier design, and operating conditions. Thermodynamic studies of UCG were also presented with an emphasis on optimization of gas generator operation based on thermodynamics and kinetic models of the process built.

Study [29] presented an overview of fundamental physical phenomena in underground coal gasification and related modeling challenges. Transfer phenomena and chemical reactions occurring in a permeable layer of coal and ash as well as in the hollow space were considered. Modelling of heat and mass transfer, including pollutants, in the near and far fields surrounding the underground coal gasifier was carried out. Integrated UCG models were considered and recommendations for further model development were provided.

Experimental studies are carried out, aimed at obtaining well-grounded results on UCG [17, 30], including obtaining optimal compositions of gasifying agents, which plays an important role in the economy of underground coal gasification.

As it can be seen from the review, most of the research on technologies behind producing electricity, heat, and SLF from UCG gas worldwide and in Russia alike deal with the study of individual processes and devices. In comprehensive studies of technologies of electricity and heat production and SLF synthesis, for the most part it is the thermodynamic efficiency analysis that is carried out. Optimization studies of such complex combined systems as power engineering installations of combined production of SLF and electric power, using detailed models of power and engineering elements taking into account non-linearity of processes, have not been carried out. On the other hand, without such an analysis it is impossible to obtain optimal technical solutions and sufficiently unbiased economic performance indicators that determine the conditions of competitiveness of the technologies that are studied. Therefore, taking into account these circumstances is one of the main objectives of the present study.

2 A concise overview of the method of underground coal gasification and the use of gas for methanol production

A state-of-the-art underground gas generator engineered by Gazprom Promgaz was selected for the pilot industrial UCG enterprise at the Rakovsky brown coal deposit. The novel UCG process implements a directed oxidizer supply to the hot reaction surface of the coal seam, which provides a higher temperature level and CO discharge. In addition, the sustainability and stability of the gas formation process is due to the movement (as the coal seam is extracted) of the reaction channel of constant geometric parameters [16, 17]. The pilot industrial gas generator includes a series of parallel directional gas exhaust and injection wells, which are crossed on the horizon of the initial gasification channel by a horizontal directional well. The transfer of the air supply point to the coal seam reaction zone (from bottom to top) is provided for as the coal seam is extracted. A schematic of the presented technology of using UCG gas is shown in Fig. 2.

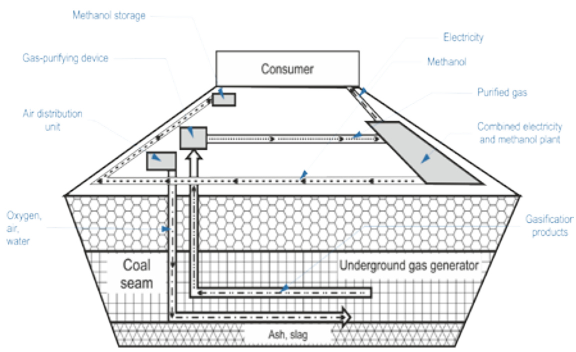


Fig. 2. Schematic of energy resources production complex based on UCG gas.

The new CCGT technology provides higher sustainability and stability of the gas generation process, higher efficiency of gasification, reduction of the number and volume of production wells drilling, the possibility of controlling the process of thermal reactions inside the seam.

The UCG gas deemed optimal for the synthesis of methanol gas is characterized by a sufficiently high H_2/CO ratio and calorific value.

3 Production of methanol and electricity from UCG gas

Below is presented a study of the ICPME operating on the products of underground coal gasification under the conditions specific to Far East. The process flow diagram of the installation is shown in Fig. 3.

The synthesis gas coming from the underground coal gasification station is compressed by fresh gas compressors (1) to a pressure of 2.7 MPa. The gas is then successively heated in a regenerative heater (2) to 340^0 C and an end electric heater (3) to 350^0 C. Heated gas is directed to the desulfurization reactor (4) where hydrogen sulfide is absorbed. From the reactor the purified gas passes through a regenerative heat exchanger and compressor cooler (24) where it is cooled. The gas is then compressed by the compressor to a pressure of 8 MPa and supplied to the methanol synthesis unit. The synthesis unit includes three stages. Each stage has a methyl alcohol synthesis reactor (5), regenerative heat exchanger (6), cooler/condenser of crude methanol (7), and separator (8). The gas is heated in a regenerative heat exchanger up to 210^0 C, then it enters an isothermal synthesis reactor, where a process of methanol formation takes place with a copper-zink-aluminum catalyst at 260^0 C. The heat generated there is used to produce steam at a pressure of 4.3 MPa. Downstream of the reactor, the gas is directed to a regenerative heat exchanger and a cooler/condenser, where it is cooled down to 30^0 C. This condenses methyl alcohol and water vapors. The separator separates the condensate from the gas. The gas passes sequentially through three stages of the synthesis unit.

From the third stage, the purging gas enters the expansion gas turbine (9), where its pressure is reduced to 1.0 MPa. The gas is cooled by the coolant in the heat exchanger (10). The heat dissipation is 140 kcal/s. The coolant can be used in a gas treatment system or for other purposes. The gas downstream of the heat exchanger is directed to the combustion chamber (11) of the main gas turbine (12). The air from the compressor is also supplied there (13).

The main and expansion gas turbines, air compressor, and electric generator are located on the same shaft. After the gas turbine, the combustion products are fed into the recovery boiler that includes five heating surfaces: low- (14) and high- (16) pressure economizers, low- (15) and high- (17) pressure vaporizers, and a steam superheater (18). The high- and low-pressure steam generated in the recovery boiler from the separator drums (19) is directed to the steam turbine (20).

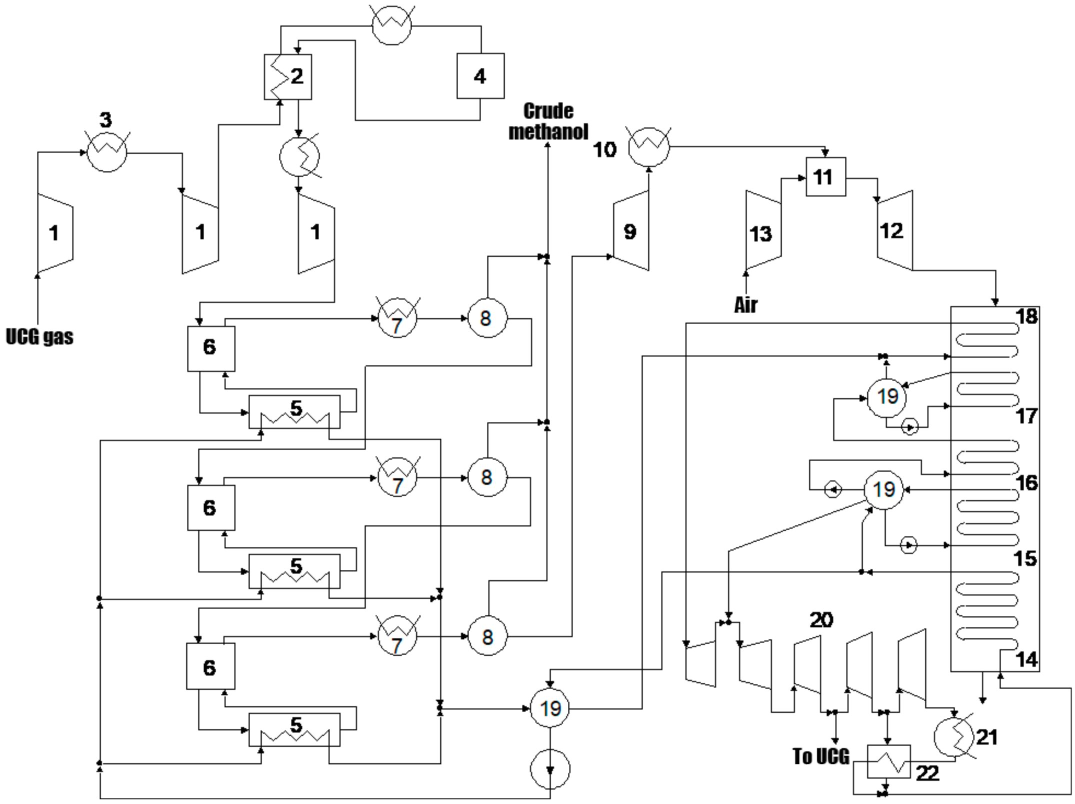


Fig.3. Process flow diagram of the ICPME

From the turbine, steam is supplied into the condenser (21). Feedwater is heated in a regenerative heater (22). From the steam turbine, Steam is extracted from the steam turbine for underground coal gasification.

4 Mathematical modeling of ICPME

Models of individual energy and technological elements (methanol synthesis) were used in the development of a mathematical model of the installation as a whole: heat exchangers of various types, combustion chambers, compressors, gas and steam turbines, built-in gas-water, regenerative gas-gas heat exchangers of a methanol synthesis reactor, refrigerators-condensers, methanol separators, etc.). The issues of modeling energy and technological elements are considered in the previously published works of ESI SB RAS [31-34].

A catalytic reactor for the synthesis of methanol is a fundamentally new element that is absent in power plants. The state of the gas mixture in the reactor differs significantly from the equilibrium state and is described by differential equations of chemical kinetics. The mathematical model of the reactor is based on the methyl alcohol synthesis mechanism and kinetic equations developed at A.V. Topchiev Institute of Petrochemical Synthesis of Russian Academy of Sciences [35-37]. The methanol synthesis reactor consists of several adiabatic zones filled with a catalyst, between which convective heat exchangers are located to recover the heat of synthesis. To simplify calculations, the zones are divided into sections.

The following conditions were taken into account when developing an algorithm for solving the system of equations for a reactor section. The rates of CH_3OH and CO formation are determined by the equilibrium and rate constants, which are uniquely dependent on the gas temperature, pressure, and molar fractions of the components of the gas mixture. The change in pressure, as well as in the equilibrium and rate constants in the working range of the synthesis process is small. The change in the mole fractions of individual components is very significant. In addition, their effect on the rates of CH_3OH and CO formation is significant. Therefore, the pressure of the gas mixture, the rate constants and equilibrium constants can be considered constant in much larger sections of the adiabatic zone of the reactor than the mole fractions of the components (we will call the first sections large, and the second small). This allows you to significantly reduce the amount of calculations when calculating the adiabatic zone.

For the numerical integration of the system of equations describing the processes in a small section of the reactor, the fourth-order Runge-Kutta method is used. The component-wise molar flow rates, gas temperature and pressure at the outlet from the adiabatic zone are determined from expressions corresponding to the integration of differential equations by the Euler method.

The investigated installation is a difficult combined technical system with a large number of dissimilar elements connected by various technological connections. The software and computer complex developed at ESI SB RAS - the system of machine construction of programs (SMPP-PC) - was used to construct a mathematical model. Based on the information about the mathematical models of the individual elements of the installation, the technological connections between them and the purposes of the calculation, the SMPP-PC automatically generates a mathematical model in the form of a calculation program in the Fortran language [14, 31]. This model corresponds to the design scheme shown in Figure 3. The calculation program contains about 1500 variables, several hundred algebraic and transcendental equations. The solution of the systems of equations describing the entire installation is carried out by the Zeidel method [32].

On the basis of the mathematical model of ICPME, the design calculation of the installation elements is carried out: determination of the heating surfaces of heat exchangers and the mass of metal, the volume of the catalyst in the reactors, the drive power of pumps and compressors, the power of gas and steam turbines, thermodynamic parameters, the consumption of synthesis gas, combustion products, water and steam at various points in the circuit.

5 Research the ICPME

The purpose of studies backed by mathematical models of the ICPME that make use of UCG gas is to determine optimal parameters of the installation and sensitivity of its economic performance indicators to changes in external conditions, first of all, the cost of gas of underground coal gasification. This is required in order to assess the prospects of applying this method to using UCG gas.

Problem statement for ICPME parameters optimization

$$\min_{dl} c_{UCG}(x, y, dl, V_{cat}, G_{ms}, G_{lps}, B_{UCG}, KI, P_{meth}, P_{el}, c_{meth}, c_{el}, IRR_z),$$

given that

$$H(x,y)=0,$$

$$G(x,y)=0,$$

$$x_{min} \le x \le x_{max},$$

$$T_{sg} \ge T_{cat},$$

$$IRR = IRR_z,$$

where c_{UCG} is a price of gas UCG, x is a vector of independent optimized parameters; y is a vector of dependent calculated parameters; H is a vector of constraint equalities (constraints on material balances, energy balances, heat transfer, etc.); G is a vector of constraint inequalities; $x_{\min}$, $x_{\max}$ are a vectors of boundary values of optimized parameters; dl - length of the synthesis reactor; V_{cat} - volume of catalyst in synthesis reactors; G_{mg} - main steam consumption; G_{lps} - low pressure steam consumption; B_{UCG} - annual gas UCG consumption; KI - investment in ICPME; P_{el} - annual electricity production; P_{meth} - annual methanol production; c_{meth} - methanol price; c_{el} - produced electricity price; IRR_z is a predefined internal rate of return on capital investment, T_{sg} - the temperature of the synthesis gas in the synthesis reactors, T_{cat} - the maximum permissible temperature of the synthesis gas according to the operating conditions of the catalyst.

The parameters to be optimized were the enthalpies, pressures and flow rates of main, high- and low- pressure steam in the power generation unit, the volume of catalyst in the sections of the synthesis reactor, etc. The system of restrictions contains the conditions for non-negativity of the end temperature drops of heat exchangers, pressure drops along the flow path of steam and gas turbines, restrictions on the design temperatures and mechanical stresses of heat exchanger pipes, on the minimum and maximum synthesis temperatures, etc.

Input technical and economic data was assumed on the basis of previous studies carried out at the ESI SB RAS that dealt with the subject of technologies of solid fuel processing into SLF and on the basis of an analysis of cost estimates of process and power facilities taking into account ICMPE operating conditions [7, 14, 15, 31-34].

Input data for calculations of the ICPME.

Table 1 shows the main input data that was used to determine the technical and economic performance indicators of the ICPME. The capital costs calculations were based on the unit costs of equipment presented in the table, with the unit cost increase due to its small scale being taken into account by a cost factor of 1.5.

Table 1. Input data for ICPME calculations

Name	Unit	Value
1	2	3
Synthesis process pressure	*MPa*	8
Gas temperature at the inlet of synthesis reactors	*K*	493.15
Gas temperature at the outlet of synthesis reactors	*K*	543.15
Gas temperature downstream of coolers/condensers	*K*	303.15
Gas temperature upstream of the main gas turbine	*K*	1373.15
Gas pressure upstream of the main gas turbine	*MPa*	0.96
Main steam pressure	*MPa*	13
Main steam enthalpy	*kcal/kg*	800
Superheated steam pressure	*MPa*	2.1
Superheated steam enthalpy	*kcal/kg*	800
Steam pressure in low pressure vaporizing circuit	*MPa*	1.2
Catalyst unit cost	*USD/kg*	25
Gas turbine unit cost	*USD/kW*	700
Unit cost of a synthesis gas compressor	*USD/kW*	200
Air compressor unit cost	*USD/kW*	150

End of the table 1

1	2	3
Unit cost of heating surfaces made of low-alloy steel	*USD/m²*	1800
Unit cost of heating surfaces made of carbon steel	*USD/m²*	1350
Unit cost of synthesis unit housings	*thous. USD doll./m*	180
Unit cost of process water supply system channels	*thous. USD/(t/h)*	120
Unit cost of process water supply system coolers	*thous. USD /MW*	50
The share of costs for construction and installation work of the synthesis unit		0.6
The share of costs for construction and installation work of the power unit		1
Percentage of depreciation charges	*%*	3.5
Percentage of expenses for running and major repairs	*%*	4.5
Deposit interest rate	*%*	6
Loan interest rate	*%*	7
Plant operation period	*years*	30
Installation construction time	*years*	3

Annual fresh gas consumption is 250 million nm^3 (29.8 nm^3 /hour, 8.27 nm^3/sec), operating hours of the unit per year are 8.400.

The underground coal gasification gas composition at the ICPME inlet (after pre-treatment) is presented below.

Gas components, vol. %:

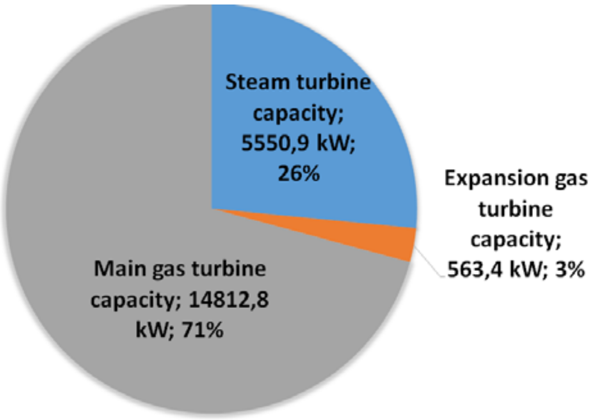
- Carbon dioxide, 6.2
- Hydrogen, 41
- Carbon oxide, 31.4
- Nitrogen oxides, 16.7
- Methane, 1.4
- Water, 3
- Oxygen, 0.2
- Sulfur oxides, 0.01
- Ammonia, 0.01
- Tar, 0.05

As a result of calculations performed with the aid of the mathematical model of the ICPME, we determined the structural characteristics of the main elements of the plant (volume of catalyst in the reactor, areas of heat exchanger heating surfaces, etc.), parameters of material and energy flows between the elements of the scheme, as well as methanol and electricity production. Based on these data, the capital investment in the plant and current costs were estimated.

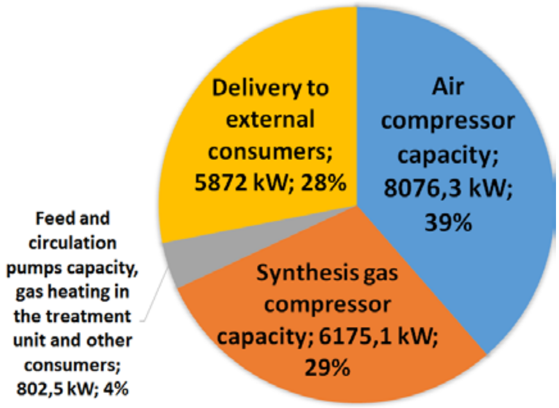
The results of the calculations are given in Tables 2-3, Figure 4 below. Gas composition at the outlet of the synthesis unit is presented below.

Gas components, vol. %:

- Carbon dioxide, 14.4
- Hydrogen, 16.4
- Carbon oxide, 29.2
- Nitrogen oxides, 36.5
- Methane, 3.1
- Water, 0.08
- Methanol, 0.4



a) Output.



b) Consumption and delivery to external consumers

Fig. 4 a, b. Power balance of the UCG ICPME.

Table 2. Synthesis unit equipment specification

Name	Stage 1	Stage 2	Stage 3	Total
Catalyst weight, *t*	9	3.9	2.6	15.5
Reactor volume, *m²*	20.9	9.2	6.3	36.4
Reactor height, *m*	7	7	7	
Reactor diameter, *m*	2	1.3	1	
Regenerative heater heating surface area, *m²*	26.4	32.5	32	90.9
Regenerative heater weight, *t*	0.21	0.26	0.26	0.73
Regenerative heater length, *m*	14.7	21.9	23.9	
Regenerative heater diameter, *m*	0.18	0.17	0.16	
Cooler/condenser heating surface area, *m²*	265.	250.	170.	685.
Cooler/condenser weight, *t*	2.12	2	1.36	5.48
Cooler/condenser diameter, *m*	0.36	0.22	0.17	
Cooler/condenser length, *m*	4.63	4.6	4.4	
Methanol production, *kg/s*	1.16	0.55	0.28	1.99
Steam production at pressure of 4.3 MPa, *kg/s*	1.29	0.49	0.22	2

Table 3. Power unit equipment specification

Name	Unit	Value
Gas temperature upstream of the expansion gas turbine	*K*	303.15
Gas pressure upstream of the expansion gas turbine	*MPa*	7.86
Gas pressure downstream of the expansion gas turbine	*MPa*	0.96
Gas temperature downstream of the expansion gas turbine	*K*	202.2
Gas temperature upstream of the main gas turbine	*K*	1373
Gas pressure downstream of the main gas turbine	*MPa*	0.114
Gas temperature downstream of the main gas turbine	*K*	923
Main steam temperature of the steam turbine	*K*	781.2
Main steam pressure of the steam turbine	*MPa*	4.2
Main steam consumption by the steam turbine	*kg/s*	5.6
Low-pressure separator drum pressure	*MPa*	1.4
Steam flow from the low-pressure separator drum	*kg/s*	1.1
Low-pressure economizer heating surface area	m^2	201
Low pressure economizer piping weight	*t*	5.4
Low pressure vaporizer heating surface area	m^2	971
Low-pressure vaporizer piping weight	*t*	33.6
High pressure economizer heating surface area	m^2	297
High-pressure economizer piping weight	*t*	8
High-pressure evaporator heating surface area	m^2	296
High-pressure vaporizer piping weight	*t*	10.2
Steam superheater heating surface area	m^2	222
Steam superheater piping weight	*t*	7.9
Exhaust gases temperature	*K*	413
Exhaust gases volume	nm^2/s	33.7
Harmful emissions weight: ash sulphur oxides nitrogen oxides	*t/year*	 1.77 0.16 25.1

Table 4 shows the general technical and economic performance indicators of the ICPME. When determining these indicators, the price of methanol was assumed to be 550 USD/tce, and the electricity price was assumed to be 8 cents per kWh, which corresponds to the cost in power-hungry regions of the Far East [18, 38-40].

6 The discussion of the results

As it follows from the calculations performed, methanol and electricity production on the basis of the UCG gas is possible only if the high cost of electricity and liquid fuel in the area under consideration is combined with a sufficiently low cost of gas produced as a result of underground coal gasification.

Table 4. Technical and economic performance indicators of the ICPME

Name	Unit	Value
Annual methanol production	*t*	60087
Annual power supply to external consumers	*mln. kW*	50.1
Annual gas consumption of underground coal gasification	*tce*	77253
Methanol synthesis unit capital costs	*mln. USD*	28.4
Power unit capital expenditures	*mln. USD*	39.2
Total capital costs required by the ICPME	*mln. USD*	67.6
Number of employees	*persons*	80
Annual payroll	*mln. USD*	1.2
Depreciation charges	*%*	3.5
Allowance for running and major repairs	*%*	4.5
Cost of methanol produced	*mln. USD*	23
Cost of electricity produced	*mln. USD*	4
Cost of UCG gas required to ensure: IRR=15% IRR=20% IRR=25%	*USD/tce*	 124 75 52

A mathematical model of ICPME based on gas from underground coal gasification of the Rakovskoye deposit in the Far East, which is effective from the point of view of the adequacy of the presentation of the processes under study, has been developed.

The technical and economic optimization of the parameters was carried out on the basis of the model. The optimal ICPME parameters are found. The conditions for the competitiveness of the studied installations are estimated. The main findings of the study are as follows.

For the synthesis of methanol, unconventional once-through reactors were used with intermediate cooling of synthesis gas between the catalyst beds with steam to produce low pressure steam. This allows the use of synthesis gas with a low (compared to stoichiometric) H_2/CO ratio and eliminates the expensive CO conversion system in the synthesis unit. In this regard, the combined production of methanol and electricity increases thermal efficiency and reduces the specific capital investment in the plant.

An important feature of the combined processes is their environmental friendliness, which is due to the high requirements for the purity of synthesis gas from the synthesis catalysts and low NO_x emissions due to the small volumes of purge gases burnt in the gas turbine combustion chamber.

The sensitivity of the ICPME to changes in external conditions (cost of UCG gas) was investigated. Based on the analysis of the cost of diesel fuel in the eastern regions of Russia, it was concluded that even at present, methanol produced at ICPME is competitive with the expensive diesel fuel supplied. The introduction of such systems is economically feasible in the near future.

Thus, the ICPME presented here have a competitive environment. Practical implementation requires pre-design studies: increasing the stability of the gasification process, improving synthesis catalysts, parameters of a gas turbine, gas generators, etc.

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Using of Viola and Jones Method to Localize Objects in Multispectral Aerospace Images based on Multichannel Features

Sergey Usilin [1,2], *Oleg* Slavin [1,2,*]

[1]Federal Research Center "Computer Science and Control" of Russian Academy of Sciences, Moscow, Russian Federation
[2]Smart Engines Service LLC, Moscow, Russian Federation

Abstract. A new algorithm for localizing engineering objects on multispectral images based on the Viola and Jones method has been developed. The proposed algorithm uses multichannel features allowing to construct classifiers that are sensitive to features of joint brightness distribution and the brightness distribution in different channels. The algorithm described in the paper provides a precision value of 0.96 and a recall value of 0.99 in the problem of localizing oil storage tank images in a set of aerospace images. The proposed algorithm can be used for visual analytics and automatic detection of various critical objects in aerospace images.

Keywords. Viola and Jones method, multispectral aerospace, multichannel features

1 Introduction

To date, visual data obtained from various remote sensing systems are widespread. As a result, remote diagnostics of aerospace monitoring objects is gaining popularity due to modern computing tools for processing remote sensing data [1-3]. In this situation, models and algorithms for recognizing object images observed on remote sensing data that is usually represented as digital multispectral images become fundamental [4].

In the field of digital image processing and pattern recognition, machine learning methods are often used to solve the problem of object localization and identification. One of such methods is the Viola and Jones method [5] allowing to efficiently solve the problem of detecting rigid images. However, despite its universality, the Viola and Jones method should be adapted to solve a specific problem and to achieve high precision indicators.

In this paper, we propose an original method for localizing objects on multispectral images obtained by terrain aerospace images. The proposed method is based on the Viola and Jones method and uses multispectral features to build a stable object detector that is invariant to possible changes in brightness.

2 Problem Statement

In addition to direct aerospace photography, remote sensing includes the decryption of the information received. This information includes knowledge about spatial coordinates of interesting objects.

As initial data, remote sensing systems have images that were obtained in different visibility ranges. Most remote sensing systems return images in the visible range, including near infrared area. In some complexes, images may be also obtained in thermal and radio ranges (see Fig. 1).

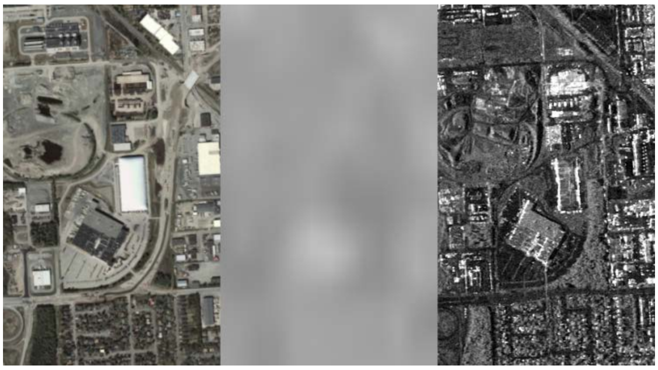

Fig. 1. A fragment of an aerospace probing image in the visible, infrared and radio ranges.

In this paper, we shall consider the problem of localizing geometric coordinates of interesting objects on multispectral images that were obtained during aerospace probing of the earth's surface. The multispectral image was obtained in the visible, infrared and radio ranges.

3 Proposed Method Description

The work proposes an original algorithm for localizing objects based on the Viola and Jones method [5], a statistical construction scheme for object detectors with rigid geometry (based on precedents). The Viola and Jones method uses Haar-like features as a feature space. Their value is based on the difference between the sums of image area pixel brightness inside black and white

* Corresponding author: oslavin@smartengines.ru

rectangles. To efficiently calculate the value of Haar-like features, an integral representation of the image $I_f(y,x)$ is used. For a grayscale image $f(y,x)$ with dimensions $\times N$, it is determined as follows:

$$I_f(y,x) = \sum_{i<y, j<x} f(i,j).$$

A binary weak classifier $h(x): \mathbb{X} \to \{-1,+1\}$ represented by a recognizing tree with one branch associates the Viola and Jones method with each feature. Such classifiers demonstrate weak localization power. So, the Viola and Jones method uses the AdaBoost algorithm to make a "strong" classifier based on a linear combination of the most powerful weak classifiers:

$$S(x) = \left[\sum_{t=1}^{T} \alpha_t \cdot h_t(x) > 0\right],$$

where $[\cdot]$ – indicator function. High performance in the Viola and Jones method is additionally ensured by cascade classifiers that are based on strong classifiers and allow to quickly (in early estimation stages) recognize "empty" images (images without the target object):

$$Cascade(x) = \prod_{i=1}^{N} [S_i(x) > 0].$$

An object in the image is searched with a built cascade classifier and the sliding window method.

The Viola and Jones algorithm was modified to search for oil storage tanks. An oil storage tank image example is shown in Fig. 2.

Fig. 2. Oil storage tank image example

To effectively train the Viola and Jones detector for the type of objects specified, a feature space allowing to use geometric features of an object, rather than brightness characteristics, should be chosen [6-7]. So, Haar-like features estimated over gradient norm images were used as the space of a feature.

Image processing and analyzing tasks usually considered the term "gradient norm" as its L_2 norm that is estimated by the following formula:

$$G_{L_2} = \sqrt{\frac{\partial f}{\partial x}^2 + \frac{\partial f}{\partial y}^2},$$

where $\frac{\partial f}{\partial x}$ – partial derivative of an image $f(y,x)$ by x, and $\frac{\partial f}{\partial y}$ – partial derivative of an image $f(y,x)$ by y. In recognition problems, from a productive point of view, it turns out to be beneficial to determine its L_1 norm [8] considered as the sum of individual component modules, instead of determining L_2 the gradient norm:

$$G_{L_1} = \left|\frac{\partial f}{\partial x}\right| + \left|\frac{\partial f}{\partial y}\right|.$$

The monotonicity of the difference between rectangle sum values, and not absolute values of these sums, is an important aspect of Haar-like features. So, in this case, the use of the norm L_1 for determining gradient norm is a justified Viola and Jones method improvement.

Regarding the multispectral information, a modification of the Haar-like features is used to determine the difference between total brightness values in different channel sub-windows (each channel of a multispectral image contains an image belonging to one range) [7].

4 Experiments

A training dataset consisting of 20×20 px 70 oil storage tank images, as well as 22 full-size remote probing images without oil tanks was prepared to train the oil storage tank detector. Since the initial number of the training dataset was small, we used augmentation [8-10]. A cascade classifier was used as a high-level classifier structure. The trained cascade diagram is given in Fig. 3.

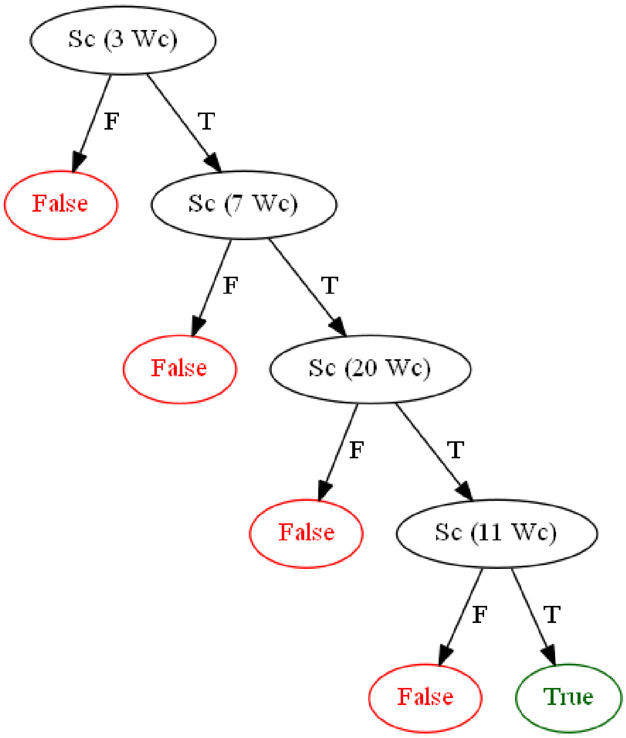

Fig. 3. The trained cascade scheme

The distribution of features can be analyzed with the information saturation map (see Fig. 4), a digital image meeting a classifier in size, where each feature is assigned to a pixel covered by this feature. The more features cover an image area, the brighter this area is on the information saturation map.

From the information saturation map, it follows that trained classifier features are mainly concentrated around the object perimeter. In addition, the information map shows that the classifier uses target object features -

axial symmetry, color uniformity, the border around the perimeter.

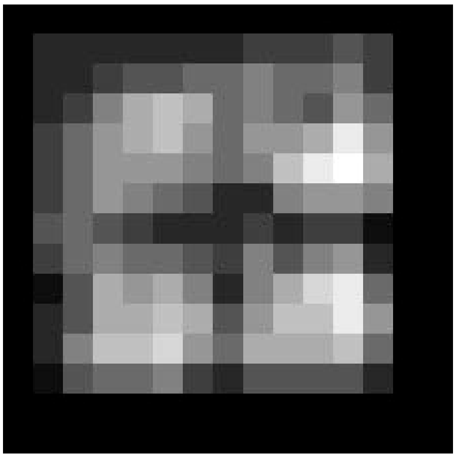

Fig. 4. Trained cascade information saturation map

The trained cascade was applied on test images to assess the classifier's quality. The test set of images contained 73 target objects.

To determine the number of correctly localized objects, we shall use the technique proposed in the PASCAL Visual Object Classes (VOC) Challenge framework [11]. As an answer, a trained cascade returns a framing rectangle, as well as its confidence value that can be used to find a compromise between the first and second kind of errors. Table 1 shows experimental results with quantities for given self-confidence values

Table 1 gives experimental results. The following statistics was determined for the given confidence degree values: the number of correct localizations (true positive, TP), the number of false localizations (false positive, FP), the number of false omissions (false negative, FN), as well as the precision, recall and F-measure were determined.

Table 1. Experimental Results

Conf.	TP	FP	FN	Precision	Recall	F_1
0.0	73	4	0	0.948	1.000	0.973
0.3	72	3	1	0.960	0.986	0.973
0.6	70	2	3	0.972	0.959	0.965
0.9	66	0	7	1.000	0.904	0.950

Table 1 shows that the highest F-measures are achieved in the first two lines, while the highest precision is achieved with a confidence level of 0.9 or higher.

The average number of determined features in the image is 3.1908. With regard to the trained classifier structure (with three features at the first cascade level), this means that, in case of the majority of analyzed image sections, at the first cascade level, the trained classifier presented a confident answer that the specified region does not belong to the target object.

The detector's operation is given in Fig. 5.

Fig. 5. An example of oil storage localization with a trained cascade

5 Conclusion

Nowadays various remote sensing systems are widespread. As a result, different methods of automatic object detection and recognition of aerospace images are very actual. In this paper, a new algorithm for localizing engineering objects on such multispectral images are proposed. The algorithm is based on the Viola and Jones method and adapted for efficient work on multispectral images.

We have applied the proposed algorithm to solve the problem of localization of oil tank storages on aerospace images. The algorithm provides a precision value of 0.96 and a recall value of 0.99.

The proposed algorithm can be used for visual analytics and automatic detection of various critical objects in aerospace images.

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Economic Theoretical and Legal Issues of Antimonopoly Regulation in the Russian Electric Power Industry

Mikhail Vasilyev[1,2,*]

[1]Melentiev Energy Systems Institute of SB RAS, 664033, Lermontov st. 130, Irkutsk, Russia
[2]The All-Russian State University of Justice, Irkutsk Law Institute, 664011, Nekrasov st. 4, Irkutsk, Russia (Master's Degree Student)

Abstract. The paper discusses the antimonopoly regulation of the Russian wholesale electricity and capacity market as an interconnection of economic theory and legal science. Research of results and by-effects of different regulation mechanisms and understanding the public danger of abusing monopoly power are problems of the economic theory and there are serious contradictions in these spheres nowadays. The legal science reflects these contradictions and transfers them into legal acts. The three legal acts that regulate pricing and bidding in the wholesale electricity and capacity market in Russia are analyzed. Findings show that the concepts of price manipulation and monopolistically high and low pricing are not clearly defined and allow violent interpretation.

1 Introduction

The electric power industry is one of the economic sectors, whose efficient or inefficient functioning influences the whole national economy and people's welfare. Legal regulations are applied to control the functioning and development of the industry. Law principles set requirements to the industry structure, behavior of the objects of regulation, powers, and authority of public agencies. The regulation purposes include the limitation of market power and maintenance of competition. From the legal perspective, antimonopoly regulation is based on Article 34 of the Constitution of the Russian Federation [1], which prohibits economical actions aimed at monopolization and unfair competition.

Interdisciplinary connection of economics, law, and technical sciences is important for research of regulation in electric power systems. Economics deals with people's behavior under different conditions, industrial organization, regulation mechanisms, their results, and by-effects. The principles of regulation are implemented in the legal framework. Rules, captured in legislation, determine the behavior of market participants and authorities.

Under these conditions, interdisciplinary coordination is important, i.e. the actual legal arrangements should comply with the purposes and objectives of regulation from the viewpoint of economics. Law principles should also comply with each other to prevent different behavior signals to market participants and investors.

Researchers have already been mentioned repeatedly the lack of such coordination, which leads to negative by-effects. DiLorenzo [2] noted that certain companies (including those in the electric power industry) received monopoly privileges without understanding and proving these privileges by economists. As a result, the regulation caused price growth. The theory of economic regulation describes how monopoly rights are set and prices are regulated depending on the political process and regardless of economic advancements [3]. In this case, the price growth is also a result of the regulation applied. Authors in [4] note that the antimonopoly regulation applied in Russia is the reason for higher market concentration i.e. in fact the regulation provided results contrary to those expected. Incoherence between economic theoretical approaches to regulation and its manifestation in law leads up to unreasonable regulation and its unpredictable results, higher risks for market participants, and investors.

There can be different reasons for such incoherence. One of them is political, where the lawmaker consciously writes a law that does not correspond to what the economic theory suggests. This reason is not subject to

* mikhail-vasilyev@yandex.ru

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economic research. Another reason is the lack of economic knowledge in the specific field. In particular, there are two main concepts in the antimonopoly regulation: "perfect competition market" and "marginal costs". However, there has been no sufficient research on how to calculate the marginal costs of electricity market participants. Moreover, different researchers understand marginal costs differently [5].

In addition to this interdisciplinary incoherence, there is incoherence between different legal acts, i.e., the law principles set by different legal acts in the same legal relations sphere are not compatible with each other. For example, the study [6] shows that the capacity market participants in Russia, which control more than one generating unit, can never be sure that their bids comply with all legal requirements.

2 The public danger of market power and price manipulation

Addressing the abuse of monopoly position and price manipulation as a manifestation of such abuse, one needs to build on the concept of public danger [7]. No public danger means no need to prevent it through statutory regulation. Description and proof of the public danger of monopolistic behavior is a task of economic theory and, particularly, industrial organization. The essence of public danger is normally reduced to a smaller social welfare in comparison to a certain perfect condition.

The development of economic thought in this field can be tracked from publications of Joan Robinson. Early researchers believed that perfect competition is an ideal pattern of markets and all the deviations should be corrected by government intervention. Any firm under perfect competition has the volume of production at which the marginal costs are equal to the average costs and the price [8]. If competition is not perfect due to a monopoly position, the volume of production is lower, and the economic efficiency of a certain market declines.

The industrial organization theory has been developing since the 1950s. According to Joe Bain and Edward Mason, the structure of the industry (competitive or concentrated) is determined by the fundamental conditions (technology, production volume, product differentiation, etc.). The structure of the industry determines the degree of market power, which manifests itself in the ability of sellers to set prices above marginal costs of production. There is a widespread idea that the profit of the industry is proportional to the market concentration of producers, which can be measured by the Herfindahl-Hirschman index.

Later [9], the focus of research on market power shifts. "New empirical industrial organization" sets the following basic principles:

- The marginal costs of a firm cannot be observed directly; they are derived from the firm’s behavior or estimated without knowing costs.
- The conditions of a certain industry determine firms' behavior as well as the data for analysis. Comparative analysis can hardly be applied except that for closely related industries.
- Actions of firms and industry conditions are unknown parameters that should be estimated.
- An alternative to the concept of market power is the hypothesis of perfect competition.

At the same time, the theory of contestable markets was developed [10]. Its main idea is that the one and only commodity producer cannot exercise market power if the industry entrance barriers are zero. This is due to potential competition with new entrants. Nevertheless, if such barriers exist, certain behavior of large producers can create obstacles and risks for new market participants. The concept of "predatory pricing" [11] implies setting low prices to drive competitors out from the market with the following period of high prices to get an excess profit.

The work [12], which is up-to-date in the field of the electric power industry, gives two definitions of market power: as (1) an ability of market participants to get additional profit from moving prices from the competitive level and as (2) an ability of a seller to get additional profit from keeping the prices above the competitive level during a long time. Both definitions are based on a "competitive price level" corresponding to the marginal costs, as clarified in Chapter 4-1.

Thus, the concept of perfect competition (the ideally efficient market structure) has been permeating the theoretical basis of antimonopoly and antitrust regulation during the last century. The two main problems are formulated:

- Prices above the marginal costs of production are a result of the market power and, thus, reveal the market inefficiency, which can/should be corrected by regulation.
- Prices below the marginal costs are an attribute of predatory pricing, which should be limited for competition protection.

An alternative understanding of market power is based on a dynamic approach to competition. In the process of competition, higher prices at this moment are an incentive for potential competitors to enter the market to make prices lower. It is shown that these dynamic effects manifest themselves also in naturally monopolistic industries [13-15].

In sum, the modern economic theory is controversial when discussing the public danger of market power abuse. The researcher identifying the danger considers it as a decrease in social welfare compared to a certain perfect competition condition.

3 Mechanisms of statutory regulation

Different regulatory mechanisms are developed to prevent the monopolistic behavior of market participants. These mechanisms slightly differ in different countries. Preventing predatory pricing is the aim of the Areeda-Turner rule. According to the rule, the price, which is lower than the marginal costs, is aimed at squeezing competitors. This kind of pricing is forbidden in some countries. Since marginal costs are not easy to calculate, some researchers suggested using average variable costs instead of marginal costs. Although the Areeda-Turner rule was widely applied in antitrust cases in the USA, some courts applied full costs as a criterion of fair competition [11]. In Russia, the mechanism is applied in the form of full costs and it is stated by the Federal law "On competition" in the term "monopolistically low price".

To prevent high prices due to market power there are mechanisms of direct price regulation and control of mergers and acquisitions. The Russian law includes concepts of dominant and unique position, monopolistically high price, etc. There is no widespread concept of marginal costs in Russian regulation.

Additionally to the criteria of fair competition and permissible market behavior, antimonopoly incentives are embedded into mathematical models and market organization [12] and also into the regulation of the capacity market [16].

Important regulatory element is the status of natural monopoly and other ways to grant and protect monopoly privileges for certain firms. The essence of this kind of regulation is that it is forbidden to produce some goods or to provide some services to all the companies but the privileged one. In the Russian electric power industry, this is applied in transmission networks and nuclear generation.

4 The disparity of economic approaches to regulation and statutory provisions

As shown above, there is no harmony in understanding the public danger of monopolistic behavior in the economic theory. Nevertheless, the dominant theory assumes perfect competition as an abstract ideal market condition and insists on legal regulation as a tool to draw the market participants to behave "perfectly". The regulation faces the following problems:

- The concepts of "perfect competition" and "marginal costs" are not well defined. Studies in this field are conducted in an abstract style. The problem of calculation of the marginal costs is not solved and is not a research priority. Statements like "in a competitive market the price is equal to the marginal costs" are often met, but it is unclear how to calculate the marginal costs in most real situations. Moreover, upon a closer view, different researchers understand marginal costs differently [5].

Consequently, in real cases of abusing a monopoly position, it is impossible to apply the concepts of the perfect competition and marginal costs to establish a fact of illegal behavior and punish the monopolist. Therefore, another approach based on full costs is applied. Compared with the marginal costs, the full costs are easy to document and control their changes with time.

However, the full costs are not a perfect solution since:

- For a multiproduct firm that takes advantage of the economy of scale, it is not easy to determine the part of full costs to be assigned to a certain product. The applied methods of cost estimations are inevitably of voluntarist nature.

- The full costs have nothing to do with the theoretical understanding of the perfect competition. Therefore, the full cost regulation will hardly result in an efficient market.

The economic theory developed a concept of natural monopoly, but it stays away from discussing if compulsory monopolization can be rational or not. In the practice of legal regulation, the mechanism is widely applied.

Thus, the interdisciplinary disparity between the economic theory and the practice of regulation is usually based on shortcomings and controversies of the economic theory.

5 The disparity of statutory provisions in the regulation of the Russian electric power industry

Regulation of the Russian electric power industry differs from regulation in other countries [for example, 17]. Three legislative acts regulate the behavior of the market participants in the electric power industry in Russia: the Federal Law «On the electric power industry», the Federal Law «On the competition protection» and the Decree of the Federal Antimonopoly Service No. 378 [18-20]. Some requirements are set by the Agreement on connection to the trading system of the wholesale market, which is signed by every market participant.

Article 3 of the Federal Law "On the electric power industry" defines the concept of "price manipulation":

> *“Price manipulation in the wholesale electricity (capacity) market is the commission of economically or technologically unjustified actions, including using the dominant position in the wholesale market that leads to a significant change in prices (price) of electric energy and (or) capacity in the wholesale market by:*
>
> *- submission of unreasonably high or low price bids for the purchase or sale of electricity and (or) capacity. A price bid can be estimated as unreasonably high or low if it exceeds the price formed at a comparable commodity market or the price formed at this commodity market previously (for similar hours of the previous day, for similar hours of the day of the previous week, for similar hours of the day of the previous month, previous quarter);*
>
> *- submission of a price bid for the sale of electricity with an indication of the volume that does not correspond to the volume of electric energy generated using the maximum generating capacity of the equipment of the market*

participant. The maximum generating capacity of the equipment is determined by the System operator according to the Wholesale market code established by the Government of the Russian Federation;

- submission of a price bid that does not correspond to the economic criteria established by the authorized federal government agency;"

From the definition, we can understand that price manipulation (as an act injurious to the public) is the behavior of a market participant that simultaneously meets the following criteria:

- it is economically or technologically unjustified;
- results in a significant change in electricity and capacity prices;
- the price bid includes either the price or the volume that does not fit the criteria established in the definition.

A dominant position of the market participant has no essential meaning since smaller participants can also be identified as price manipulating. A unique position does not mean anything either since it is not mentioned in the definition at all.

It is worth mentioning that the criteria of technological and economical behavior justification are independent, i.e., an act can be either economically or technologically unjustified to be identified as price manipulation. The exact meaning of a technologically unjustified act is not provided in the law.

The behavior of a market participant complies with the law and is not manipulating if it fits the following criteria simultaneously:

- The participant bids the maximum volume of capacity and electricity production. A smaller volume should be set only according to regulatory requirements or repair/maintenance schedule.
- It is not clear what market can be considered to be comparable to the wholesale electricity and capacity market. An analogy can be drawn between the same market at different times. The law mentions similar hours of the previous day, similar hours of the day of the previous week, month, and quarter as the price benchmarks. Therefore, all of these benchmarks should be taken into account simultaneously, and the bid should be not higher than any of the prices that were yesterday, a week ago, a month ago, and a quarter ago.
- Any bid is technologically justified.
- There should be no causal relation between the change in a bid of a certain market participant and the change in the overall market price. It is important to understand that the mechanism of the wholesale electricity market does not allow individual market participants to estimate the market price while bidding. Therefore, no bidder can know the consequences of his actions while acting. The contribution of a certain market participant to the overall price change can be determined only through market modeling that assumes different bids of the participant given the bids of the other participants.

The same process of bidding is regulated by the Federal Law “On the competition protection”, which defines the concepts of “monopolistically low price” and “monopolistically high price”.

“A monopolistically high price of a product is a price set by the dominant economic entity if the price exceeds the number of costs and profits necessary for the production and sale of such a product, and the price that has formed under the condition of competition in the product market comparable with respect to the number of buyers or sellers, conditions of commodity circulation, conditions of market entry, public regulation including taxation and customs tariff regulation (hereinafter, comparable product market in the presence of such a market on the territory of the Russian Federation or abroad. The price is set:

1) by increasing the earlier set price if the following conditions are met simultaneously:

a) the costs necessary for the product production and sale remained unchanged, or their change does not correspond to the change in the product price;

b) the number of product buyers and sellers remained unchanged, or the change is insignificant;

c) the conditions for the product circulation including those determined by the public regulation measures and in particular by taxation and customs tariff regulation remained unchanged, or the change does not correspond to a change in the price;

2) by maintaining the earlier set price of the product if the following conditions are met simultaneously:

a) the costs necessary for the production and sale of the product decreased significantly;

b) the number of buyers and sellers of the product determines the possibility of reducing the product price;

c) the product circulation conditions, including those determined by the public regulation measures and in particular by taxation and customs tariff regulation determine a possibility to decrease the price of the product.

From the analysis of the definitions, we can see that the socially dangerous acts, i.e., abuse of monopoly power that manifests itself in setting monopolistically high prices, are the acts that meet the following criteria simultaneously:

- The price is set by the dominant economic entity. If the price is set by an economic entity without a dominant position it cannot be identified as a monopolistically high price.
- The price exceeds the costs necessary for the production and sale of the product and also exceeds the price at a comparable product market. If the price exceeds the necessary costs, but it is not higher than a

comparable market price, it cannot be identified as monopolistically high.

The regulatory scope of the two federal acts intersects partially. For example, a bid submitted by a large power plant in the capacity market will be subject to both regulations. It can be considered as price manipulation, as monopolistically high/low pricing, or as both illegal acts simultaneously. A bid of a smaller seller is never monopolistically high/low, but if it results in a changing price, it can be identified as price manipulation.

Thus, there is no clear distinction between the concepts – the same act can be determined as one illegal act or the o the other depending on circumstances.

The procedure of determining the facts of price manipulation is provided by the Decree of the FAS No. 378:

"11. The cases of price manipulation are detected in the course of antimonopoly violation proceedings, by comparing the prices in the price bids with the actual costs of the wholesale market participants for the electricity production in the corresponding hour, by comparing the volume in the bids with the possible volume of electricity production in the corresponding hour, given the technical characteristics of the generating units, limitations determined by heat consumption, fuel availability, and also considering the maximum economically justified costs for the electricity production (regardless of capacity) differentiated by the power plant type, and approved by the federal tariff regulating authority."

The following problems should be recognized in the phrase above:

- "*.......by comparing the prices…*" means that comparing the prices is not the only method to detect price manipulation. What are the other methods then? They are not defined in the act, which leaves the possibility of abusing power.

- comparison is performed with the production costs in the corresponding hour. However, the full costs can not be calculated correctly over such a short time range. Probably the expression takes into account fuel costs? But it should be stated clearly to prevent wrong interpretation. On the other hand, a bid, that is set according to the fuel costs only, does not include other costs and can be identified as a monopolistically low price.

Thus, the three legislative acts regulating the pricing of electricity and electric capacity at the Russian wholesale market and monopoly power can be characterized as follows:

- there is no accurate definition of the concepts of price manipulation and monopolistically high/low price;

- the criteria of legal and illegal acts of electricity suppliers, the procedure for calculating costs, detecting illegal acts, and proving the fault of the supplier are not determined accurately either.

6 Conclusions

1. There is an interdisciplinary connection between the economic theory and the legal studies in the sphere of antimonopoly policy. The economic theory defines the forms and methods of antimonopoly regulation and researches their results and by-effects.

2. Understanding of public danger of monopoly abuse is a problem of economic theory and there are serious contradictions in this scientific subdiscipline.

3. Three legal acts regulate pricing and bidding at the wholesale electricity and capacity market in Russia. The concepts of price manipulation and monopolistically high/low prices are not clearly defined and allow violent interpretation.

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Russia's electric power reintegration with Central Asia and Caucasus and entering South Asia and Middle East electricity markets

Lev Belyaev[1], *Lyudmila* Chudinova [1] , and *Sergei* Podkovalnikov[1*]

[1]Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

Abstract. Results of the next round of studies on Russian interstate electric ties are described. A part of the Eurasian region including European and Siberian part of Russia and countries of Central Asia, Caucasus, Southern Asia and Middle East is considered for 2040 target year. Great effectiveness of creation of interstate power grid in this region is shown.

1 Introduction

The current political conditions, the desire to synchronize the electric power systems (EPSs) of the Baltic states, Ukraine, Moldova with the EPSs of the EU countries, the restoration of the Central Asian energy connection, the development of the Eurasian Economic Union (EAEU), which has significant energy reserves, and some other circumstances, served as a motivation for additional research of integration electric power projects of Russia in the Caucasian, Central Asian and Middle East directions [1-3 et al.]. The idea of creating a Caspian electric power ring, uniting the power systems of Russia, the countries of Central Asia, the Caucasus, Iran and Turkey, arose. [4]. The target year was assumed to be 2040. These studies are also relevant in the framework of signed in 2019-2020 documents, such as: Agreement on the joint development of a feasibility study for the project to create the North-South energy corridor between the power systems of the Republic of Azerbaijan, the Islamic Republic of Iran and the Russian Federation [5] and the Protocol on the creation of a common electric power market of five EAEU member states: the Russian Federation, the Republic of Armenia, Belarus, Kazakhstan and Kyrgyzstan [2].

The object of research is a part of the Eurasia region, shown in Fig. 1, where the Interconnected Power Systems (IPSs) of Russia and the countries of Eurasia participating in this interstate power grid (ISPG) are indicated. The countries are shaded with colors corresponding to different nodes of the diagram of the considered ISPG, which will be discussed later. Fig. 1 shows the main interstate electric ties (ISETs) among countries with the direction and the resulting volume of the annual electricity flow (as of 2018). For the cross-sections between the nodes, the large arrows show the number of ISETs of different voltages currently connecting these nodes. The dotted line shows the designed and constructed ISETs.

A distinctive feature of the countries of this region is a significant difference in the provision of energy resources, natural and climatic conditions, economic and political development, and the structure of electricity consumption. Table 1 shows the availability of energy reserves for the countries and subregions of the region.

Table 1. Energy reserves of countries and subregions of Eurasia.

	Russia	Central Asia	Afghanistan &Pakistan	Turkey &Iran	Caucasus
Coal reserves, bln t	160.4	28.3	3.1	1.6	0.4
Conventional oil reserves, bln t	14.5	4.1	< 0.1	21.6	1.0
Conventional gas reserves, trln m3	35.3	21.8	0.5	33.2	1.5
Uranium resources (<USD 130/kgU), mln t	214.5	472.8	n. a.	7.6	n. a.
Technical potential of hydropower resources, TWh/year	1670.0	510.0	292.0	266.0	23.0
Technical potential of wind energy, TWh/year	21846.0	139.2	71.0	297.0	31.0
Technical potential of solar energy, TWh/year	76821.0	10310.0	4994.0	7392.0	635.0

The problem statement was set out in 2019 at the International Scientific Workshop "Methodological problems in reliability study of large energy systems" (Tashkent, 23-27.09.2019) [6]. The purpose of the study is to assess the energy and economic efficiency of strengthening and building new interstate electric ties of Russia. Economic efficiency is determined by comparing the values of the annualized costs for the scenarios of the development and functioning of the interconnected EPS with different transfer capacity of ISETs. For this purpose, a special model of optimization of expansion and operation of power

* Corresponding author: spodkovalnikov@isem.irk.ru

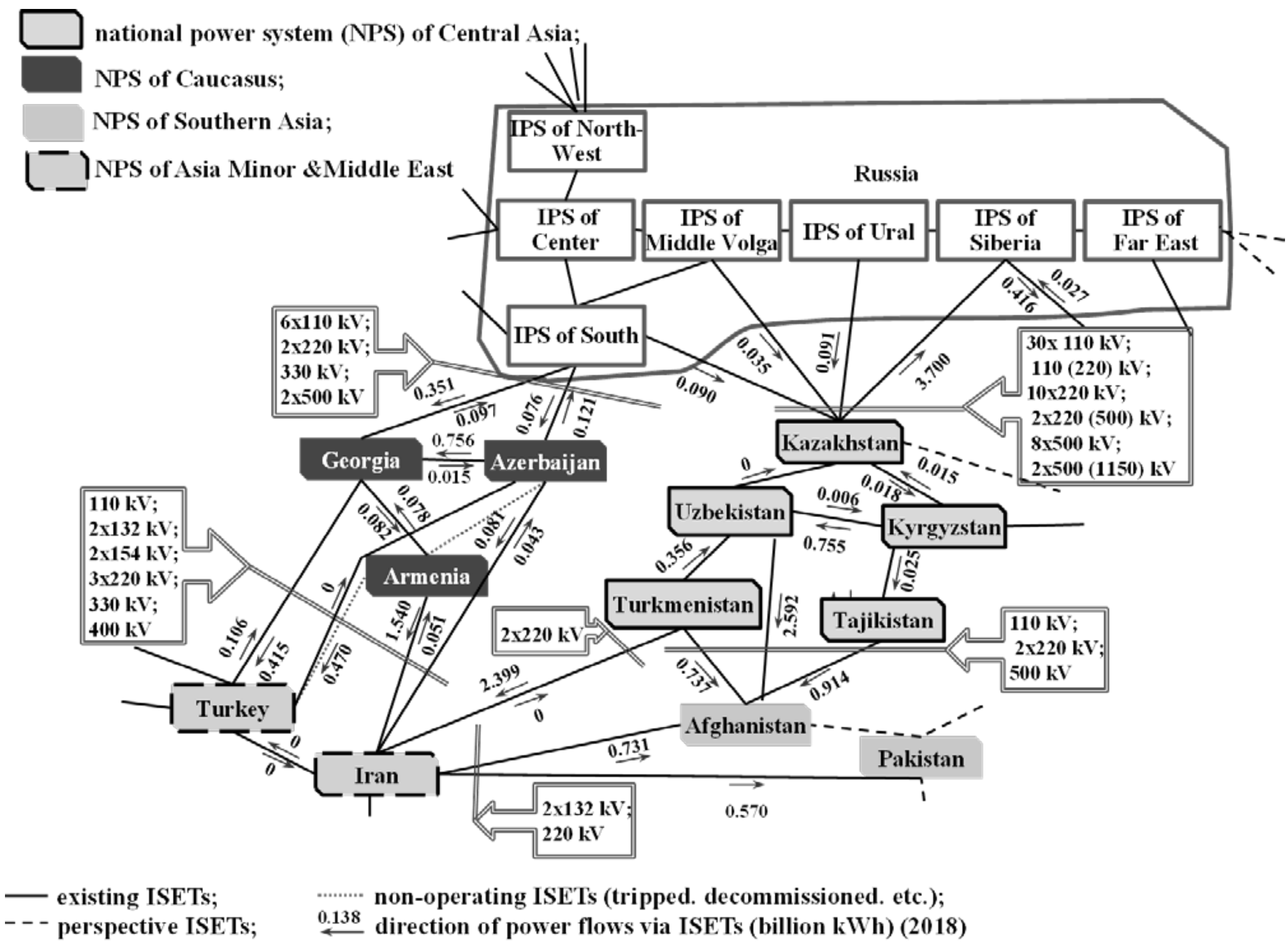

Fig. 1. A diagram of external electric ties among Russia, Central Asia, Caucasus, Southern Asia and Middle East

systems (ORIRES) developed at Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences (ESI SB RAS) was used [3].

The diagram of ISPG is represented by six nodes: 1) the European part of the Russian Federation (including IPSs: of the Center, the Middle Volga, the Urals and the South); 2) node of the IPS of Siberia; 3) Central Asian hub of National Power Systems (NPSs) of Kazakhstan, Uzbekistan, Turkmenistan, Kyrgyzstan, and Tajikistan; 4) Caucasus (NPSs of Armenia, Georgia, Azerbaijan); 5) partially Southern Asia (NPSs of Afghanistan and Pakistan); 6) Asia Minor and Middle East (NPSs of Iran and Turkey) (Fig. 2).

The goal was to determine optimal formation of Eurasian ISPG with effective participation of member countries, including Russia. For this, it was envisaged to build new ISETs of direct current and voltage of ± 800 kV with high transfer capacity - according to the most efficient technology, currently mastered in China.

To carry out this work, an assessment of the current and future state of generating equipment, interstate power grid infrastructure was done, programs for the development of the electric power industry of the studied countries were considered, the technical and economic parameters of the facilities under consideration, including power transmissions of ± 800 kV, were studied. Two scenarios were considered:

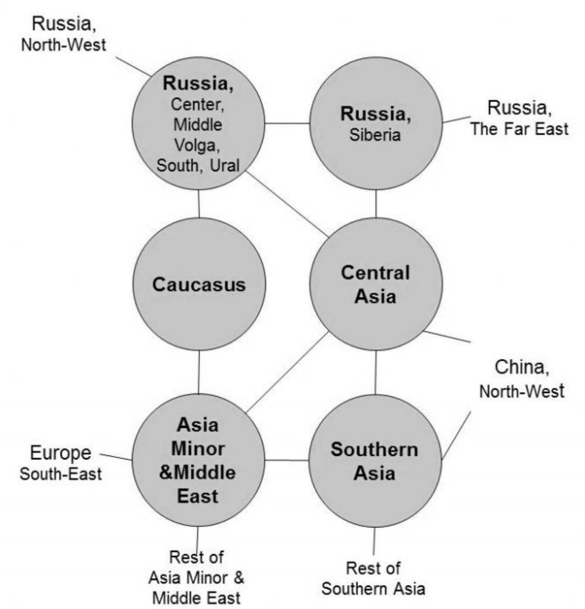

Fig. 2. The diagram of the ISPG

Scenario 1. ISETs parameters correspond to its current state with additional consideration of the transfer capacities of interstate electric ties that are being planned, constructed and will soon be commissioned.

Scenario 2. New interstate transmission infrastructure consisting of ± 800 kV DC transmission

* Corresponding author: spodkovalnikov@isem.irk.ru

lines in addition to existed one was assumed to put in place. This substantially rises the transfer capacities of the ISETs allowing countries to exchange intensively electricity and power among each other..

Comparison of the main indicators (capacities additions, investments, objective function value, etc.) of Scenario 2 with the similar total indicators of Scenario 1 allows us to evaluate the optimal development of the transfer capacities of ISETs and the maximum possible system integration effects of NPSs in the ISPG.

2 Main input data

Table 2 presents the forecasted combined annual maximums of the electrical load of the IPSs or NPSs included in this node of the ISPG diagram for the considered target year [6].

Table 2. Forecasted annual maxima of electric load, 2040, GW.

Russia (Center, Middle Volga, South, Ural)	Russia (Siberia)	Caucasus	Central Asia	Asia Minor and Middle East	Southern Asia
140.9	41.8	13.3	61.3	234.3	65.0

Table 3 shows the technical and economic parameters of transmission lines, constituting the interstate DC transmission infrastructure of ± 800 kV of the considered ISPG [7].

Tables 4 and 5 present main economic indicators of power plants of different types and different fuels [6].

Table 3. Technical and economic indices of interstate electric ties.

	Capital investment, USD/kW	Transmission losses, %	Route length, km
Russia (Siberia) - Central Asia	377	7.8	1486
Russia (Center, Middle Volga, South, Ural) - Central Asia	333	6.8	131
Russia (Center, Middle Volga, South, Ural) - Caucasus	267	4.7	1183
Central Asia - Southern Asia	202	3.4	858
Central Asia - Asia Minor and Middle East	484	7.5	1867
Southern Asia - Asia Minor and Middle East	381	6.0	1502
Caucasus - Asia Minor and Middle East	272	4.3	1081

Table 4. Capital investment in new power plants, USD/kW.

	Hydro	Pumped storage	Thermal, coal	Thermal, gas	Thermal, oil	Nuclear
Russia	3000	1100	1800-2000	1200		2800
Central Asia	2100	1600	2150	1250		4300
Southern Asia	2600		1700	1200	1400	5200
Caucasus	1500		2000	1000	1500	5500
Asia Minor and Middle East	2250	1000	1800	670	1400	4500

Table 5. Fuel costs, USD/kWh.

	Thermal, coal	Thermal, gas	Thermal, oil	Nuclear
Russia	0.014-0.25	0.027-0.030		0.004
Central Asia	0.014-0.017	0.034-0.038	0.099	0.004
Southern Asia	0.034	0.041	0.100	0.006
Caucasus	0.030	0.050	0.100	0.010
Asia Minor and Middle East	0.034	0.050	0.090	0.007

This information has been obtained from various available sources, including the forecast works of national agencies and companies in the region. The indicators of power plants, naturally, reflect differences in natural and climatic conditions and in the cost of fuels. The specific capital investments of power plants were also influenced by the factor of scientific and technological development (progress) of specific countries. This factor had a particularly strong impact on the cost of building nuclear power plants - the most complex technology for generating electricity, mastered in the considered part of Eurasia only in Russia. The rest of the countries are forced to import equipment for nuclear power plants, which leads to an increase in the cost of their construction. This rise in price, apparently, was the reason for the almost double difference in capital investments in nuclear power plants in Russia and other countries.

3 Results of studies and analysis

Comparison of the results of optimization calculations for scenarios 1 and 2 shows that enlargement of transfer capacity of the interstate power grid infrastructure (in scenario 2) leads to a decrease in the total costs of the ISPG by $ 15.9 billion per year, including fuel cost by 10.3. At the same time, the total capital investments in power plants and ISETs are reduced by $ 29.9 billion, and the need to commission new power plants by 26.6 GW for the considered target year (Fig. 3, Table 6).

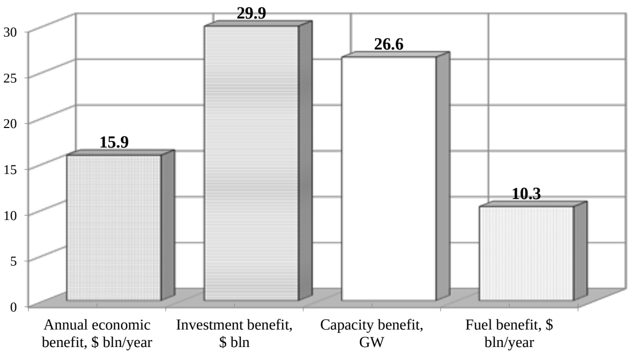

Fig. 3. System benefits of Eurasian Power System Interconnection, 2040

Table 6. Capital investment, billion US$.

	Plants	Lines	Total	Generating capacities additions, GW
Scenario 1	352.593	0.121	352.714	180.3
Scenario 2	280.650	42.126	322.776	153.7
Integration benefits				
(1)-(2)	71.943	-42.005	29.938	26.6

To achieve this effect, the construction of about 127 GW of ISETs is required (in Scenario 2 compared to Scenario 1) with capital investments of $ 42 billion; however, reducing the commissioning of power plants saves $ 71.9 billion, i.e. almost 2 times more (Tables 6, 7).

Table 7. Optimal transfer capabilities of interstate electric ties, MW.

Lines	Russia (Siberia)- CA	Russia (Center, Middle Volga, South, Ural)-	Russia-Caucasus	CA- SA	CA - AM&ME	SA- AM&ME	Caucasus-AM&ME
Scenario 1	1795	5510	2580	3300	900	240	4230
Scenario 2	11200	16000	29814	19385	32000	4846	32000
Changes (2)-(1)	9405	10490	27234	16085	31100	4606	27770

Figure 4 demonstrates the change in the structure of commissioning of power plants and the distribution of the power effect by country in Scenario 2 in comparison with Scenario 1. The reduction in capacities occurs in the countries of Asia Minor and Middle East (59.7 GW), Southern Asia (13.9 GW) and the Caucasus (1.5 GW). At the same time, Russia and Central Asia are introducing additional capacities of 23.0 and 25.5 GW, respectively. In general, for ISPG, the capacity effect is determined by an increase in the commissioning of gas-fired thermal power plants (TPP) and a reduction, to one degree or another, of all other types of power plants. The largest reduction in the commissioning of TPPs on oil (in the Asia Minor and Middle East), which have high fuel costs is 25.6 GW.

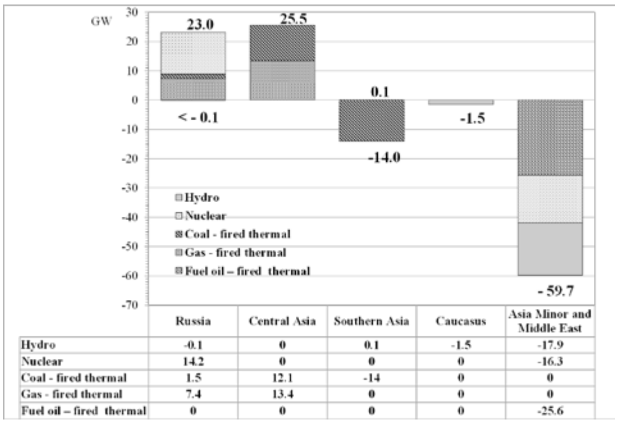

Fig. 4. Change in the structure of power plants, GW

Nuclear power plant (NPP) commissioning is undergoing interesting changes: in the Middle East, they decrease by 16 GW, and in Russia, on the contrary, they increase by 14 GW. This is explained by the large difference noted above in specific capital investments in NPP in Russia and in the Middle East (in Turkey and Iran). The situation is interesting in that NPP in Turkey and Iran are being built with the participation and support of Russia, and during the construction of the considered ISETs and the creation of the ISPG, these NPP are replaced by new NPPs in Russia itself. In other words, when creating an ISPG in the considered part of Eurasia, competition arises between new NPPs by Russian projects in the Middle East and NPPs in Russia itself. This issue requires a special, more in-depth study.

Changes in the structure of capacities, in turn, lead to a redistribution of electricity production, both by type of generation and by country (Table 8). Fuel costs also change accordingly (Table 9).

Table 8. Electricity generation, TWh/year.

	Hydro& Pumped storage	Thermal, coal	Thermal, gas	Thermal, oil	Nuclear	Wind &Solar	Total
Scenario 1							
Russia	190.2	256.3	947.8		238.9	18.3	1651.5
Central Asia	95.8	183.2	168.9	7.9	12.8	10.8	479.4
Southern Asia	164.4	122.3	69.9	17.2	10.1	67.7	451.6
Caucasus	24.1	0.1	66.5	4.1	4.0	2.8	101.6
Asia Minor and Middle East	130.1	421.5	614.0	217.2	212.8	191.2	1786.8
Total	604.6	983.4	1867.1	246.4	478.6	290.8	4470.9
Scenario 2							
Russia	191.0	269.3	1089.1		376.7	18.3	1944.4
Central Asia	96.0	287.3	325.2	8.0	12.8	10.8	740.1
Southern Asia	165.0	6.9	95.9	13.1	10.1	67.7	358.7
Caucasus	19.9	0.1	44.2	4.2	4.0	2.8	75.2
Asia Minor and Middle East	99.6	421.5	541.8	68.0	68.5	191.2	1390.6
Total	571.5	985.1	2096.2	93.3	472.1	290.8	4509.0
Changes in generation of electricity (2) – (1)							
Russia	0.8	13.0	141.3		137.8		292.9
Central Asia	0.2	104.1	156.3	0.1			260.7
Southern Asia	0.6	-115.4	26.0	-4.1			-92.9
Caucasus	-4.2		-22.3	0.1			-26.4
Asia Minor and Middle East	-30.5		-72.2	-149.2	-144.3		-396.2
Total	-33.1	1.7	229.1	-153.1	-6.5		38.1

Table 9. Fuel costs, US$ billion / year.

	Thermal, coal	Thermal, gas	Thermal, oil	Nuclear	Total
Scenario 1					
Russia	4.666	27.566		0.956	33.188
Central Asia	3.014	5.847	0.784	0.051	9.696
Southern Asia	4.159	2.867	1.716	0.061	8.803
Caucasus	0.003	3.323	0.408	0.040	3.774
Asia Minor and Middle East	14.331	30.700	19.548	1.490	66.069
Total	26.173	70.303	22.456	2.598	121.530
Scenario 2					
Russia	4.900	31.675		1.507	38.082
Central Asia	4.889	11.243	0.788	0.051	16.971
Southern Asia	0.233	3.932	1.308	0.061	5.534
Caucasus	0.003	2.208	0.418	0.040	2.669
Asia Minor and Middle East	14.331	27.090	6.119	0.480	48.020
Total	24.356	76.148	8.633	2.139	111.276
Changes in generation of electricity (2) – (1)					
Russia	0.234	4.110		0.551	4.895
Central Asia	1.875	5.396	0.004		7.275
Southern Asia	-3.926	1.065	-0.408		-3.269
Caucasus		-1.115	0.010		-1.105
Asia Minor and Middle East		-3.611	-13.430	-1.010	-18.051
Total	-1.817	5.845	-13.824	-0.459	-10.255

The total electricity production increases in scenario 2 by 38.1 TWh, due to transmission losses in ISETs (Table 3). However, fuel costs are reduced by $ 10.3 billion / year due to the improvement of the structure of generation by power plants.

Electricity production is growing strongly in Russia and Central Asia with cheap energy resources, and is decreasing in other nodes of the ISPG diagram, where fuel is much more expensive. In addition, the already noted phenomenon of moving nuclear power plants from the Asia Minor&Middle East to Russia is emerging. Reducing the capacity and production of electricity from coal, oil and nuclear power plants can provide additional environmental benefit.

As shown above (Table 7), the transmission capacity in all directions of the considered ISETs is increasing significantly, the most development is received by the lines in the directions of Asia Minor & the Middle East with Central Asia and the Caucasus, 32 GW each, and Russia with Central Asia (up to 27, 2 GW) and the Caucasus (up to 29.8 GW). The volumes of transmitted electricity also increase six fold from 320 TWh / year in Scenario 1 to more than 1900 TWh / year in Scenario 2. Moreover, in both scenarios, the main exporters of electricity are Russia - in the directions of the Caucasus and Central Asia; and Central Asia towards Southern and Asia Minor & the Middle East.

5 Conclusion

1. The results obtained confirm the high effectiveness of the development of ISETs in Russia in the Caucasian-Central Asian direction and the formation of the ISPG in this part of Eurasia. In particular, the reintegration of the Unified Power System of Russia and the national power systems of the countries of the Caucasus and Central Asia is highly effective. Moreover, this reintegration is carried out at a new technological level, which ensures intensive exchanges of power and electricity with the corresponding implementation of systemic integration effects that exceed those achieved during the Soviet period. The resulting concentration of the electric power potential of these countries allows them to jointly enter the electric power markets of the countries of Southern and Asia Minor&Middle East, also receiving economic effects. In addition, the studies carried out made it possible to fill the idea of the Caspian energy ring with concrete content, having preliminarily identified its main parameters, such as the transfer capacities of ISETs, the volumes of electricity and power transmitted through them, and economic indicators. It is advisable to envisage and investigate the relevant projects in bilateral and multilateral negotiations with the countries of the region.

2. The creation of the ISPG is economically beneficial, in fact, to all countries of the Region:

- for Russia and Central Asian countries in the light of electricity exports;
- for the countries of the Caucasus, Southern Asia and the Asia Minor& Middle East when importing electricity.

3. The construction of new Interstate Electric Ties within the framework of the considered ISPG is expedient to focus on power transmission ± 800 kV. For their design and construction, specialists and companies from the People's Republic of China should be involved, while developing this technology in Russia. There are prerequisites for this in the form of scientific and technical groundwork, made back in the Soviet period.

4. The issue of construction in Russia of export-oriented nuclear power plants for the transmission of electricity to the countries of Southern and Asia Minor and the Middle East, instead of Russia's participation in the construction of nuclear power plants on the territory of these countries, requires a special study. The construction of export nuclear power plants may turn out to be economically efficient and expedient from the point of view of nonproliferation of nuclear weapons, decrease of unemployment and other circumstances.

Acknowledgments

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Efficiency of solar and wind energy use in the countries of Central and North-East Asia

Oleg Marchenko[1,*] and *Sergei* Solomin[1]

[1]Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

Abstract. This paper investigates the effectiveness of renewable energy sources using solar and wind energy in the countries of Central and North-East Asia. The analysis was carried out in two stages. At the first stage, the efficiency of wind and solar installations in different climatic conditions was compared by the criterion of the cost of electricity. At the next stage of analysis, an optimization mathematical model was used to study the system that simultaneously includes wind and solar installations, backup energy sources and batteries. The model takes into account system effects caused by the interaction of the system elements between themselves and with the environment. It solves the problem of mathematical programming — the search for the minimum of the objective function (total costs) at some constrains. The model is used to study the economic efficiency of the large-scale construction of solar power plants in the Gobi Desert. It is shown that the joint use of solar and wind energy gives a positive economic effect, i.e. energy cost are less than with separate use of these energy sources. Under suitable wind conditions such systems reduces the cost of electricity by more than a quarter compared to the option of using solar energy only.

1 Introduction

Many countries are implementing activities aimed at reducing greenhouse gas emissions. This reduces the negative impact of energy on the climate system. 77 countries announced their commitment to net zero carbon emissions by 2050. In this regard, great importance is attached to the development of renewable energy sources (RES) [1, 2]. By the end of 2019, 166 countries had renewable power targets [3]. Among renewable energy sources, solar and wind energy are developing at the fastest rates [3, 4]. In the period from 2009 to 2019 installed capacity of wind power plants (WPP) has grown more than in 4 times (average growth rate more than 15 %), and solar power stations (SPP) – more than in 26 times (just under 40 % per year) (Fig. 1).

The installed capacity of solar power plants based on solar photovoltaics increased by 115 GW in 2019 and reached 627 GW, and the capacity of concentrating solar thermal power plants is slightly more than 6 GW. The installed capacity of wind power plants increased by 60 GW and reached 651 GW (621 GW onshore and about 30 GW offshore). Wind turbines (WT) produce about 6% of the world's electricity, solar photovoltaics (PV) produce about 3% [3].

By the end of 2019, at least 39 countries had a cumulative solar PV capacity of 1 GW or more. The number of countries with some level of wind power capacity exceeded 102, and 35 countries had more than 1 GW in operation [3].

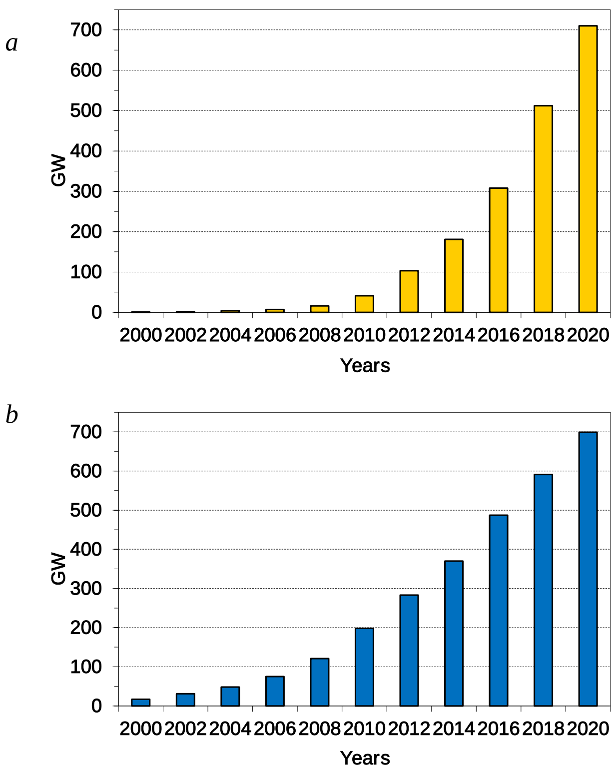


Fig. 1. Installed capacity of SPP (*a*) and WPP (*b*) in the world by years, GW (forecast for 2020).

* Corresponding author: marchenko@isem.irk.ru

In 2020 the installed capacities of both the solar power plants and the wind power plants will exceed about 700 GW. According to the forecasts of the International energy Agency, in the period 2019–2024, the RES capacity will increase by 1200–1500 GW (including 700–880 GW of PV) [5].

The crisis associated with the novel coronavirus (COVID-19) slowed the growth rate of solar and wind power in the first half of 2020. Some projects hit by labour and supply chain disruptions. However, as the consequences of the crisis are overcome, it is highly likely that the growth rate of solar and wind energy will be restored.

The cost of electricity from solar and wind power sources have fallen sharply over the past decade (especially for PV). Solar and wind power generation technologies have become the cheapest option for new capacity in almost many parts of the world [6].

Currently, the issues of electric power integration of producers and consumers of electric energy in different regions of the world are being actively discussed [7, 8]. It is expected that between Russia and Asian countries (Fig. 2) interstate electrical connections will develop, which can provide both economic and environmental effects, including due to the large-scale introduction of renewable energy sources [9, 10].

Fig. 2. Russia and neighboring Asian countries (Google Maps).

The most promising direction of interstate electric communications development for Russia is the southern one, which provides for the integration of electric power systems of Russia, Central Asia and North-East Asia [9, 11]. At the same time, there are quite favorable conditions for the development of solar and wind energy in this region.

One of the projects under discussion involves large-scale construction of wind and solar power plants in the Gobi Desert and subsequent export of electricity to neighboring countries [12, 13].

The Gobi is the third largest desert in the world. It stretches 1,600 km from southwest to northeast and 800 km from north to south. The area of the desert is 1.3 mln km^2. The distance to the Mongolian capital Ulaanbaatar is about 400 km, to the Chinese capital Beijing about 700 km.

Information on the use of renewable energy in the countries of Central and North-East Asia is presented in Table 1. The world leaders in the use of solar and wind energy are the countries of North-East Asia, especially China (about a third of the installed capacities of solar and wind power plants). In Central Asia, solar and wind power plants are being built only in Kazakhstan and Uzbekistan.

Table 1. Capacity of RES (2019), GW [3, 4].

Country	Solar energy	Wind energy	RES*, total
World	633	651	2588
Russia	1	< 1	55
Asia	331	283	1150
including			
China	205	236	790
Taiwan	4	1	7
Japan	63	4	98
N. Korea	0	0	5
S. Korea	11	2	16
Mongolia	< 1	< 1	< 1
NEA,total	283	243	916
Kazakhstan	< 1	< 1	4
Kyrgyzstan	0	0	4
Tajikistan	0	0	5
Turkmenistan	0	0	0
Uzbekistan	< 1	< 1	2
CA, total	< 1	< 1	15

Note: * including other types of RES (hydropower, biomass, geothermal and marine energy). NEA is North-East Asia, CA is Central Asia.

The countries of North-East Asia plan to increase the share of RES in electricity generation primarily due to the development of solar and wind generation [3]. China should strengthen its position as a world leader in the use of wind and solar energy (up to 40 % of the new installed capacity in the world in the next five years). New tens of gigawatts of installed capacity will be introduced by 2025 in Japan, Korea, Taiwan (Chinese Taipei). Mongolia also has ambitious targets to develop solar and wind generation (Table 2).

Table2. National targets for renewable share of electricity generation [3].

Country	Share, %		Year
	Status in 2018	Target	
China	27	35	2030
Taiwan	5	20	2025
Japan	8	24	2030
S. Korea	6	35	2030
Mongolia	0	30	2030
	0	100	2050
Kazakhstan	2	50	2030
Tajikistan	0	10	no date
Uzbekistan	13	20	2025

Kazakhstan has set a target to increase the share of renewable energy sources in electricity generation to 3% in 2018 and 50 % in 2030. In the near future, it is planned to increase the installed capacity to 0.8 GW at 28 solar stations and 1.8 GW at 34 wind stations.

Uzbekistan plans to install 1.2 GW of solar power plants and 0.3 GW of wind power plants by 2025 [3].

2 Statement of the problem and description of the method

The goal of the present research is to assess the competitiveness of various types of power plants and the impact of carbon dioxide emission constraints on it, as well as to determine the optimal structure of wind-solar power plants for different combinations of economic and climatic conditions of Russia and neighboring countries of Central and North-East Asia.

The solution to the problem is proposed to be divided into two stages. At the first stage, the unit cost of electricity production (the cost of electricity) for various types of energy sources were determined [6, 14, 15]. This allows you to pre-evaluate and compare their economic efficiency. When calculating the cost of electricity, individual plants are considered and it is assumed that all energy is fully used.

The cost of energy is equal to the unit cost of energy production and at the same time represents its minimum price at which the energy supply project remains efficient. The cost of electricity can be represented as the sum of terms that take into account the cost of construction and operation, the fuel cost and the carbon cost [15, 16]:

$$S=\left[F\frac{e^{\sigma\Delta T}-1}{\sigma\Delta T}+\mu\right]\frac{k}{CF\cdot H\cdot(1-\beta)}+\frac{p}{8.15\cdot 10^{3}\eta}+\frac{ap^{*}}{8.15\cdot 10^{3}\eta}.$$

The first component of the cost of electricity is directly proportional to the specific investment k, inversely proportional to the capacity factor CF (in the above formula H=8760 hours/year) and depends on the capital recovery factor F, the annual discount rate d, the construction time ΔT, lifetime T, the annual fixed costs μ and energy consumption for own needs β [15, 16].

The fuel component is directly proportional to the fuel price p and inversely proportional to the efficiency η. The emission component depends on emission factor a and carbon tax p^* [14, 16]. PV and WT have no fuel and emission components.

At the second stage, mathematical model was used that takes into account the system effects that occur when energy sources interact with each other and with the environment, additional conditions and constrains.

The optimal structure of the power supply system was chosen from the solution of the mathematical programming problem: minimizing the total (reduced to a year) discounted costs for the creation and operation of the system, taking into account the balances of primary, secondary and final energy and a number of additional constrains. These include constrains, for example, on power consumption levels, on the installed capacity of energy sources to back-up RES stochastic generation, battery operation modes, etc.

For calculations, the mathematical model REM-2 was used. The model takes into account changes in electricity generation from solar and wind installations by the hours of the day and the seasons of the year. The variability in the time of energy production of renewable energy makes their joint use reasonable. The model is described in detail in [17, 18].

In Fig. 3 the power supply system is considered. It consists of photovoltaic converters (PV), wind turbines (WTs) with the possibility of short-term accumulation of electricity. The system includes battery charge controllers, voltage converters and network interface devices (network inverters) and a back-up energy source, conventionally called "Network" (Grid).

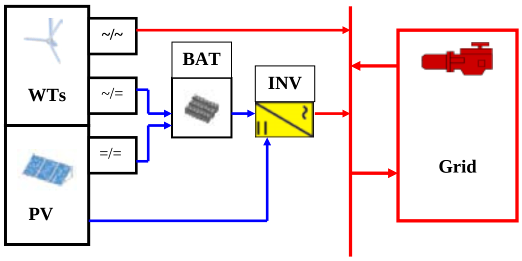


Fig. 3. Diagram of the power system. WTs – wind turbines, PV – photovoltaic, BAT – batteries, INV – inverter, Grid – network, back-up energy sources.

At certain points in time photovoltaic converters and wind turbines can be in an idle state, moreover, these moments in some cases may coincide (period of energy "standstills"). At other times, they produce surplus electricity for a power system with a limited load level.

In this regard, it is assumed that at any time the electric power system (the "Network") is able to supply electrical energy to system at a given price and is able to accept surplus electricity generated by renewable energy sources. Surplus electricity is sold to the grid at the same price.

3 Initial data

The economic efficiency and competitiveness of PV and WT are determined primarily by the technical and economic indicators of power plants, the price of electricity of a backup energy source and the capacity factor. The variation of capacity factor for solar cells depends on the arrival of solar radiation on the surface of the solar panel, and for wind turbines it depends on the wind speed at the height of the rotor blade [15, 19, 20]. It is assumed that PVs have optimal tilted solar panels with the corresponding tracking system for the Sun, and the WT tower height exceeds 100–120 m.

Tables 3 and 4 show the initial data. The uncertainty interval of the initial data is formed on the basis of information from [6, 12, 13, 15, 16, 18, 19]. The discount rate is assumed to be 5%, lifetime is 25 years.

Table 3. Technical and economic indicators of solar power plants.

Region / country	*k*, $/kW	μ, %	CF
Siberia and Far East (Russia)	1500 – 2000	1.5 – 2.0	0.11 – 0.17
Mongolia	1100 – 1400	1.5 – 2.0	0.15 – 0.24
China	1000 – 1300	1.5 – 2.0	0.15 – 0.25
Korea	1800 – 2300	1.5 – 2.0	0.15 – 0.17
Japan	2000 – 2500	1.5 – 2.0	0.14 – 0.16
Central Asia	1100 – 1400	1.5 – 2.0	0.16 – 0.25

Table 4. Technical and economic indicators of wind power plants.

Region / country	*k*, $/kW	μ, %	CF
Siberia and Far East (Russia)	1500 – 2000	2.0 – 2.5	0.18 – 0.48
Mongolia	1300 – 1600	2.0 – 2.5	0.18 – 0.42
China	1300 – 1500	2.0 – 2.5	0.22 – 0.59
Korea	1500 – 1700	2.0 – 2.5	0.23 – 0.32
Japan	1600 – 1800	2.0 – 2.5	0.20 – 0.37
Central Asia	1300 – 1500	2.0 – 2.5	0.18 – 0.36

4 Calculation results and their analysis

Fig. 4 shows the values of the cost of electricity for thermal power plants (TPPs) using fossil fuels (minimum for coal or gas TPPs) and for renewable energy sources. It can be seen that, taking into account the charge for carbon dioxide emissions, the intervals of uncertainty in the cost of electricity from thermal, wind and solar power plants intersect. This indicates that, under certain conditions, wind farms and solar power plants are competitive with fossil fuel power plants.

In North-East Asian countries, the cost of electricity for organic fuel power plants under construction is usually 3–10 cents/kWh, in the Eastern regions of Russia and Central Asia, it does not exceed 4–8 cents/kWh. Under favorable conditions for solar and wind power plants, the cost of their electricity (3–5 cents/kWh) is less than the costs of electricity from competing thermal power plants (coal, gas, liquid fuel). Under less favorable conditions, RES requires the introduction of special tariffs and other measures to encourage investors, in particular, the establishment of a fee for greenhouse gas emissions (carbon tax) [14, 15, 21].

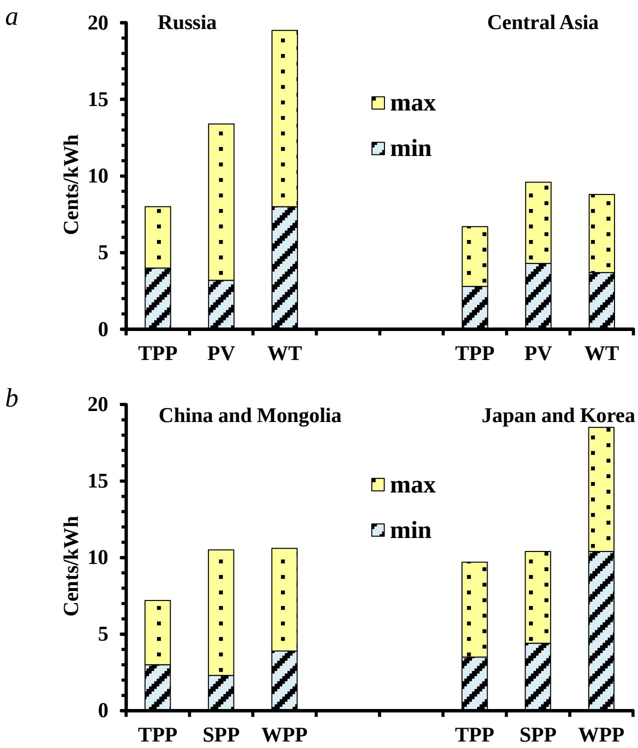


Fig. 4. Comparison of cost of electricity for Eastern Russia and Central Asia (a) and North-East Asia (b). TPP – thermal power plants, SPP – solar power plants, WPP – wind power plants.

The most favorable conditions for the construction of wind turbines are characteristic of China (Tibet), where the capacity factor can reach 0.59 [19]. On the territory of the Russian Far East (the Pacific coast) and Mongolia (the Mongolian part of the Gobi Desert) there are also favorable conditions for the development of wind energy. In Korea and Japan, wind turbines can also be competitive due to high tariffs in the energy systems of these countries. The good conditions for the construction of PV are characteristic of the southern regions of China and Mongolia, in particular, the Gobi Desert [13, 20, 22].

To study energy systems that simultaneously include PV, WT, backup energy sources and batteries, an optimization mathematical model is used.

Fig. 5 shows the results of calculating the optimal power generation ratio between a PV and a WT on the REM-2 model at different prices of electricity from a network backup source and different climatic conditions. The following tariffs are typical for the regions: 4–5 cents/kWh in Central Asia, 6 cents/kWh in Russia and 8–29 cents/kWh in North-East Asia (China and Japan respectively) [23]. The characteristics of solar radiation and wind given in the corresponding editions of climate reference books for Russia (RU), Central Asia (CA) and North-East Asia (NA) were used. The Northern (North) and southern (South) regions are considered separately. At the same time, territories with the best conditions for solar and wind energy use were selected for each of the regions.

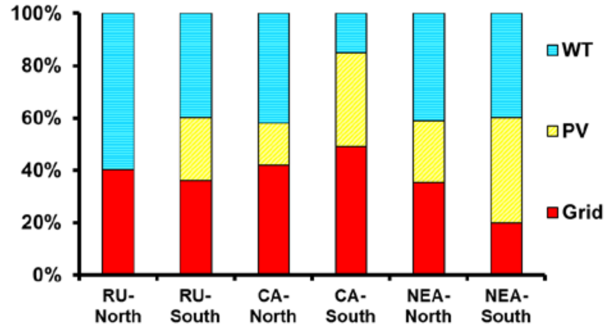


Fig. 5. Optimal ratios of power generation.

With cheap energy from the network, the use of PV and wind turbines is not required. At a higher price, the joint use of solar and wind energy is effective.

As solar radiation increases from northern to southern, the role of solar cells increases. In the northern regions of Russia (RU-North) (the arrival of solar radiation does not exceed 1200 kWh/m^2 per year) the use of solar cells is impractical, and the main part of the generation is provided by wind turbines. In the southern regions (RU-South), with an increase in insolation to 1400 kWh/m^2 per year and a decrease in the average long-term wind speed from 7 to 6 m/s, the role of solar cells and a backup energy source increases.

In Central Asia, three energy sources are included in the optimal plan; as the amount of solar radiation increases, the optimal proportion of solar cells increases. Given that the price of electricity in this region does not exceed 5 cents per kWh, the role of the network backup source is relatively large. As electricity tariffs increase, the role of wind farms (in the northern regions) and solar power stations (in the southern regions) will increase and the role of a backup source of electricity will decrease.

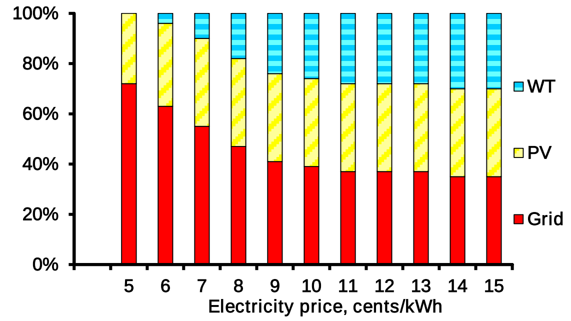
In the southern regions of North-East Asia, the conditions for the development of solar and wind energy are among the best in the world [19, 20], therefore, the share of the duplicate source is minimal.

Below are the calculations for the conditions of the Gobi Desert. It is assumed that the complex of wind-solar power plants in this area will represent one of the first stages of the electric power integration of the countries of North-East Asia. It works for consumers who, along with electricity from renewable energy sources, also consume electricity from systems in North and North-East China, which compensate for the uneven generation of renewable energy sources. The power of these electric power systems is much greater than the power of the wind-driven power plants under consideration.

The amount of solar radiation arrival in the Gobi desert varies in a fairly narrow range and is acceptable for the development of solar energy. Wind conditions vary over a wide range. In some places, the wind conditions are good, in others they are bad and obviously not suitable for the effective use of wind turbines.

Fig. 6 shows the data for calculating the optimal ratio of power generation between PV and WT at different electricity prices in the power system and under different climatic conditions. The price of electricity varied in the range of 5–15 cents/kWh to account for the uncertainty of future conditions. In particular, the price of electricity may increase with the introduction of a carbon tax [16, 21].

a



b

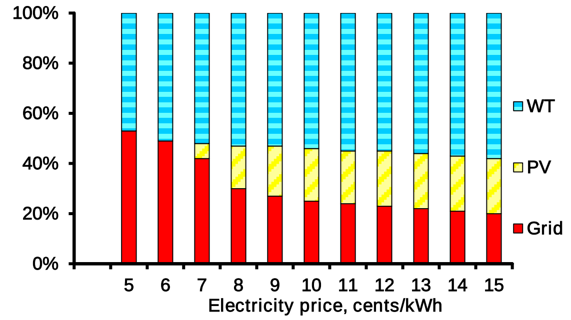


Fig. 6. Share of energy sources in electricity production at different prices of electricity from the network and climatic conditions (*a* – Q=1650 kWh/m^2/year and V=3.5 m/s; *b* – Q=1600 kWh/m^2/year and V=5.5 m/s) (Q is the annual solar radiation input on a horizontal surface, V is average long-term wind speed at a standard height of 10 m).

With cheap energy from the network (less than 4 cents/kWh), the use of solar cells and wind turbines is not required. In areas with a large influx of solar radiation and poor wind conditions (Fig. 6, *a*) with the increase in the price of electricity, the use of solar modules becomes economically effective. At a price above 5 cents/kWh, the joint use of solar and wind energy is effective. With an increase in the price of electricity, the share of wind turbines in the total generation increases, which is due to the advisability of replacing the expensive energy of the power system with cheaper energy of wind turbines.

In areas with good wind conditions (Fig. 6, *b*), the use of wind energy is a priority (the cost of wind energy is less than the same indicator for PV). As the price of electricity rises, installed capacity and production of WT and PV increase.

The dependence of the share of energy sources in energy supply of consumers on the average long-term wind speed for wind turbines is shown in Fig. 7 at a price of electricity from the network of 8 cents/kWh (the price of electricity in the power system of China).

In areas with low average annual wind speeds, only solar energy are used. In areas with an average long-term wind speed (at 10 m height) of 4 m/s, the optimal power of the solar cells and wind turbines are approximately equal, the differences in power generation are more significant. At an average long-term wind speed of 5–6 m/s, the share of renewable energy increases to 70–75%, and the joint use of solar and wind energy allows reducing the total costs of the power supply system by 26–28% compared with the option of using only solar energy (Fig. 8).

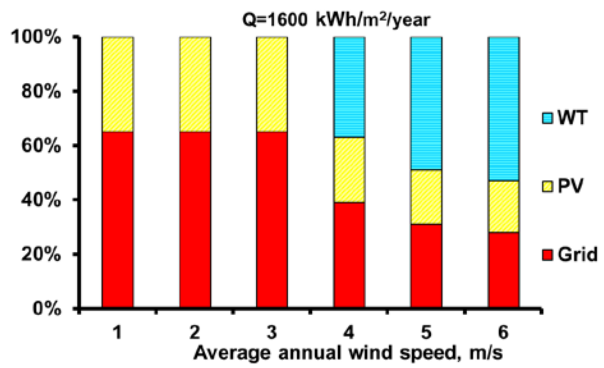


Fig. 7. Dependence of energy sources share in electricity generation on average long-term wind speed (with the price of electricity from the network of 8 cents/kWh).

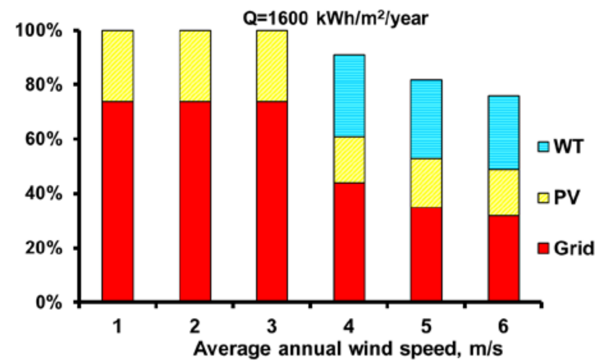


Fig. 8. Dependence of relative costs for electricity supply on average long-term wind speed (with the price of electricity from the network of 8 cents/kWh).

5 Conclusions

A comparison of renewable and non-renewable energy sources by the criterion of the cost of generated electricity is carried out. Under favorable conditions, PV modules and wind turbines in a number of regions can generate cheap electricity at a cost of 3–5 cents/kWh. It is shown that taking into account the payment for emissions, renewable energy sources can be competitive in the energy markets (under certain conditions).

An additional comparison of different types of energy sources, taking into account system effects, was performed using the REM-2 (Renewable Energy Model) mathematical model. The calculations showed the efficiency of the joint use of solar and wind energy and allowed us to identify the optimal share of solar cells and wind turbines for a combination of different conditions in the regions of Central and North-East Asia.

The economic efficiency of the joint use of solar and wind energy in the Gobi Desert is shown, with the exception of some areas with low average long-term wind speeds. The optimal share of renewable energy is 70–75% with an average long-term wind speed of 5–6 m/s (at 10 m height). With the joint use of wind and solar energy, you can reduce the electricity cost by more than a quarter compared with the option of using solar energy only.

Acknowledgement

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RENEWABLES EXPANSION IN NORTHEAST ASIAN POWER GRID

Sergei Podkovalnikov[1,*], *Lyudmila* Chudinova[1]

[1]Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Electric Power Systems Department, 664033, 130, Lermontova Str., Irkutsk, Russia

Abstract. The paper considers effectiveness of a penetration of renewables into potential Northeast Asia power system interconnection. Renewables are currently in the mainstream of expansion of energy sector in the world and in Northeast Asia, particularly. Formation of NEA power interconnection will increase utilization of variable and poorly predictable renewable generation. Economic incentive for penetration of renewables, like CO_2 emission tax, is studied. The study revealed that quite significant tax is needed to be imposed to induce non-fossil fuel generation capacities, including renewable ones, to be added to power systems.

1 Introduction

Electric power integration with the creation of interstate electric ties (ISETs) and large power grids, including the interstate ones (ISPGs), as well as large-scale use of renewable energy sources (RES) are among the dominant trends in the global power sector. Northeast Asia (NEA) is also on the way of creating ISPGs. A process of active penetration of renewable energy in the national power system of China, the Republic of Korea (ROK), Japan is currently taking place. Further large-scale development of RES in these countries and in Mongolia, Russia is possible under conditions of the ISPG creation in the region.

The process of electric power integration in NEA is at an early stage. It is necessary to study scenarios of the future formation of ISETs and ISPG in the region, particularly with large-scale penetration of RES. This meets the requirements of the Paris agreement on the constraint of emissions of carbon dioxide (CO_2) and other greenhouse gases [1], ratified by Russia in 2019 [2]. Only a few studies of this kind were performed so far. The study was conducted on the "environmental" scenario for the expansion of the ISPG in NEA, taking into account the tax on CO_2 emissions [3]. At the same time, RES generation was not optimized, but was set according to national development strategies. The study of an "idealized" ISPG in the NEA region based entirely on RES was performed in [4]. Meanwhile, Russia, which has a significant potential for renewable energy, was not considered in the study.

In the presented paper, we have studied the prospects for expansion of RES in the framework of a potential ISPG in NEA with optimization of their capacity and power along with the capacity and power of traditional power plants (thermal, nuclear, hydraulic). At the same time, a tax on CO_2 emissions was used as a mechanism for stimulating renewable energy sources expansion. The computational tool for the study was a specially improved optimization model of expansion and economic dispatching of electric power systems (EPSs) named ORIRES [5].

The results of the study showed that RES can take a important place in the potential electricity balance of NEA, and the ISPG will contribute to their more complete and effective utilization to cover the joint electric load of consumers in the region.

2 Fundamentals of research

2.1 Assumptions

This research continues the previous studies of the authors aimed at investigating formation of ISETs and ISPG in Northeast Asian region with deeper consideration given to environmental issues and renewable energies, which is a mainstream of energy and power development in the world and NEA, particularly, as was noted above. It was assumed that solar and wind energies can be intensively developed in China, ROK, Japan, Mongolia (Gobitec project) and tidal energy – in Russia.

CO_2 emission tax was used in the study as economic lever for stimulating RES generating facilities (and also other non-carbon generating capacity, like nuclear one) expansion. CO_2 emission tax was assumed to be equal to USD 60 per ton as a medium value from the range of values given in [6] for 2040 (see below). Besides, zero CO_2 emission tax level was also considered as a ground level for comparison.

*Corresponding author: spodkovalnikov@isem.irk.ru

The target year for the study (for which all calculations are performed) was assumed to be 2040, as the last year of the time period considered in the study.

The ISETs in the region were assumed to be installed as HVDC ±800 kV transmission lines and submarine cables. The cables are needed to cross the sea straits (between mainland and Japan, mainland and Sakhalin). This rated voltage has already reached for overhead lines, and is supposed to be reached for submarine cables in the course of the time period considered in the study (from nowadays up to 2040).

2.2 Basic methodology

General methodology for the study involves comparison of base case scenario (with no ISETs) with scenario of ISPG formation and estimation of its benefits as differences between main economic characteristics (like total cost, fuel cost, required generating capacities, investments, etc.) of these scenarios. The methodology has been described in [7,8] and is not presented here.

The above scenarios were detailed to take into account CO_2 tax emission. Pairs of scenarios including Base case one and scenario of NEA ISPG formation were presented for assumed levels of CO_2 tax, including zero CO_2 emission tax, and level of tax in the amount of USD 60 per ton of carbon dioxide emission accordingly. These scenarios were optimised by using mathematical model for expansion and dispatching of electric power systems ORIRES [5,9].

The model was modified for the study. Particularly, optimisation of RES capacity expansion is fulfilled in the modified model that was not done earlier. Power generation of RES was set by daily generation profiles, based on available statistics on solar and wind activities in the considered regions. Amount of RES power generation depends proportionally on the RES capacity and calculated by the model according to optimised RES capacity.

2.2 Data

Interstate power grid in NEA is presented in the study as 10-node diagram (Fig.1). Russia and China are presented by three interconnected nodes, the rest countries are presented by one node each.

It should be noted that for the base case scenario ISETs are absent, and the diagram given in Fig.1 breaks apart into separate national EPSs presented by single nodes or several interconnected nodes (as in the case of China and Russia).

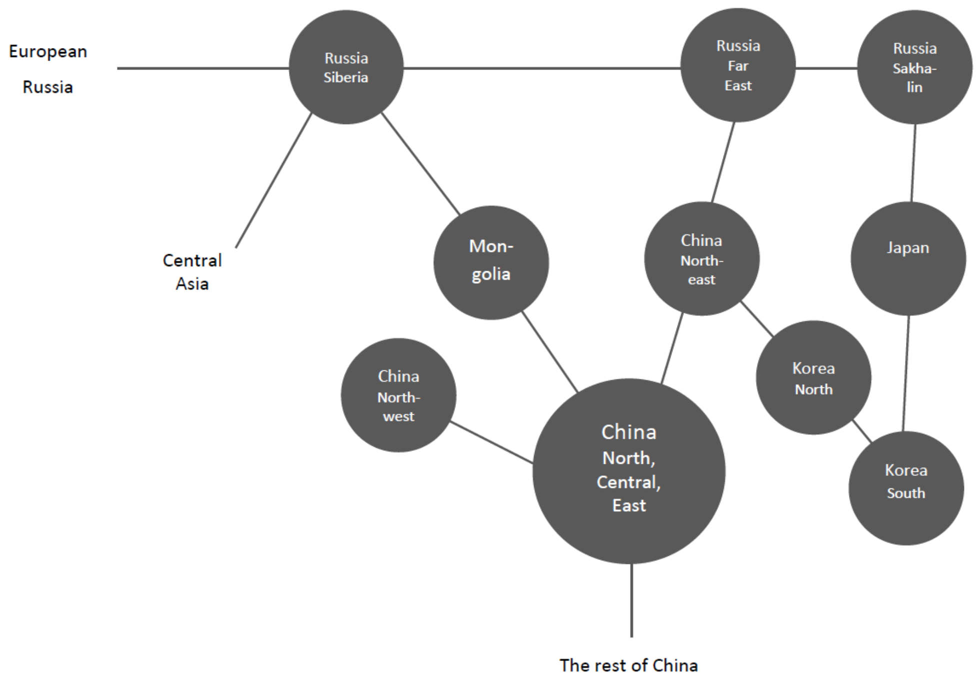

Fig. 1. Diagram of the interstate power grid in NEA.

Major economic and technical input data for the research was taken from reports and studies made by international, governmental and scientific organizations of the considered Northeast Asian countries [6,9-12, etc.]. The data was collected, processed and presented by authors in research papers [3,7,9] and that is why is not given here. Renewables development was not optimized in these researches and, therefore, their input data was not presented there.

Investment cost of wind and solar capacity by NEA country is given in Table 1. Annual fixed operation and maintenance cost of RES was assumed to be 2-2.5% of their investment cost.

Prospective electricity demand in the countries was assumed to grow according to business-as-usual national scenarios [11].

Table 1. Specific investment cost in renewables, USD/kW.

Country \ Capacity	Wind	Solar
China	1200	930
DPRK	1600	1500
Japan	3000	2500
RoK	2500	1800
Monglia	1250	950

3 Results and discussions

Presented in the Table 2 are integration system benefits obtained due to creation of interstate power grid in NEA. As can be seen, high positive benefits take place under different assumed levels of carbon dioxide emissions tax. Resulting economic benefit and investment benefit decrease substantially with the introduction of CO_2 emission tax, because capital intensive RES capacity is added and increases its generating capacity and share in the total installed capacity of NEA ISPG. Cost of ISETs including investment cost decreases with the introduction of CO_2 tax. This means that electric ties expansion and accordingly intensity of power exchange declines when the tax is in place. This point will be considered further. On the contrary, fuel benefit grows when the tax is imposed. This is because carbon dioxide tax is translated into fossil fuel cost in the model.

Table 3 gives detailed data on capacity additions by type of power plant and country for scenarios of absence and presence of ISPG and CO_2 emission tax. This data confirms values of capacity benefit given in Table 2 (as difference between total capacity addition for the cases of no interconnection and presence of interconnection), and additionally shows contribution of different types of power plants and countries into capacity benefit.

Data from the Table 3 shows substantial effect of CO_2 emission tax introduction on volumes and mix of installed generating capacity of power systems no matter they are separate or interconnected. As it follows from Table 3, CO_2 tax stimulates introduction of non-carbon (wind and solar in the amount of 205-214 GW and nuclear – 147-180 GW) and low carbon (gas thermal –

Table 2. Benefits of the interconnection.

Components of benefits		Economic benefit, \$ Bln/year				Investment benefit, \$ Bln.			Capacity benefit, GW
		Power plants	Fuel	ISETs	Total	Power Plants	ISETs	Total	
Carbon dioxide emission tax, \$/ton of CO_2	0	19.6	4.9	-4.9	19.6	109.5	-39.1	70.4	58.5
	60	8.0	7.0	-4.3	10.7	48.1	-34.5	13.6	54.7

Table 3. Capacity additions by type of power plants and country, no CO_2 emission tax/ USD 60 per ton of CO_2 emission tax, GW.

Country \ Capacity	Hydro	Pumper storage	Thermal, coal	Thermal, gas	Nuclear	Wind	Solar	Total
No power system interconnection								
Russia	0/0.74		1.27/0	2.23/0.2	0/3.0			3.50/3.94
China	72.42/ 72.17	88.09/ 42.41	345.5/ 237.6		50.85/ 188.25	0/91.2	0/112.8	556.86/744.43
DPRK	2.24/2.91		4.24/4.04	7.40/7.40		0.23/0.23	0.19/0	14.30/14.58
Japan			21.80/0	19.09/38.00	0/6.80			40.89/44.80
RoK	0.51/0.51	2.00/0	9.91/0	0.93/12.83	19.84/ 19.84			33.18/33.18
Monglia	0.26/1.13	0.20/0.20	2.50/1.63			0/0.15	0/1.82	2.96/4.93
Total	75.42/ 77.46	90.29/ 42.61	385.21/ 243.27	29.65/58.43	70.69/ 217.89	0.23/91.58	0.19/114.62	651.68/845.86
Power system interconnection								
Russia	4.15/8.59		0.24/0	0.45/1.08	0/3.00			4.84/12.67
China	72.42/ 72.17	88.09/ 6.86	345.5/ 243.74		18.31/ 188.25	0/91.2	0/112.8	524.32/715.02
DPRK	2.91/2.91		0.76/0	0/3.67				3.67/6.58
Japan			21.80/0	0/19.77	0/6.80			21.80/26.57
RoK	0.51/0.51	2.00/0	9.91/0	3.57/0	19.84/ 19.84			35.83/20.35
Monglia		0.20/0.17	2.50/0				0/9.86	2.70/10.03
Total	79.98/ 84.18	90.29/7.04	380.71/ 243.74	4.02/24.52	38.15/ 217.89	0/91.20	0/122.66	593.15/791.22

20-29 GW) power sources. This causes substantial decrease of coal-fired thermal capacity in the amount of 137-142 GW.

In presence of CO_2 emission tax RES expands in China. Additionally, solar panels are brought on line in Mongolia in the case of NEA power interconnection. Without interconnection even though in presence of CO_2 tax large capacity of renewables is not introduced in Mongolia because of limited national electricity market. NEA-wide power interconnection opens up opportunities for Mongolian renewables to enter international electricity market and thus induces their large-scale development.

It is needed to note that power system interconnection stimulates additionally introduction of non-carbon power sources (9 GW for RES and 33 GW for nuclear – as difference between high and low values of the given above ranges). Effect of interconnection (in presence of CO_2 tax) on pumped storage capacity is dramatic. The capacity decreases six fold in comparison with the case of absence of interconnection (and presence of tax). This is because interconnected power system has extended capability to regulate and adopt stochastic injections and withdrawal of power from RES that decreases needs of power system in power storage facilities.

The share of RES (with CO_2 emission tax in place) in total capacity additions is quite high being 25% in the case of no interconnection and reaching 27 % in the case of interconnection.

The total capacity of power systems no matter they are separate or interconnected increases with large-scale introduction of RES by 194-198 GW. This is because wind and solar facilities are plants with non-firm variable power generation and they need to be reserved by firm power sources.

Figure 2 presents capacity by type of power plants for the case of power interconnection in NEA. As can be seen coal-fired thermal power plants still dominate in the capacity mix being three-four times more that solar or wind capacity. As it follows from the Figure 2, the share of RES in total installed capacity of potential NEA ISPG (with presence of CO_2 tax) slightly exceeds 20%.

The share of all non-carbon facilities considering additionally traditional hydro and nuclear in the total capacity is more than twofold and takes 45%. If low-carbon facilities are considered additionally (particularly, gas-fired power plants) the share of non-carbon and low carbon capacity is over than half of total NEA ISPG capacity, being about 55%. Thus, the share of environmentally dirty coal-fired power plants in NEA ISPG installed capacity is still expected to be quite high reaching 45% in the target year in spite of taking the measures of environmental protection like CO_2 emission tax.

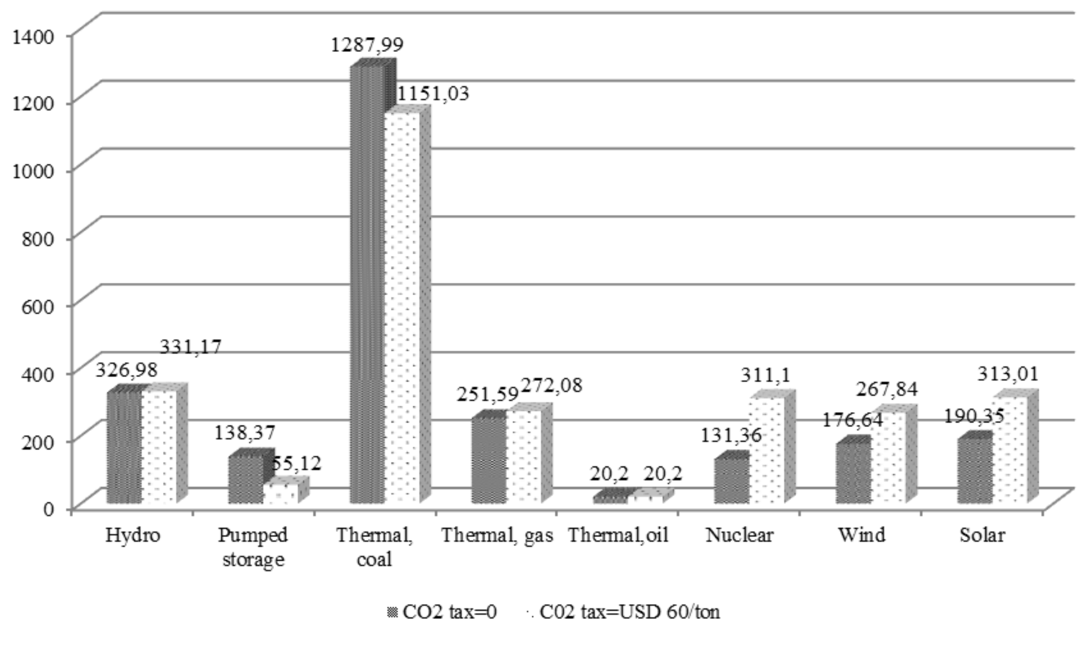

Fig. 2. Installed capacity of NEA power grid for 2040 target year, GW.

Figure 3 presents power generation of potential NEA interconnection and its breakdown by type of power plants. As is seen, RES, having more than 20% of the total installed capacity (as it follows from the above), takes much smaller share of the total power generation being about 8%. This is due to small number of utilization hours of RES capacity determined by climatic conditions. However, total share of non-carbon and low-carbon power generation is again equal to 55% of the total generation. This is mainly due to substantial contribution of nuclear capacity having high number of utilization hours typical for this type of power plants. Thus, share of environmentally dirty coal-fired power plants in power generation as well as in installed capacity of NEA ISPG is still expected to be quite high reaching 45% in the target year subject to a CO_2 emission tax.

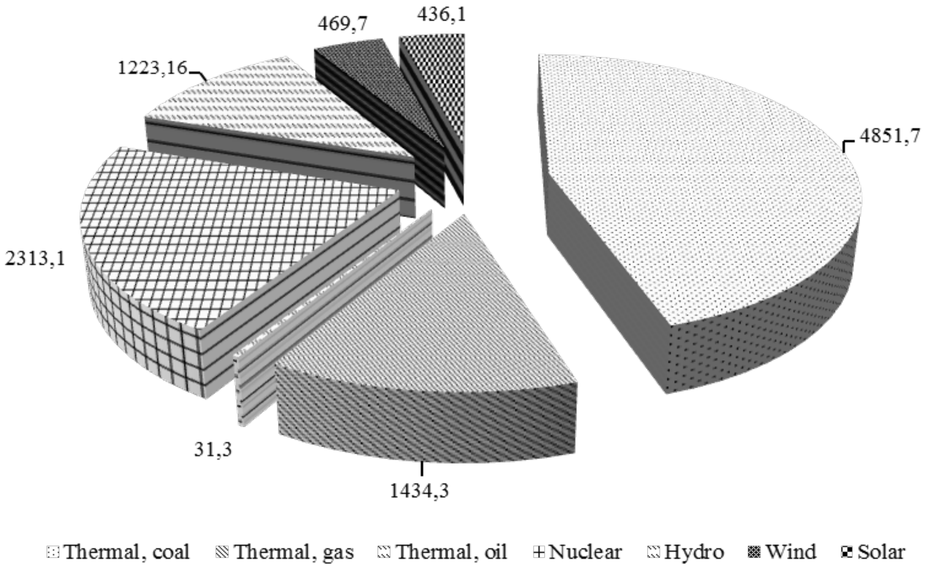

Fig. 3. Power generation of NEA power grid for 2040 target year, CO_2 tax=USD 60/ton, TWh/year.

Optimal transfer capacities of ISETs for scenario of NEA power interconnection depending on presence or absence of CO_2 emission tax are given in Table 4. As is seen, presence of the tax suppresses development of interstate transmission infrastructure. This corresponds to given above note that cost in ISETs decreases when CO_2 emission tax is in place. Transfer capacities decreases because the need for power exchange reduces in presence of the tax. This is explained further.

Table 4. Transfer capacities of ISETs in presence of NEA ISPG, GW.

ISETs \ CO_2 emission tax	0	USD 60/ton
Russia (Siberia)-Mongolia	14.4	12.9
Russia (East)-DPRK	2.7	3.6
Russia (East)-China (Northeast)	5	5
Russia (East) -Japan	5	5
Mongolia-China (North-Central-East)	14.7	11.3
China (Northeast)-DPRK	15	15
DPRK-RoK	15	15
RoK-Japan	15	11.1
Total	86.8	78.9

Figure 4 presents amounts of power exchange over ISETs among countries to be participated in NEA ISPG under presence and absence of CO_2 emission tax. Total amount of export-import exchanges is quite large – 1000 TWh/year with no CO_2 tax and 830 TWh/year with tax equals to USD 60/t of CO_2.

As has already been noted introduction of CO_2 emission tax curbs power exchange. Particularly, China substantially decreases its electricity export. This is because of the following reason. China having large fleet of cheap coal-fired power plants in the case of NEA power interconnection and with no CO_2 tax can supply power abroad and compete on international electricity market. CO_2 tax introduction makes power from Chinese coal-fired power plants more expensive and less competitive on NEA electricity market, and China decreases its power supply abroad. Thus, China decreases its power export by more than 20% (or by 41 TWh/year), and overall NEA-wide decrease of export in presence of CO_2 tax is 17% (or 89 TWh/year).

As can be seen from Figure 4, the largest electricity importer is Japan. Countries of Korean Peninsular are both large importers and exporters. This means that they are mostly transient countries, providing corridors to transmit power over their territories to Japan.

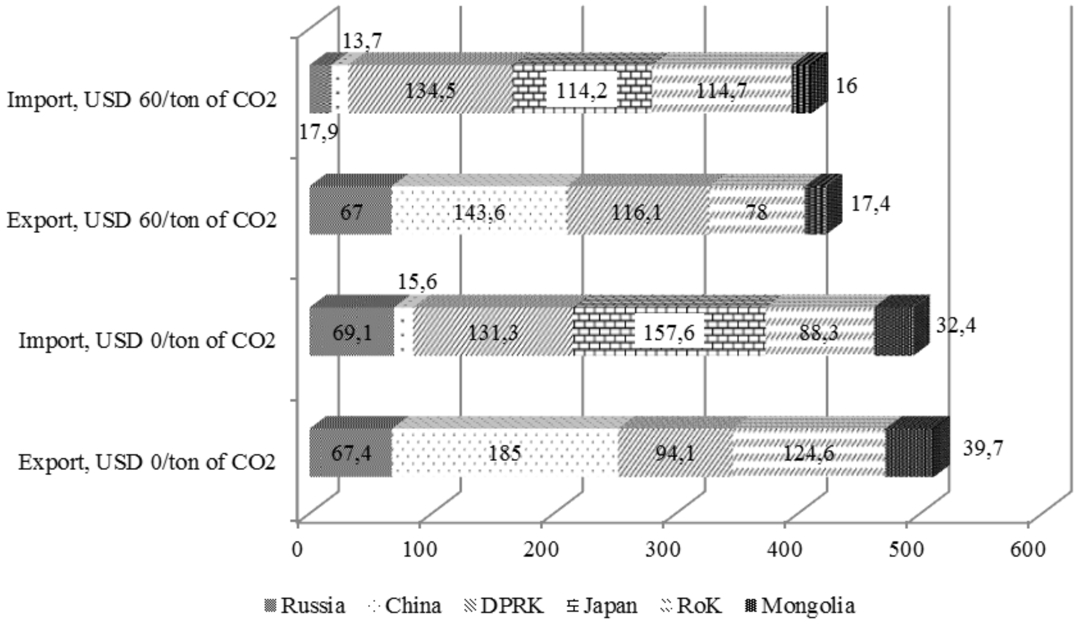

Fig. 4. Expor/import power flows within NEA ISPG, 2040, TWh/year.

4 Conclusions

The conducted research has confirmed possibility and economic feasibility for extensive renewable energy integration into potential interstate power system interconnection in Northeast Asia. NEA power system interconnection remains beneficial no matter CO_2 emission tax is introduced or not. However system integration benefits as well as transfer capacity of and power exchange over international network infrastructure of NEA power interconnection are reduced when the tax is in place. This is mainly due to decrease of power export from Chinese coal-fired power plants in presence of the tax.

Mid-level CO_2 emission tax used in the study induced expansion of renewables and in general non-carbon (nuclear) and low-carbon (gas-fired) generating capacities. Nonetheless, the tax does not allow renewables to take prevailing position in NEA interconnection by the assumed target year. Wind and solar facilities are massively developed in China and in case of NEA power interconnection in Mongolia. Thermal environmentally dirty coal-fired power plants still take important role in NEA interconnection even in presence of CO_2 emission tax.

Further research needs to be done to study large-scale renewables expansion in NEA power interconnection at more powerful economic tool inducing such an expansion.

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DEVELOPING A NEW SOFTWARE TOOL FOR RESEARCH OF INTERSTATE POWER GRIDS EXPANSION

Ivan L. Trofimov[1], *Leonid N.* Trofimov[1,*]

[1]Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Electric Power Systems Department, 664033, 130, Lermontova Str., Irkutsk, Russia

Abstract. The aim of our research is to develop a new software tool – the Computing and Geo-information System for study of prospective interstate power grids expansion. The new software tool developed by the authors consists of several functional parts (software modules): graphic module for visual analysis of processed data, geo-information and cartographic module, module for working with the integrated ORIRES model (model for optimization of power systems expansion and their operating modes). In this paper, we consider features and technical description of the new software tool. The obtained results of the integrated ORIRES model in tabular, graphic and cartographic forms are presented.

1 Introduction

The formation of interstate power grids (ISPG) in various regions of the world is due to positive effects to be obtained: increased reliability of electric power systems and uninterrupted power supply, wide involvement of renewable energy sources, and significant economic benefits. ISPG requires justification of its technical and economic efficiency, forecast of further expansion, coordination of economic and political interests, compliance with the technical standards of the participating countries, and consideration of many other aspects [1-3]. These researches require a lot of preliminary work to collect and analyze a huge amount of energy and power data, technical and economic calculations, and significant intellectual and information resources. A mathematical model for optimization of power systems expansion and their operating modes (named ORIRES) has been developed and applied at the Energy Systems Institute for the analysis and forecasting of the prospective ISPG expansion [4-6]. Without new information technologies that reflect the specifics of this subject area, research on the model takes a lot of time and human resources. To increase efficiency of research and to analyze multidimensional results, a convenient software interface is required.

To solve these problems, the authors have developed the *Computing and Geoinformation System* (the CGIS), which consists of a graphical (geoinformation) part and a computing part with an integrated ORIRES model and with the ability of its multiple configurations [7-9].

2 Functional modules of the CGIS

The CGIS, developed by the authors consists of several functional parts (software modules): graphic module for visual analysis of processed data, geo-information and cartographic module, module for working with the ORIRES model.

Using a special CGIS interface, the user can configure the parameters and nodes of the model, launch the optimizer, and get the optimal solution for the objective function. All data used in the CGIS are stored and processed in the own object-oriented database. Each module is intended to solve specific problems. They can be divided into three groups:

1. Optimization and computing problems:
   a. assessment of the effectiveness of interstate electric ties;
   b. assessment of the integration level and efficiency of interstate power grids;
   c. optimization of electricity generation capacities and operating modes for energy power systems (EPS);
   d. study of EPS and ISPG expansion in different regions.
2. Information-analytical problems:
   a. storage of energy and power data, collected from various sources in a uniform structure;
   b. data analysis over various periods to reveal trends of electric power industry development;
   c. graphic and cartographic data representation – atlas geo-information mapping [10].
3. The research results coverage in Internet to attract of international scientific community. Based on the CGIS, the authors have developed an external energy informational and analytical web-service.

* Corresponding author: t_john88@isem.irk.ru

3 Object-oriented data base

Figure 1 shows the data loading and analysis processes in the CGIS.

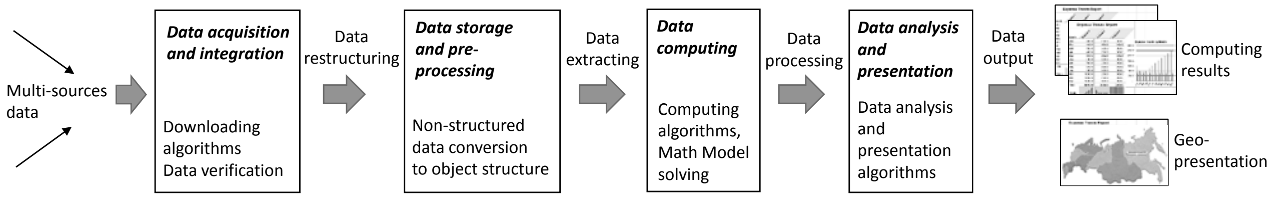

Fig. 1. The data loading and analysis processes in the CGIS.

All information received from various sources is structured and stored as unique database objects. Then the user can configure scenarios of ISPG and run the model. The resulting output is a set of tables with optimal parameters for all ISPG nodes. The obtained data are analysed in tabular, graphical, and cartographic forms in the CGIS, and exported to Excel.

The object-oriented database (OODB) developed by the authors is used for storing and processing data in the CGIS. The essence of data storage technology in OODB is that all data received/written to the system are structured using a special software algorithms and stored as unique database objects, that describe (modelled) the energy and power parameters of real-world objects (power plants, transmission lines, power systems etc.). Types of objects in the OODB can be different and independent. DB objects can be regions or countries, national power systems, power plants, electric ties, figure 2.

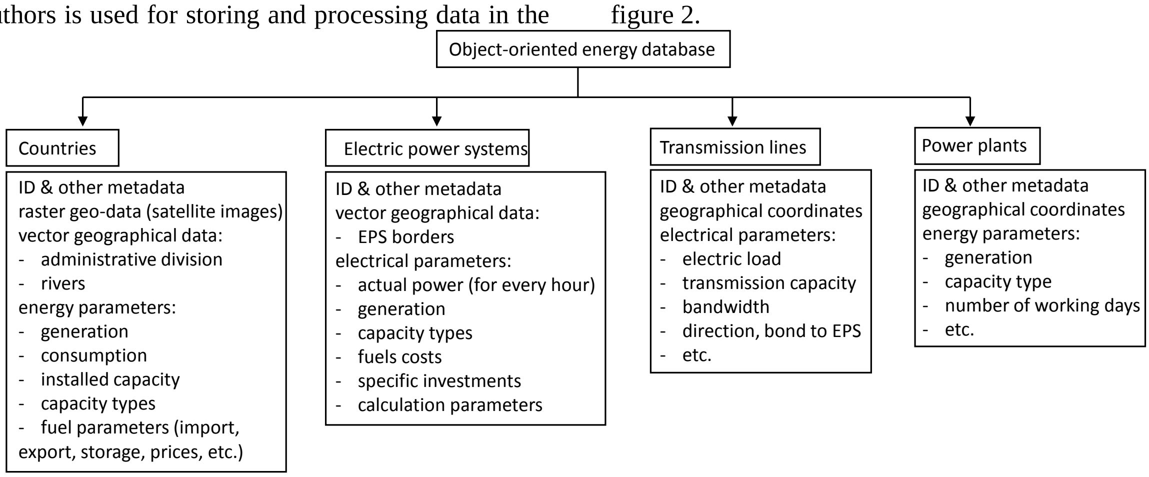

Fig. 2. The CGIS database logical structure.

Each object is a logical record containing a unique object identifier, a set of parameters describing it, and the values of each parameter in text or numeric form, stored by year, month, day, and so on. This type of storage allows one to accurately verify objects collected from various sources and external databases. OODB has a file data structure. The internal structure of files is convenient not only for machine processing, but also understandable to human. The data structure’s flexibility and accessibility makes it almost independent of the software components and processing procedures.

The authors have developed special software algorithms for data input / output and their analysis in the CGIS interfaces.

4 Computing part of the CGIS

The computing module of the CGIS is designed to work with the integrated optimization model. A special interface allows experts to configure and to change the parameters and constraints of the model and the configuration of nodes and links of the ISPG scheme, to run the "optimizer" and to generate a final set of tables with the results of the optimal solution.

For the ORIRES model, objects of the "node" type are used – these are national EPSwith their energy parameters from OODB.

In this model, a linear optimization method is used to find a solution, which determines:

- the optimal installed capacity and generation type mix of the considered power systems and their interconnections,
- the intersystem and interstate electric ties transfer capabilities,
- the operating modes of these capacities and ties.

The optimal solution of the model is determined by the minimum of annualized costs for the ISPG as a whole. The model is optimized within certain constraints: on capacity and power balances and other constraints - on installed capacity, on electric ties expansion, etc. A detailed description of the model can be found in the book of Lev S. Belyaev et al. *The effectiveness of interstate electric ties* (Novosibirsk: Nauka, 2008) [11].

Figure 3 shows a graphical representation of the optimized parameters of one of ISPG nodes.

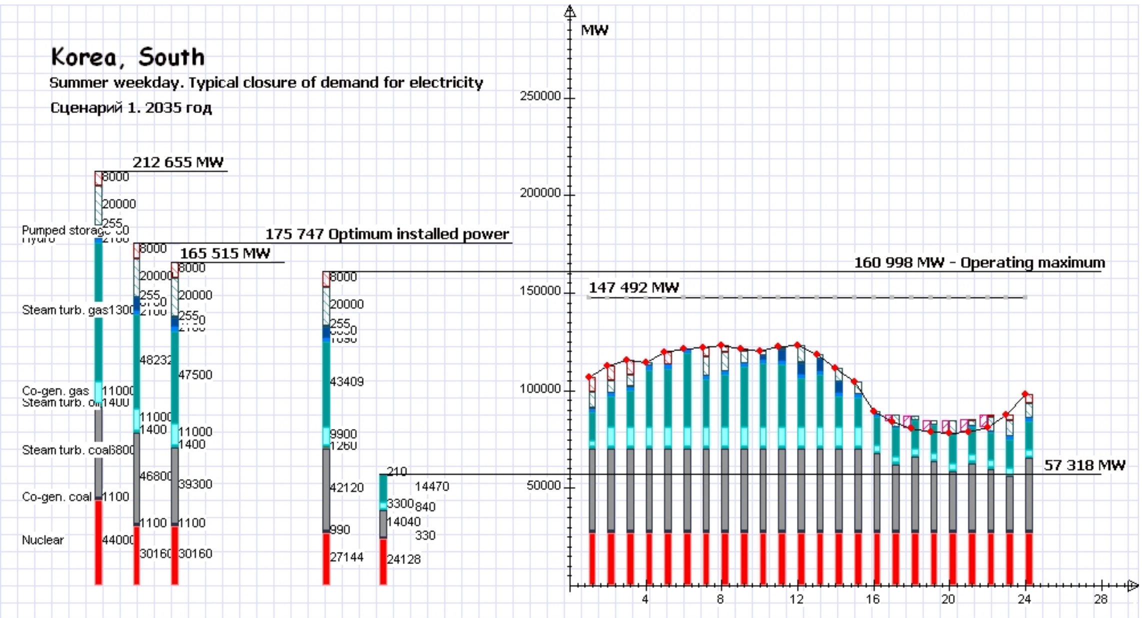

Fig. 3. Graphical representation of South Korean node's parameters and constraints.

Consumers demand is characterized by graph of daily electrical load, which determines how much electricity needs to be generated for each hour (of all 24 hours). The problem of determining the actual power for each type of power plants (co-generation coal fired power plants, gas fired, oil fired, hydro power plants, pumped storage, nuclear, wind, solar and others) is solved, taking into account the electricity transfer between nodes of ISPG diagram.

The main result is a solution, which takes into account the minimum annualized costs, computing the optimal structure of various capacity types (in each node of the ISPG) and their optimal operating modes (at each hour of the day and in different seasons of the year).

All the above parameters and constraints of the model (input data) are configured in forms via the CGIS interface. The interface for entering input parameters and model constraints includes:

- form for setting parameters and constraints of the node,
- form for setting the graph of electric load,
- form for setting the parameters of electric ties between nodes, Figure 4.

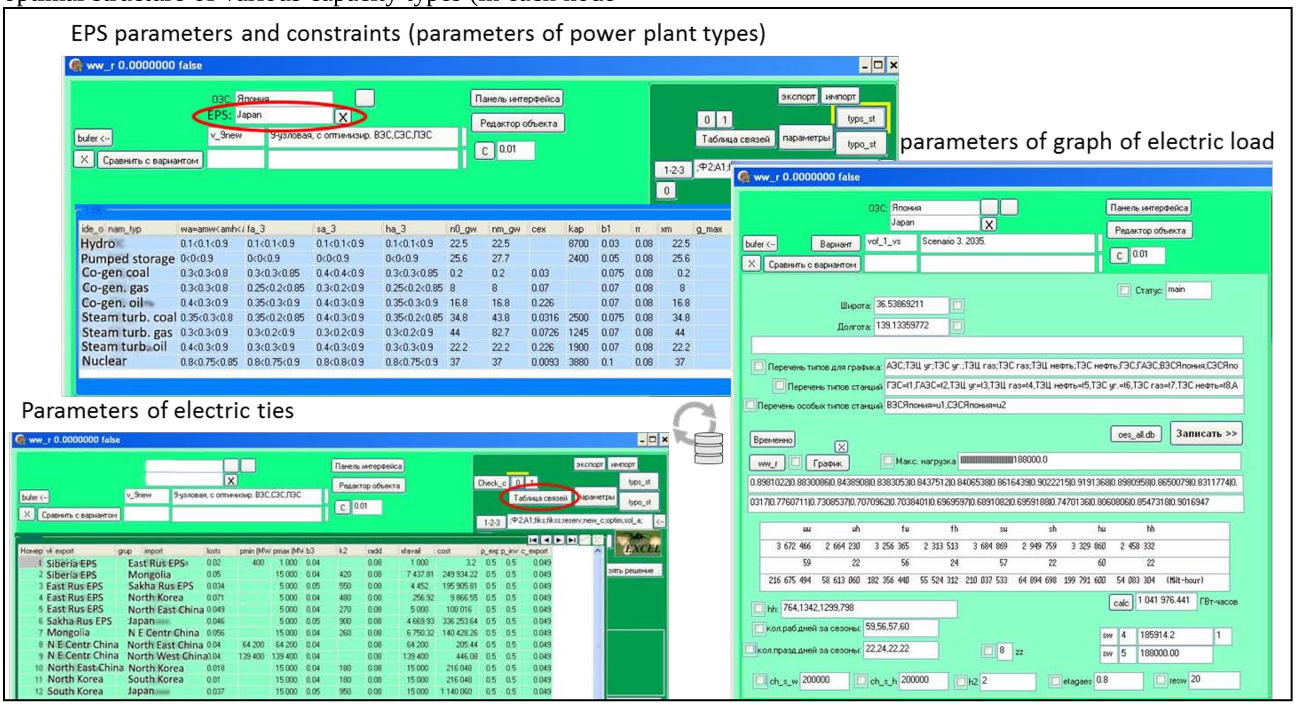

Fig. 4. Forms for input model parameters and constraints in the CGIS interface.

In the software implementation of the ORIRES model, all its equations and parameters are written in a special language of the algebraic modelling system GAMS (also it can be any other optimizer), which is

* Corresponding author: t_john88@isem.irk.ru

launched from the CGIS, reads the model parameters set in the CGIS interface, and creates the optimal solution. The output spreadsheets are presented in tabular form with a very large dimension. Therefore, further work consists in aggregating the output spreadsheets for their subsequent analysis and representation.

5 Cartographic module of the CGIS (geoinformation mapping)

The results obtained by the model also can be presented in the cartographic module of the CGIS.

The cartographic module uses three different types of data:

1) raster data used as a background layers for analysis of the map of selected territory,

2) vector data – borders of all administrative regions; the CGIS can be used to study of ISPGs in any regions, not only for the Northeast Asia (NEA),

3) graphical layers for visual analysis, containing certain energy information from the database about the modelled objects, as well as obtained during calculations on the model.

The database of the CGIS contains data collected from various sources, Figure 5.

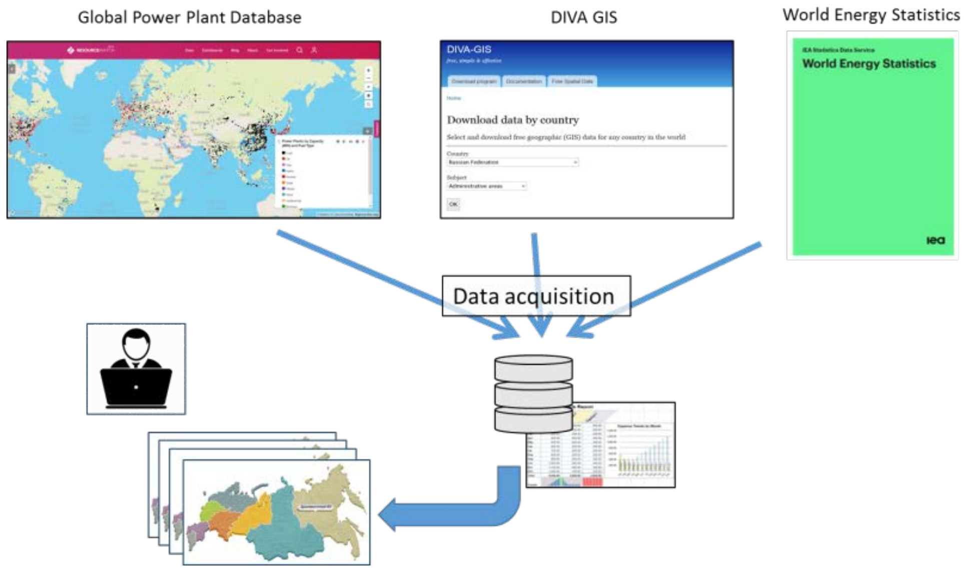

Fig. 5. Various sources for the CGIS database.

One of the key sources for the cartographic module is the “DIVA GIS” resource [12]. Contour maps of more than 200 countries with their provinces and cities were uploaded to the CGIS database. Several thousand power plants of the world with their geographical coordinates and energy parameters were downloaded from the “Global Power Plant Database” [13]. The CGIS database contains data from the fuel and energy sector of various regions of the world, downloaded from the “IEA world energy balances” [14]. Parameters for model nodes are also collected from various external sources and uploaded to the CGIS database.

The internal structure of the OODB for various types of objects collected from various external sources is universal.

Navigation in the cartographic module of the CGIS is based on the concept of “Atlas geoinformation mapping”, Figure 6. The cartographic module uses both offline data from the CGIS database and online data downloaded from free servers of Google Maps, Yandex Maps, and others.

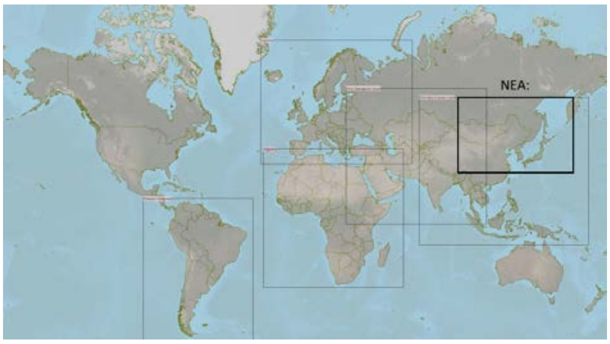

Fig. 6. Atlas geoinformation mapping in the CGIS cartographic module.

At the required scale, the user can combine vector layers with the borders of administrative regions or national power systems, with raster layers of the selected territory. The CGIS allows one to display the geographical coordinates of power plants from the database on the map of selected region, and aggregate their parameters by provinces, power systems, or countries.

To analyze the results of solving the model in the cartographic module, the user can build on the map a scheme of ISPG with the certain parameters and connections between the nodes (interstate electric ties). Figure 7 shows the hybrid map with the 10-node scheme of Northeast Asia Interstate power grid for 2040 target year.

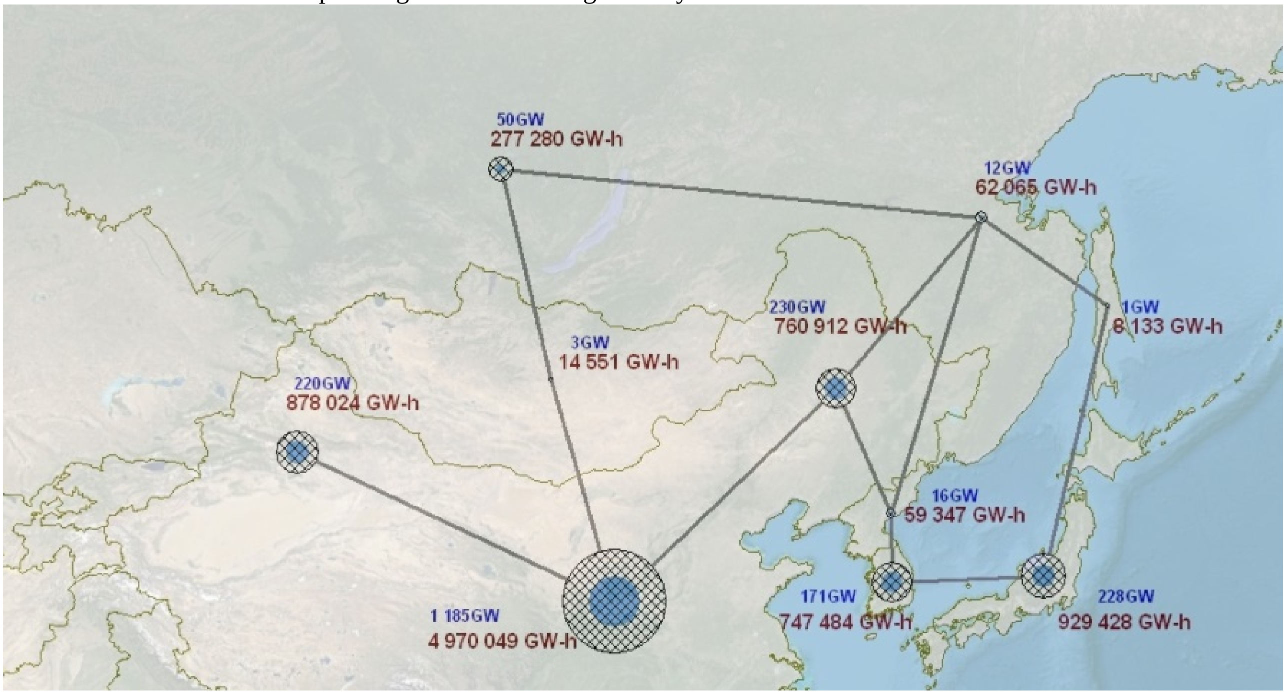

Fig. 7. Hybrid map. The 10-node scheme of NEA ISPG for 2040.

4 Conclusions

The new software tool (the CGIS) developed by the authors allows one to carry out a comprehensive analysis of prospective interstate electric ties and power grids of the selected regions. With the CGIS, some new opportunities have appeared for presenting the results of optimization by the ORIRES model (reflecting the operation of power systems in various configurations / scenarios, in tabular and graphical forms).

Now it is possible to flexibly adjust (edit) the initial parameters of the model, the new ability to modernize the model (edit equations and model constraints, add new variables, etc.). This year the authors have carried out the study of optimization of renewable energy capacities at the Northeast Asia interstate power grid.

The new software tool developed by the authors for the study of prospective interstate power grids expansion improves the quality and efficiency of scientific research in this area.

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OPTIMIZATION OF CAPACITIES OF WIND AND SOLAR POWER PLANTS IN THE INTERSTATE POWER GRID IN NORTH-EAST ASIA TAKING INTO ACCOUNT THE INTERMITTENCE OF THEIR POWER OUTPUT

Leonid N. Trofimov[1], *Ivan L.* Trofimov[1,*]

[1]Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Electric Power Systems Department, 664033, 130, Lermontova Str., Irkutsk, Russia

Abstract. The paper considers the problems of optimization of wind and solar power plants (WPP and SPP) expansion and it operating modes in the prospective interstate power grid (ISPG) in Northeast Asia, taking into account the intermittence of their power output. A series of experiments with variations in the profiles of WPP and SPP in the model nodes were carried out. Also authors carried out some additional experiments with the increase in fuel costs for fossil fuel power plants due to environmental restrictions. As a result, an assessment of the character of the changes in the solution of the model for new installed capacities and their costs, depending on the variations for the profiles of the contributions generation of WPP and SPP to cover daily electrical load graphs, is obtained.

1 Introduction

The increase in the share of power plants on renewable energy sources (RES) is a global trend. However, the operation of these types of power plants (Wind - WPP and Solar - SPP) has its own characteristics that require study and analysis when integrating them into power grid.

A feature of RES is the intermittence of their power output (contribution to the power system), which is difficult to predict. Taking into account the contribution of WPP and SPP to electricity generation, it is impossible to plan the amount of this contribution to cover the average daily electric load. Therefore, when optimizing new capacities in power system expansion scenarios, taking into account the required 20% of capacity reservation at peak load points, WPP and SPP contributions must be completely eliminated. In other words, the power system must be able to pass all peak load points without considering the generating capacity WPP and SPP. Taking into account the economic parameters of these power plants, the quantitative ratio of capacities for renewable and non-renewable energy resources in scenarios of interstate power grid expansion is an important parameter calculated when solving the optimization problem.

2 Computational experiments on the ORIRES model taking into account the increase in fuel costs for fossil fuel power plants due to environmental restrictions

A number of computational experiments were carried out on the ORIRES model by using the Geo-information computing system [1-6]. In this model the optimization of generation capacities expansion and it operating modes are determined by the minimum cost of their construction, operation and fuel consumption, if all technical constrains are satisfied. Along with optimization of new capacities of thermal, nuclear and hydraulic power plants, the involvement of each type of power plants in covering graphs of daily and annual electric load is optimized too. The obtained installed capacities and generation profiles of these types of power plants are optimal in terms of minimizing total costs.

It was some scenarios with the possible increase in fuel costs due to an increase in the CO_2 emission tax. In relation to the basic scenario, CO_2 tax of 30, 40 and 60 USD per 1 ton of emission was taken into account [7-9]. In each of these three scenarios, fuel costs were recalculated in USD / kWh, respectively.

For each of these scenarios, non-interconnected power systems and interconnection of power systems into Interstate Power Grid in Northeast Asia (NEA ISPG) were considered. Eight possible scenarios for ISPG expansion in Northeast Asia were analysed. Calculation of two basic scenarios, for non-

* Corresponding author: t_john88@isem.irk.ru

interconnected nodes (power systems) and ISPG showed the integration effect (benefits) of interconnection in the form of reducing the total costs and saving the additions of new generating capacities. Table 1 shows the results of calculating two basic scenarios, non-interconnected power systems and interconnection. The bottom raw of the table shows the integration effects.

Table 1. Benefits of the interconnection of power systems.

Name	Capital investments, $ Bln.			Capacity, GW	
	power plants	electric ties	Total	installed capacity	addition
Base case scenario 2040 Non-connection	854.8	0.214	855.05	2 582.3	651.68
Base case scenario 2040 interconnection	745.3	39.27	784.63	2 523.7	593.15
Resulting effect	**109.5**	**-39.05**	**70.42**	**58.5**	**58.53**

The interconnection of power systems in NEA ISPG, as shown by the experiments, can save up to 70 $ Bln. capital investments and 58 GW of new generating capacities. Scenarios with a consistent and substantial increase in the cost of the fuel component showed that the integration effect of interconnection remains for all scenarios.

When the cost of the fuel of thermal power plants increases, the generation of these types of power plants is replaced by the generation of wind and solar facilities. The next two diagrams illustrate the percentage of annual generation of various types of power plants in the basic scenarios (without fuel cost increases) – Figure 1, and with an increase of fuel costs due to introduction of emission tax in the amount of USD 60 per ton of CO_2 – Figure 2.

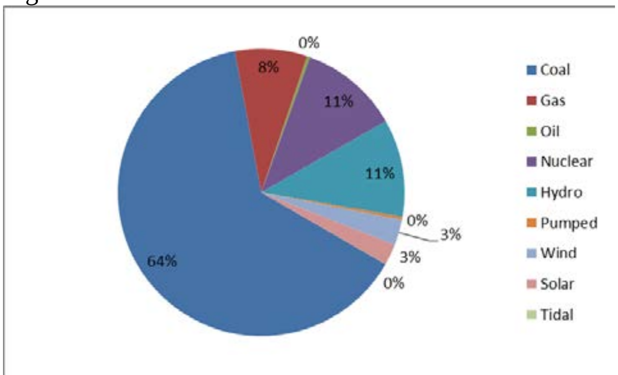

Fig. 1. Base case scenario (without CO_2 emission tax), non-interconnected power systems.

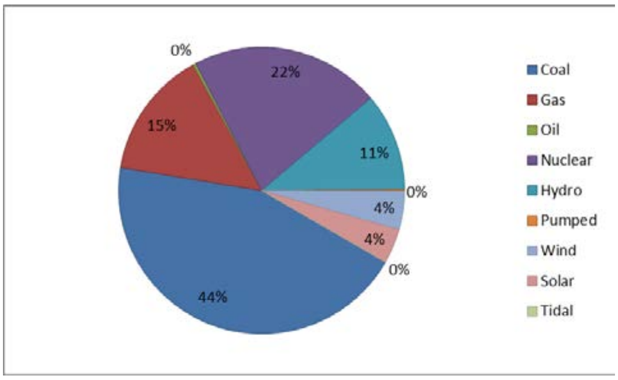

Fig. 2. Base case scenario, tax on CO_2 is equal to 60 **$/ton**, non-interconnected power systems.

The calculation of each scenario optimizes the additions of new capacities by type of power plants. Table 2 shows the additions of new capacity for four scenarios of non-interconnected power systems: the base case scenario and scenarios with the CO_2 taxes (30 **$/ton**, 40 **$/ton** and 60 **$/ton**).

Table 2. New capacities by fuel type, GW, non-interconnected power systems, scenarios with CO_2 taxes.

	Base case scenario (no taxes)	**30 $/ton**	**40 $/ton**	**60 $/ton**
Coal	385.21	312.15	286.94	243.74
Gas	29.65	45.53	56.45	24.52
Hydro	75.42	56.16	76.02	84.18
Pumped storage	90.29	87.40	2.20	7.04
Nuclear	70.69	132.80	217.53	217.89
Wind	0.23	0.23	0.23	91.20
Solar	0.19	0	0	122.66
Total	**651.68**	**634.27**	**639.37**	**845.86**

Table 3. New capacities by fuel type, GW, interconnection of power systems, scenarios with CO_2 taxes.

	Base case scenario (no taxes)	**30 $/ton**	**40 $/ton**	**60 $/ton**
Coal	380.71	302.23	255.09	243.74
Gas	4.02	22.49	19.78	24.52
Hydro	79.98	58.88	84.18	84.18
Pumped storage	90.29	85.20	0	7.04
Nuclear	38.15	104.33	217.89	217.89
Wind	0	0	0	91.20
Solar	0	0	0.97	122.66
Total	**593.15**	**573.13**	**577.91**	**791.23**

When the cost of the fuel increases, new coal capacity additions are reduced. First, this is due to increase in the new capacities of nuclear power plants, and in the last scenario, when the increase in capacities of nuclear power plants is not possible – this is due to increase in the new capacities of WPP and SPP. As a result, the addition of new capacities of wind and solar took place only in the scenario with increasing fuel costs, corresponding to the CO_2 emission tax to 60 **$/ton**.

Table 3 shows four other scenarios with the power interconnection in NEA. Due to the integration effect, the addition of new capacities decreased, but the trends in their capacity structure remained the same. There is still a tendency to reducing the addition of new coal-fired capacities in NEA ISPG, primarily due to the increase of new capacities of nuclear power plants, and then – WPP and SPP. In all scenarios, the savings in addition of new capacities due to interconnection are 7-10%, which confirms the integration effect for all scenarios.

3 Computational experiments taking into account the intermittence of the power output of wind and solar power plants

The specifics of optimizing the new capacities of wind and solar are the intermittence of their electric power output. The ORIRES model for all other types of power plants optimizes not only the addition of new capacities, but also their power generation, taking into account the daily electric load graph for each node (power system).

In the base case scenario, the profiles of daily power generation graphs of WPP and SPP in the model are fixed. The profile of the graphs of WPP and SPP in the solving process of the optimization problem does not change, but installed capacities can be optimized in a given range by minimizing the costs of the ISPG as a whole.

For WPP and SPP, utilization hours and power output configuration are not optimized. Due to this, the hourly distribution of power output of WPP and SPP for each calculation is set by a fixed graph.

It was necessary to find out how changes in utilization (operation) hours and configuration of daily power generation of WPP and SPP affect the solution of the optimization problem.

For this purpose, a number of computational experiments were carried out, in which the volume of the contribution of WPP and SPP to the total generation was varied, and the shape of their daily power generation graph was changed.

In these experiments, the graphs of electric load of WPP was changed for all electric power systems (EPS) of China for each of the four seasons of the year. Particularly, capacity factor of WPP is increased up to 40%. Previously, for different nodes, depending on the year seasons, the capacity factor of WPP was ranged from 12% to 35%.

As an example, the authors used the graph of electric load of WPP in Northeast and Center (NEC) of China, in the autumn season, in which the capacity factor of WPP was 18%, which corresponds to 4.3 utilization hours per day. For the experiment, this capacity factor of WPP was increased up to 40%, which corresponds to 9.6 utilization hours. Figures 3 and 4 show correspondingly the above noted graphs of electric load of WPP for the NEC of China (autumn), normalized to 1.

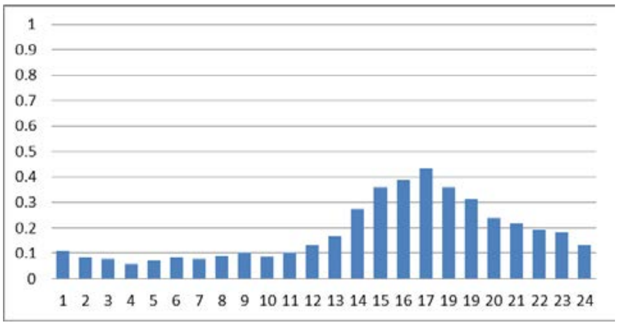

Fig. 3. Utilization hours of WPP are 4.3 (18% capacity factor), wind speed is 3-4 m/sec.

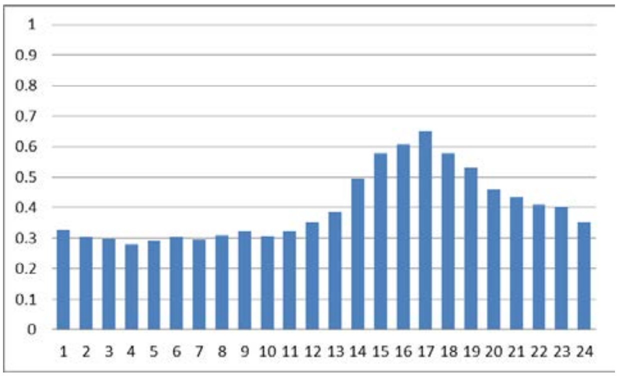

Fig. 4. Utilization hours of WPP are 9.6 (40% capacity factor), wind speed is 8-9 m/sec.

The second graph of the daily power generation of WPP differs from the first in that the area under it (reflecting generation for each of the 24 hours) corresponds to utilization (operating) hours is 9.6 per day, wind speed 8-9 m / sec. This is interpreted as an increase in the average total wind generation during the day.

It is quite obvious that all of this entailed changes in solving the optimization problem. Figure 5 shows the increase in the share of WPP electricity generation for the 2040 target year from 4% to 7% compared to the diagram in Figure 2. As a result, generation on non-renewable energy resources decreased.

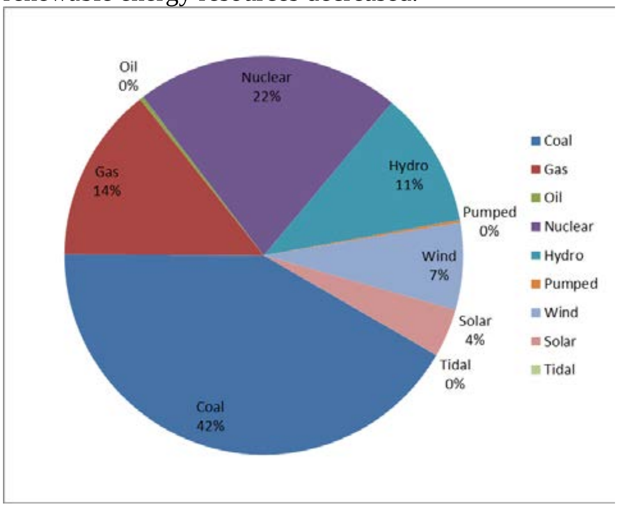

Fig. 5. Non-interconnected power systems, tax on CO_2 is equal to 60 **$/ton**. Wind speed is 8-9 m/sec.

Comparison of the diagrams in figures 2 and 5 shows significant changes in the structure of electricity generation for the target year. Generation can be calculated similarly if we assume that the power output of WPP is reduced. However, a change in the generation structure only leads to higher or lower costs for the fuel component of the annual balance, but does not change the structure and additions of new generating capacity.
Table 4 shows a comparison of the main indicators of two scenarios in which the CO_2 emission tax is 60 **$/ton**, and they differ from each other by the increased utilization (operating) hours for WPP in China power systems (the second one).

Table 4. Scenarios comparison: normal and increased utilization hours of WPP.

Name	Values of the objective function, $ Bln./year				Capacity, GW	
	power plant	fuel cost	elect ric ties	Total	Installe d	addition s
60$/t wind 3-4 m/sec	307.7	516.9	0.01	824	2 776	845.8
60$/t wind 8-9 m/sec	307.9	506.6	0.01	814	2 776	845.8
Result ing effect	**-0.2**	**10.3**	**0**	**10**	**0**	**0**

The cost of the fuel component of the objective function has decreased due to the greater share of generation at WPP. At the same time, the structure of addition of new capacities has not changed. As a result, with increasing utilization hours of WPP, the addition of new capacities will still not change.

To check the influence of the profile (configuration) of the graphs of electric load of WPP, the authors were carried out the additional calculations with a change in the hourly profile (configuration) of the graphs of the electric load of WPP, with the same numbers of utilization hours.

In the NEC of China, the peak of the maximum of the graph of electric load of WPP was assumed to move from evening hours to morning hours (see the article of L.N. Trofimov et al. "*The assessment of integration effects accounting the stochasticity of wind and solar power plants generation in the Asian Power Grid*" [10]).

At the same time, the number of utilization hours of WPP for all EPS of China was also increased to 9.6 hours (which is equal to 40% capacity factor). In addition to this, the authors carried out some calculations where the graphs of electric load of WPP were given in a stochastic manner, with the same number of utilization hours.

As a result, a series of experiments on changing the profiles (configuration) of graphs of the electric load of WPP, with the same utilization hours, showed that these changes practically do not affect the solution of the optimization problem.

The annual fuel costs of the objective function were changed within 0.1% - 0.2%. A much more important parameter is the average number of utilization hours (or capacity factor) of WPP for the total generation of the node.

4 Conclusions

The experiments carried out showed:

1. Changes in the average annual utilization hours of wind and solar power plants affect only the structure of electricity generation. This leads, respectively, to a decrease or increase in the consumption of fossil fuel in the target year. At the same time, the structure of the addition of new capacities remains unchanged.
2. The increase in the tax on CO_2 emissions will cause, first of all, the replacement of new capacities of coal-fired power plants with the new capacities of nuclear power plants. Only when the limit on their additions is exhausted, the addition of the new capacities of wind and solar power plants become profitable.
3. With the maximum increase in CO_2 tax, the share of installed wind and solar capacities will increase to 20%, compared to 10% in the basic scenarios (without the CO_2 emission taxes).

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Research and Outlook on Northeast Asian Energy Interconnection

Yi Gao[1,*], *Zhe Liu*[1], *Xinzhi Xu*[1], *Yanfen Guo*[1], *Jun Li*[1]

[1]Global Energy Interconnection Development and Cooperation Organization, Beijing, China

Abstract. Northeast Asia is the most developed region in Asia with large energy demand, and plays an important role in the global economic development. Northeast Asia has been facing severe challenges in ensuring energy security, protecting the environment, and coping with climate change, because of their high dependency on fossil fuels and imports of oil from outside the region, and inverse distribution between energy resources and demand. In order to actively respond to climate change, promote the transition to low-carbon energy and sustainable development in the region, achieve the grand purpose of economic prosperity, social progress and ecological protection, this study is conducted with a focus on power grid interconnection in Northeast Asia. Based on the historical energy and power data in Northeast Asia, this paper studies the development trends of energy and power demand in future by combining qualitative and quantitative methods. Considering the distribution of clean energy bases, this paper proposes an energy interconnection scheme in Northeast Asia with high clear energy penetration scenario. To form the Asia-Europe energy interconnection, the construction of the Asia-Europe interconnection channels is briefly analyzed in this paper.

1 Research background

Northeast Asia consists of seven main parts in six countries, namely, the Russian Far East, Northeast China, North China, Mongolia, the Democratic People's Republic of Korea (DPRK), the Republic of Korea (ROK). It is the most economically and culturally developed region in Asia and also one of the regions in the world top in economic vitality and energy demand. By 2017, the GDP of the six countries in Northeast Asia reached 20.3 trillion USD with an average annual growth rate of 5.1%. It accounted for about 25% of the world total. The GDP of China and Japan was 12 trillion USD and 4.9 trillion USD, respectively, making them the world's second and third largest economies. With the continuous development of regional bilateral and multilateral cooperation, Northeast Asia is ushering in new opportunities for sustainable development.

Energy is an important material basis for economic and social development. The total primary energy demand in Northeast Asia increased from 1.7 billion tonnes of standard coal equivalent (tce) in 2000 to 2.99 billion tce in 2017, with an average annual growth rate of 3.4%. Large consumption of fossil fuels leads to a series of severe problems such as a shortage in fossil resources, environmental pollution, climate change and health issues. It is a key factor in triggering the challenge of regional sustainable development. The essense to meet these challenges and pursue sustainable development is to promote clean development. In energy sector, it is necessary to promote "clean replacement" in energy development, replacing fossil fuels with clean alternatives such as solar, wind and hydro power, and "electricity replacement" in energy consumption, replacing coal, oil and natural gas with electricity[1].

Clean energy resources in Northeast Asia are rich, but unevenly distributed. The wind energy in Northeast Asia is relatively rich with a theoretical potential of approximately 162 PWh/year. At a height of 100 m from the ground, wind speed ranges from 2 m/s to 12 m/s [2]. There are several areas with wind speed exceeding 7 m/s throughout the year, mainly in southern Mongolia, northern China and the Russian Far East. Solar energy resources in Northeast Asia are also abundant. The theoretical potential is 9189 PWh/year. The global horizontal irradiance (GHI) in Northeast Asia ranges between 600 kWh/m^2 and 1800 kWh/m^2 [3]. The regions with GHI exceeding 1500 kWh/m^2 include mainly southwestern Mongolia and parts of northern China. The hydropower resources in Northeast Asia are mainly distributed in the Lena and the Amur River Basins, with a technical potential of about 40 GW and 14.5 GW, respectively. Currently, about 10% of the hydropower potential has been exploited [4].

* Corresponding author: gao-yi@geidco.org

In general, regional renewable energy resources are mainly concentrated in the Far East of Russia, Mongolia and the Northeast & North China, while the main energy consumption centers are mainly located in Japan, ROK and North China. The distribution of regional energy resources and demand centers is unbalanced. Cross-border allocation of clean energy resources is one of the effective ways to improve the balance of regional energy supply and demand. Renewable energy generation outputs are intermittent, and the most efficient development and utilization way is to convert them into electricity on the site and integrated into the power grid. A wide range of interconnected power transmission network in the Northeast Asia will provide a platform for large-scale development, wide-range transmission and efficient utilization of renewable energy. The construction of the power grid interconnection in Northeast Asia has been widely concerned by many studies [5-12].

Under the overall research framework of the Global Energy Interconnection (GEI), and considering the research on the climate change, energy and power, this paper studies the development trends of power demand in future, and analyzes a development scheme in the region with energy mix dominated by clean energy to achieve the 2℃ temperature control target of *Paris Agreement*. According to the development characteristics and clean energy resources endowment in Northeast Asia, the overall pattern of energy interconnection in Northeast Asia and relative cross-border transmission projects are proposed in this paper. In addition, this paper briefly analyzes the possible connection channel between Asia and Europe in the future based on the formation of Northeast Asian Energy Interconnection.

2 Study platform and methods

This study mainly focuses on the integrated and coordinated planning of energy and power sectors to carry out unified prediction and research. The overall framework of Global Energy Interconnection comprehensive study platform is shown in Figure 1.

In the platform, there are two key factors connecting the three fields of climate, energy and power. One is the energy emission related to climate and energy, and the other is energy converted to electricity. Based on these connection factors, the energy and power forecast results are optimized as the boundary conditions of each other, and the development trend of energy and power is predicted.

For energy demand study, "top-down" method is used to analyze the influence of economic development on energy demand from macro to micro. On the other side, "bottom-up" method is used to analyze the impact of technology progress, efficiency improvement, environmental constraints, energy policies and other factors on energy demand from micro to macro. Then, the future energy mix and energy consumption intensity are studied. The regional primary energy demand is finally analyzed by considering the future energy and power demand and the efficiency of power generation, heating, oil refining and other conversion processes.

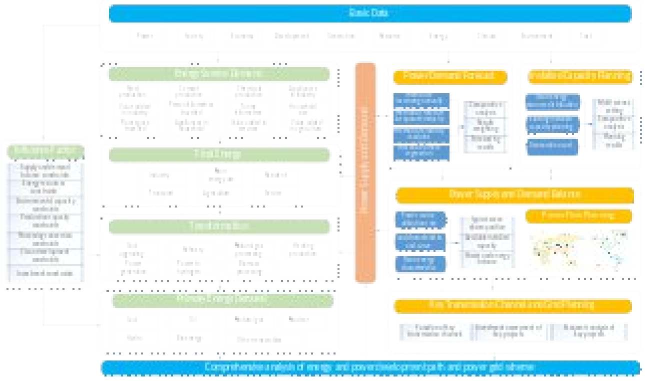


Fig. 1. Comprehensive study platform for energy and power analysis of GEI

For power demand research, the result of power demand in final energy demand obtained in previous stage is taken as a boundary condition. More analysis algorithms such as the power elasticity coefficient algorithm, the electricity consumption per capita algorithm, industry analysis method and the regression method are preferentially selected. A comprehensive load prediction results are finally calculated by weighting the prediction results under different analysis methods [13].

For power generation planning, the objective function is the minimization of total social cost including construction, operation and maintenance and fuel costs during the planning period, and constructing problems on optimization based on environmental constraints, energy resources, and power balance and to solve the planned annual power generation installed capacity, various types of installed components, timing of development, carbon emissions, etc.

On the basis of power demand forecast and power generation planning analysis, the balance analysis of power supply and demand is carried out to evaluate regional power exchange potential. Then, the network frame planning of key channels is conducted and the function of cross-border transmission channel are evaluated. Finally, the relative key projects are proposed and the investment and benefit estimation of key projects are studied.

3 Energy and power outlook for Northeast Asia

3.1. Energy demand

In a long run, the primary energy demand in Northeast Asia will first maintain flat and then slowly decline. Calculated by the partial substitution method, from 2017 to 2035, the total demand in Northeast Asia will maintain at around 3 billion tce and reach a peak of about 3.05 billion tce in 2025. After 2035, the total demand in Northeast Asia will begin to slowly decline. The demand will fall to 2.91 billion tce in 2050, seeing a 3% decrease from 2017. The per capita demand in Northeast Asia will be expected to increase from 5 tce in 2017 to 5.1 tce in 2050. The forecast of primary energy demand in Northeast Asia is shown in Figure 2.

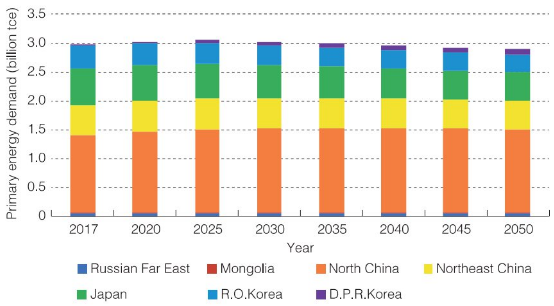


Fig. 2. Primary energy demand in Northeast Asia

From 2017 to 2025, the coal and oil demands in Northeast Asia will steadily decline, with average annual decrease rate of 2% and 1.4%. The reduction in coal demand will be mainly contributed from North China, and the reduction in oil demand will be mainly contributed from Japan and the R.O.Korea. From 2025 to 2050, the declining rate of coal and oil demands will climb to 4.6% and 2.6%, respectively, and the demand in 2050 will reach 450 million tce and 320 million tce which are about 75% and 55% lower than the 2017 levels. The natural gas demand will reach a peak of about 370 million tce in around 2035, and then drop to 290 million tce in 2050, similar to the 2017 level. The demand of renewable energy such as wind and solar energy will rapidly expand with an average annual growth rate of 8%, and reach 1.36 billion tce by 2050, accounting for 51% of the total primary energy. The energy demand by fuel in Northeast Asia is shown in Figure 3.

The final energy consumption in Northeast Asia will gradually decline and the rate will accelerate after 2025. From 2017 to 2025, the final energy consumption in Northeast Asia will slowly decline from 2.11 billion tce to 2.08 billion tce, with an average annual decrease rate of 0.2%. The rate will accelerate after 2025, making the consumption reach 1.73 billion tce in 2050. It is estimated in around 2030, electricity will overtake coal and have the highest share in the final energy.

3.2 Power demand

It's estimated that the power demand in the region will continue to grow. By 2025, 2035 and 2050, the electricity consumption in Northeast Asia will reach 4.5 PWh, 5.5 PWh and 6.4 PWh, respectively. The electricity consumption in 2050 will be doubled compared with that in 2017. The annual growth rate of electricity consumption in Northeast Asia will be about 3.7% from 2017 to 2025, 2% from 2026 to 2035, and 1% from 2036 to 2050.

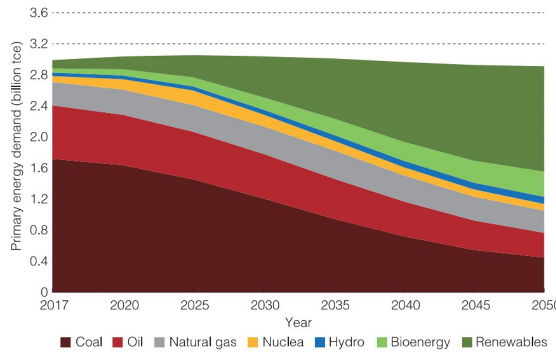


Fig. 3. Primary energy demand by fuel in Northeast Asia

North China, Northeast China, Japan and the R.O.Korea will be the major power consumers in Northeast Asia. In 2050, the electricity consumption of North China and Northeast China will be 3200 TWh and 844.9 TWh, respectively, accounting for 50% and 13% of that in Northeast Asia. The electricity consumption in Japan will reach about 1300 TWh, accounting for 21% of that in Northeast Asia. The number will be 726 TWh in the R.O.Korea, accounting for 11% of that in the region. The D.P.R.Korea and Mongolia will consume about 184 TWh and 31.9 TWh, respectively. The power consumption in the Russian Far East will reach 88 TWh. The proportion of electricity consumption in Northeast Asia is shown in Figure 4.

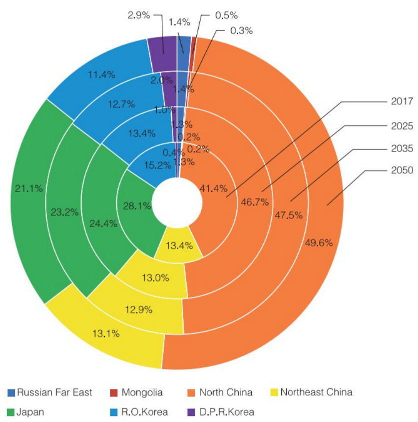


Fig. 4. Share of electricity consumption in Northeast Asia

This paper analyzes the power demand brought by electric vehicles (EVs) in the future. For passenger EVs, the development scale of passenger EV ownership is predicted through the population, per capita car ownership and proportion of EVs in the total passenger vehicles. For freight EVs, there is a close relationship between the GDP and the freight turnover in a country or a region. Therefore, the total freight turnover is predicted by assuming the total road freight turnover in the future will share the same growth rate with the GDP. For example, by 2015, the total number of passenger vehicles in North China and Northeast China was approximately 54.84 million, of which EVs accounted for 0.29%. The per capita car ownership was about 0.14, and the average annual mileage was between 8000 km and 16000 km. It is estimated that by 2050, the per capita car ownership in North China and Northeast China will be 0.52 and 0.48 respectively, and the total number of passenger vehicles will reach 229 million. The proportion of EVs will increase to 40%-60%, and thus, the annual electricity consumption for passenger EV will be 182.8- 274.2 TWh. By 2015, the total turnover of the road freight in North China and Northeast China was 4615.7 billion t-km. It is estimated that by 2050, the electrification ratio of the road freight in North China and Northeast China will reach 30%-50%, and thus, the annual electricity consumption for freight EVs will be 300.7-501.2 TWh.

3.3 Power supply

Based on the model of optimal planning for power generation installed capacity, the total installed capacities in 2025, 2035 and 2050 are expected to reach 1.44 TW, 2.05 TW and 2.89 TW, respectively, and the increment will be 44%, 42% and 41% during 2017~2025, 2026~2035 and 2036~2050, respectively. The outlook for power generation installed capacity in Northeast Asia is shown in Figure 5.

With the rapid development of clean energy generation technology, the competitiveness of clean energy power generation will be significantly enhanced. The average levelized cost of electricity (LCOE) of centralized on-shore wind power and photovoltaic (PV) is expected to fall to 2.4 US cents/kWh and 1.4 US cents/kWh by 2050, respectively. By 2035, the proportion of clean energy will surpass that of fossil energy and become the dominant power source. The installed capacity of clean energy in Northeast Asia in 2025, 2035 and 2050 will reach 0.67 TW, 1.41 TW and 2.43 TW respectively, accounting for 47%, 69% and 84% of total installed capacity in Northeast Asia.

4 Power grid interconnection

According to the natural endowment and spatial distribution of clean energy resources in Northeast Asia, and with reference to the energy and power development plans of various countries, clean energy and power grids development require to be coordinated so as to accelerate the upgrading of national and regional power grids. Relying on advanced transmission technologies such as UHV, Northeast Asia should give full play to the regional advantages and promote the interconnection of power grids, to form a strong grid that covers clean energy bases and load centers.

Considering the power generation development, power demand distribution and the distribution of clean energy in Northeast Asia, based on the power balance analysis, North China, Japan, the R.O.Korea and the D.P.R.Korea will become the main power receiving centers. The large-scale hydro, wind and solar power plants in the Russian Far East and Mongolia will not only supply the domestic power demands but also become the main power exporting bases. The overall power flow pattern in Northeast Asia will be "West to East, North to South". The cross-border power flow within Northeast Asia will be 11.75 GW, 59.75 GW, 110 GW by 2025, 2035 and 2050, respectively.

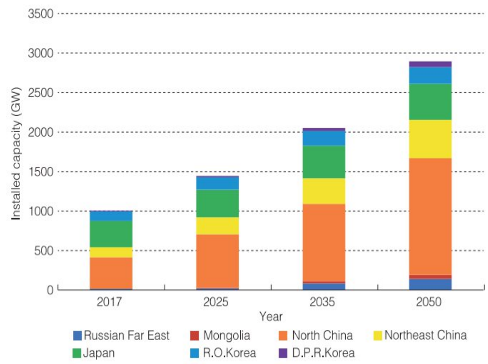


Fig. 5. Power generation installed capacity in Northeast Asia

With the development of the power grids and the large clean energy bases in Northeast Asia, through the construction of multi-directional cross-border transmission channels, clean energy electricity can be transmitted to load centers by multiple directions. A "three-ring and one-line" energy interconnection pattern will be formed by 2050, illustrated in Figure 6.

Fig. 6. Overall pattern for power grid interconnection in Northeast Asia

This interconnection mainly includes five corridors, namely, Mongolia - China - R.O.Korea - Japan, China - Russia, Russia - Japan, China - D.P.R.Korea - R.O.Korea and Russia - D.P.R.Korea - R.O.Korea. In the north, these corridors will connect the hydropower of the Russian Far East and the wind power in Okhotsk Sea and Sakhalin; in the west, they will connect the wind power in North China and Northeast China, as well as the solar and wind power in the Southern Mongolia; in the center, they will connect the load centers in North China, the R.O.Korea and Japan.

In order to construct the power grid interconnection in Northeast Asia, a large number of cross-border transmission projects are proposed and illustrated in Figure 7.

Fig. 7. Cross-border transmission projects in Northeast Asia

Northeast Asia is the most developed region in Asia with large energy demand. The Northeast Asian Energy Interconnection will play an important role in optimally allocate the energy resources and efficiently use the clean energy, deliver the sustainable development of the economy, society and environment in Asia, and promote the overall development of Asian Energy Interconnection.

5 Asia-Europe interconnection channel prelimary analysis

Asia is geographically connected to the Europe. Asia-Europe energy interconnection is an essential corner stone for realizing power grid interconnection between the two continents. According to the GEI research [14], the Asia-Europe connectivity channel includes the north and the south, as shown in the Figure 8.

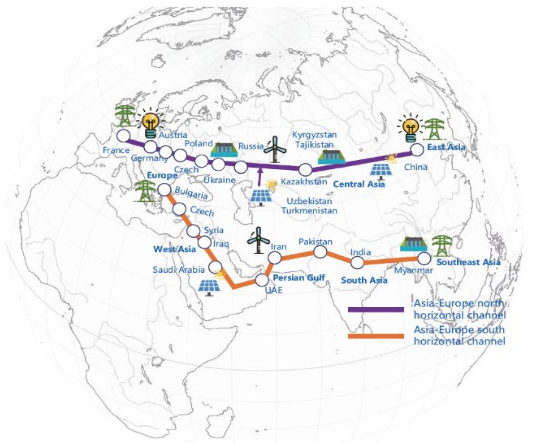
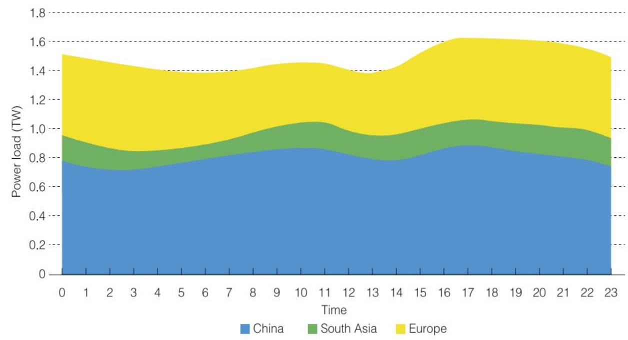


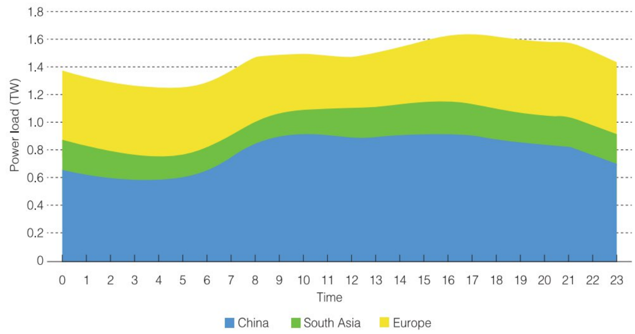
Fig. 8. Asia-Europe interconnection channels

Asia−Europe north horizontal channel will interconnect countries such as China, Kazakhstan, Germany, France, and deliver clean energy from Central Asia to Europe and China. Together with the UHV backbone grid of China, clean energy will be further delivered to Northeast Asia to provide inter-continental power support. The channel length will be about 10000 km. Asia−Europe south horizontal channel will interconnect Southeast Asia, South Asia, West Asia and Southern Europe, and deliver solar power from the West Asia to load centers in Southeast Europe and South Asia through the UHV DC projects. The channel will also deliver hydropower from Southeast Asia and China to South Asia. The channel length will be about 9000 km.

Asia−Europe interconnection channels will bring the benefits of different resources, time zones and seasons. For example in China, South Asia and Europe, with a 7-hour time difference at most, it will result in a diurnal load complementarity. The inter-regional and cross-border interconnection will also increase the system regulation capabilities. As shown in Figure 9, peak loads in China and South Asia are at noon in summer, and peak loads of Europe are in the evening during winter. The complementarity provided by grid interconnection between China, South Asia and Europe can reduce the peak-valley load gap by 30%−40%.



(a) Winter



(b) Summer

Fig. 9. Typical load curves for China, South Asia and Europe

6 Conclusions

Under the research framework of GEI, this paper analyzes the development of energy and power in Northeast Asia in the medium and long term according to the large-scale clean energy development scenario. The study results show that the primary energy demand in Northeast Asia will reach a peak of about 3.05 billion tce in 2025, and then slowly decline. The demand will fall to 2.91 billion tce in 2050, seeing a 3% decrease from 2017. With the improvement of electricity replacement level in energy consumption, by 2025, 2035 and 2050, the electricity consumption in Northeast Asia will reach 4.5 PWh, 5.5 PWh and 6.4 PWh, respectively. The electricity consumption in 2050 will be doubled compared with that in 2017. With the rapid decreasing of clean energy power generation cost, clean energy generation will become the dominant power source by 2035. The installed capacity of clean energy in Northeast Asia in 2025, 2035 and 2050 will reach to 0.67 TW, 1.41 TW and 2.43 TW respectively, accounting for 47%, 69% and 84% of total installed capacity in Northeast Asia. With reinforcing power grid interconnection between countries, a "three-ring and one-line" energy interconnection pattern will be formed by 2050 in the region. Sustainable economic, social and environmental development in Northeast Asia are expected to be promoted. Significant benefits obtained by different time zones and seasons will be achieved through the establishment of north and south interconnection channels between Asia and Europe, which will be a foundation for building the GEI.

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Features of the Mongolian Electricity Market

Bat-Ochir Batzaya[1,*] and *Choijiljav*[1]

[1] MUST, Electrical Engineering Department, Mongolia

Abstract. Energy is one of the basic sectors of the country's development. It is closely related with all sectors of the economy, providing the possibility of their stable development including mining, manufacturing, agriculture, transport, communications and others.

Keywords. Model single buyer, energy, electricity market.

1. Introduction

There are many different electricity market designs in use around the world. Each component of the market design is described briefly below [1,2,3].

Monopoly Model. Monopoly at all levels. One entity may have responsibility for all functions, or the distribution companies may be separate bodies from the generation and transmission entity. This model was in common use around the World prior to the introduction of Independent Power Projects.

Single Buyer Model. A single wholesale buyer of electricity can choose from a number of different generators encouraging competition in generation. Access to the transmission system is not permitted for sales to final consumers. The single buyer model was in common use around the World following the introduction of IPPs.

Wholesale Competition Model. Wholesale buyers (distribution companies and in some cases, large customers directly connected to the transmission networks) can choose their supplier, bringing competition into generation and wholesale supply. This requires open access to the transmission system. Distribution companies maintain a monopoly over retail consumers.

Retail Competition Model. All customers can choose their supplier. This requires open access to the transmission system and distribution systems. The distribution activity can be separated into wires (asset management) and retail, or supply, activities, with the latter being competitive.

Electricity market in Mongolia

Electricity is the primary industry that affects economic development and competitiveness. Each country, by virtue of its specifics, with respect to its geographical location, natural resources and economic potential, develops an energy policy and determines its own market model.

The energy sector of Mongolia consists of four independent electric power systems:

- Central Energy System (CES),
- Western Energy System (WES),
- Eastern Energy System (EES),
- Altai-Uliastai energy system (AUES).

The main Mongolian electric system is the CES representing 80% of all Mongolian electricity supply [4,5].

Energy production, before reaching the end user, passes through multiple stages, which includes, in particular, the extraction, transportation and storage of raw materials, the conversion of primary reserve energy into the electric heat, transmission of generated electricity via high voltage lines and their transformation for distribution according to the specific needs of the user. At each of these stages, it is possible to introduce competition mechanisms, from which such a variety of market models derive.

Since the crisis in the basic sector of the economy had reached a level that could have the most negative impact on the entire course of economic reforms, significant adjustments were made to the state energy policy in 2001. The “Energy Law” was re-adopted and structural changes were made in the industry. The cornerstone of these structural changes was the issue of transferring the functions of energy regulation to an independent institution [6]. Important was the realization of economic management methods at enterprises, and support of the private sector for developing profitable small-scale systems, which became possible due to the undertaking of the following concrete measures:

- resolution of credit and debt problems of enterprises involved in fuel and energy production;
- intensification of work on collecting underpayments from consumers and making changes to the system;
- decrease in technical and commercial losses during the transmission and provision of electric energy;
- changes in price and tariff structures, establishment of fully self-sustaining prices and tariffs;
- reducing the volume of electricity imports and improving the management of external debt.

As for the regulation of the energy market, it is under the control of the Energy Regulatory Committee, the National Dispatch, and the Metropolitan Energy Regulatory Council.

* Corresponding author: z_zaya12@mail.ru

The National Central Dispatch Center plays the role of coordination by providing integrated technological management of the entire energy market.

As for economic issues, the Energy Regulatory Committee resolves them, including those related to the participation of economic organizations in the market relations, as well as matters on prices and tariffs for energy-bearing and other regulated services, and questions about the standards for consumer services.

According to this model, payments made to consumers are accumulated in a bank single income account with a zero balance (figure 1). Moreover, on the same day, according to a coefficient determined by the Energy Regulatory Committee, it is distributed to the accounts of the generating company, as well as transmission and distribution companies. This mechanism creates the fairest basis for the distribution of income between all participants in the energy business, since the specific costs of each company are taken into account depending on forecasts for production and consumption [7,8].

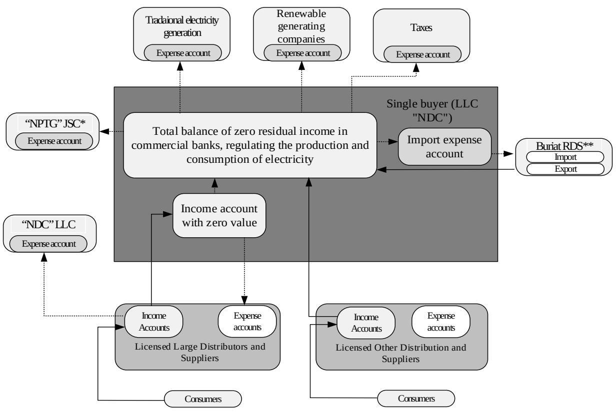

Fig. 1. Cash flow the models "Single Bayer"
* National Power Transmission Grid, ******Regional Dispatch Services

Problems of the Single Buyer model. It is clear that the Single Buyer model implemented in Mongolia, apart from relying on central planning for decision making, is not suitable for introducing competition and does not promote accountability of the electric companies for complying with their obligations and operate efficiently in the long run. For instance, the payments to the Gencos depend on the amounts collected by the Discos, which are consistently below the amounts due. In fact, some of the electric utilities that we have interviewed have the same opinion regarding the need to abandon the Single Buyer model. It is certain that a market structure based on bilateral supply contracts is more suitable for evolving to a competitive market.

Advantages of competitive markets: Competitive markets substitute central planning and price regulations by competitive forces that foster decentralization, efficiency in operation and development and accountability of the agents. The existence of unregulated supply prices, in a competitive environment, guaranty that sellers and buyers will always agree on prices and supply conditions that will allow the development of the most efficient power plants required by the market. The world experience has shown that competitive structures, if well designed, can be applied both in large and in small electric system [9].

Conclusion

For improving the efficiency of the energy sector, it is important to continue liberalization policies and ensure the mirror openness. Although the model with a "Single Bayer" is being implemented quite successfully, the overall performance of the industry is improving at a relatively slow pace.

Retail competition is far too costly and carries a significant risk at this time in Mongolia. Wholesale competition is the favored market model as it provides a reasonable balance of the objectives of the market reform effort with reasonable cost and risk while maintaining the flexibility to move to retail competition if and when it is desirable in the future.

In the articles [10,11] the proposed pricing mechanism generates four component electricity prices that relates to an annual average power, deviation from the seasonal average power, electric power deviations from the weekly and daily respective averages. The number of component prices can be either increased or decreased depending on the desired accuracy or other purposes.

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State Patronage on Heat and Electricity Markets of the Russian Far East

Olga Dyomina[1,*], and *Svetlana* Naiden[1]

[1]Economic Research Institute of Far Eastern Branch of the Russian Academy of Sciences, Khabarovsk, Russia

Abstract. The paper examines the conditions and goals of state patronage on heat and electricity markets of the Russian Far East. The distinct characteristic of market organization in the region is the lack of a unified energy system, high share of districts with decentralized energy supply, and segmentation of the electricity market. Based on the technological and institutional similarities, scale and form of state patronage, three zones of electricity market were established: market, semi-market, and regulated. The forms of state patronage on heat and electricity markets of the Far East are the following: state regulation of heat and electricity tariffs, setting the tariffs below actual costs, subsidies for providers and consumers of energy, state-sponsored construction of energy capacities. The paper evaluated the scale of patronage on heat and electricity markets and reached the conclusion that without state patronage the Far Eastern consumers of heat and electricity will not be able to purchase energy in market conditions.

1 Conditions for state patronage on heat and electricity markets

Perfect competition is traditionally viewed as an idealized – and unattainable – model of a market [1]. The extreme case is monopoly, including natural monopoly, that generates the conflict between economic efficiency and competition, where the increasing number of sellers is accompanied by losses due to the lack of economies of scale. The typical examples of natural monopoly are public utilities sphere (electricity, heat, and water supply, etc.), transportation (railways), where the element of monopoly is concentrated in the network [2, 3]. For a long time, the most acceptable market model for heat and electricity markets was regulated monopoly [4-8]. In this case, state patronage was aimed at containing consumer prices. The idea was that the prices should be as close as possible to the level of marginal costs or provide only normal profit. The fact that energy capacities were owned by the state was an additional argument for state patronage, which allowed substituting external control with internal.

From the end of 1980s there is an active search of state regulation methods that allow for competition, differentiation of state control forms, and partial privatization in the naturally monopolistic sphere. A new paradigm – market-oriented state regulation – was developed as a transition from direct control over monopolies to regulating their behavior on industry markets. It covers expansion of anti-monopoly regulation to all industries, removal of vertical integration barriers, and clarification of pricing mechanisms. The goal of these measures is creation of the market structure and the mechanism that would allow for competition [9].

This is the way that Russia follows, starting from electricity reform in the beginning of 2000s, and heat supply market reform in 2017 [10]. The main goal of Russian reforms is liberalization of market conditions and elimination of direct state patronage. However, for the Far East[a] – the region with harsh climate conditions, a unique system of spatial distribution of economic activity, extremely uneven population density – the state regulation of heat and electricity markets remains. The latter is caused by technical limitations of the local energy system and the impossibility of fostering competition.

2 State regulation of energy markets

The peculiarity of the Russian Far East is the lack of prospects of creating a unified energy system. About 40% of the territories do not have a centralized energy supply systems, primarily remote districts isolated from the electrical and sometimes transport infrastructures of the country. Most energy companies of the region remain vertically integrated and continue functioning as part of the traditional system with state regulation of expenses and tariffs.

Centralized energy supply of the Far Eastern consumers is carried out by the following energy systems:

[a] Now and then the Far East is considered to be Far Eastern Federal District (FEFD)

* Corresponding author: demina@ecrin.ru

– unified energy system of Siberia (UES Siberia), which includes Republics of Buryatia and Transbaikal Krai;
– unified energy system of the East (UES East), which covers Primorsky Krai, Khabarovsk Krai, Amur Oblast, Jewish Autonomous Oblast, and Sakha Republic (Yakutia);
– four technologically isolated energy systems: Sakhalin Oblast, Magadan Oblast, Kamchatka Krai, Chukotka Autonomous Okrug.

The similarity of technological characteristics and institutional conditions of energy market organization in the Far East allows classifying them as a market zone (UES Siberia), a semi-market zone (UES East) and a regulated zone (the four isolated systems). Each zone differs in scale and forms of state patronage.

Unlike electricity supply, centralized systems of heat supply work in individual localities (seldom a large city can have several heat supply systems). The organization of heat supply systems in the Far East largely resembles the one in the rest of the country. The uniqueness is in the low level of energy capacity utilization, complicated logistics, and high costs of delivering fuel into remote and hard to reach parts of the Far East. As a result, economically justified tariffs in some parts turn out to be quite high.

The state patronage on energy supply markets takes different forms:
– state regulation of electricity and heat energy tariffs,
– setting the tariffs bellow actual costs,
– subsidies for producers and consumers,
– state funding for construction of energy facilities (Table 1).

Table 1. Forms of state patronage in the Far East

UES Siberia (market)	UES East (semi-market)	Isolated energy systems (regulated)
Preferential tariffs below economically sound for supplying heat and electrical energy to the general population		
-	Preferential tariffs on electricity for industrial-scale consumers only in Sakha Republic (Yakutia)	Preferential tariffs on electricity for industrial-scale consumers
Subsidized fuel delivery for energy producers as part of the “Northern supply” in remote and hard to reach parts of the Far East		
-	State-sponsored construction of energy supply facilities	

Semi-market and market zones have elevated costs on energy production, which influences higher prices for consumers. Economic availability of electrical and heat energy for the general population is ensured by setting preferential tariffs below actual costs. It is especially obvious in the de-centralized zone.

For example, population of Khabarovsk Krai pays about 14.4% of the electricity cost, population of Transbaikal Krai – 5%. The difference is reimbursed by the state through subsidies for producers. This increases the burden on regional budgets. In 2019 the whole of the Far Eastern Federal District (FEFD) saw more than 82 billion rubles spent on subsidies of electricity and heat tariffs, which constituted 8% of total expenses of all budgets. The regions with the highest costs on electricity (Chukotka Autonomous Okrug, Magadan Oblast, Kamchatka Krai, and Sakha Republic (Yakutia)) also have the highest expenses on reimbursing the tariffs (between 9% and 17% of budget expenses). However, despite this support the tariffs on electricity in the Far East are 13% higher than the country average and twice as high in Chukotka Autonomous Okrug [11].

To ensure the competitiveness of the Far Eastern producers the state introduced a new form of support for the industrial consumers in 2017: subsidies to equalize the tariffs with the average “basic” level in the country. The basic tariff is calculated as the weighted average price of electricity on the markets of other Russian regions excluding isolated parts where energy is more expensive. Since now the consumers in the FEFD pay only the “basic” tariff for electricity, which is lower than the actual costs, the Government of Russia establishes the monetary value of reimbursing the income that energy suppliers in the region did not receive. Annually the Government sets the increase on energy prices for all consumers in the European Russia, the Urals and Siberia to accumulate the necessary means [12]. The Far Eastern energy companies receive compensation through Far Eastern budgets. In 2017-2018 alone, the non-refundable earmarked contributions of “RusHydro” into Far Eastern budgets comprised 59 billion rubles. The volume of subsidies in 2017-2020 is estimated at almost 130 billion rubles. Since no changes into regulation of market conditions are expected in the immediate future, this support measure (expected to be prolonged till 2028) in the authors’ opinion will become another regular form of state patronage of Far Eastern consumers [13].

The principles of tariff regulation acting in non-price zone of the Far East do not include the returns on investments, unlike in other parts of Russia where making contracts on providing capacities is the norm. Main energy facility constructions are sponsored by the state: as part of target programs or through purchasing additional stock shares of the main operator “RusHydro”.

The Far East has seen the construction of 4 electrical energy supply facilities in 2016-2020: the second stage of Blagoveshchenskoj CHP plant (2016), the first stage of Yakutskoj GRES-2 (2017), Sahalinskaya GRES-2 (2019) and a CHP plant in Sovetskaya Gavan’ (launching in 2020). The funds were provided by the federal budget, 50 billion rubles of which were transferred by the government into the authorized capital of “RusHydro”. The modernization of existing and construction of new CHPs in the Far East until 2026 is too planned to be funded by the subsidies, which will be sponsored by the increase of prices on wholesale energy markets of Russia. The following constructions are planned: Khabarovskaja CHP-4, Yakutskaja GRES-2 (second stage), Artyomovskaja CHP-2, and the modernization of the Vladivostokskaja CHP-2. The total volume of investments is estimated at 171.2 billion rubles, which would increase the burden on the consumers of the unified country-wide energy systems by about 29 billion rubles. As a result, the expenses on electricity carried by the consumers of price zones of Russia who fund the subsidization of Far Eastern tariffs will increase 3-4% [12].

According to the current rules, subsidies distributed thanks to the new increase do not directly decrease electricity prices for consumers, the share of which in the consumption in the FEFD constitutes 20%. The state uses different measures to support population.

3 The scale of state patronage of consumers' expenses on public utilities

For population the state controls the growth of tariffs by annually setting the maximal level of their increase and keeping the level of reimbursement costs below the expenses on production for public utilities, including energy supply.

The level of reimbursement of public utilities costs in 2019 was 92.3% of established tariffs on average, ranging from the minimal level in Chukotka Autonomous Okrug (56.3%) to the maximal level in Republics of Buryatia, Transbaikal Krai, Primorskiy Krai, and Amur Oblast (100%) (Table 2).

Table 2. Formatting The established level of reimbursement of expenses on public utilities by the population, %

	Directly to resource suppliers	Through management companies
Republics of Buryatia	100.0	100.0
Sakha Republic (Yakutia)	31.4	73.3
Transbaikal Krai	71.1	99.9
Kamchatka Krai	49.2	90.8
Primorsky Krai	76.1	100.0
Khabarovsk Krai	82.3	99.4
Amur Oblast	88.3	99.9
Magadan Oblast	52.8	97.5
Sakhalin Oblast	63.7	99.2
Jewish Autonomous Oblast	97.5	95.8
Chukotka Autonomous Okrug	15.0	56.3

By encouraging the general population to conclude contracts directly with resource supplying companies, bypassing management companies, the state decreased the level of expense reimbursement of public utilities: to 63.1% in general in the Far East, ranging from minimal in Chukotka Autonomous Okrug (15.0%) to maximal in Republics of Buryatia (100%)

The compensation of difference between established expenses of the population and the actual costs carried by the providers of the utilities (according to economically sound tariffs) rests on the FEFD budgets, which is an additional burden for them.

The regions, for which the state sets a lower level of reimbursement, include the isolated energy systems (Kamchatka Krai, Magadan Oblast, Sakhalin Oblast, Chukotka Autonomous Okrug) and part of UES East (namely, Sakha Republic (Yakutia)). These parts of the FEFD have the highest expenses on generating electricity and heat energy, which is explained by high fuel costs and its delivery to remote districts. Besides, these regions have low population density and unequal distribution of local economic activity, which decreases the utilization of energy capacities significantly and increases the costs of maintaining the infrastructure. Thus, despite keeping the growth of tariffs in check (in 2019 the increment was 4.8% compared to 2018 level) there is a significant difference in prices on public utilities for population among the FEFD subjects. Even with lower reimbursement level the heat prices range from 1380 rubles per Gcal in Transbaikal Krai to 3805 rubles per Gcal in Kamchatka Krai; electricity prices range from 283 rubles per 100 kWh in Republics of Buryatia to 589 rubles per 100 kWh in Chukotka Autonomous Okrug. Considering limited opportunities for population income growth, especially in remote and economically depressive parts of the Far East, this creates an additional burden on household budgets.

Through the policy of social support in the Far East, the state continues to patronize the population, maintaining the privileges for certain population categories and paying allowance to low-income families. Taking into account the newly attached to the FEFD territories, (Republics of Buryatia and Transbaikal Krai in 2017-2019 the state spent more than 75.6 billion rubles on compensating the costs of public utilities (16.6 billion on subsidies and 59.1 billion on reimbursing privileges). The compensation of electricity and heat supply took about 49.4 billion rubles or 65.2%.

But even with lower tariffs and taking into estimation the subsidies and privileges, the burden on households is higher than the national average values: 10.5% against 9.6%. For isolated regions, the share of expenses on public utilities is even higher: it is 15% of all consumer expenses in Kamchatka Krai, 14% in Magadan Oblast, 12.6% in Chukotka Autonomous Okrug. And the main share in these expenses is the cost of heat and electricity, which comprises 75-80% of public utilities costs for northern parts of the region.

It is especially important for the Far East since 15.7% of its population is considered poor. Sakhalin Oblast has 9.6% of the population with incomes below the living wage, while Transbaikal has 21%, and the Jewish

Autonomous Oblast – 24.6%. The high spatial heterogeneity is reflected in the different purchasing power of the population between and inside the territories of the Far East, which creates additional problems when choosing the methods of state support and its realization. Applying general nation-wide methods in the Far East gives controversial results [14].

In case the expenses on heat and electricity are fully compensated and the limit on maximum share in population expenses is retained, the volume of subsidies (preferences included) in the FEFD will increase from 25.3 billion rubles to 28.1 billion rubles in 2019 prices, which is almost the same as the traditional expenses of regional budgets spent on limiting tariffs. The biggest increase of subsidies will be seen in Chukotka Autonomous Okrug (+44.8%), Sakha Republic (Yakutia) (+32.4%), Kamchatka Krai (+13.9%), Jewish Autonomous Oblast (+11.1%). If the state completely moves away from subsidizing the population, then the voluntary expenses of the population will not exceed 77% in the Far East in general and will not reach even 60% in Sakha Republic (Yakutia) and Chukotka Autonomous Okrug.

Conclusions

As such, all attempts of the state at removing direct regulation and support of consumers and suppliers on the markets of heat and electricity in the Far East are doomed to fail. Without state patronage on the electricity and heat supply market the Far Eastern consumers are not capable of purchasing energy in market conditions. Even with state patronage the tariffs on energy for the Far Eastern consumers of heat and electricity are higher than national average. Without a way of decreasing energy production costs, introducing changes into technological and institutional conditions of energy markets works only through maintaining state patronage. In these conditions, it is logical to expand measures of state support and gradually make temporary measures permanent.

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State-private partnership - the growth factor of gasification of Russian region

Irina Filimonova[1,2,*], *Anna* Komarova[1,2], *Vasily* Nemov[1,2], *Irina* Provornaya [1,2] and *Yuri Dzyuba*[1,2]

[1]Trofimuk Institute of Petroleum Geology and Geophysics SB RAS, 3, Koptug, 630090, Novosibirsk, Russia
[2] Novosibirsk State University, 1, Pirogova, 630090, Novosibirsk, Russia

Abstract. The gasification of Russian regions is one of the most important problems for the national economy. The development of the gas supply system contributes to the socio-economic development of the regional economy, to the increase increasing the level and quality of life, and to the solution of the key environmental issues. The Krasnoyarskiy Kray is the only region in the east of the country that has a significant resource potential of natural gas but at the same time, it can't be connected to the trunk gas pipeline in the short and long term perspective. The purpose of the study is to assess the efficiency of investments in the construction of gas supply facilities, gasification, and their exploitation in the southern and central regions of the Krasnoyarskiy Kray. In this study authors solved the following objectives: we systematized information about the current state of the Krasnoyarskiy Kray gasification and the prerequisites for its development (resource base and transport infrastructure); we assessed economic efficiency of the investments in the construction, gasification, and exploitation of gas supply facilities in the southern and central regions of the Krasnoyarskiy Kray; we formulated proposals to ensure economic efficiency using the mechanism of public-private partnership. The authors recommend an option according to which federal budget investments will amount to 70% of their total investment in the Krasnoyarskiy Kray gasification program. Under this option, the selling price of gas will drop to 4708 rubles per 1000 cubic meters of natural gas excluding VAT. Organization of production, preparation for transport, and transportation of natural gas in the central regions of the Krasnoyarskiy Kray will create new highly paid jobs, significantly increase the GRP, and improve the demographic situation.

1 Introduction

Gasification of Russian regions is one of the most important tasks named by V.V. Putin in the annual message of the Russian Federation President to the Federal Assembly on January 15, 2020 [1]. The development of the gas supply system contributes to the socio-economic development of the regional economy, to the increase increasing the level and quality of life, and to the solution of the key environmental issues. Gasification of the regions in the east of the country will strengthen the energy security of the territories and create the basis for the development of equal trade relations with the countries of the Asia-Pacific region (APR).

The preconditions for increasing the level of gas supply of Russian regions are the presence of the world's largest natural gas reserves, and the high production and export rates of gas resources. The main factor that hinders the development of gasification in the region (primarily in the east of the country) is the absence of trunk gas pipelines and gas pipelines-branches for organizing gas supplies to settlements and industrial facilities [2].

Thus, the level of gasification in Russia on average in 2019 was around 70%, and it should reach 90% in 2030, following the General Scheme for the Development of the Gas Industry until 2030 [3-5]. However, the gasification of the regions is extremely uneven. The European part regions of the country are being gasified at a faster pace, while in the Eastern Siberia and the Far East regions the level of gasification is significantly lower than the average gasification values in the country. Also, in some regions, full-scale gasification programs have not yet begun. At the same time, the construction and commissioning of the Power of Siberia gas trunkline (December 2, 2019) had a positive impact on the development of gas supply in the east of the country. The gas pipeline route passes through the territory of five constituent entities of the Russian Federation - the Republic of Sakha (Yakutia), the Amurskaya Oblast', the Jewish Autonomous Oblast', the Khabarovsky Kray, and from 2023 through the territory of the Irkutskaya Oblast' [6-7].

Thus, the Krasnoyarskiy Kray is the only region in the east of the country that has a significant resource potential of natural gas [8]. Nevertheless, it can't be connected to the trunk gas pipeline in the short and long term perspective. The significant and negative feature of

* Corresponding author: filimonovaiv@list.ru

the socio-economic situation in the Krasnoyarskiy Kray is the extremely tense ecological situation in the main industrial centers [9-10]. One of the goals of this territory gasification should be improving the current situation.

The purpose of the study is to assess the efficiency of investments in the construction of gas supply facilities, gasification, and their exploitation in the southern and central regions of the Krasnoyarskiy Kray. To achieve this goal, we set the following objectives: we systematized information about the current state of the Krasnoyarskiy Kray gasification and the prerequisites for its development (resource base and transport infrastructure); we assessed economic efficiency of the investments in the construction, gasification, and exploitation of gas supply facilities in the southern and central regions of the Krasnoyarskiy Kray; we formulated proposals to ensure economic efficiency using the mechanism of public-private partnership.

The basis for the development of the gas transmission system in the east of the country was the completion of the Power of Siberia gas pipeline at the end of 2019. The gas pipeline has been laid across five constituent entities of the Russian Federation - Irkutsk and Amur Oblas', the Jewish Autonomous Oblast', the Republic of Sakha (Yakutia), and the Khabarovsky Kray region. The “Power of Siberia” route is laid along the existing oil trunk pipeline “Eastern Siberia - Pacific Ocean”. At present, this allows significant savings in infrastructure and energy supply costs. In the future, it helps to organize the sale of natural gas from already developed oil and gas fields, which now supply oil to the ESPO and are experiencing problems with the commercial development of gas potential. The distance between the two pipelines ranges from 700 m to 17 km. The total length of the gas pipeline is about 3 000 km, and the design capacity is 38 billion cubic meters of gas per year.

2 Resource base and transport infrastructure as the basis for efficient gasification

2.1. The current state of Krasnoyarskiy Kray gasification

On the territory of the Krasnoyarskiy Kray, network natural gas is currently supplied only to Norilsk and the Norilsk industrial hub. Gas supply to other consumers of the region is carried out according to autonomous schemes due to liquefied petroleum gas (LPG). LPG is a mixture of light hydrocarbons liquefied under pressure. The main components of LPG are propane and butane.

According to the established procedure, the gasification program for the Krasnoyarskiy Kray must be implemented by the General Scheme for Gas Supply and Gasification of the Krasnoyarskiy Kray developed and approved by the Administration of the region and by the PJSC "Gazprom". These programs were developed and approved in 2009 and 2016. Table 1 shows a comparative analysis of these two gas supply and gasification programs for the Krasnoyarskiy Kray region. The table shows that in 2009-2015 the general scheme of gasification and gas supply of the Krasnoyarskiy Kray was almost not implemented.

Moreover, for some indicators (the number of gas distribution stations, the number of gasified settlements, the number of the population served by gas, the number of gasified households and apartments, etc.), the General Scheme of 2016 provides for the value of target indicators that are significantly lower than in the 2009 scheme. It should be noted that the General Scheme provides for the construction of gas distribution networks, gas branch pipelines, inter-settlement gas pipelines and does not provide for the construction of the trunk gas pipeline. Therefore, the development of a new General Scheme, synchronized in time with strategic documents for the development of the energy and oil and gas industry of Russia and coordinated in terms of funding at the state and corporate levels, is relevant and timely.

Table 1. Comparative analysis of gas supply and gasification schemes for the Krasnoyarskiy Kray according to the General Schemes of 2009 and 2016.

Index	General Schemes, year	
	2009	2016
Number of gas distribution stations, units	19	12
Length of gas pipeline branch, thousand km	61.8	61.8
Length of inter-settlement gas pipelines, km	3 012.3	3 130.1
Number of gasified settlements, units	415	396
Population served by gas, thousand people	1 567.0	480.0
Number of gasified households (apartments), thousand units	603.5	207.4
Total annual consumption, million cubic meters m	3 637.2	3 398.1
including: population, million cubic meters	542.4	413.7

2.2 Resource base for gasification of the region

The largest initial natural gas resources in the east of the country are in the Krasnoyarskiy Kray (Figure 1), which has concentrated about 60% of the gas potential of Eastern Siberia and the Republic of Sakha (Yakutia) (more than 28 trillion cubic meters). However, the region is characterized by the lowest degree of exploration (4%) among the East Siberian regions, which is associated with the difficult geological structure of the deposits, the removal of subsoil use objects from potential consumers, and the lack of transport infrastructure.

Therefore, the share of industrial-grade reserves in the Krasnoyarskiy Kray is only 20% of the region's reserves as a whole. The largest deposits of the region in terms of total reserves of natural gas are Yurubcheno-

Tokhomskoye, Pelyatkinskoye, Tagulskoye, Sobinskoye and Kuyumbinskoye gas and oil, and gas-condensate fields.

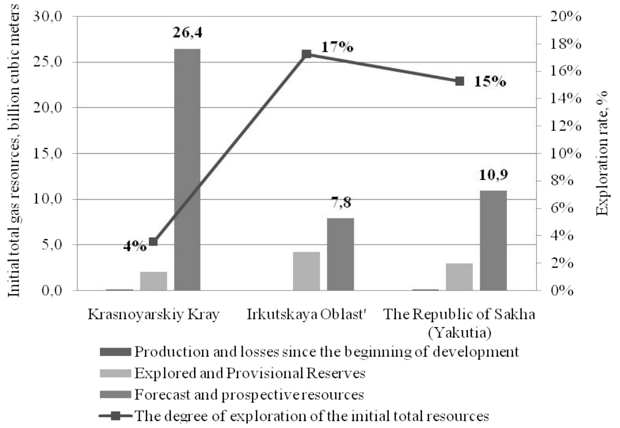

Fig. 1. The structure of the initial total gas resources in Eastern Siberia and in the Republic of Sakha (Yakutia).

In the Krasnoyarskiy Kray region, gas production in 2019 amounted to 12.8 trillion cubic meters, which is 9.0% more than the level of gas production in 2018. Associated petroleum gas (APG) prevails in the structure of gas production in the Krasnoyarskiy Kray. The growth of its production is associated with the active development of oil fields after the commissioning in 2008 of the trunk oil pipeline "Eastern Siberia - Pacific Ocean". In the period 2017-2019, the growth in gas production in the region is associated with the intensive development of the Yurubcheno-Tokhomskoye and Kuyumbinskoye fields and, as a result, an increase in associated petroleum gas production. At the end of 2019, gas production at the fields increased by 2.3 billion cubic meters. Most of the gas is injected back into the reservoir to maintain reservoir pressure to increase the oil recovery factor and minimize the impact on the environment.

A decline in associated gas production was noted at the Vankor field, which is at a declining stage of oil production. Thus the volume of gas production at the field is 3.7 billion cubic meters lower now than at its peak in 2015. The Suzunskoye and Lodochnoye fields are located in the immediate vicinity. And on the border with the Turukhansk district in the Taimyr Dolgan-Nenets municipal district situated the Tagulskoye field. These fields have been consistently brought into development during the past three years and maintain the level of APG production in the Krasnoyarskiy Kray.

Free gas is produced within the local gas supply system based on the Pelyatkinskoye and Severo-Soleninskoye fields in the north of the Krasnoyarskiy Kray. Gas production in 2019 amounted to 2.8 billion cubic meters. In the Norilsk industrial region, gas is supplied for the needs of the energy sector, including the generation of heat and electricity. The main gas consumers are JSC Norilsk-Taimyr Energy Company, enterprises of the Polar Division of PJSC MMC Norilsk Nickel, and the city of Dudinka. There is no gas supply to the population, since earlier, during the construction of urban infrastructure, it had been agreed to use electric stoves in households. The household needs of the population are met through centralized power supply and heat supply to housing.

Traditionally, the main gasification of the country's territory was the trunk pipeline system. The main gas transportation system in Russia is the Unified Gas Supply System with an endpoint in the east of the country in the village. Proskokovo (Kemerovskaya oblast'). That is why the level of gasification in the regions of Eastern Siberia and the Far East (about 10.0%) is almost seven times lower than the national average level (68.5%). Due to the absence of main transport infrastructure in the east of the country, several local gas supply systems have been formed, including in the north of the Krasnoyarskiy Kray region.

Until now, a unified gas transmission system has not been formed in the East Siberian region, which hinders the development of gas fields already prepared for exploitation. In these conditions, subsoil users independently construct gas supply pipelines that provide gasification of individual settlements and industrial enterprises. The gas supply system and operation of gas transportation facilities in the region are located in the production area of JSC Norilskgazprom, JSC Taimyrgaz, and JSC Norilsktransgaz (not included in the PJSC Gazprom group). Gas transportation through the Pelyatkinskoye gas condensate field - Severo-Soleninskoye gas condensate field - Yuzhno-Soleninskoye gas condensate field - Messoyakhskoye gas field - Norilsk is carried out by Norilsktransgaz. The length of the gas pipeline is 300 km. Most of it passes through the territory of the Krasnoyarskiy Kray.

The basis for the development of the gas transmission system in the east of the country was the completion of the Power of Siberia gas pipeline at the end of 2019. The gas pipeline has been laid across five constituent entities of the Russian Federation - Irkutsk and Amur Oblas', the Jewish Autonomous Oblast', the Republic of Sakha (Yakutia), and the Khabarovsky Kray region. The “Power of Siberia” route is laid along the existing oil trunk pipeline “Eastern Siberia - Pacific Ocean”. At present, this allows significant savings in infrastructure and energy supply costs. In the future, it helps to organize the sale of natural gas from already developed oil and gas fields, which now supply oil to the ESPO and are experiencing problems with the commercial development of gas potential. The distance between the two pipelines ranges from 700 m to 17 km. The total length of the gas pipeline is about 3 000 km, and the design capacity is 38 billion cubic meters of gas per year.

The Chayandinskoye field in the Republic of Sakha (Yakutia) and the Kovyktinskoye field in the Irkutsk Oblast' have been laid down as the resource base for the "Power of Siberia" gas pipeline in the short term. The connection to the gas pipeline of the fields of the Krasnoyarskiy Kray has been postponed for the long term, which acts as a limiting factor in the development of gasification of the Krasnoyarskiy Kray according to the scheme of connection to the trunk pipeline system.

3 Methodology for assessing the effectiveness of the gasification program

3.1 Schematic diagram of gasification of the Krasnoyarskiy Kray

Long-term prospects for gasification of the Krasnoyarskiy Kray are associated with the construction of branches from the Unified Gas Supply System (UGSS) in the area of the Proskokovo compressor station of the Kemerovo Region or the Volodino compressor station of the promising "Power of Siberia-2" gas pipeline, and with the formation of new gas production centers in the Krasnoyarskiy Kray itself at the base of deposits of the Evenki municipal and Boguchansky regions. The Sobinskoye oil and gas condensate field, which is large in terms of gas reserves, located in the Tungusko-Chunsky district of the Evenki municipal district, can become the basis for the formation of such a gasification center. The operator of the field is Gazprom Ltd Geologorazvedka, which is part of PJSC Gazprom.

The initial plan until 2023 for the preparation of gasification in the south of the Krasnoyarskiy Kray includes additional exploration and the start of the development of fields in the Evenk regional and Boguchansky districts; the beginning of the creation of the Krasnoyarsk gas transmission system with the trunk gas pipeline "Sobinskoye oil and gas condensate field - Boguchany - Achinsk - Krasnoyarsk".

After 2023, it is planned to transfer a significant part of the utility sector and boiler houses to LNG. Also, the action plan includes the use of natural gas in transport in the form of compressed natural gas (CNG) from 2020. In Krasnoyarsk, in 2020-2021, it is planned to purchase 50 units of a bus fleet that will operate on this CNG. After 2023, similar activities will be carried out in other cities and districts of the region.

3.2 Algorithm for calculating the economic efficiency of the implementation of the gasification scheme of the Krasnoyarskiy Kray

Assessment of the economic efficiency of gas supply and gasification projects is based on the methodology for evaluating the effectiveness of investment projects, developed by the Methodological Recommendations for Evaluating the Efficiency of Investment Projects (approved by order of the Ministry of Economic Development of Russia, the Ministry of Finance of Russia and Gosstroy of Russia No. VK 477 dated June 21, 1999).

The calculation of the costs for the construction of the trunk gas pipeline was carried out based on the aggregated figures of JSC Gazprom promgaz. According to the current practice in economic assessments, the program defines a list of gas supply and gasification facilities, and proposes the sequence of their construction, taking into account the geographical location and reserves of the selected natural gas sources.

The taxation system is adopted by the Tax Code of the Russian Federation, and the distribution of taxes paid by the budgets of various levels is following the Budget Code of the Russian Federation.

To assess efficiency, according to the recommendations, we use indicators that characterize commercial and budgetary efficiency (Table 2).

Table 2. Economic Performance Indicators.

Definition	Formula	Criterion
Net present value	$NPV = \sum_{t=1}^{T} \frac{NP_t + D_t - C_t}{(1+r)^t}$	$NPV > 0$
Internal rate of return	$IRR = r^*: NPV_t(r^*) = 0$	$IRR > r$
Profitabilityindex	$PI = \frac{\sum_{t=1}^{T} \frac{NP_t + D_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{C_t}{(1+r)^t}}$	$PI > 1$
Discounted payback period	$DPP = t^*: \sum_{t=1}^{t^*} NPV_t = 0$	min
Budgetefficiency	$BE = \sum_{t=1}^{T} \frac{Tax_t}{(1+r)^t}$	$BE > 0$

where NP_t – net profit; D_t – depreciation; C_t– capital investment; r– discount rate; Tax_t – taxes and fees.

3.3 Public-private partnership mechanism

The sources and mechanisms of financing regional gasification programs in the Russian Federation are defined by Article 17. “Legal framework for the development of gasification of the territories of the Russian Federation” Federal Law No. 69 “On gas supply in the Russian Federation”. According to this article, financing of regional gasification programs for housing and communal services, industrial and other organizations can be carried out through:

- federal budget funds;
- budgets of the respective constituent entities of the Russian Federation;
- other sources not prohibited by the legislation of the Russian Federation.

Based on the existing practice in Russia, PJSC Gazprom expands the concept of “other sources not prohibited by the legislation of the Russian Federation” and understands by them:

- investments of PJSC Gazprom within the framework of its programs;
- funds of enterprises - promising gas consumers;
- public funds for the construction of internal gas pipelines, the purchase of gas equipment, installation of equipment;
- gas distribution company funds;

- other mechanisms of investment and attraction of investments in the development of the regional gas market not prohibited by the legislation of the Russian Federation.

Therefore, when forecasting funding sources, the Gas Supply Programs for the Krasnoyarskiy Kray included, together with PJSC Gazprom, PJSC Rosneft, PJSC MMC Norilsk Nickel, RN-Vankor, AO Norilskgazprom, JSC Norilsktransgaz, JSC Taimyrgaz. This list can be expanded during the implementation of the program.

To increase the efficiency of the gasification program implementation, the mechanism of public-private partnership was taken into account. The federal budget is supposed to finance part of capital investments in gasification of the Krasnoyarskiy Kray. Ten options have been developed and evaluated, where the share of state participation varies from 0% to 100% in 10% increments.

4 Results and discussion

According to our calculations, the development of gas supply and gasification of the Krasnoyarskiy Kray is economically efficient at the sale price of natural gas excluding VAT - 6 125 rubles per 1 000 cubic meters. This scenario assumes the development of gas fields in the Boguchansky and Evenkiysky municipal districts with the technological schemes of development adopted by Gazprom VNIIGaz and JSC Gazprom promgaz, gas transportation through the predicted pipeline infrastructure and its implementation to end consumers under the established price and tax conditions in the option when all these investments are made by PJSC Gazprom. The calculations were made for the period up to 2050, taking into account a discount rate of 10%.

We took the internal rate of return (IRR) of PJSC Gazprom's investments as an efficiency criterion when evaluating the project. The project is considered profitable if the IRR of the investment is not lower than the initial threshold value. According to the concept of JSC Gazprom's participation in the gasification of the regions of the Russian Federation (approved on November 30, 2009), the required level of return on investments must be at least 12%.

No other region of the Russian Federation has such a high gas price. For example, let us point out that the minimum level of wholesale prices for natural gas excluding VAT varies in the regions of the Russian Federation under consideration as of July 1, 2020, from RUB 4 105 to RUB 4 792 per 1,000 cubic meters.

In terms of the average monthly wages of the population, the Krasnoyarskiy Kray is in 20th place among the subjects of the Russian Federation. The average monthly salary in 2019 in the Krasnoyarskiy Kray was about 35 thousand rubles. In the central and southern regions of the region, it is significantly lower.

With a gas selling price of 6125 rubles per 1000 cubic meters, excluding VAT, network gas will not be able to compete with brown coal, and the population will not be able to purchase such services.

To reduce the selling price of gas, we considered options for the federal budget to participate in financing the gas supply and gasification system in the central and southern regions of the Krasnoyarskiy Kray region.

When assessing the budgetary efficiency of the federal budget for the extractive industries as a whole, it should be borne in mind that the Krasnoyarskiy Kray ranks first in the Russian Federation in the production of gold, platinoids, nickel, lead, and one of the first in oil (fourth) and copper production. Thus, if we take into account the revenues to the federal budget of enterprises of all these extractive industries, then the actual efficiency of budget investments in the economy of the Krasnoyarskiy Kray will be higher.

We considered several options in which the federal budget contribution varied from 0 to 90%. In these options, the selling price of gas without VAT will vary from 6 125 rubles of gas to 4 380 rubles per 1 000 cubic meters of gas. In the program, we recommend focusing on the option according to which the federal budget investments in the objects of PJSC Gazprom's responsibility will amount to 70% of their total amount. Under this option, the selling price of gas without VAT will be 4 708 rubles per 1 000 cubic meters of natural gas (Table 3).

Table 3. Economic efficiency indicators.

Index	Values
Source of financing	100%
Federal budget	70%
PJSC Gazprom	30%
Sales price including VAT, rubles / thousand cubic meters	5650
Sales price excluding VAT, rubles / thousand cubic meters	4708
Natural gas consumption, million cubic meters / year	8150
Natural gas consumption, million cubic meters	165650
Sales proceeds, million rubles	935923
Capital investments, million rubles	28525
Operating costs, million rubles	746162
Taxes, million rubles	180673
Federal budget	152091
Regional budget	16214
Local budget	12368
Net profit, million rubles	9087
Cash flow, million rubles	66828
Net present value (NPV), million rubles	2947
Internal rate of return (IRR),%	12%
Discounted payback period, years	22

According to the recommended option, by 2050, due to the payment of taxes based on the results of the gas supply and gasification system in the central and southern regions of the Krasnoyarskiy Kray, investments from the federal budget will be fully returned to the budget, and the GNI of budget investments (budgetary efficiency) will reach 7%.

4 Conclusion

The implementation of the gasification program for the central and southern regions of the Krasnoyarskiy Kray will provide a significant contribution to the economic and social development of the Krasnoyarskiy Kray in several areas:

- a new large gas production center will be formed in Eastern Siberia, which will allow gasification of the central and southern regions of the Krasnoyarskiy Kray, the Republic of Khakassia and the Republic of Tyva;
- the implementation of the program will ensure that the budgets of all levels for 2024-2050 will receive at least 176 148 billion rubles, the budget efficiency of the program will exceed 7%;
- due to the gasification of power plants, boiler houses, automobile transport in large cities (Krasnoyarsk, Achinsk, Kansk), the ecological situation in the central and southern regions of the Krasnoyarsk Territory will improve, and at the enterprises of the energy and metallurgical complexes will increase the life expectancy and improve the quality of life of the population.

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Analysis of foreign experience in implementing state policies to ensure energy supply to remote areas

Maxim Gubanov[1], *Dmitry* Morkovkin[1], *Arthur* Gibadullin[2*], *Olesya* Dontsova[1], *Olga* Gavel[1], and *Manuchehr* Sadriddinov[3]

[1]Financial University under the Government of the Russian Federation, 49, Leningradsky avenue, Moscow, 125993, Russia
[2]State University of Management, 99, Ryazan Avenue, Moscow, 109542, Russia
[3]Tajik State Finance and Economics University, 64/14, Nakhimova Street, Dushanbe, 734067, Republic of Tajikistan

Abstract. The article discusses the problems of providing consumers of electric energy in the decentralized energy supply zone by the example of economically developed countries with territories at the level of the Arctic Circle. An increase in the share of renewable energy sources in the energy balance of many fears as the main direction of regional energy development is shown. The energy policy of most Scandinavian states has a pronounced focus towards the maximum use of renewable energy sources along with the implementation of measures to save energy and increase energy efficiency. The provision on the priority use in the countries of the Arctic region of locally available energy sources, which include all types of renewable sources, as well as local hydrocarbons, is justified in order to ensure independence from external fuel supplies.

1 Introduction

The problem of energy supply to the territories in the decentralized energy supply zone is relevant not only for many northern countries, but also the determining energy policy for many island states. For the purposes of this study, the most economically developed countries with territories at the Arctic Circle are of particular interest, which include the USA, Canada, Denmark, Norway, Sweden, Finland and Iceland.

2 Materials and methods

The purpose of this study is to analyze foreign experience in implementing the state energy policy to ensure the supply of energy to remote areas in the Arctic zone. To achieve this goal, the following tasks:
- To conduct a comprehensive analysis of the problems of energy supply in the territories in the decentralized energy supply zone of the countries of the Arctic region;
- To determine the role of the electric grid infrastructure, which allows using the potential of geothermal and hydropower to ensure the reliability of the functioning of energy systems.

The study used general scientific and specific methods of system analysis, the method of analogy and comparison, the method of expert assessments, which allowed the authors to solve the goal and objectives of the study.

3 Results

USA (Alaska). The centralized power system in the state provides power to major cities and the railroad. The power supply of most small towns is local in nature and is mainly provided through the use of diesel power plants. Fuel is delivered by air, sea and road. The main primary energy resource in the region is natural gas (65%), water energy (22%) and coal (10%), while successful experience in implementing renewable energy projects, including wind and solar energy, whose total balance is about 2 % The total installed capacity of renewable energy is about 60 MW.

An example of the successful integration of renewable energy sources is the hybrid energy supply system of Kodiak Island, which consists of a 33 MW power plant, a 30 MW power plant, a 5 MW wind farm, and a 3 MW energy storage system. This allows you to provide more than 90% of electricity generation based on renewable energy sources. In addition, projects have been implemented for the construction of wind-diesel complexes in the settlements of Kotzebue, Wales, Kasigluk and villages on the west coast. In addition, a regional wind farm in the city of Anchorage (17.6 MW) is connected to the regional power system.

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One example of this type of installation is a system with a capacity of 16.8 MW, installed at the Bering Strait Corporate Corporation in Nome in 2008. Another example is a 6.7 MW photovoltaic project to power a school in Galen. SES was installed in 2012 and showed its effectiveness; in 2015 its capacity was increased to 10 MW.

Depending on the availability of geographically accessible resources of the province, the regions prioritize

*Corresponding author: 11117899@mail.ru

the use of renewable energy sources. For the Aleutian Islands, this is an increase in the efficiency of the use of diesel fuel, the use of flue gases for heating, insulation and energy efficiency in the residential sector, wind-diesel stations. For the Copper River region, this is an increase in the share of energy use of water, natural gas, wind and the sun. Inner Alaska sets energy efficiency in the construction of new buildings and the use of biomass as priority areas. The Northwest Arctic focuses on the use of wind and solar energy, as well as the energy of sewage facilities [1].

The main direction of regional energy development is to increase the share of renewable energy sources in the energy balance to 50% by 2025 and to reduce the dependence of isolated energy systems on the "northern delivery" of fuel. As a primary measure, energy efficiency programs are in place. An additional program is being implemented to support the use of renewable energy sources through grants and soft loans from the Alaska Renewable Energy Fund. The reduction in diesel costs through the implementation of these measures is about $ 45 million per year.

The Green Bank concept provides a different model, pushing the government away from direct support for energy projects to the strategic and cost-effective use of public funds. This approach encourages a shift from one-off subsidies and grants to market-based financial instruments. The Green Bank provides cheap, long-term financing for supporting renewable energy projects by attracting private investment [2].

Canada (Yukon, Northwest Territories, Nunavut). Energy supply for most of the northern territories of the country is carried out through the use of hydropower potential in conjunction with diesel power plants. On the territory of the Yukon, the share of hydroelectric power plants in the total balance is more than 65%, in the North-Western territories it is about 30%. The largest project is a hydropower plant in Whitehorse (Yukon) with a capacity of 40 MW. In addition, projects in the field of wind and solar energy are being implemented. In particular, a 60 MW solar power plant was built in Fort Simpson. On the island of Ramee, a project was completed to build a wind-diesel complex with a hydrogen storage system comprising a wind turbine (690 kW), a hydrogen fuel cell (250 kW) and diesel generator set (3 * 925 kW).

At the same time, out of 80 communities in 53 territories, exclusively diesel electric generators are used to generate electricity in locally isolated networks. Diesel dominates the territory because, in many cases, it is the only guaranteed source for reliable energy supply in remote communities and isolated mining areas. In recent years, there has been a practice of using LNG for energy supply of certain settlements in coastal regions, in particular, the city of Inuvik [3].

RES projects are financed as part of energy conservation and energy efficiency programs, as well as environmental programs to reduce greenhouse gas emissions into the atmosphere. The search for a rational energy balance and an increase in the share of renewable energy is one of the main areas of territorial development.

Denmark (Greenland). More than 50 thousand inhabitants of the island are located on a vast territory and live in small communities along the fjords of the west coast. Most of these communities have complex transport accessibility. By natural conditions, the energy supply to the Greenland communities is ensured by the functioning of local energy centers. Historically, energy supply on the island was provided by imported diesel fuel, and was the largest source of greenhouse gas emissions. The change in European energy policy and the dynamics of world prices for petroleum products provided motivation for the use of geographically accessible resources, which include melt water energy.

Currently, up to 70% of the region’s demand for electricity is provided by the operation of 5 hydroelectric power stations with capacities from 1.2 to 30 MW, providing autonomous power supply to urban settlements. In addition, about 70 autonomous energy systems operate in the region, where imported petroleum products are used as the primary source.

The Greenland government plans to build another 5 hydropower plants by 2030 to bring their share in the total balance to 90% and a corresponding reduction in greenhouse gas emissions. In addition, individual projects of private power supply through the use of solar and wind energy are being implemented. An example is the project in the Igaliku community, which includes a 100 kW SES, a 20 kW wind farm and an energy storage system [4].

Norway. Most of the country's territory is covered by a centralized power supply network. The main source of electricity production is hydroelectric power plants with a capacity of 33.8 GW, the share of which in the balance is more than 95%, the remainder is thermal coal-fired power plants and wind power plants, the total installed capacity of which already reaches 800 MW.

As autonomous energy supply projects, one can pay attention to the energy supply system of Utsira Island, where an experimental combined wind turbine unit with a capacity of 2 * 600 kW was installed.

In 2017, the final energy consumption in Norway amounted to 213 TW*h. Production and transportation were the sectors that used the most energy in 2015, followed by services and households. Other sectors, such as construction, agriculture and forestry, and fisheries, provided only a small share of energy consumption.

The main focus of Norway's energy policy is to support renewable energy technologies in private households and energy efficiency in the residential sector. Due to the implementation of this direction, the average energy consumption per capita in the household sector decreased from 7% between 1990 and 2017. Various factors have helped reduce energy consumption in the household sector, including the introduction of more energy-efficient equipment, stricter building codes and the increased use of electric and heat pumps for heating homes.

Central heating is carried out with the priority use of various fuels. In 2017, about 50% of central heating was generated from waste and about 20% from bioenergy. The use of bioenergy has increased over the past ten years, while the use of fossil fuels has decreased. Biofuel makes up the second largest share of energy used for heating in households. In 2017, biofuels consumed about 5.8 TW*h of energy. Most of this energy is in the form of firewood, but households also use pallets and biomass. Oil and gas accounted for about 5% of the production of district heating systems [5].

Sweden. The lack of hydrocarbon deposits in the country was a determining factor in the development of energy. The main share in the energy balance is occupied by nuclear power plants (43%), hydroelectric power plants (41%) and wind energy (7%). The remainder is provided through the use of other types of renewable energy sources, thermal power plants and the import of electricity from neighboring countries. Electric grid infrastructure provides coverage of almost the entire territory of the country.

Swedish nuclear power needs large investments, which is necessary to ensure increased safety requirements. The government says it is necessary to meet these requirements by 2020, otherwise nuclear reactors will be decommissioned. Decisions have already been taken to decommission four reactors by 2020, which will require an increase in the share of renewable energy in the energy balance.

Electricity consumption in 2013 amounted to 125 TW * h. The residential and service sectors used the most electricity, then the industrial sector. Petroleum products are the next largest energy carrier after electricity, and the total end use was 96 TW * h, which represents an ongoing decline in recent years. In Sweden, the use of petroleum products is almost exclusively in the transport sector.

For heating and hot water supply of residential buildings, the most common use of electrical energy. Consumption in 2015 amounted to about 15 TW * h. In addition, biomass is used, including firewood, wood chips, sawdust and pallets. The use of oil for heating continues to decline with the development of a heat pump system, which is especially effective for heating low-rise buildings. District heating is the most common form of energy used for heating apartment buildings, and in 2015 amounted to 23 TW * h. Electric heating was a little over 1 TW * h, and the use of fuel oil was less than 0.2 TW * h.

Central heating is also the most common form of energy used for heating and producing hot water in non-residential premises. In 2013, district consumption was 18 TW * h. Electricity was the second largest and amounted to 3.3 TW * h. The use of oil for heating and hot water also continues to decline in non-residential premises. The total use of oil during the year is equivalent to 0.5 TW * h.

The main long-term goals of the country are to increase energy efficiency in energy-intensive sectors of the economy and utilities, as well as simulate the development of renewable energy. The main support tools are the introduction of carbon dioxide emissions fees, tax benefits for renewable energy sources and green certificates [6].

Finland. The country's energy balance is determined by nuclear energy (28%), hydropower (16%), coal (13%), natural gas (5%), peat (5%), wood and other renewable energy sources (10%). In 2017, electricity production amounted to 65 TW * h, and from this 33.2 TW * h were produced at nuclear power plants, 22.5 TW * h at hydroelectric power stations, 14.4 TW * h at coal and gas power plants, and 16 at biomass , 8 TW * h. Taking into account imports of 23.9 TW * h, the total electricity consumption was 85.5 TW * h.

With its rich forest resources, Finland is a world leader in the development of biofuel. Forest industry by-products and wood waste are used as fuel for generating electricity and heat or are processed into second-generation biofuel, especially biodiesel, where Finnish industry leads the world. Since 2007, the supply of biofuel and waste has increased by 30%, while the supply of oil has fallen by 9%, while the supply of coal, natural gas and peat has decreased by almost 50%. The global demand for Finnish forest products is growing, and as a result, the supply of these wood-based energy sources is also growing.

The government has set strategic climate goals for 2030 with an increase in the share of renewable energy in the energy balance to 40%. A key goal in promoting renewable energy is to reduce greenhouse gas and waste emissions. Finland is a leader among countries in public and private spending on research, development and implementation of renewable energy projects. The long-term political framework for 2050 will be critical in guiding investment in clean energy technology innovation, which is a critical factor in achieving the goals of decarburization.

Finland's priority is energy efficiency, including utilities, the public sector, industry, energy and transport. The national energy efficiency program includes the following main areas: conducting an energy audit, developing energy conservation programs, using secondary energy resources and renewable energy sources, changing tax policies, conducting comprehensive research and implementing demonstration projects.

As one of the projects, it is worth bringing the integrated energy supply system of the city of Uusikaupunki, combining the use of waste, growing in greenhouses, fish farming and the production of biodiesel. In this closed-loop system, waste, energy and nutrients are recycled to minimize the total use of materials and emissions [7].

Iceland. The country's electricity needs are almost completely met through the use of renewable energy sources, including hydroelectric power plants (12.8 GW * h or 71%) and geothermal thermal power plants (5.2 GW * h or 29%). Wind energy and the use of hydrocarbons (less than 1%) have an insignificant share. The installed capacity of geothermal stations is 665 MW (the largest 300 MW), hydroelectric power stations - 1880 MW (the largest 690 MW).

Electric grids cover the area around the entire island and provide transport of electricity from large sources of generation. 220 kV power lines connect all the major plants serving the southwestern part of Iceland with the municipal district of Reykjavik and surrounding cities in the eastern part of Iceland. The largest hydropower plant is associated with the largest aluminum smelter in Fjardal.

The 132 kV energy ring is used for transmission throughout the country and ensures the operability of the transmission network in post-accident conditions.

The main consumer of electricity is aluminum industry (68%), silicon industry (8.7%), services (5.7%), household services (4.6%), utilities (4%), agriculture (1, 2%). Heat supply for more than 90% of houses is provided through the use of geothermal energy sources.

The main goal of state policy is to achieve carbon neutrality, which implies the complete exclusion of the use of fossil fuels through the use of renewable energy and increase the energy efficiency of economic sectors.

The main goals for the long term are: the diversification of industry with an emphasis on environmentally friendly technologies, the development of industrial parks and plants for the production of technological equipment for renewable energy sources, the development of centralized and individual heat supply through the use of geothermal energy sources, and the replacement of petroleum products in transport for environmentally friendly fuel [8].

4 Conclusions

Based on the analysis, it should be concluded that the countries of the Arctic region use priority sources of locally available energy sources, which include all types of renewable sources, as well as local hydrocarbons, in order to ensure independence from external fuel supplies.

The energy policy of the Scandinavian countries has an obvious direction towards the maximum use of renewable energy in conjunction with the implementation of measures to save energy and increase energy efficiency, which corresponds to the pan-European trend for the implementation of the “energy transition”. A significant role is played by the developed electric grid infrastructure, which makes it possible to maximize the potential of geothermal and hydropower to ensure the reliability of the functioning of energy systems [10-21]. The North American countries and Denmark (Greenland) are seeking a rational balance between the development of electric grid infrastructure in extended territories and the use of local renewable energy sources to replace imported fuel.

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Multi-criteria placement and capacity selection of solar power plants in the “Baikal-Khövsgöl” Cross-Border Recreation Area

Irina Ivanova [1], *Vladislav* Shakirov [1,*]

[1]Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Department of Complex and Regional Problems in Energy, Irkutsk, Russia

Abstract. The problem of power supply to remote consumers in the “Baikal-Khövsgöl” Cross-Border Recreation Area, associated with the high length and low reliability of power lines is discussed. The assessment of the modes of the power distribution grid showed that the introduction of new consumers in this territory will lead to unacceptable voltage deviations, even taking into account the installation of reactive power compensating devices. Since the area under consideration has a high solar energy potential, it is advisable to use distributed solar generation. The choice of locations and capacities of solar power plants is a multi-criteria optimization problem. Four criteria are proposed: total voltage deviation, total active power losses, reliability and capital costs for construction. An algorithm for multi-criteria optimizationis developed and implemented as a program in the MATLAB, which consists in sequential verification of the feasibility of installing additional power of solar power plants at the consumers of each of the substations under consideration. For each variant, the electric grid mode is assessed using the Power system analysis toolbox program. Solutions for the choice of locations and capacities of solar power plants are obtained, providing high scores by criteria in accordance with the given criteria importance coefficients.

1 Introduction

“Baikal-Khövsgöl” cross-border recreation area runs from the southern part of Lake Baikal through Tunkinsky and Okinsky regions of the Republic of Buryatia (Russia) to Lake Hubsugul through somon Khanh (Mongolia). This area is very promising for international tourism development. There are two major national parks – Khövsgöl (Mongolia) and Tunkinsky (Russia), many health resorts, recreation centers, places of tourist and recreational type. In close proximity, on the Russian-Mongolian border, is the highest peak of the Sayan – Mount Munku-Sardyk, which is a popular site for sports tourism [1].

At present, specially protected natural areas (SPNAs) are actively involved in ecotourism: new economic mechanisms for their functioning are being introduced; they are being integrated into the sphere of social and economic development; budget financing is being increased; and participation in conservation projects is being expanded [1, 2].

For the sustainable socio-economic development of “Baikal-Khövsgöl” cross-border recreation area, it is necessary to ensure environmentally efficient and reliable power supply to existing and prospective consumers in accordance with the requirements to power quality GOST R 32144-2013 and European standard EN 50160-2010 [3].

At present, the power supply system has low reliability. On the Russian side, the key elements of the power supply system are the 110/35/10 kV "Kyren" and 110/35/10 "Zun-Murino" substations located in Tunkinsky Raion (Fig. 1). Consumers in Okinsky Raion are supplied with electric power via a single-circuit 110 kV power line "Kyren – Mondy – Samarta", a single-circuit 35 kV power line "Mondy – Sorok – Samarta" and a single-circuit 35 kV power line "Sorok - Orlik". Long radial single-circuit power lines are characterized by significant wear and frequent prolonged shutdowns [4]. For example, if one of the power lines is damaged, about 4360 people, 1 hospital, 6 schools, 6 kindergartens, 7 boiler houses and 5 settlements are disconnected. There are no redundant power lines available. The restoration work is complicated by the mountainous terrain and the long length of power lines. These districts are among the underdeveloped and hard-to-reach places in the Republic of Buryatia.

In Mongolia, the considered cross-border area within the borders of the Khanh somon is not provided with its own generation, there is no connection with the state energy system. Power supply to the Khankh settlement is carried out from the Republic of Buryatia through the interstate 10 kV transmission line “Mondy-Zavod” with a length of 35 km (Fig. 1).

An additional problem is the low voltage level of consumers, due to the long length of power lines. The introduction of new consumers raises the question of using additional voltage regulation devices.

Thus, according to the Strategy of socio-economic development of the Republic of Buryatia for the period

* Corresponding author: shakirov@isem.irk.ru

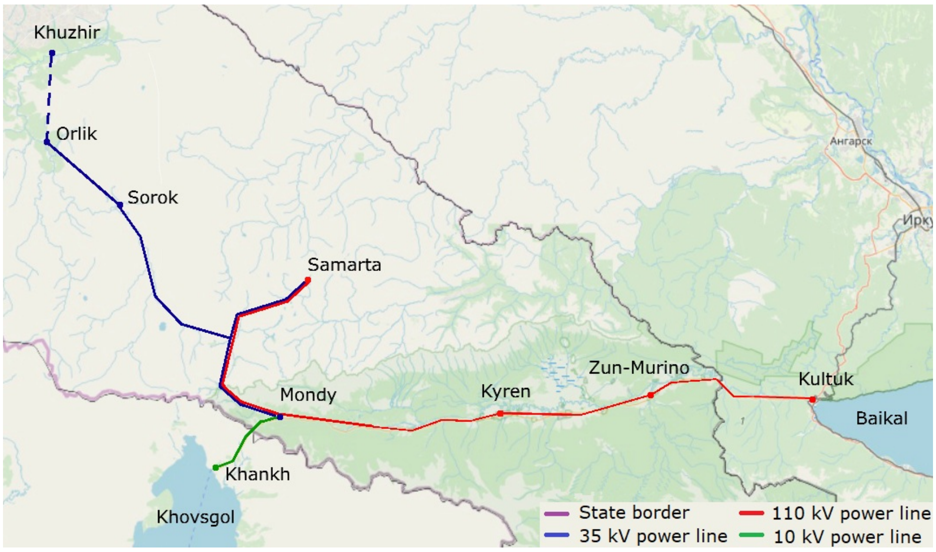

Fig. 1. General layout plan of the “Baikal-Khövsgöl” cross-border recreation area.

up to 2035, in the period up to 2021 it is planned to develop and start operation of Konevinsky gold deposit [4]. For its power supply the construction of Khuzhir substation is planned (Fig. 1). The assessment of electric modes performed in [4] showed that the use of reactive power compensating devices will not allow to solve the problem of voltage level at consumers.

The territory under consideration has a high level of solar energy potential [4]. The average annual total solar radiation entering the horizontal surface is 1200-1350 kWh/m^2. The expected capacity utilization factor of photovoltaic converters is at a relatively high level, in the range of 18.3-19.7%. Installation of solar power plants (SPP) in settlements will improve the reliability of power supply, provide the required voltage level for consumers, and reduce the active power losses [5-8].

The problem of choosing the locations and capacity of renewable energy sources (RES) to improve the efficiency of power distribution grids has been considered in many works [9-13]. Heuristic optimization methods are widely used to solve this problem. In papers [14-17] the approaches on the basis of the intersect mutation differential evolution algorithm, back-tracking search algorithm, genetic algorithm, bionic algorithms are offered. The placement and selection of the capacity of renewable energy sources is carried out mainly from the standpoint of minimizing active power losses and voltage deviation among consumers.

In addition to the abovementioned criteria, the factors of power supply reliability and economic efficiency play a major role. As a rule, it is impossible to achieve high marks on all criteria at the same time. To find effective options for installed capacity and locations of RES, it is necessary to use a multi-criteria approach, which allows to determine compromise solutions, according to the relative importance of the criteria.

A multi-criteria heuristic approach to placement and selection of SPP installed capacity in the power distribution grid is proposed using 4 criteria: total voltage deviation at consumers, active power losses, reliability of power supply and capital costs for construction of SPP.

2 Power flow analysis using the Power System Analysis Toolbox

Fig. 2 shows the principal scheme of power supply to the territory under consideration, dashed line shows the planned construction of power transmission line and 35/10 Khuzhir substation for power supply of Konevinsky gold deposit.

To assess the mode of the power distribution grid, the Power System Analysis Toolbox (PSAT) was used, which is controlled in the MATLAB environment [18].

PSAT raw data can be imported from electrical system models created in MATLAB Simulink. In Figure 3 shows a 35 kV power distribution grid model created in MATLAB Simulink with the supply substation Samarta 110/35/6 kV. The model includes an interstate 10 kV transmission line Mondy-Khankh.

Tables 1, 2 show the accepted values of the electrical loads and the results the bus voltage estimation for several modes of the power grid:

Mode 1 – without taking into account the commissioning of the Khuzhir substation;

Mode 2 – taking into account the commissioning of the Khuzhir substation;

Mode 3 – taking into account the commissioning of the Khuzhir substation and full compensation of reactive power at consumers.

As a result of commissioning of Khuzhir substations, the voltage at the consumers of Monda, Khanh, Sorok, Orlik substations have inadmissible deviations from the nominal values according to GOST R 32144-2013, EN 50160-2010, more than 10%. It is also possible to note rather high active power losses.

With full compensation of reactive power at the considered substations, inadmissible high voltage deviations are preserved at the substations Sorok, Orlik and Khuzhir, the active power losses are reduced, but remain at a high level.

* Corresponding author: shakirov@isem.irk.ru

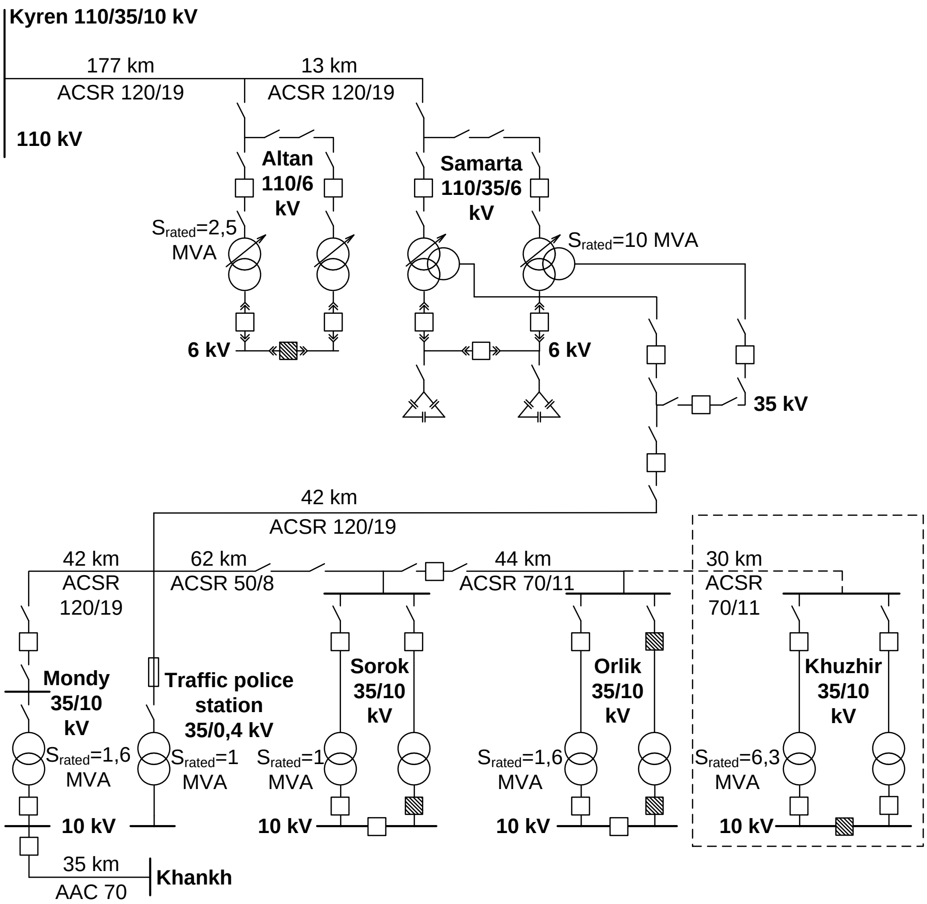

Fig. 2. Schematic diagram of the power distribution grid.

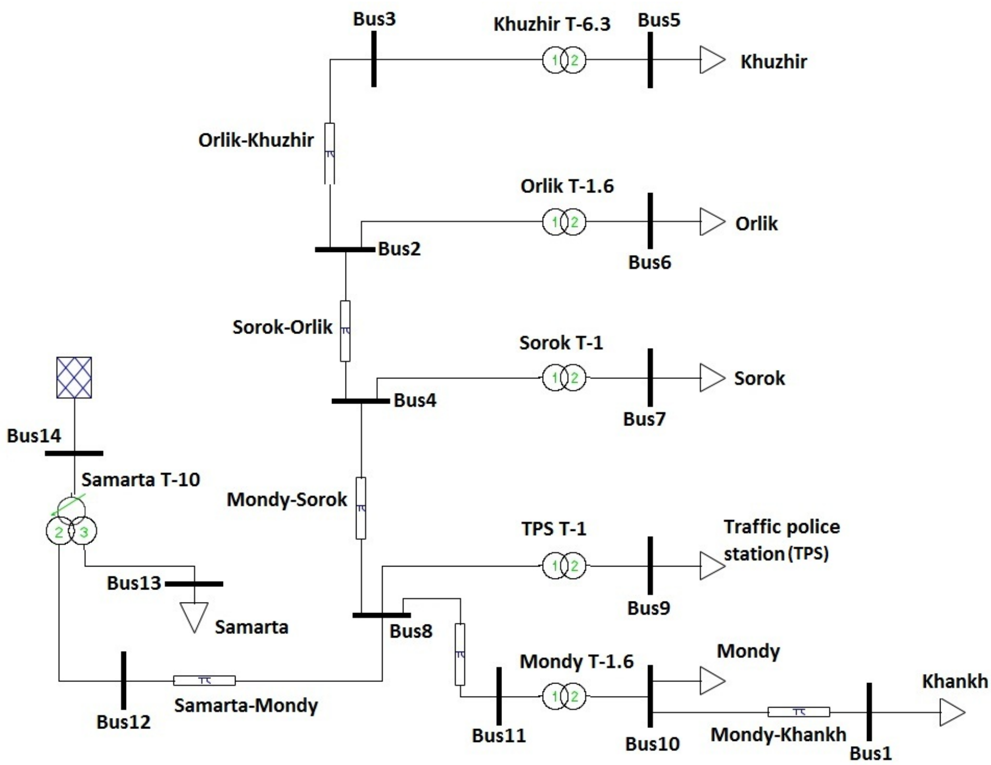

Fig. 3. Power distribution grid model for the PSAT.

* Corresponding author: shakirov@isem.irk.ru

Table 1. Accepted values of electrical loads.

Locality	P, MW			Q, MVar		
	Mode 1	Mode 2	Mode 3	Mode 1	Mode 2	Mode 3
Samarta	11.6			5.3		0
Mondy	1.3			0.6		0
Khankh	0.35			0.1		0
TPS	0.1			0.1		0
Sorok	0.7			0.2		0
Orlik	0.7			0.2		0
Khuzhir	0	1.8	1.8	0	0.5	0

Table 2. Results of assessing the voltage on the load buses and active power losses in the power grid.

Locality	Samarta		Mondy		Khankh		TPS		Sorok		Orlik		Khuzhir		ΔP_{Σ}, %
Parameters / Mode	U, kV	δU, %	U, kV	δU, %	U, kV	δU, %	U, кВ	δU, %	U, kV	δU, %	U, kV	δU, %	U, kV	δU, %	
Mode 1	6.47	2.74	9.79	-6.75	9.2	-12.39	10.55	0.45	9.8	-6.68	9.77	-6.99	-	-	2.2
Mode 2	6.38	1.22	8.93	-14.94	8.27	-21.23	9.77	-6.92	7.54	-28.20	6.79	-35.32	6.44	-38.70	10.87
Mode 3	6.77	7.42	10.43	-0.62	10.0	-4.79	10.74	2.29	9.43	-10.16	8.99	-14.42	8.77	-16.43	6.02

Distributed generation units, including those based on RES, can be used to increase reliability of power supply, reduce voltage deviations and decrease active power losses in the grid.

3 Multi-criteria placement and capacity selection of solar power plants

The choice of locations and capacities of RES in the power distribution grid is a multi-criteria optimization problem. In the paper, the optimization process was aimed at improving four indicators:

1. Minimization of the total voltage deviation at load buses:

$$\delta U_{\Sigma} = \sum_{i=1}^{n} \left| \delta U_i \right|, \tag{1}$$

where δU_i is the voltage deviation from the nominal value at load bus i, %.

2. Minimization of total active power losses:

$$\Delta P_{\Sigma} = \sum_{j=1}^{k} \left| \Delta P_j \right|, \tag{2}$$

where ΔP_j – the loss of active power in j-th element of the power grid, kW.

3. Maximizing the indicator of the reliability of power supply to consumers, which was estimated by the share of load coverage of the important consumers by renewable energy sources at each substation:

$$R = \sum_{i=1}^{n} \frac{1}{n \cdot L_i} \left[min\left(L_i ; \frac{P_{rei}}{P_i} \right) \right], \tag{3}$$

where n is the number of substations; L_i is the share of the load of the i-th substation attributable to the important consumers, p.u.; P_{rei} is the capacity of RES installed at the consumers of the i-th substation, kW; P_i is the load of the i-th substation, kW.

4. Minimization of capital costs for RES:

$$C = \sum_{i=1}^{n} w_t \cdot P_{rei} \ , \tag{1}$$

where w_t is a specific capital investments in construction of the type t renewable energy sources with installed capacity of 1 kW, thousand rubles/kW.

The objective function is defined by the expression:

$$V(x) = k_1 \frac{\delta U_{1\Sigma} - \delta U_{x\Sigma}}{\delta U_{1\Sigma}} + k_2 \frac{\Delta P_{1\Sigma} - \Delta P_{x\Sigma}}{\Delta P_{1\Sigma}} + \\ + k_3 R_x + k_4 \frac{C_{max} - C_x}{C_{max}}, \tag{5}$$

where k_1, k_2, k_3, k_4 are criteria importance coefficients, p.u.; $\delta U_{1\Sigma}$, $\Delta P_{1\Sigma}$ – total voltage deviation and active power losses corresponding to the power grid without RES; $\delta U_{x\Sigma}$, $\Delta P_{x\Sigma}$ – total voltage deviation, active power losses, corresponding to power grid with the x option of locations and capacity of RES; R_x is the assessment of the reliability of power supply to consumers with the x option of locations and capacity of RES; C_x – capital costs for the construction of RES with the x option of locations and capacity of RES, million rubles; C_{max} – capital costs with full coverage of consumers' load using renewable energy sources, million rubles.

A larger value of the objective function corresponds to a more preferable option of locations and capacity of RES in the distribution power grid.

The determination of the importance coefficients values can be carried out by direct assignment by a decision-maker (DM), or determined using well-known procedures implemented within the AHP [19], MAUT [20] methods. Coefficients k can take values from 0 to 1.

Optimization of the locations and installed capacity of SPP is carried out in accordance with the algorithm presented in Fig. 4.

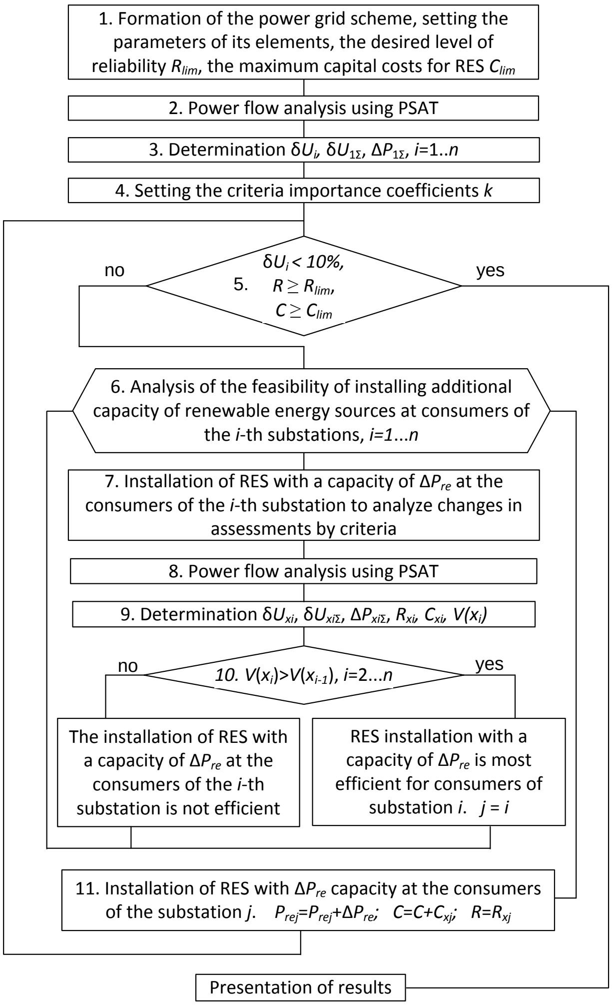

Fig. 4. Multi-criteria optimization algorithm.

At the first stage of the algorithm the desired level of reliability R_{lim} is set, which determines what proportion of the load of the important consumers it is reasonable to reserve by RES. The limit of capital costs C_{lim} is also set.

Further, using PSAT, the power flow analysis for the initial scheme is carried out, δU_i, $\delta U_{1\Sigma}$, $\Delta P_{1\Sigma}$ are determined by formulas (1)-(2).

Depending on the results of the previous stages, the DM determines the criteria importance coefficients k_1, k_2, k_3, k_4.

The optimization process is performed in blocks 5-11. At the fifth stage the conditions are checked, the set and parameters of which are set by DM. For example, if the voltage deviation at the consumers is less than 10%, the desired level of reliability is reached and the costs have reached the limit value, optimization can be completed. If the conditions at stage 5 are not met, then a sequential check of the feasibility of adding power ΔP_{re} to each of the considered substations supplying consumers is carried out. For this, the power flow analysis is carried out using PSAT and the objective function is calculated using expressions (1)-(5).

The decision to increase the RES installed capacity by ΔP_{re} is made for the substation with the largest increase in the objective function relative to the initial value. After that, the conditions in block 5 are checked, the end or continuation of optimization is carried out.

The algorithm shown in Fig. 4 was implemented in MATLAB as a program. The working screen of the program (Fig. 5) contains a table, which reflects the results of the power flow analysis, performed in the PSAT at stages 2 or 8 (Fig. 4). On the left side of the screen, curves of the voltage on the load buses and voltage deviation are shown for the original power grid (in red) and for the power grid with RES (in green). On the right side of the screen, there are a curves showing the change in the objective function (in green) and individual indicators ($\delta U_{x\Sigma}/\delta U_{1\Sigma}$ – in red, $\Delta P_{x\Sigma}/\Delta P_{1\Sigma}$ – in cyan, R_x – in blue, C_x – in black) at each iteration in the optimization process.

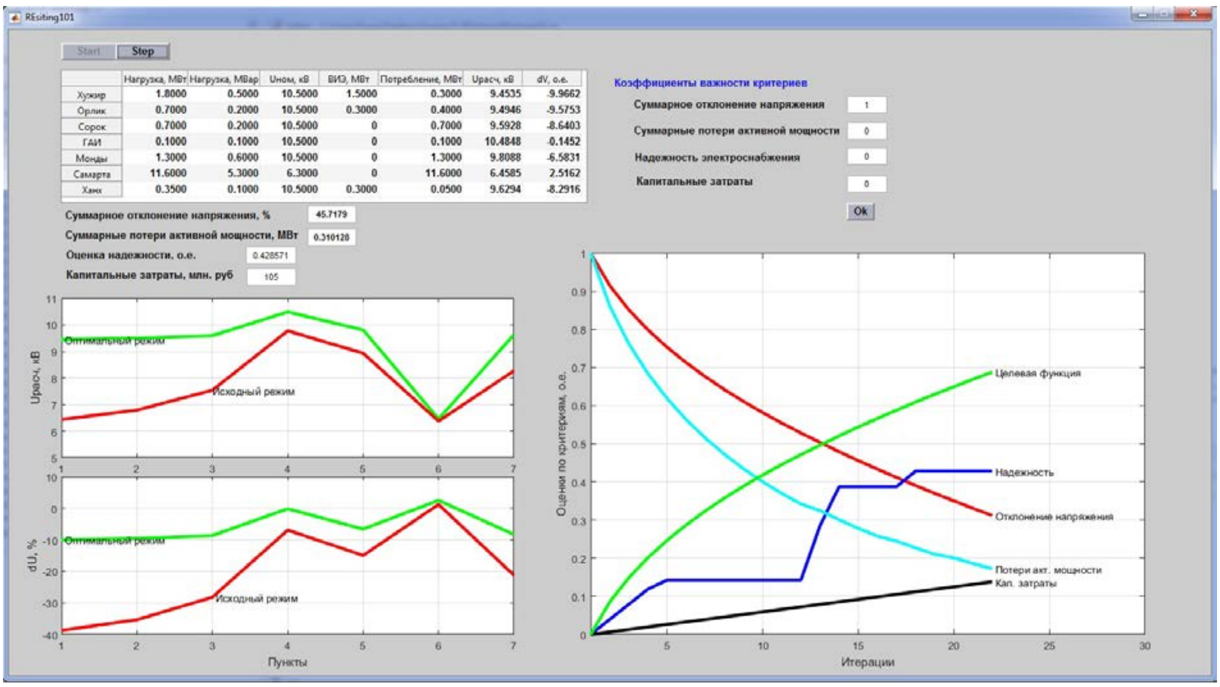

Fig. 5. Program interface for multicriteria optimization of RES locations and capacity. Results of one-criterion optimization.

Presented in Fig. 5, Table 3 results correspond to the optimization performed according to one criterion k_1 - total voltage deviation (k_1=1; k_2=0; k_3=0; k_4=0) (Table 3). The optimization step ΔP_{re} was equal to 0.1 MW.

Table 3. Results of assessing the voltage on the load buses.

Locality	RES capacity, MW	Calculated voltage, kV	Voltage deviation, %
Khuzhir	1.5	9.45	-9.97
Orlik	0.3	9.49	-9.58
Sorok	0	9.59	-8.64
PTS	0	10.48	-0.15
Mondy	0	9.81	-6.58
Samarta	0	6.46	2.52
Khankh	0.3	9.63	-8.29

Table 3 shows that to reduce the voltage deviation at load buses to the permissible 10% by installing the SPP, it is advisable to place the photovoltaic modules in Khuzhir, Orlik, Khanh. The installed capacity of the SPP should make in the sum about 2,1 MW taking into account solar energy potential and climatic conditions of the regions. The total voltage deviation from the nominal value at the substations will make 45.72%. Total active power losses ΔP_{Σ}=1.87%. However, such variant of installation of SPP does not provide high assessment of power supply reliability. According to formula (3) at L_i=0.2, reliability assessment R=0.43 (with the maximum possible value equal to 1), since only three substations have RES redundancy. Capital costs for this option, according to (4), at w=50 thousand rubles / kW will be C = 105 million rubles.

Fig. 6 and Table 4 show the results of optimization carried out taking into account all criteria (k_1=0.6; k_2=0.1; k_3=0.2; k_4=0.1).

Table 4. Results of assessing the voltage on the load buses.

Locality	RES capacity, MW	Calculated voltage, kV	Voltage deviation, %
Khuzhir	1.4	9.45	-10
Orlik	0.2	9.5	-9.56
Sorok	0.2	9.67	-7.87
PTS	0.1	10.53	0.26
Mondy	0.3	9.9	-5.74
Samarta	0	6.46	2.57
Khankh	0.2	9.59	-8.68

As a result of multi-criteria optimization, the assessment of the reliability of power supply increased to R=0.86, since the consumers of 6 substations have a reserve of RES with a load coverage share of more than 20%. The total active power losses decreased to ΔP_{Σ}=1.75%. However, in order to achieve permissible voltage deviations, it will be necessary to install SPP with a total capacity of 2.4 MW, the costs will be C=120 million rubles.

The performed review and obtained results allow to draw the following conclusions.

1. For sustainable socio-economic development of the “Baikal-Khövsgöl” Cross-Border Recreation Area, it is necessary to ensure environmentally efficient and reliable power supply to existing and prospective consumers in accordance with the requirements for the quality of electricity. The expected commissioning of the Konevinsky gold deposit will lead to unacceptable voltage deviations on the load buses of the Mondy, Khankh, Sorok, Orlik, Khuzhir substations, as well as high active power losses in the power distribution grid.

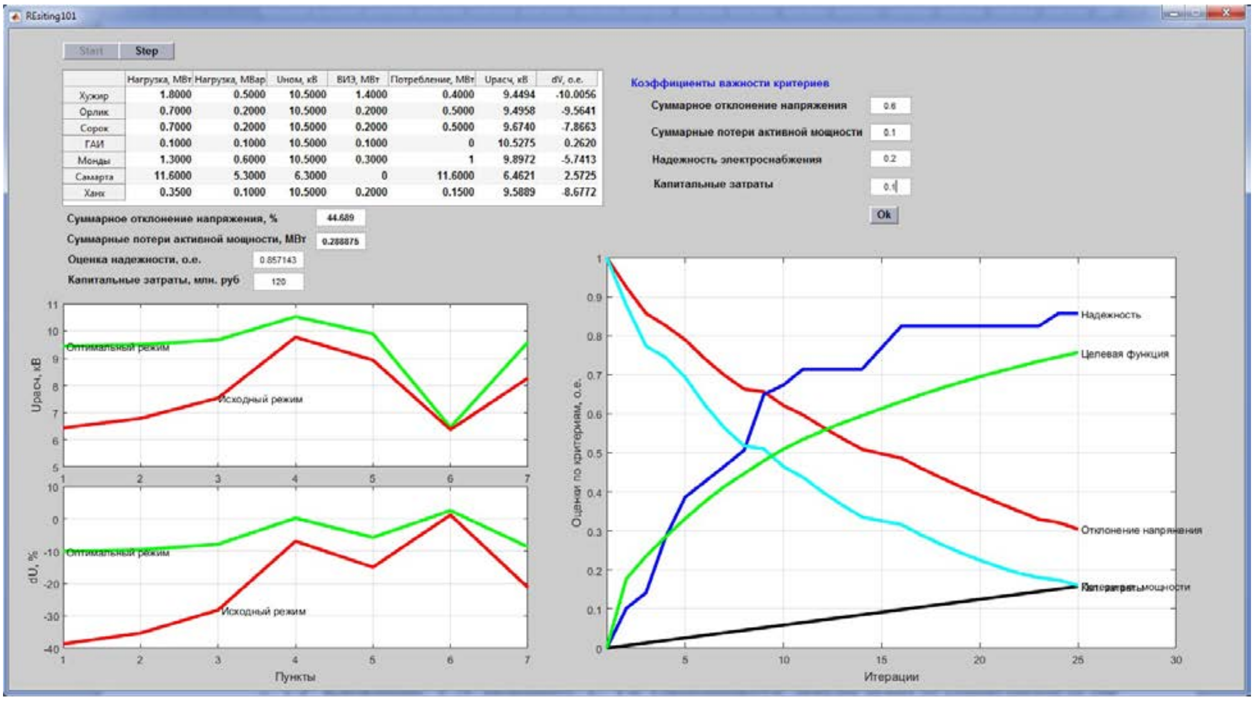

Fig. 6. Results of multi-criteria optimization of locations and capacity of SPP

* Corresponding author: shakirov@isem.irk.ru

2. The area under consideration has a high level of solar energy potential. Installation of SPP in settlements will improve the reliability of power supply, ensure an acceptable voltage on the load buses, and reduce the loss of active power.

3. An algorithm and a program for multi-criteria optimization of RES locations and capacity are proposed. The program allows to get solutions that meet the preferences of the DM, expressed through the coefficients of importance.

4. Using the program, the variants of locations and installed capacity of SPP were obtained, which provide permissible voltage deviations at consumers, low total active power losses, high reliability of power supply.

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* Corresponding author: shakirov@isem.irk.ru

Low-carbon development strategy of Russia considering the impact on the economy

Andrey Kolpakov[1*]

[1]Institute of Economic Forecasting of the Russian Academy of Sciences (IEF RAS), 47 Nakhimovsky Prospect, Moscow, Russia

Abstract. The article considers the impact of national climate policy on the development of the Russian economy and energy sector. Implementation of an aggressive scenario (which is aimed at containing at any cost the rise in global temperature within 1.5 °C compared to the pre-industrial era) is unacceptable to Russia from socioeconomic perspective given it leads to lowering the average annual GDP growth rate by 1.8 percentage points by 2050. Effective long-term development strategy with low GHG emissions level should focus on structural and technological modernization of the economy; improve the absorption potential of the LULUCF sector; stimulate only those structural changes in the energy sector that involve production and technological chains within the country and do not provide for excessive price growth. Russia retains a significant potential for energy efficiency growth, and the necessary condition for activating this process is sustainable economic growth as it involves modernization of the production facilities and using available and competitive industrial capacities. The implementation of a reasonable scenario, based on these principles, would allow Russia to fulfil the nationally determined contributions within the Paris Agreement while ensuring economic growth at the rate not less than the global average one.

1 Overview

The climate agenda and the goal of transferring the world economy on a development trajectory characterized by low greenhouse gas (GHG) emissions is one of the priority areas in the modern world politics. The Paris Agreement adopted in December 2015 is a document declaring the aspiration of the international community to limit the anthropogenic impact on the planet's climate. The goal of the Paris Agreement is to preserve the increase in average global temperature by the end of the 21st century within 2 °C relative to pre-industrial indicators, and also to make every possible effort to weak the climate warming even more and stay within 1.5 °C.

Russia signed the Paris Agreement in 2016, stating as a nationally determined contribution (NDC) the goal of restraining net GHG emissions 25-30% below the 1990 level, and ratified it in 2019.

In 2017, net GHG emissions in Russia (taking into account the LULUCF sector – Land use, land use change and forestry) amounted to 1578 mln tCO_2-eq., being at 51% of the 1990 level. On the one hand, the country has a certain "margin of safety" in terms of a potential increase in emissions. On the other hand, there are several arguments that force us to take the topic of limiting emissions seriously.

First, over the past decade, the average annual GDP growth rate in Russia did not exceed 1%. The current situation is perceived as unacceptable by both the political and the expert community. A sound consequence was the President's May decree, the key goals of which are related to accelerating the national economic dynamics (to the level not lower than the world average one), the growth of the population's real income, the fight against poverty. The problem is that the reaching of these goals with the existing production and technological structure of the Russian economy may cross the "Paris" limit on GHG emissions already in 2030-2035. [1]

Second, in the retrospective period, the most important driver for reducing net GHG emissions in the country was the carbon absorption by Russian forests. During 1990-2010 the absorption of GHG emissions by forests has grown 3 times from 225 to 749 mln tCO_2-eq. However, a turning point occurred then, and by 2017 this indicator decreased by 13% to 655 mln tCO_2-eq. There are risks of a further serious decrease in the absorbing capacity of Russian forests. Given the current scale of logging and the level of fire protection, as well as taking into account the increase in forest age, the level of annual carbon accumulation in Russian forests will halve by the mid-2030s [2].

Third, the Paris Agreement involves the principle of increasing ambition, which means a gradual lowering the GHG limiting cap. Therefore, after 2030, Russia's goal to curb net GHG emissions may well be 65-70% or even 60-65% of the 1990 level, which will seriously aggravate the GHG emission regulation agenda.

The largest source of GHG emissions is the combustion of carbon-containing fossil fuels to meet energy demand, with the accompanying production of CO_2. Energy

* Corresponding author: ankolp@gmail.com

related CO_2 emissions accounted for two thirds of all GHG emissions in Russia (excluding LULUCF). Table 1 shows the drivers of forming the energy related CO_2 emissions.

Table 1. Drivers of energy related CO_2 emissions in Russia and worldwide (1990 = 100).

	1990	2000	2017
Russia			
Energy related CO_2 emissions	100	68	71
Population	100	99	97
GDP per capita	100	68	122
Energy intensity of GDP	100	105	70
Carbon intensity of energy	100	97	85
World			
Energy related CO_2 emissions	100	113	160
Population	100	116	142
GDP per capita	100	116	173
Energy intensity of GDP	100	85	65
Carbon intensity of energy	100	99	100

Source: IEA

In 1990-2017, energy related CO_2 emissions in Russia decreased by 29%. The main increasing driver for them was the economic dynamics – GDP per capita grew by 22% with a slight decline in the population (by 3%). And the key restraining factor was the 30% decline in the energy intensity of GDP. The carbon intensity of consumed energy (which depends on the structure of the various energy resources use) also contributed (but less than the energy efficiency parameters), decreasing by 15%.
In fact, the main restraining factor globally is also the energy efficiency improvement. In 1990-2017, energy related CO_2 emissions in the world increased by 60%. The main drivers of the increase in emissions were the growth of the population (by 42%) and GDP per capita (by 73%). The main limiting factor for CO_2 emissions was the reduction in the energy intensity of the world GDP by 35%. At the same time, the carbon intensity of consumed energy on the global scale has changed little over the past almost 30 years (and it has not decreased but increased by 0.4%). This is the reason why the low-carbon strategies developed and adopted in different countries, while continuing to rely heavily on the energy efficiency, are trying at the same time to activate the “structural” factor, promoting ideas for a complete transition to the energy system based on renewables, electrification (including transport) and hydrogen technologies.
Russia has significant potential to reduce the carbon intensity of its economy. The list of principal directions includes maximizing the absorption capacity of natural ecosystems, increasing energy efficiency in all areas of the economy, and structural transformation of industries towards reducing the GHG emissions. Moreover, many particular measures can be distinguished in each direction (use of the best available technologies; increasing the degree of processing the raw materials; forest planting; elimination of GHG leaks on the energy infrastructure; spread of renewables and smart grids in the electric power industry, electric furnace – in metallurgy, electric vehicles – in transportation; electric stoves – in the residential sector, modern systems of municipal waste management – in communal services, soil-saving technologies – in agriculture, etc.). The only question is which of the existing measures are effective in the Russian conditions and which are not.

2 Methods

In order to analyze the economic efficiency of different measures of decarbonizing the Russian economy, we used a system of macrostructural models developed at the IEF RAS. It includes the interindustry model of the Russian economy [3-4], supplemented by the calculated energy balance and the unit of net GHG emissions (Fig. 1).
Measures to reduce the GHG emissions are the exogenous factor that allows the transition between different scenarios. They affect most macroeconomic indicators through the dynamics of capital expenditures and restrictions/incentives on the output of particular products. Thus, the dynamics of production by type of economic activity is formed, which, among other things, is influenced by technological changes associated with shifts in the cost structure. Structural shifts in the economy, along with the parameters of the development of the external market and the structural characteristics of electricity generation, determine the indicators of the energy balance, which, as a factors for the output of the energy sector, return to the interindustry model providing the looped calculation structure.
The unit of GHG emissions is based on the results of the interindustry maroeconomic model (for non-energy emissions) and the energy balance (for energy related emissions). Another element of the emissions unit includes GHG removals in the LULUCF sector, which is mostly exogenous and based on the existing forecast for the carbon balance of Russian forests, but also involves the measures to increase their absorption potential.
Such approach allows to reconcile the dynamic and structural (sectoral) characteristics of the economy in the chosen scenario, as well as to take into account the specific issues of energy sector development in order to obtain the basis for calculating net GHG emissions.

3 Scenarios

The Baseline Scenario assumes the achievement of the goal to reach the Russian GDP growth rate not lower than the world average one as well as the targets of national development strategies in different areas. This scenario is based on the realization of the resource potential of Russia for the formation of incomes, which are used to achieve the adopted targets and provide the limited technological modernization of the economy (by financing technological imports).

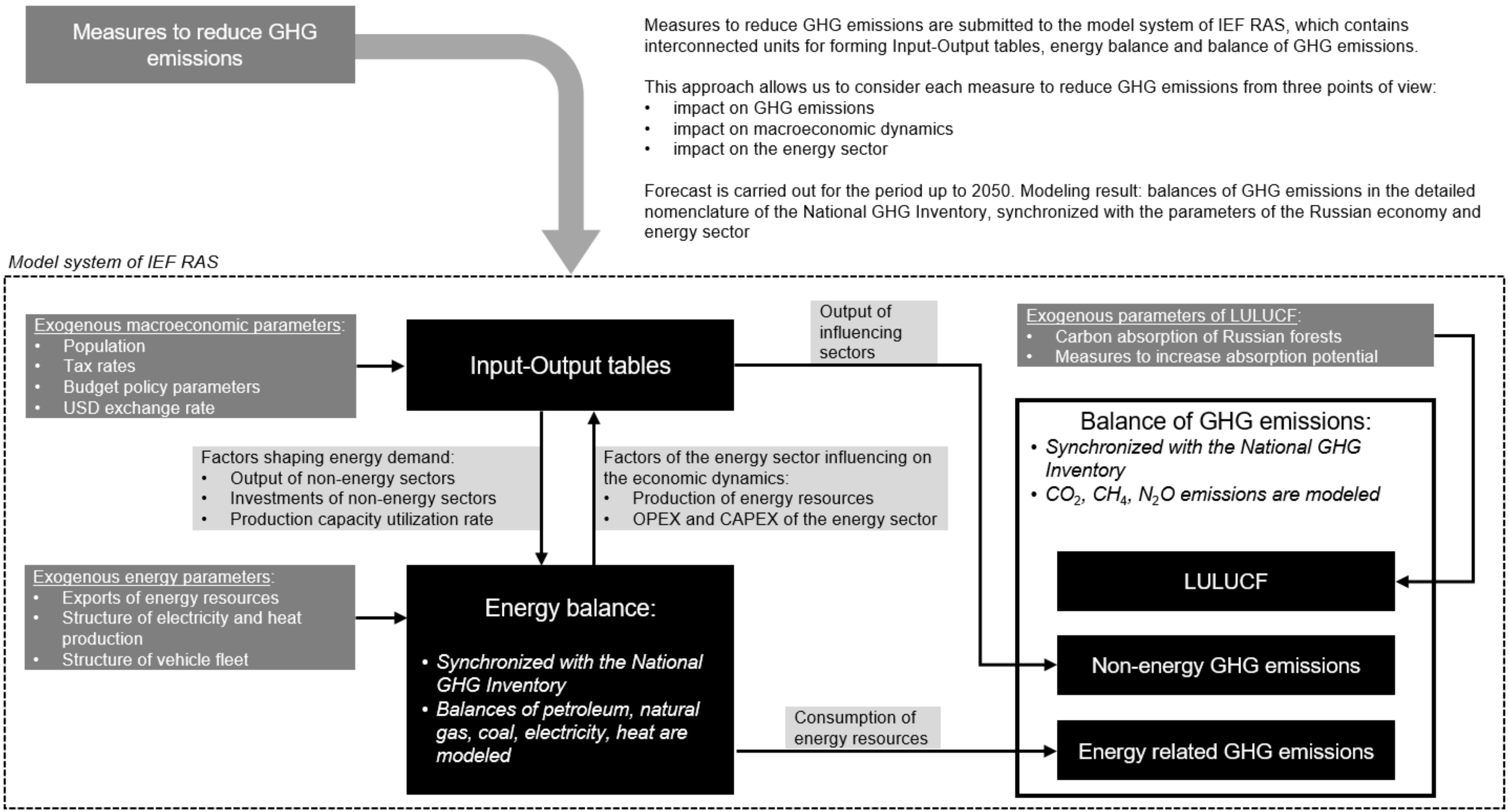

Fig. 1. Model system of IEF RAS for estimating the economy-energy-emissions triangle.

The key risk of the Baseline Scenario is that, without eliminating Russia's technological lag, net GHG emissions may reach the critical values (not allowing to fulfill Russia's NDC under the Paris Agreement) already by 2030-2035. In this regard, there is a task to build the scenarios of Russia's development which are in line with its existing climatic ambitions. This alternative includes two principle options.

The Reasonable Scenario is based on compliance with the Paris Agreement (taking into account the increase in the ambitiousness of the stated goals after 2030 to 60-65% of the 1990 level by 2050) mainly due to the internal potential of the Russian economy. In this scenario, the ultimate goal is to improve the quality and standard of living of people on the basis of structural and technological modernization of the Russian economy (which strongly relies on the income from the exports of energy resources and raw materials until 2030). A comprehensive increase in efficiency not only positively affects the carbon intensity of the Russian economy, but also allows financing of specialized measures to limit GHG emissions.

The Aggressive Scenario targets the reduction of net GHG emissions as the main tool for achieving the ultimate goal – preventing the global temperature from rising by more than 1.5 °C by the end of the century compared to the pre-industrial era – regardless of the possible consequences for sustainable development of the Russian economy.

Table 2 shows the characteristics of the developed scenarios.

4 Results

Fig. 2 shows the dynamics of net GHG emissions in Russia corresponding to each developed scenario; Fig. 3 shows the dynamics and structure of primary energy consumption; Table 3 presents a factor analysis of changes in the net GHG emissions and the average annual growth rate of the Russian GDP in the period up to 2050.

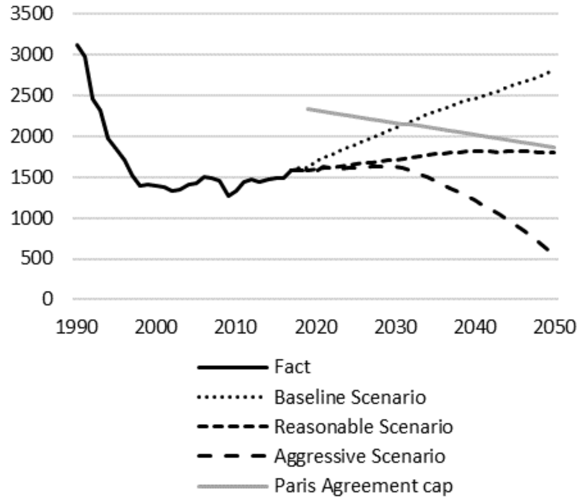

Fig. 2. Net GHG emissions in Russia for developed scenarios, mln tCO_2-eq.

The key features of the Reasonable Scenario (compared with the Baseline scenario) are as follows: a) lower total primary energy consumption due to higher energy efficiency given comparable rates of economic dynamics (more on this below); b) the decrease in the share of hydrocarbons in the primary energy consumption balance down to 74% by 2050 (for comparison, in the Baseline Scenario, their share is 84% in 2050, and their actual share in 2017 is 87%); c) the expansion of carbon-free forms of energy occurs mainly due to nuclear energy; d) the consumption of liquid and gaseous fuels is growing, but this is largely due to their non-energy use, because diversification of the economy will be associated with a dynamic expansion of chemical production (in 2017 a fifth of all petroleum products were sent for non-energy needs, and by 2050 already half of them can be used for such needs. The same values for natural gas are 10% and 25% respectively).

Features of the Aggressive Scenario: a) significantly lower primary energy consumption due to the decline in the economic growth (more on this below); b) the share of carbon-containing energy resources will decrease to 40% by 2050, and the expansion of the carbon-free energy resources share is based on renewables, which are massively replacing natural gas and coal in the power sector; c) though electric vehicles will occupy two-thirds of the vehicle fleet, the consumption of liquid fuels until the middle of the century will remain at a comparable level with the current indicators (which happens mostly due to non-road use).

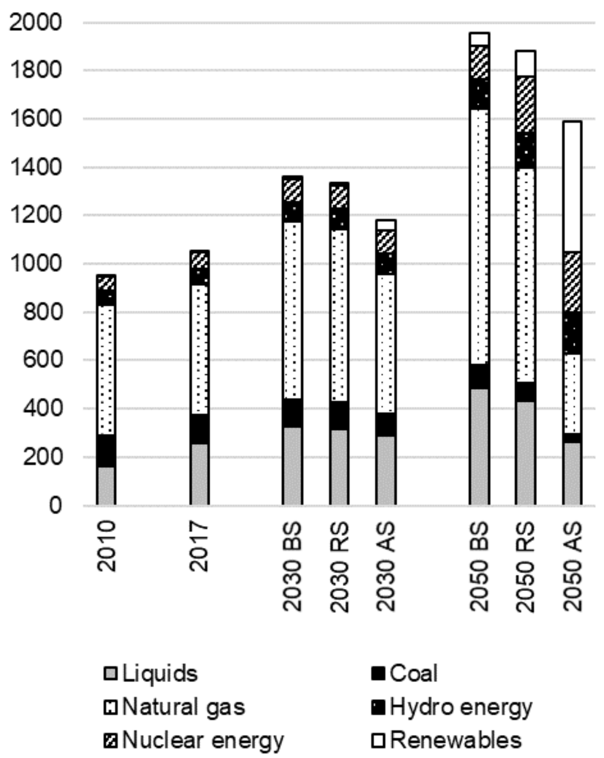

Fig. 3. Primary energy consumption in Russia for developed scenarios, mln tce (BS – Baseline Scenario, RS – Reasonable Scenario, AS – Aggressive Scenario).

Table 2. Parameters of GHG emissions scenarios in Russia (target values are presented for 2050).

	Baseline Scenario	Reasonable Scenario	Aggressive Scenario
General principles	Economic growth ensuring the improvment of the resource use efficiency	Economic growth ensuring the improvment of the resource use efficiency and diversification of the economy	Decrease in hydrocarbons exports by 90%; implementation of carbon tax ($10 per tCO2-eq. in 2030 with a gradual increase to $50 in 2050)
Production of electricity and heat	Reduction of hydrocarbons share in the fuel structure from the current 72% down to 55%; uniform growth in the shares of nuclear, hydro and renewable energy	Reduction of hydrocarbons share in the fuel structure down to 40%; accelerated growth of nuclear energy share (including with storage)	Reduction of hydrocarbons share in the fuel structure down to 15% and transition to renewables + storage system (50% share); capturing 25% of CO_2 emissions
Road transport + Refining	Increase in the share of electric vehicles in the personal car fleet up to 10%; improvement of the fuel efficiency (for personal cars) to 6.5 liters per 100 km	Increase in the share of electric vehicles in the personal car fleet up to 25%; improvement of the fuel efficiency (for personal cars) to 6 liters per 100 km	Increase in the share of electric vehicles up to 65% in the personal car fleet and up to 50% in the truck fleet; improvement of the fuel efficiency (for personal cars) to 5.5 liters per 100 km; capturing 25% of CO_2 emissions at refineries
Pipeline transport	No special measures	Reduction of CH_4 leaks by 30%	Indirect effect of hydrocarbons exports decrease; reduction of CH_4 leaks by 30%; capturing 25% of CO_2 emissions from pumping stations
Production of hydrocarbons	Stable rate of useful utilization of associated petroleum gas at the level of 85%	Increase in the rate of useful utilization of associated petroleum gas up to 99%; reduction of CH_4 leaks by 50%	Indirect effect of hydrocarbons exports decrease; increase in the rate of useful utilization of associated petroleum gas up to 99%; reduction of CH_4 leaks by 50%; capturing 25% of CO_2 emissions
Residential	Increase in energy efficiency of buildings by 25%	Increase in energy efficiency of buildings by 40%; transferring 50% of gas stoves to electricity	Increase in energy efficiency of buildings by 50%; transferring 90% of gas stoves to electricity; transferring 50% of heating to electricity
Agriculture	Increase in the average productivity of cows up to 5500 kg per year	Increase in the average productivity of cows up to 7000 kg per year, which makes it possible to reduce their livestock by 15%	Decrease in the number of cattle by 50%; changing the diet of the population; switching 50% of farming to organic methods
Metallurgy	Increase in efficiency of coke use by 30%	Increase in efficiency of coke use by 35%; transferring 30% of converters to electric furnace	Increase in efficiency of coke use by 35%; transferring 75% of converters to electric furnace; capturing 25% of CO_2 emissions
LULUCF	Decrease in LULUCF absorption by 85%	No growth in logging, voluntary reforestation projects at the level of 1% of business profit	No growth in logging, voluntary reforestation projects at the level of 1% of business profit
Waste	Inertial growth of waste associated with GDP per capita increase	Recycling 50% of waste associated with GHG emissions	Recycling 90% of waste associated with GHG emissions
Air transport	Increase in fuel efficiency by 25%	Increase in fuel efficiency by 25%	Increase in fuel efficiency by 25%; transferring 30% of air transportation to high-speed railway communication

Table 3. Factor analysis of the impact of measures to reduce GHG emissions on the economic dynamics in Russia under the developed scenarios.

Factor	GHG emissions, mln tCO_2-eq.	GDP growth rate (%) / Impact on average annual GDP growth rate up to 2050 (percentage points)
	Baseline Scenario analysis	
Fact – 2017	**1578**	**1.6%**
Baseline increase in output	+2534	+1.5 p.p.
Vehicle fleet growth by 65%	+127	
Baseline increase in energy efficiency of the economy (in all areas)	-1151	
Change in the sectoral structure of output	-713	
Baseline change in the fuel structure of energy consumption	-190	
Baseline reduction in the LULUCF absorption	+512	
Baseline waste growth	+105	
Baseline Scenario – 2050	**2803**	**3.1%**
	Deviations of the Aggressive Scenario from the Baseline Scenario in 2050	
Reduction of hydrocarbon exports by 90% (with an accompanying devaluation of the ruble)	-627	-1.4 p.p.
Decline in energy efficiency of the economy (due to a slowdown in the economic growth and investment)	+238	
Imposition of the carbon tax ($10 per tCO2-eq. in 2030 with a gradual increase to $50 by 2050)	-89	-0.07 p.p.
Spread of renewables – 50% share in the structure of power sector generation	-473	+0.27 p.p.*
Spread of electric vehicles (taking into account the imports required)	-150	-0.25 p.p.
Transferring 90% of gas stoves to electricity in residential sector	-234	-
Transferring 75% of converters to electric furnace in metallurgy	-18	-0.02 p.p.
Refusing of agriculture from cattle and nitrogen fertilizers by 50%	-111	-0.04 p.p.
Capturing 25% of GHG emissions in the real sector	-152	-0.19 p.p.
Waste recycling	-178	-0.02 p.p.
Increase in the LULUCF absorption (no growth in logging, reforestation projects)	-385	-0.03 p.p.
Other measures	-84	-0.06 p.p.
Aggressive Scenario – 2050	**540**	**1.3%**
	Deviations of the Reasonable Scenario from the Baseline Scenario in 2050	
Improving the structural and technological efficiency of the economy and exports	-155	+0.12 p.p.**
Additional change in the structure of power sector (mainly due to nuclear energy)	-121	+0.02 p.p.
Spread of electric vehicles (taking into account the imports required)	-34	-0.1 p.p.
Transferring 50% of gas stoves to electricity in residential sector	-71	-
Useful utilization of associated petroleum gas at the level of 99%	-73	-0.01 p.p.
Reduction of infrastructural GHG leaks	-49	-0.01 p.p.
Waste recycling	-94	-0.02 p.p.
Increase in the LULUCF absorption (no growth in logging, reforestation projects)	-385	-0.03 p.p.
Other measures	-17	-0.03 p.p.
Reasonable Scenario – 2050	**1804**	**3.0%**

* Large-scale spread of renewables will require a significant increase in electricity prices and investments. As a result, additional income will appear in the power sector and related industries that ensure the implementation of renewable energy projects. However, there will be negative effects from rising electricity prices and the need to increase imports. The cumulative effect turns out to be positive, but benefits will be generated in the infrastructure sector at the expense of non-energy sectors, which will only sharpen the structural problems in the Russian economy.

** Structural and technological modernization of the economy will require a significant increase in technological imports, which to some extent restrains the positive effect on economic growth.

Our estimations show that implementation of the Aggressive Scenario turns out to be incompatible with sustainable economic growth in Russia. The collapse of hydrocarbon sector, the devaluation of the national currency, high mitigation costs that are unproductive from the economic point of view at times, and the import of technologies to reduce emissions are factors that cannot be leveled out. The price of the Aggressive Scenario for the Russian economy is lowering the average annual GDP growth rate by 1.8 percentage points by 2050. In addition, tough measures to reduce GHG emissions involve energy costs increase to unprecedented levels – from the current 13% of the GDP to 30% of the GDP by 2040. Such a burden would hardly be compatible with economic growth. In any case, with such dynamics, economic growth will not translate into an improvement in the standard of living of the population. An important factor in the degradation of economic dynamics in this scenario is the inability to use the potential of the oil and gas sector in order to finance the modernization of the economy and the inability to fully replace its contribution to the formation of GDP with other sectors.

Following the Reasonable Scenario involves structural and technological modernization of the economy, which leads to an increase in its efficiency. It is the main resource that provides income to finance costs aimed at reducing net GHG emissions (a significant part of which is unproductive and associated with imports). As a result, the loss of the GDP growth rate turns out to be minimal (-0.1 percentage points in the period up to 2050).

Thus, with the correct alignment of priorities and the formation of a balanced climate policy, it is possible to achieve compliance with the Paris Agreement with a simultaneous growth of the Russian economy at rate not lower than the world average one.

5 Conclusions

Russia needs the long-term development strategy with low GHG emissions level focused on improving the quality of living, modernizing and increasing the competitiveness of the national economy. Such a strategy should rest on the following principles: 1) Russia has been the world leader in the GHG emissions reduction since 1990, so no solid reason exists for its soonest switching to excessively strict climate policy which result in additional restrictions to its socio-economic development; 2) The core obstacle to sustainable development of Russia is not a high level of the GHG emissions, but economic stagnation. Therefore, in terms of macroeconomic priorities, only such a scenario of restricting emissions is acceptable, which allows the Russian economy to develop with an average annual growth rate of at least 3%; 3) Action priorities in the area of the GHG sinking should involve improvement of the LULUCF sector potential by promoting sound natural resources management policy and voluntary projects to increase carbon absorption capacity of the ecosystems; 4) Action priorities to reduce GHG emissions assume the stimulating only those structural changes in the energy sector that involves production and technological chains within the country and do not lead to an excessive price growth. Such change includes increasing use of natural gas (as the «cleanest» fossil fuel) and nuclear energy (given Russia's leading position in the nuclear technology area), as well as cogeneration of electricity and heat. Pronounced increase in using renewables, energy storage systems and electric vehicles should be acceptable only if production of these is successfully localized and costs are reduced; 5) At the same time, Russia retains a significant potential for energy efficiency growth. A necessary condition for activating this process is sustainable economic growth as it involves modernization of the production facilities and using available and competitive industrial capacities. Specific measures targeted at energy savings will be inefficient given economic stagnation.

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Japan’s Energy Policy towards the SCO Member States: Current Situation and the Perspectives

Konstantin Korneev[1,*], and *Liudmila* Pechishcheva[2]

[1]Institute of Far Eastern Studies of the Russian Academy of Sciences, Centre for Japanese Studies, 117997, Nakhimovsky Av. 32, Moscow, Russia

[2]Russian State University for the Humanities, Faculty of International Relation and Foreign Area Studies, 125993, Miusskaya Sq. 6, Moscow, Russia

Abstract. The Shanghai Cooperation Organization is undoubtedly an important economic and geopolitical player in the Central, East and South Asia regions, bringing together countries of different size and potential. This is primarily about the economy and energy sectors, but the military-strategic partnership within the framework of the association shouldn’t be ignored too. Japan does not have a coherent policy towards the SCO as a single structure, at least it is not reflected in official documents, but individual member States are of significant interest. These are mainly Russia and China, and Russia is considered as one of the chief energy resources suppliers, which contributes to the implementation of the Japanese concept of energy security, aimed at maximum diversification of supply geography. China is regarded as one of the largest buyers of Japanese high-tech industrial products and an exporter of coal. The countries of the Central Asian region, which are rich in energy resources and do not have sufficient financial and technological capabilities to explore them, are also attracting more and more attention from Japan, but there is great competition with Chinese companies. India and Pakistan, that joined the SCO in 2017, are important for Japan as a counterweight to China's expansion in South Asia and also markets for Japanese nuclear power plant construction technologies and various types of renewable energy generators. All in all, Japanese energy policy towards the SCO member States is balanced and flexible, but the presence of certain geopolitical contradictions with the founders of the organization still hinders the building of a meaningful multilateral dialogue, although options for involving Japan in the Shanghai Cooperation Organization periodic work, for instance, in the observer status, have been repeatedly voiced.

1 Japan’s energy policy towards China

China like Japan belongs to the states with a deficit of its own primary energy resources, that are necessary to provide the growing economic and energy needs. Therefore, the main directions of energy cooperation between the countries are aimed at both supplying equipment and materials (for instance, generators for power plants based on renewable energy sources) and exchanging technologies in various energy sectors, including mining operation, electric power and mechanical engineering, etc.

Since the mid-2000s Japan-China relations have been temporarily alienated due to the strengthening of China's geopolitical positions and increased competition for sales markets from Chinese companies that have largely kept on the Japanese track. That is, at first, they actively borrowed technologies from abroad as well as placed stacks on their own manufacture and export of products at attractive prices.

Nevertheless, in the 1980s and 1990s Japan's role in modernizing the Chinese economy and energy sector as an integral part of it was enormous enough. During this time, more than 200,000 Chinese students have been trained at Japanese Universities. Japanese companies have also created more than 10 million jobs in China and invested approximately 130 billion USD in industry, agriculture and non-manufacturing business.

However, Japan quickly lost the status of China's key economic partner, yielding the palm to the US and the EU. In the near future, South Korea, whose trade turnover with China is only increasing, will probably drop Japan to the third place. As a long-term trend for the past decade and a half Japan has been trying to maintain the certain segments of the Chinese market for export of its own energy technologies. That is why the most promising is renewable and hydrogen energy [1].

According to the Japanese state forecasts, by 2030 the share of Japan's coal generation should be reduced to 26 % from the current approximately 40 % that implies a decrease in coal exports. Nowadays China takes sixth place on the list of Japan's coal suppliers. In 2019 Japan purchased about 10 million tons of Chinese coal for 306 million USD. The main import is from Australia (worth about 14 billion USD in 2019). By all accounts there are plans to further increase the share of Australia in

* Corresponding author: korinf2@yandex.ru

Japanese coal imports. If China-Japan cooperation faces a turn of instability and reciprocal reproaches, this is to be expected the coal supplies' reduction, especially as its significance for Japan's market is not so vital [2].

Since the early 2000s, China has been actively importing technologies for the renewable energy development, and Japan has consistently participated in this process. The matter concerns the sale of patents on production of individual units as well as wind power and solar power plants' ones, technological samples for the construction of low-power nuclear plants and the production of biofuel electric power, the operation of hydrogen fuel cell transport.

Until 2017 Japan has invested more than 200 million USD in China's renewable energy, with most of this amount was made up of loans for the purchase of appropriate materials from Japanese companies. Furthermore, among the major investors were Germany, Denmark, the USA, and Canada. According to some Chinese think tanks that deal with renewable energy issues, thanks to these technologies China was able to increase its capacity input growth by 30 % from 2007 up to 2016 and became the world's top power producer both in terms of the number and generation of electricity based on renewable energy sources [3].

Stress the point that among the significant areas of bilateral energy cooperation is China-Japan Comprehensive Forum on Energy Saving and Environmental Protection, first held in 2006 at the ministerial level. The recent Forum was held in Tokyo in December 2019. This platform is of great importance for the development of the energy dialogue between the two largest economies in Asia as well as the meeting point for politicians, economists, business and research representatives.

Despite its high status, the Forum is in fact still a discussion platform because the conclusion of any significant energy contracts that need fund-raising and production solutions is rare. For example, about 20 different treaties and agreements are annually signed in the field of energy saving, hydrogen energy, renewable energy sources' innovations, and so on, but most of these documents are optional [4].

Japan's energy policy towards China is in focus of the overall economic and geopolitical system of the bilateral relations. China is actively promoting the "One Belt One Road" initiative, that includes a wide range of economic and energy development proposals for Central, East, South and South-East Asian countries. In fact, today's China's role is more typical for the USA insomuch as China is trying to embrace the entire economic space surrounding it and strengthen its position as a global power that can provide its foreign partners with profitable projects.

On the other hand, Japan focuses on the project's development of the Trans-Pacific Partnership (TPP) even without the US participation. In 2018 11 countries signed a new trade agreement called Comprehensive and Progressive Agreement for Trans-Pacific Partnership that foresees the reduction or complete elimination of duties on industrial and agricultural goods. Tokyo officially is seeking to attract India, the largest Asian democracy, to participate in this Association, but so far these efforts have not succeeded, because New Delhi is not aimed at unambiguously joining any bloc, but it wants to maximize the benefits of cooperation with all states [5].

Actually, at the level of rhetoric, China and Japan offer each other to participate in their large-scale initiatives, but in fact the geopolitical gap between them is only growing, that is clearly based on ideological, not economic factors. An illustrative example is that during 2013-2018 Japanese companies' investment in China's economy fell by 60 % compared to previous five years. Among the 10 most developed countries in the world, this is the highest index, for example, for the US, the same indicator is 15 %, for Germany is 18 %. South Korea, which has currently complicated relations with Japan, only increases the presence of its capital in China by several percent a year.

Evidently, that the Chinese and Japanese perspectives on both regional and global systems of multilateral international trade and economic cooperation are fundamentally different. Tokyo stands for the so-called "new Atlanticism", which has covered the Pacific Ocean, and aims to build long-term partnerships with countries that are wary of Chinese expansion (Australia, Canada, India, and some Latin American states). Beijing is vice versa consistently pursuing a course of "New Eurasianism" or "Middle Way" with an emphasis on drawing neighbors into its economic and civilizational orbit, for geographical or strategic reasons, these states are far from the Atlantic camp. Naturally, Russian is one of the first countries in this emerging system [6].

2 Japan's energy policy towards Central Asian States

After the collapse of the Soviet Union in the 1990s, Japan provided a substantial financial and humanitarian assistance to Central Asian states. At that time, there wasn't any underplot; it was regarded as part of a program of assistance to newly formed transitional economies of the post-Soviet area. The situation changed by the mid-2000s, when China started actively promoting its interests in the region. China was looking for opportunities to create a safe and reliable corridor for the primary energy resources' supply in the future.

Japan also started building relationships with Kazakhstan, Kyrgyzstan, Tajikistan, Uzbekistan and Turkmenistan (the first four countries are now members of the SCO), trying to ensure a favorable attitude of the elites of these former Soviet republics at the intergovernmental level. Japan's key topic was power energy, namely, its participation in new oil and gas-field development. However, despite the efforts of officials, Japanese business responds cautiously to invest in the extractive sectors of these countries. Moreover, excessive Japan's activity in the post-Soviet area could cause disapproval from China, because at that time Japan-China economic relations were stable.

The 2010s were considered as the period of a new turn of official Tokyo's interest in the Central Asian republics, which was caused by a growing competition between Japanese, Chinese and Korean companies for the mining fields' access. The political dialogue "Central Asia plus Japan", launched in 2004, went into overdrive, according to which quite enormous investments were expected in various sectors of economy and energy of the Central Asian states.

Thus, Japan supposed to invest 8 billion USD for a few years in the post-Soviet area. Uzbekistan's economy has been modernized in such areas as geological exploration and mining operations (mainly natural gas), chemical and automobile industries. In Kazakhstan it was announced a nuclear power plant construction using Japanese technologies. Kyrgyzstan could receive a financial assistance for the modernization of the Manas airport in Bishkek as well as Tajikistan could count on several long-term loans in the amount of 7 million USD [7].

In some degree Japan tried to offer an alternative to China's "One Belt One Road" Initiative but the scale and nature of Japanese politics in Central Asia couldn't get rid of the perception of such a foreign policy as of minor importance. This is largely due to the Central Asian states' poverty, a small capacity of their domestic markets for Japan's industrial and digital products, and historically strong economic ties with Russia.

Nevertheless, Japan still takes a line on strengthening interaction with Kazakhstan and Uzbekistan, the largest economies in Central Asia. This especially concerns Kazakhstan, whose mutual trade turnover reached 1.5 billion USD in 2019. The matter concerns not only Kazakhstan's wealthy natural resources, but also Japan's "soft power" policy in the state. Japan allocates significant funds for the training of Kazakh experts, various humanitarian and cultural programs. Therefore, the perception of Japan among the Kazakh people is generally positive, which can't be said, for example, about China. Mention may be made of repeated mass demonstrations in 2018 and 2019 against China's purchase of land for plants' construction and making appropriate amendments to the Code of land laws in Kazakhstan.

Moreover, an important part of Japanese policy in Central Asia is the so – called "resource diplomacy" or the structure of trade, when Japan sells higher-value-added products (for instance, cars), and buys with these countries primary energy resources, ferrous, non-ferrous and rare-earth metals, and other mineral raw materials.

The "resource diplomacy" basis is to stimulate the export–oriented Japanese economy due to the development of new markets, but the Central Asian region does not fully comply with this concept because of weak trade and economic institutions and limited legislative efforts by governments to protect foreign investment. But it is of great importance that this region is really a strategically influencial bridgehead for Russia and China, so Japanese capital is not particularly welcome over there [8].

When it comes to Russian-Chinese dominance in Central Asia, it should not count out the national interests of Kazakhstan, Kyrgyzstan, Tajikistan and Uzbekistan. Despite their membership in the SCO, these states are trying to pursue an independent foreign policy, and here Japan can find its niche as a supplier of technologies for building new and upgrading old energy infrastructure. The Japanese experience in creating an efficient and sustainable electric power industry that is resistant to long-term natural and climatic impacts is one of the most advanced in the world, which is important for countries with outdated generating supplies and electric power transmission lines.

If there are prospects for mutually beneficial cooperation and appropriate institutional mechanisms, participation of Central Asian countries in projects under the SCO auspices won't be an obstacle for Japanese companies in the future. It is highly likely that Japan is about to continue its policy of strengthening its presence in Central Asia.

3 Japan's energy policy towards India

India-Japan energy cooperation as a reflection of the general state of the bilateral relations was formal and declarative until the mid-2000s, having the nature of memoranda of intent and framework agreements. However, in the 2010s India became one of the leading countries in terms of economic growth, which did not fall below 5 % a year. By 2030 India is likely to become the world's third economy and be beforehand with China on annual GDP growth, that will help to create more than 100 million jobs in India, especially in such promising industries as digital technology, information systems and robotics [9].

China is trying to expand methods and ways in promoting its national interests and presence in South Asia. The inclusion of South Asia in the strategically important regions for Beijing could not help but evoke response in Tokyo. By the way, it is a well-known fact that India as one of the key players in South Asia is in favor of non-alignment with military blocs. This means that Japan stands a good chance to establish successful rapport with its Indian partners and do the groundwork for investment cooperation in many sectors of the economy and power industry.

Two documents became the bedrock for the bilateral cooperation such as "Joint Statement towards India-Japan Strategic and Global Partnership" (signed in 2006) and "Japan and India Vision 2025 Special Strategic and Global Partnership" (signed in 2015). These agreements, that were signed almost 10 years apart, still formed the institutional basis for partnership not only at the foreign policy level, but also at the level of specific business projects in various spheres [10].

Japanese companies are investors and projectors of the Delhi-Mumbai industrial corridor, aimed at the comprehensive development of transport links, industrial and agricultural clusters, housing construction and various non-manufacturing business. The total project cost is about 100 billion USD, and about 26 billion USD falls to the Japanese investment. This corridor is a good opportunity for exporting Japanese technologies. More than one and a half thousand joint Indian-Japanese enterprises have already been launched.

As for the power industry, within the framework of the Delhi – Mumbai corridor it is expected to build power plants and power grid infrastructure, with a possible focus on renewable energy, because India as a resource-deficient country has to import primary energy resources. Wind and solar power plants' construction technologies from Japan are the most advanced in the world as well as they can be successfully applied in Indian realities thanks to climate, especially sunshine duration and strong seasonal winds in coastal zones [11].

Another integral part of Japan's energy policy in India can confidently be called the atomic power energetics. In 2016 it was signed "The India-Japan Agreement for Cooperation in the Peaceful Uses of Nuclear Energy", aimed at applying Japanese technologies in the field of peaceful atom for the construction of nuclear power plants in India. So, India is the first country on the list among those states that have not signed Treaty on the non-proliferation of nuclear weapons (but actually India possesses it). However, the Japanese government signed such an agreement with India insomuch as Tokyo is concerned in these potential projects [12].

The key current mechanism for India-Japan integrated energy cooperation is undoubtedly the bilateral Energy dialogue, which has been held annually at the ministerial level since 2009. In 2019 New Delhi hosted regular meetings within this format under the aegis of "3E+S", where it was debated such topics as energy security, energy conservation, economic efficiency and environmental issues. The Dialogue has a working group on electric power engineering, aimed at setting up and promoting a roadmap for the Japanese companies' activities in the construction and operation of new power plants and electric power transmission lines in India, as well as the modernization of existing capacities.

In the field of energy conservation, it was set up a joint energy conservation plan for India's energy-intensive industrial plants. It is assumed that pilot enterprises for experimental implementation of practical plan's provisions will be selected. Thus, in a few years it will be able to decide how effective the proposed methods were. However, if it takes into account Japan's wealth of experience in the field, the outcomes are expected to be positive. As for oil and gas sectors, the matter concerns the joint development of deposits in such countries as Russia, The United Arab Emirates, Canada, Mozambique and Sri Lank in cooperation with local companies.

In addition, one of the Plan's items refers to the development of hydrogen energetics in India based on the Japanese experience (transport and electrical generation). A worth-while project is the construction of pumped-storage station in West Bengal (the commissioning term is 2027), as well as other renewable energy plans aimed at gradually reducing CO2 air emissions [13].

Thus, India does not play a vital role in Japan's foreign energy strategy, but the situation is gradually changing in a positive direction and closer relations between two states. India is concerned in attracting Japan's energy technologies and investment. Japan is seeking to conduct an alternative trade and economic policy to China in South Asia, relying on states with a great development potential and high capacity of domestic markets.

4 Japan's energy policy towards Russia

The evolution of Japan-Russia energy cooperation is a complex and multifaceted topic. The collapse of the Soviet Union and the sequel market reforms of Russia's economy along with the liberalization of foreign policy, contributed to a certain rapprochement with Japan. In the mid and late 1990s, it was discussed and scientifically established various options for linking the electric energy systems of the two countries. The Sakhalin – Hokkaido power bridge project was the most significant one.

Leading Russian and Japanese think tanks such as Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, the Institute of Energy Economics, Japan (IEEJ) as well as major electric power holding companies RAO "UES of Russia" and Sumimoto have been working on this project. The potential exports' volume of Russian electric power was well-grounded, options for building an underwater cable were proposed as well as the project cost was calculated from 3 to 6 billion USD, depending on the conditions and technical characteristics. However, this initiative has not been carried out rather for political reasons, and it was replaced by new plans which are also periodically reviewed [14].

In terms of location the Russian Far East with its wealthy natural resources is close to Japan, aimed at diversifying energy supply. All these factors led to the serious debates since the mid-2000s on projects to export Russian oil and gas to Japan through terminals on Sakhalin. So, it was established the Sakhalin-1 and Sakhalin-2 Projects that were subsequently implemented. The basis of Sakhalin-1 Project was a consortium of such companies as American Exxon (30 %), Japanese Sodeco (30 %), Indian ONGC (20 %) and Rosneft (20 %). In 2018 on shelf deposits in the northeastern Sakhalin about 9.2 million tons of oil was produced, the main share of it (7 million tons) was sent by tankers to Japan.

Among the Sakhalin-2 shareholders are Gazprom (50 %), Shell (27.5 %), Mitsui and Mitsubishi (12.5 % and 10 % respectively). The Project produces annually approximately 10 million tons of liquefied natural gas, the lion's share of which is sent to Japan (providing 9 % of the natural gas demand) and South of Korea (4 % respectively) [15]. The researchers pay much attention to the history and future prospects of these Projects, so there is no sense to study it in detail, especially for the reason that the international cooperation on them is developing successfully. Evidently, if the parties are sufficiently interested in cooperation (with corresponding benefits at hand), political contradictions are safely "forgotten" and pale into insignificance exactly to the moment until they are needed again to cope with any immediate problems.

The Japanese-Russian trade turnover shows expository figures. At the end of 2019, it was 20 billion USD, and 8.5 billion USD accounted for the sale of power resources (total exports from Russia estimate 11 billion USD plus ferrous metals, aluminum, wood, precious and semiprecious stones) [16]. Japan supplied to Russia various goods on the sum of 9 billion USD, including vehicles, energy equipment, finished products made of ferrous and non-ferrous metals, digital equipment, and so on [17]. This pattern hasn't essentially altered for more than 15 years and it is likely to remain unchangeable in the future. First of all, this is a task for Russia's economy, which needs modernization and gradual but steady movement towards the development of globally competitive high-tech industries.

Nevertheless, an investment in the extractive sector is still a fundamental element of Japan's energy policy towards Russia. In addition to the system of agreements on the development of gas and oil fields on Sakhalin, Japan and Russia have signed a number of treaties, including some in the energy sector cooperation. In May 2009 Tokyo hosted the Russian-Japanese Economic Forum the main purpose of which was finding the ways to overcome the crisis, including the energy dialogue intensification.

In November 2010 it was a meeting of the Russian-Japanese Advisory Council on modernization of Russian economy and power industry. Despite Japan's formal access to anti-Russian sanctions, in November 2014 another APEC summit was held as well. A similar meeting was held at the II Eastern Economic Forum in September 2016 and the III Eastern Economic Forum in September 2017. In 2019 the Japanese delegation visited St. Petersburg International Economic Forum, at the end of which it was signed an agreement on the purchase by a consortium of Japanese companies of 10 % of the Arctic LNG 2 Project that is worth about 3 billion USD (the field development is headed by Novatek).

At the events listed above, both major energy projects were discussed, and issues of cooperation in the development of electric grid infrastructure in Russia together with Japanese companies, especially in remote Northern regions, the construction of low-power nuclear power plants and power plants based on renewable energy sources. All these proposals are still in the nature of intent, but the situation itself, when Japanese businesses are concerned in investing in Russian energy on a broader list of projects, seems to be optimistic. Japan and Russia understand that the geopolitical conditions may change, that is why they keep a restrained interest in each other, despite the circumstances [18].

However, Japan is not trying to make Russia a leading supplier of energy resources, despite its geographical proximity and, therefore, lower logistics costs. This is due to Japan's constant position on the primary energy imports, which stems from energy security issues. Excessive dependence on any one exporter puts Japan in a vulnerable position that is unacceptable. Therefore, Japan is about to purchase annually no more than 2 million tons of liquefied natural gas from the gas-fields of the Arctic LNG 2 Project. The plant is expected to be launched in 2022 – 2023. In the future it is possible to increase purchases of Russian liquefied natural gas, but it will also much depend on the situation on world markets [19].

Nowadays there are debates how to attract Japanese investment to construct an annual 6.2 million-ton liquefied natural gas plant (in addition to an export oil terminal) within the framework of the Sakhalin-1 Project. The building cost of the plant is worth 9 billion USD, and the first gas will be shipped to Japan not sooner than 2027. It is also planned to build a 200 km length gas pipeline from Sakhalin to Russia's mainland. According to preliminary forecasts, liquefied natural gas supplied from the new terminal is about to provide up to 10 % of Japan's needs, which together with the existing capacity of the Sakhalin-2 Project, will help Russia's gas to possess up to 15-17 % of the Japanese market. The Japanese presence in Russian gas projects is also likely to be consolidated through the participation in the building of the Murmansk LNG terminal (with a capacity of 21 million tons per year) and the Kamchatka terminal with a capacity of 21 million tons per year by 2023 [20].

If the matter concerns Japan's energy policy towards Russia, it should be taken into account two factors. The first one is the solution of the "Northern Territories" issue in Japan's favor, and the second one is the decline in the importance of China as the most promising energy Russia's partner. As for the "Northern Territories" issue premier-minister Shinzo Abe said it time and again that he is seeking to a successful solution of this issue for Japan until the end of his term (autumn 2021). However, an essential progress has not been achieved yet. Japanese society is not fully satisfied with "Joint development" program because it is very limited and, in fact, do not bring the moment of islands' transfer to Japan.

Therefore, many economic and energy Japanese projects and initiatives in Russia should be viewed precisely through the prism of the territorial belonging of the Kuril ridge. If Tokyo understands that the solution of the Kuril Islands issue is high, it will be a temporary intensification of Russia-Japan cooperation as well as Japanese investment boom. However, there are other strictly economic restrictions (the peripheral position of the Far East in Russia's economic development model, the region's sparse population) that determine both low business activity and low level of consumption of goods and services. It should be also mentioned the geopolitical aspects (countries' aspiration for different global centers of power and visions of the world order).

As for the "competition" with China on energy projects in Russia, this rather follows from the multi-vector nature of Japanese foreign policy and is an echo of the general Japan-China tension due to China's active trade, economic, military and strategic expansion in the Asia-Pacific region as well as Beijing's cautious but consistent promotion of the idea of China's global leadership. Somehow or another, Tokyo officially takes up a moderate position on the "resource dialogue" issues with Russia, emphasis is placed on its national interests and understanding that there are no suitable conditions for enhancing today's cooperation.

5 Conclusions

The SCO member-states are perceived variously by Japan in the context of its regional energy policy that is due to significant differences between these states. While Russia and Central Asian countries are playing the role of suppliers of primary energy resources to Japan, a more complex and multi-vector interactions are being built with India and China because Japanese companies are interested in the presence of the energy technologies and services on the Indian and Chinese markets, that have a large capacity and development potential.

Japan's foreign energy policy is pragmatic and primarily pursues the goal of providing the country with the most efficient and uninterrupted energy supply. In general, Japan follows "soft power" means and tactics, when, in addition to obtaining financial and economic benefits, the bet is also placed on promoting the country's positive image abroad. This is the partner's position that is ready to help with technology and qualified personnel in the major energy projects' implementation, without setting strict conditions and requiring in return the inclusion in a certain orbit of "civilizational influence", which latently implies a number of Chinese initiatives.

Japan has its own position on many regional economic and political issues in spite of that fact that it is still a key US ally in the Asia-Pacific region. Against the background of rising China, the Asia-Pacific region is becoming the arena of the future geo-economic clash, and the SCO influence in this game will be only soaring.

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Areas of using environmentally friendly fuel combustion technologies at TPPs of the Irkutsk Region

Georgiy Lachkov[1*]

[1]Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

Abstract. The use of coal as the main fuel at thermal power plants in the Irkutsk Region, the significant moral and physical depreciation at many of them of the main generating equipment, mainly boiler plants, due to the long service life, determine the relevance of environmental considerations in organizing rational energy supply to regional consumers in the future. The study of the age composition, technical and environmental characteristics of the boiler equipment of thermal power plants in the region. A review of advanced technologies for burning fuel in large installations with the aim of producing thermal and electric energy. Based on an analysis of the state and environmental characteristics of thermal power plants in the Irkutsk Region, a review of advanced technologies for burning fuel in large thermal power plants, the main directions of the future use of these technologies at thermal power plants in the region are considered, taking into account their features and environmental characteristics in order to reduce harmful emissions. The list of thermal power plants recommended for conversion to natural gas burning is determined, as well as the list of thermal power plants where it is advisable to use boilers with a ring furnace or boilers with a low-temperature vortex furnace. The potential volume of reduction of harmful emissions from the introduction of advanced technologies for fuel combustion at thermal power plants of the region is estimated.

The main commissioning of generating capacities of thermal power plants (TPP) in the Irkutsk region was carried out in the 60s of the last century. As a result, most of the main equipment of power plants, primarily boiler equipment, is physically and morally obsolete, causing significant harm to the environment (see table). In the foreseeable future, thermal power plants in the region will require significant measures to improve their environmental performance. This is primarily relevant for power plants with the highest specific emissions of harmful substances.

Table. Annual emissions of pollutants at the HPPs of the Irkutsk energy system, t

Name	Total emissions, t	Fuel burned, t of fuel equivalent	Specific emissions, kg / t of reference fuel
Irkutsk CHP-10	57678	1010579	57,1
Novo-Irkutsk CHP	56349	1230877	45,8
Irkutsk CHP-9	50794	954455	53,2
Novo-Ziminskaya CHP	23533	473301	49,7
Irkutsk CHP-11	21869	409859	53,4
Ust-Ilimsk CHP	20048	483036	41,5
Irkutsk CHP-1	18573	382359	48,6
Irkutsk CHP-6	15863	589343	26,9
Irkutsk CHP-5	5869	124535	47,1
Irkutsk CHP-7	3515	196343	17,9
Irkutsk CHP-12	2532	64148	39,5
Irkutsk CHP-16	2120	91945	23,1

According to [1], all operating large thermal power plants are divided into three groups:

• Boilers commissioned according to the projects approved by 31.12.1981;

• Boilers designed after 01.01.1982 and commissioned until 31.12.2000;

• Boilers commissioned from 01.01.2001.

The analysis of the composition and characteristics of the main generating equipment of the combined heat and power plants (CHP) of the region showed that the first group in the Irkutsk region includes: all boilers CHP-1, CHP-5, CHP-6 (except for boilers No. 9 and 10), CHP-9 (except for boilers No. 9-11), CHP-10, CHP-11 (except for boiler No. 9), CHP-12 (except for boiler No. 11), CHP-16, Ust-Ilimskaya CHP (except for boilers No. 6 and 7), boilers No. 1-4 of the Novo-Irkutsk CHP, boilers No. 1-2 of the Novo-Ziminskaya CHP, boilers No. 3-5 of the TPP-7.

For these boilers, the limiting values of technological indicators for emissions of solid particles and nitrogen oxides according to [1] are taken equal to the upper values of the range of actual indicators of specific emissions. The introduction of stricter restrictions for them is inappropriate for the following reasons: there are technical restrictions (lack of space) for the use of new emission control devices on these boilers; these boilers will be decommissioned or reconstructed in the foreseeable future due to relatively low indicators of energy efficiency, reliability, industrial safety or economic profitability.

* Corresponding author: g.lachkov@isem.irk.ru

It has been established that the second and third groups in the Irkutsk region include: boilers No. 9 and 10 of CHP-6, boilers No. 9-11 of CHP-9, boiler No. 9 of CHP-11, boiler No. 11 of CHP-12, boilers No. 5-8 Novo-Irkutsk CHP, boilers No. 6 and 7 of the Ust-Ilimskaya CHP, boilers No. 3 and 4 of the Novo-Ziminskaya CHP, boilers No. 1-2 and 6-9 of CHP-7.

For these boilers, the limiting values of technological indicators of emissions of particulate matter and nitrogen oxides according to [1] are assumed to be equal to the specific emissions that can be obtained using technologies existing in the industry.

It was revealed that at all CHPs of the Irkutsk region, the capabilities of flue gas cleaning systems are practically exhausted. Therefore, the cardinal means of ensuring environmentally friendly energy supply from TPPs in the region in the future, as noted in [2], is the use of the best available technologies (BAT) for fuel combustion.

Since all CHPs of the Irkutsk Region (with the exception of two departmental) are pulverized coal with flaring, of all the known BAT for fuel combustion in large boilers, the following are considered for use in the region: gas TPPs - taking into account the presence of the Kovykta gas condensate field (GCF) in the region; ring-fired coal-fired TPPs - taking into account the long-term positive experience of using this technology at Novo-Irkutsk CHP and coal-fired TPPs with a low-temperature vortex furnace.

The environmental benefits of gas-fired power plants are well known. According to [1], the mass of pollutants generated during the combustion of 1 ton of standard fuel (t of standard fuel) of gas is about 5 kg / t of standard fuel, and when burning 1 ton of standard fuel. fuel oil and coal - up to 300 kg / t of reference fuel.

Even a simple conversion of existing coal-fired power units to natural gas leads to a significant reduction in harmful emissions. For example, the conversion of the BKZ-210-140-7 boiler of the Khabarovsk CHP-1 from coal to natural gas made it possible to reduce the annual emissions of pollutants into the atmosphere by 1670 tons, including nitrogen oxide - by 109.7 tons, sulfur dioxide - by 592 , 5 tons, carbon monoxide - by 15.5 tons, solids - by 952.9 tons. The use of gas fuel also helps to reduce ash and slag and save the resource of the ash dump of the power plant. The previous seven boiler units of the Khabarovsk CHP-1 were gasified in the period from 2006 to 2016. During this time, emissions of pollutants into the atmosphere decreased by 2.5 times, the formation of ash and slag waste - by four [3].

The most efficient of the gas-fired TPPs are CCGT TPPs operating in a steam-gas cycle [4-6], the efficiency of which reaches 60-61% [4], and in the future may increase to 63-64% [5].

Coal-fired TPPs with a ring-fired furnace allow reducing nitrogen oxide emissions by 1.5-2 times. The use of annular furnaces when creating boilers for large power units allows: to reduce the height of the boilers by 30-40%; reduce their metal consumption and cost up to 10%; to provide slag-free and highly economical combustion of slagging bituminous and brown coals.

The only boiler in the world power engineering practice with a unique ring-type furnace and the largest drum-type boiler in the country - the BKZ-820 boiler operates at the Novo-Irkutsk CHP [7]. Long-term experience of successful operation of the BKZ-820 boiler with an annular furnace at the Novo-Irkutsk CHP and the study of the profile of boilers for 330 MW units firing brown and hard coal confirm the possibility of efficient use of boilers with annular furnaces both for the construction of new stations and for replacing spent large power units. with their installation in the existing cells of the main building. In this case, the power and parameters of the steam of the new block can be preserved or significantly increased [8-9].

Coal-fired TPPs with a low-temperature vortex furnace ensure stable ignition of low-grade fuels, no slagging of heating surfaces and a decrease in harmful emissions (nitrogen oxides - by 30-70%, sulfur oxides - by 20-50%). Low-temperature vortex (NTV) combustion technology is a domestic development. The NTV technology is based on stepwise vortex combustion of coarsely ground fuel under conditions of multiple circulation of particles in a chamber furnace [10-11].

NTV combustion technology has been tested on a wide range of solid fuels, including brown and hard coal. Among the latest successfully implemented projects are the modernization (in 2008) of the BKZ-210 boiler at the Kirovskaya CHP-4 (the multi-fuel boiler technology has been tested) and the technical re-equipment (in 2013) of the P-49 boiler, which is part of the 500 MW power unit at Nazarovskaya TPP.

The main application of gas technologies in the thermal power industry of the Irkutsk region is the conversion to natural gas of Novo-Ziminskaya CHP in Sayansk, CHP-12 in Cheremkhovo, CHP-11 in Usolye-Sibirskoye, CHP-9 and CHP-10 in Angarsk, Novo-Irkutsk CHP in Irkutsk with full-scale gasification of the region on the basis of the Kovykta gas condensate field. The choice of these CHPs for conversion to natural gas is due to their location along the route of the proposed main gas pipeline Kovykta - Sayansk - Angarsk - Irkutsk.

At the same time, it seems promising to introduce a steam-gas cycle at operating CHPs with the transfer of boilers to the combustion of natural gas and the superstructure of power units with gas turbine units (GTU).

The integrated technical and economic assessment carried out at the ISEM SB RAS using the actual performance of the thermal power station of the Irkutsk region identified the zones of efficiency of existing coal-fired CHPs and gas CCGT-CHPs created on their basis (see Fig.) [12].

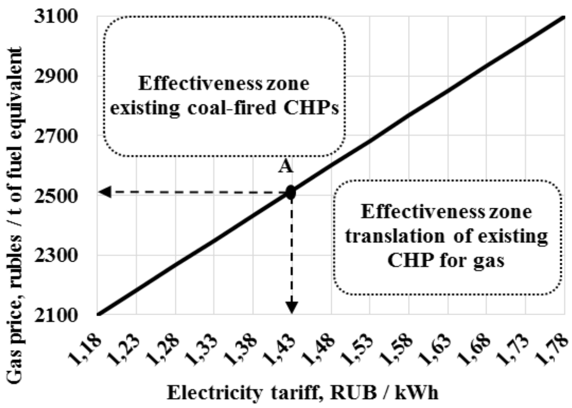

Fig. Effectiveness zones of projects for the transfer of CHPs to the combined cycle.

The constructed dependence makes it possible to choose a feasible variant of the CHP development in terms of two main external parameters - gas price and electricity tariff. So, for example, at a tariff of 1.43 rubles / kW • h and a gas price of just over 2500 rubles / tce. The options for the existing coal-fired CHP and its modernization at the CCGT-CHP are equally economical. At lower electricity tariffs, the conversion of existing coal-fired CHPs to gas seems to be ineffective, at higher tariffs - effective.

In the future, the use of gas technologies is also possible at newly constructed TPPs. So, in the Scheme and program for the development of the electric power industry of the Irkutsk region for the period 2019-2023, the commissioning of a 230 MW CCGT unit No. 1 at the gas Lenskaya TPP proposed for construction near the city of Ust-Kut is considered as additional proposals for the development of generation facilities in the region. The heat supply scheme for the city of Irkutsk for the period up to 2017 and with the prospect until 2027 as an alternative to the main variant of the development of the scheme (laying a heating main from CHP-10 in Angarsk to the Leninsky District of Irkutsk) considered the possibility of construction in different areas of the city three small CHP plants using natural gas. One of them (CCGT CHP with an electric capacity of 330 MW and a thermal capacity of 331 Gcal / h) can be built on the outskirts of Marat, and two others (GTU CHP with an electric capacity of 36 MW and a thermal capacity of 357 Gcal / h and a CCGT CHP with an electric capacity of 150 MW and thermal power 160 Gcal / h) - in the Leninsky district.

Ring-fired boilers and boilers with low-temperature vortex furnaces can be used in the reconstruction of Ust-Ilimskaya CHP, CHP-6 and CHP-7 in Bratsk, CHP-16 in Zheleznogorsk-Ilimsky.

Preliminary calculations show that the conversion to natural gas of Novo-Ziminskaya CHP in Sayansk, CHP-12 in Cheremkhovo, CHP-11 in Usolye-Sibirskoye, CHP-9 and CHP-10 in Angarsk, The Novo-Irkutsk CHP in Irkutsk will reduce annual harmful emissions by 128 thousand tons, and the replacement of coal-fired boilers with direct flaring with coal-fired boilers with a ring furnace or low-temperature vortex furnace at Ust-Ilimskaya CHP, CHP-6 and CHP- 7 in Bratsk, CHP-16 in Zheleznogorsk-Ilimsky will reduce annual harmful emissions by 5-12 thousand tons.

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Concept of Integrity, Reliability and Safety of Energy and Transport Systems for Cold Climate Regions

Valeriy V. Lepov[1,*], *Nikolay A.* Petrov[2], *Dmitry V.* Prokhorov[2], *Nikita V.* Pavlov[2], and *Vasiliy E.* Zakharov[2]

[1]Larionov Institute of Physical and Technical Problems of the North SB RAS, Fracture Modelling Department, 677980 Yakutsk, Russia
[2]Larionov Institute of Physical and Technical Problems of the North SB RAS, Energy Problems Department, 677980 Yakutsk, Russia

Abstract. The concepts of providing the integrity, reliability and safety of the energy and transport systems in the Arctic zone are considered. The inadmissibility of using the concept of acceptable, or tolerable, risk to ensure the operational safety of potentially hazardous facilities used in extreme environment has been validated by the history and reasons of risk analysis reviewing. The new concept for transport and energy systems operating in cold climates has been proposed to include in the security concept flexible information monitoring and control systems that take into account the state of environment, the engineering system and the operator himself. The promptness of implementation of the new concept of renewable development is dictated by the modern transitional state of society from thoughtless consumption of resources to the minimization of environmental damage and the inadmissibility of human casualties, called Industry 5.0.

1 Introduction

The concept of safety in modern regulatory documents is used as a synonym for providing some acceptable, or permissible, risk, which has a quantitative value, which is taken to ensure the operability of a structure or machine.

But in reality, safety is the opposite of hazard, and full-time operation eliminates any risk. Compliance with safety standards is a strict obligation of any production, construction, operation of a potentially hazardous facility. The risk is assessed only for events that can occur, subject to these standards. Risk analysis is intended rather to search a priori for unaccounted for hazards, or "weaknesses", in order to develop additional safety measures.

Therefore, setting an acceptable risk as a safety criterion only allows one to get away from the general problem of compliance with technical standards, from the human factor, the solution of social and psychological problems - and reduce it to a purely technical, engineering problem. The introduction of risk acceptability criteria into legislative practice leads to an increase in technogenic hazards for the majority of citizens, since it selfishly justifies non-compliance with safety requirements.

For example, at most modern industrial enterprises and concerns, including the domestic oil and gas complex, equipment reliability and integrity management (ESCO) is implemented on the basis of a risk-based approach and the concept of acceptable risk, in order to minimize economic damage and increase the overall economic result [1].

Moreover, in November 2017, a new version of the ISO / IEC 17025: 2017 standard was released, and in 2019 - the edition of GOST ISO / IEC 17025, where the emphasis on the organizational activities of the testing laboratory (TL) for quality assurance, including the use of process approach and risk management, which can be attributed to the main tools of the quality management system (QMS) IL [2]. The emphasis is on the conditions for meeting the requirements for risk management. Risk management moves into research laboratories, using tools: "brainstorming" and "consequences and probability matrices", which, generally speaking, are not applicable to security issues.

The need for a new concept of security is dictated by the new informational "knowledge society" and the fourth industrial revolution, so-called. "Industry 4.0" [3], as well as by the latest developments and changes in global economics associated with the pandemic, and forced to rethink modern technologies of the consumer society, the concept of "acceptable risk" and the fifty-year of sustainable development history.

2 History of the issue

Ensuring the safety of the population and the environment is a very complex engineering problem, the solution of which is impossible without improving and deepening engineering training in the field of reliability research, forecasting and ensuring the safety of engineering systems. In a number of industrialized countries, the study of the safety of engineering systems as a separate independent activity was introduced into practice in the sixties (for example, we can cite the activities of the United States since the 50s to create a

* Corresponding author: lepov@iptpn.ysn.ru

security system for aerospace technology). The focus has shifted from analysing the behaviour of individual elements of various types (electrical, mechanical, hydraulic) to the causes and consequences caused by the failure of these elements in the corresponding system. Failure Tree, Consequence Tree, Sequential Examination Method, Expert Judgment and other failure detection methods have been adopted by specialists working in the chemical and other hazardous industries, just from the military and aerospace research. It was in these countries that the 60s were marked by the beginning of the wide publication of scientific works related to the described field of research in Russia. Moreover, such the works had single editions. This followed from the concept of "absolute safety" of domestic technologies and equipment. Until recently, this concept was the foundation on which safety standards were built. Affected by the specificity of the political, economic and social development of the former USSR, which led to a lag of at least 20 years [4-5], in research in the field of industrial safety, life safety, and ecology, this attitude to safety problems hindered the formation of specialists' ideas about the principles and methods of ensuring industrial and environmental safety, which produced a lag in all areas of engineering and educational activities: design, manufacturing, operation, safety supervision, training of specialists, and on the growth of the number and scale of extreme situations and accidents at industrial enterprises, transport systems, etc. The requirement of "absolute safety", i.e. "zero risk" ultimately led to costly and even tragic consequences for the population and economy of the country. Specialists operating engineering systems and servicing hazardous technologies in the chemical industry, energy systems and pipeline transport were methodologically unprepared for the search and analysis of critical failures leading to accidents. The level of knowledge in matters of life safety in the technosphere lagged behind the level of complexity and development rates of technology, technology, engineering systems [6].

3 Risk analysis concepts

Currently, the following concepts of risk analysis have been adopted [6]:

- the technocratic risk concept based on the analysis of the relative frequencies of emergencies (emergency-initiating events) as a way of setting their probabilities. When used, the available statistics are averaged over scale, population groups and time;
- an economic risk concept in which risk analysis is considered as part of a more general cost-benefit study. In the latter, risks are expected losses of utility arising from certain events or actions. The ultimate goal is to allocate resources in such a way as to maximize their usefulness to society;
- the psychological risk concept is centered around research on interindividual preferences for probabilities in order to explain why individuals do not form their opinion about risk on the basis of mean values; why people react according to their perception of risk rather than an objective level of risk or scientific risk assessment;
- the social (culturological) risk concept is based on a social interpretation of undesirable consequences, taking into account group values and interests. Sociological risk analysis links society's judgments about risk to personal or public interests and values. The social approach assumes that existing cultural prototypes determine the way of thinking of individuals and public organizations, forcing them to accept some values and reject others.

The technocratic concept that is applicable to the engineering systems that we are considering. Within the framework of the technocratic concept, after identifying the risks (identifying the fundamentally possible risks), it is necessary to assess the consequences to which they can lead, i.e. the likelihood of related events and the associated potential damage. For this, risk assessment methods are used, which are generally divided [7] into phenomenological, deterministic and probabilistic. Let's consider the areas of their application.

The phenomenological method is based on determining the possibility of emergency processes proceeding from the results of the analysis of the necessary and sufficient conditions associated with the implementation of certain laws of nature. This method is the easiest to use, but it gives reliable results if the operating states and processes are such that it is possible to determine the state of the components of the system under consideration with a sufficient margin, and is unreliable near the boundaries of an abrupt change in the state of substances and systems. The method is preferable when comparing safety margins of various types of potentially hazardous objects, but it is of little use for analysing branched emergency processes, the development of which depends on the reliability of certain parts of the object and/or its protective equipment [8].

The deterministic method provides for the analysis of the sequence of stages in the development of accidents, starting from the initial event through the sequence of the expected stages of failures, deformations and destruction of components to the steady-state final state of the system. The course of the emergency process is studied and predicted using mathematical modeling, building simulation models and performing complex calculations. The deterministic approach provides clarity and psychological acceptability, as it makes it possible to identify the main factors that determine the course of the process. In nuclear power, this approach has long been the main one in determining the degree of safety of reactors. The disadvantages of this method are the potential to lose sight of some rarely realized but important chains of events during the development of an accident; the difficulty of constructing sufficiently adequate mathematical models; complex and expensive experimental studies are required to test the computational programs [6].

The probabilistic method of risk analysis involves both an assessment of the probability of an accident and the calculation of the relative probabilities of one or another path of development of processes. In this case, branched chains of events and equipment failures are analyzed, a suitable mathematical apparatus is selected and the total probability of accidents is estimated. The main limitations of probabilistic safety analysis are associated with insufficient information on the distribution functions of parameters, as well as insufficient statistics on equipment failures. In addition, the use of simplified design schemes reduces the reliability of the resulting risk assessments for severe accidents. Nevertheless, the probabilistic method is currently considered one of the most promising for future applications [6].

Based on the probabilistic method, various methods for assessing natural and man-made risks for the population can be built, which, depending on the available (used) initial information, are divided into [6]:

- statistical, when the probabilities are determined from the available statistical data (if any). The construction of such risk models requires a large amount of data obtained from observations or experiments, which is not always feasible;
- theoretical and probabilistic, used to assess the risks from rare events, when statistics are practically absent;
- expert (heuristic), based on the use of subjective probabilities obtained using expert assessment; are used in assessing complex risks from a set of hazards, when not only statistical data are missing, but also mathematical models (or the models are too coarse, i.e., their accuracy is low).

4 Analysis of failures and disasters in the energy industry and transport

At present, the adverse effects of energy facilities on people and the environment during their construction and operation have reached such proportions that they force us to consider the problem of safety of energy facilities as extremely important. Examples of major accidents with significant material and social damage that have occurred in recent decades in the power supply systems of a number of settlements in Sakha Republic (Yakutia) indicate that this problem remains particularly relevant [9].

The creation of databases on failures, as well as improving the quality of collection of primary statistical information, is of great importance for the development of a strategy for managing the operation of energy systems and improving the accuracy of analysis. In order to present the causes and consequences of emergency situations, some descriptions of accidents that occurred in Sakha Republic (Yakutia) are considered. For the analysis, examples were selected that contain more complete descriptions of various interrelated causes and consequences of accidents. Some of them are shown in Table 1.

In order to single out the most dangerous element in the power supply system, accidents are distributed among the main system elements, then accidents are distributed among the units of the unit within the system element. It should be noted that accidents occur in all the main elements of the power supply system, but their number and frequency of occurrence are different.

The analysis shows that the tendency to maintain high values of the risk of accidents in power supply systems is mainly due to the following reasons [10]:

1. Influence of climatic conditions on the peculiarities of the operation of engineering systems (low temperature, wind gusts, floods, thawing of frozen soils of the foundations of energy facilities);
2. High wear of engineering systems and equipment;
3. Insufficient level of development of the safety management system during the operation of electrical, water supply and heating networks;
4. Low qualification of service personnel or the so-called "human factor".

Table 1. Examples of accidents in the power supply system of Sakha Republic (Yakutia).

№	Description	Accident site	Detection date and time	Elimination date and time	Accident causes	Damage	Number of affected population
1	Disconnection of the 10kV overhead line from the "Kilyanki" substation	Churapcha district, Arylakh village	19.02.February 2014, 3:34 am	19 February 2014, 2:10 pm	Falling tree onto wires	-	-
2	Supply of heat transfer agent was stopped in 12 residential buildings	Ust-Maisky district, Petropavlovsk village	26 January 2014, 7:00 pm	26 January 2014, 10:25 am	An unidentified track brought down a section of the heating main, ∅100mm supply, and return pipelines damage	-	-
3	Stop of the boiler house "Kvartalnaya". Heat supply for 17 private residential buildings, 1 of 16 apartment buildings and 10 socially objects was disrupted (the houses have stove heating)	Vilyui district, Khalbatsy village	29 January 2014, 1:55 pm	29 January 2014, 7:30 pm	Ignition of sawdust on the roof of the building	-	-
4	Fire in the boiler room "Shkolnaya" (4 boilers, fuel oil)	Lensky district, Peleduy settlement	24 April 2013, 3:45 pm	24 April 2013, 1:10 pm	-	-	540

An analysis of measurements of the microhardness of welded joints made of 09G2S steel, used for metal structures in the North and the Arctic, was carried out, which showed that the ambient temperature practically does not affect the distribution of microhardness in the heat-affected zone (HAZ) of the welded joint, despite the significant difference in cooling rates. However, the accumulation of damage in the welding zone and HAZ is facilitated by the process of crack growth along grain boundaries, the intensity of which depends on the stiffness of the stress-strain state (SSS). High inhomogeneity of mechanical properties causes localization of stresses at microcracks and micropores. Thus, low values and high temperature gradients provoke the formation of cold cracks in the elements of welded [11] and cast structures, and also causes the destruction of elements of parts made of hardened steels [12].

On the basis of theoretical and experimental studies, a criterion for assessing the resource of structural elements is proposed, taking into account the phenomenon of ductile-brittle transition in steel by changing the value of the impact toughness KCV. Assessment of damage to metal structures during operation in different climatic zones of Russia shows significant differences (see Fig.), Which explains the earlier depletion of the resource of engineering systems in regions with extreme natural conditions [13].

At low climatic temperatures, the process of accumulation of total damage is significantly affected by a decrease in the plasticity of the material, measured by the value of impact strength. In this case, the stress-strain state of the elements of metal structures becomes much more rigid due to low climatic operating temperatures, at which a ductile-brittle transition occurs in the steels with the bcc structure [14].

Thus, it has been shown that, under low climatic temperatures, the process of accumulation of total damage is significantly affected by a decrease in the plasticity of the material, measured by the value of impact strength. In this case, the stress-strain state of the elements of metal structures becomes much more rigid due to low climatic operating temperatures, when a ductile-brittle transition occurs in the steels with the bcc structure (see Fig. 1).

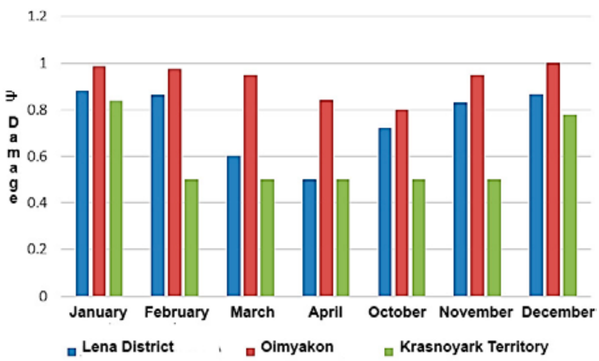

Fig. 1. Calculation of damage to metal structures made of steel 09G2S according to the data of average monthly temperatures for the regions of the North.

5 New security concept: Industry 5.0

A number of key probabilistic factors affecting safety and their interaction are not adequately taken into account, for example, the spread of properties and the accumulation of damage in the material, defectiveness of welds, external influences, as well as unskilled personnel actions, which leads to the inevitability of failures and disasters. not to prevent them. An expert, mostly economic, decision on the acceptability of risk makes it possible to avoid solving the complex problem of eliminating an accident or disaster, and leads to the inevitability of human casualties.

Until now, in modern regulatory documents, the probability of an accident or equipment failure is expressed as a classical probabilistic value, assessed by an acceptable, or admissible, statistical risk. The calculation of the probability is carried out without taking into account a priori knowledge, clarifying the values as a result of the history of observations and modeling. From the point of view of safety, setting the value of an acceptable risk allows us to get away from the general problem of protection against accidents and disasters, and reduce it to an economic problem [15].

A number of key probabilistic factors affecting safety and their interaction are not adequately taken into account, for example, the spread and change in material properties during operation, defectiveness and damage accumulation in welded structures, unskilled personnel actions (the so-called human factor), which leads to the inevitability of failures and disasters, and not to their prevention.

The application of approaches based on the non-Markov paradigm, in particular, on the Bayesian interpretation of probability, to assess the safety and resource of technology, will make it possible to make clearer predictions and prevent casualties caused by man-made factors [16].

The complexity of describing non-Markov processes is their nonlocality in time, mathematically expressed in the form of integro-differential equations, which determine the evolution of the system. One of the consequences of taking into account the history of occurring events is a change in the probabilistic picture. From the classical frequency one is moving to the Bayesian interpretation of probability, when it can be defined not as an objective accident, but as a measure of ignorance, decreasing with the receipt of additional information about the event. From this point of view, the Bayesian approach is a generalization of Boolean logic, it is more grounded and mathematically correct.

The simplest case of a non-Markov process is considered - the accumulation of damage and the destruction of a railroad wheel rim. In order to estimate the wheel temperature during operation and the corresponding reduction in toughness, a Bayesian approach was applied to estimate the probability:

$$p(\theta \mid T) = \frac{p(T \mid \theta) p(\theta)}{\int_{\theta_0}^{\theta_n} p(T \mid \theta) p(\theta) d\theta} \qquad (1)$$

where *p(Θ|T)* is a priori knowledge of the value of *T*, and probability of observing of a sample temperature $T=(T_1,\dots T_n)$ is determined by the value p(*T*|*Θ*).
The general condition of destruction will look as follows [17]:

$$\psi = \sum_{i=1}^{N} \frac{\Delta n}{N_i(T)} + \sum_{j=1}^{K} \frac{\Delta J_j}{J_C(T)} = 1 \qquad (2)$$

where ψ is a damage of material, *n* and *N* – number of current and maximum cycles of loading, *J* and J_C are the *J*-integral of the plastic zone near crack.

Determining the value of the J-integral in the general case is a rather difficult task in the real operating conditions. Therefore, one cold be used the available calculated and empirical dependencies for other characteristics of the fracture process.

Known logistic dependence of the estimate of the total accumulation of damage at different structural levels of deformation, as well as the correlation between the impact toughness *KCV* and fracture toughness J_{IC} at equal test temperatures, allows us to estimate the second term in (2).

So, proceeding from the well-known relation for the *J*-integral, assuming equal velocities of the dynamic impact on the wheel from the rail at different sections of the track, it can be assumed $J_{IC}=K_{IC}^2/2G$, where Gand *E* is Young's modulus of elasticity, and μ is Poisson's ratio. Whence, taking into account the associated flow law:

$$\psi_T = \frac{1}{K} \sum_{j=1}^{K} \left[\left(1 - \frac{KCV_j}{KCV_0} \right)^m \right], \qquad (3)$$

where KCV_0, KCV_j - impact toughness at room temperature, and at the moment of the *j*-th damage, respectively, m ~ 0.25-0.3 is a coefficient depending on the material and type of stress-strain state.

Taking into account (1), (2) and (3), the condition for the destruction of the locomotive wheel in general form will look as follows:

$$\psi_T = \frac{1}{K} \sum_{j=1}^{K} \left[\left(1 - \frac{KCV_j}{KCV_0} \right)^m \right], \qquad (4)$$

A numerical calculation of the damage accumulated in the tire of the locomotive wheel, taking into account the effect of low temperatures on the decrease in plasticity, was carried out, according to (3) and (4). On the section of the Neryungri-Tommot railway, the damage measure was $\Psi_L = 0.851$, while in the Moscow region, the calculation of the relative damage according to (1) gives the value $\Psi_L = 0.364$, which is more than 2-3 times lower than for the Neryungri-Tommot section in Yakutia. In reality, however, damage due to more severe operating conditions (the gap between the rails and the shock load will be much higher at low temperatures) differ even more. The experience of operating locomotives on the railway in the conditions of Sakha Republic (Yakutia) shows a threefold reduction in the service life of wheels compared to the resource in regions with a temperate climate.

Extreme natural conditions inherent in the regions of the Far North, Arctic and Subarctic, exacerbate a number of problems associated with the technical condition of objects in a very cold climate, and exacerbate, as the analysis shows [18], the impact of the human factor. Therefore, the new concept of ensuring security in the context of digital transformation should provide for the functioning of appropriate monitoring and control systems that take into account the impact of the environment on the technical condition of facilities and operators who ensure their operation. In the context of a recurring pandemic of viral diseases, the health indicators of workers can also be monitored along the way. The digitalization of energetics and engineering science leads to realization of Programs Industry 4.0 [19-20]:

- interoperability (compatibility of internet connections of humans, cyber-physical systems and “smart factories”);
- virtualization (creation of virtual model);
- decentralization (by making use of Artificial Intelligence ‘AI’, Internet of Things ‘IoT’, Industrial Internet ‘II’, Cloud Computing ‘CC’);
- real-time operation for monitoring and evaluation of complex engineering systems operation and human security.

On Fig. 2 shown the possible combining IoT, Industry 4.0 Programme, and energy management that suggest exciting future in Society 5.0.

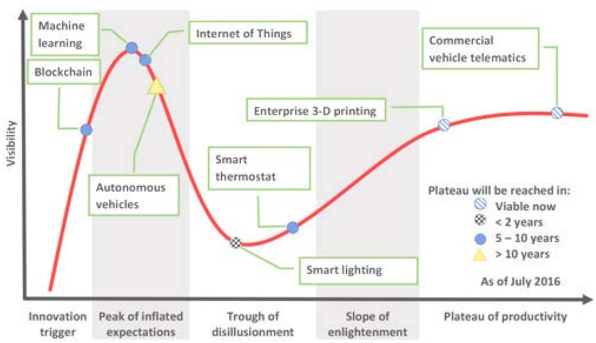

Fig. 2. Hype cycle of selected Internet of Things technologies (adapted from Gartner).

But the new concept should be more close to nature and shapes the Industry 5.0 main features:

- environment-friendly technologies, regeneration of natural resources;
- machine-learning Artificial Intelligence, Neural Networks and Neural Interfaces;
- abilities of self-heal damages and repair defects;

- Quantum Algorithms, Quantum Security and Quantum Encryption;
- self-assembly and self-improving by human supervision;
- Human Security as priority principle.

5 Conclusion

The new security concept for transport and energy complex engineering systems operated in cold climate should include the information from the monitoring and flexible control systems that takes into account the states of extreme environment, the engineering system damage and the operator health. The ‘absolute safety’ concept could be seen as a guarantee of minimal protective measures [21]. The damage accumulation processes in the complex engineering systems should by control by machine-learning artificial intelligence and switch the operation to repair and reconstruction stages.

It is proposed to move from consumer society technologies, defined by the concept of "acceptable risk" and "sustainable development" to a new concept of security based on renewable development, environment-friendly technologies for the extraction and processing of natural resources, closed production, using the achievements of the modern information society and Industry 4.0, which allows laying the foundations for the implementation of the upcoming Industry 5.0. This will mitigate the consequences of the global economic and social crisis and avoid scenarios of archaic or post-apocalyptic worlds.

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Modelling gas supply systems with a high role of autonomous consumers (the case of Mongolia)

Darya Maksakova[1,*], and *Sergei* Popov[1]

[1]Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Department of Complex and Regional Problems in Energy, 664033 130 Lermontov St., Irkutsk, Russia

Abstract. The paper presents a tool to optimize gas infrastructure systems and analyses some aspects of modelling related to autonomous gas consumers. A model of national gas infrastructure creation in Mongolia is proposed. The model is linked with the model of the regional Northeast Asian gas market and the financial models of gas infrastructure facilities. The model determines the optimal design of the national gas infrastructure system, i.e. the number of the facilities, their capacities, locations and the transport modes for connecting the consumption centres. The role of autonomous consumers is considered by introducing the demand for liquefied natural gas separately from the demand for pipeline gas. The scope of the model application is demonstrated by an illustrative example. The results show the rational natural gas import and distribution patterns. The need for expanding the energy cooperation between Mongolia and the other Northeast Asian countries to create gas industry in Mongolia is highlighted.

Keywords. Mongolia, Northeast Asia, gas supply infrastructure, modelling.

1 Introduction

Mongolia has rich coal, crude oil, solar and wind energy resources. In the cities, Combined Heat and Power Plants (CHPPs) fuelled by coal represent the basis of the energy supply systems. About a half of the county population resides in the capital city Ulaanbaatar. It is worth noting that more than 60 percent of Ulaanbaatar's population lives in traditional Mongolian houses (gers) equipped with stoves, which burn coal and are harmful to the environment [1]. The high air pollution level raise the problem of coal-to-gas switching in the energy production and petroleum-to-gas switching in the transport sector, including railways and special purpose vehicles in mining. Besides, mobile gers in agriculture can contribute to the demand for gas.

The country has no conventional gas resources, while there are significant coal-bed methane resources estimated at 3.2 trillion cubic meters [2]. Nevertheless, in spite of technical feasibility, high costs and capital investments, water supply issues and the lack of gas supply infrastructure are the barriers for the large-scale exploration and production of natural gas in Mongolia.

The issue of gas supply to Mongolia has been discussed for a long time since the end of the XX century. In 1998 Melentiev Energy Systems Institute carried out the research "The concept for development of the oil and gas industry in eastern regions of Russia and study on the possibility to export hydrocarbon resources to the APR countries" [3,4]. According to the concept, the gas pipeline "Irkutsk-Ulaanbaatar-Beijing" ought to have become a part of the unified gas supply system in the eastern regions of Russia. The pipeline has been discussed at the sessions of the Northeast Asian Natural Gas & Pipeline Forum (NAGPF). As a result of the researches conducted by the NAGPF, the demand for gas in Mongolia was estimated and the institutional and infrastructural requirements were indicated. Finally, the pipeline was included in "A Long-Term Vision of Natural Gas Infrastructure in Northeast Asia" [5].

The gas pipeline from Russia to China across Mongolia was discussed at the Shanghai Cooperation Organisation summits in 2018 [6,7] and 2019 [8] and at the Eastern Economic Forum in 2019 [9]. In September 2019 the President of Russia gave the assignment to the state-owned gas company Gazprom to analyse the opportunities to use the gas resources of Irkutsk Region, Krasnoyarsk Territory and the Yamal Peninsula for gas supplies to China across Mongolia [10]. In August 2020 Gazprom and the Government of Mongolia agreed to set up a special-purpose company for conducting a feasibility study for the construction and operation of the pipeline [11].

In 2018 by starting LNG (liquefied natural gas) imports from China and later in 2019 from Russia, the country made its first steps on the way to the gas industry creation. The construction of the gas pipeline from Russia to China passing Mongolia's territory "Irkutsk-Ulaanbaatar-Beijing" is to form the basis to meet total country's demand for gas and expand Mongolia's opportunities to participate in the regional Northeast Asian energy cooperation initiatives. Currently, the energy cooperation of Mongolia with the other countries of Northeast Asia (NEA) is limited to export of coal and crude oil, import of petroleum products, liquefied petroleum gases (LPG)

* Corresponding author: maksakova@isem.irk.ru

and a small amount of LNG, and electricity trade with the only neighbours Russia and China.

The structure of energy export of Mongolia to NEA is represented in Table 1. China is a major export market for Mongolia's coal resources and a sole importer of Mongolia's crude oil. Besides, China provides transit services for Mongolian coal.

Table 1. Energy export of Mongolia to the other NEA countries in 2019, million US dollars**.**

Importer	Coal	Crude oil	Electricity	Total energy export
China	3 073	306	-	3 379
Russia	†	-	†	†
Republic of Korea	†	-	-	†
Total world	3 073	306	†	3 379

† Less than 0.5.
Source: [12].

As Table 2 shows, almost all of the energy import comes to Mongolia from NEA. Russia is the major supplier of petroleum products and China provides most of the electricity import.

Mongolia plans to launch its first refinery with the capacity of 1.5 million tonnes of crude oil per year in 2022 [13]. Thus, the trade flows will be reshaped, as Mongolia will be able to stop petroleum products (including LPG) imports.

Table 2. Energy import of Mongolia from the other NEA countries in 2019, million US dollars.

Exporter	Petroleum products	Electricity	LPG	LNG	Total energy import
Russia	1 065	28	14	†	1 107
China	53	118	-	†	171
Republic of Korea	24	-	3	-	26
Japan	2	-	-	-	2
Total world	1 164	145	16	†	1 325

† Less than 0.5.
Source: [12].

Russia and China are the key Mongolia's trade partners. Moreover, the existent experience of energy trade and cooperation can be expanded further to exploit the advantages of bordering with Russia owning highly competitive and abundant gas reserves and China being expected to become the driver of the global gas market.

The aim of the paper is to propose a modelling framework to research the national gas supply system creation opportunities in Mongolia and to provide an illustrative example showing the opportunities of the described tools.

The objectives include:

- analysing the opportunities and limits of the existent model of Gas Infrastructure Development in the East Asian Region (GEAR),
- highlighting the special characteristics of the future gas infrastructure in Mongolia,
- formulating a model of the national gas infrastructure system of Mongolia interacting with the GEAR model,
- running an illustrative scenario to demonstrate the model opportunities and identify the areas for improvement.

2 Modelling tools

Mongolia's participation in the regional Northeast Asian gas market can be analysed by employing the GEAR model. The GEAR model is a linear programming problem that minimizes total costs to satisfy the demand for imported gas in China, Japan, the Republic of Korea and Mongolia subject to balance and infrastructure constraints [14].

It is a static model, i.e. it describes the Northeast Asian gas market for a specific year. The main inputs are gas production, pipeline transportation, marine and railway LNG transportation, liquefaction and regasification costs and aggregated demand for gas in the gas consumption centres (nodes).

The production and transportation optimisation problem GEAR allows identifying the most competitive gas suppliers and gas supply routes, estimating gas transportation volumes for the each route as well as the rent revenues, which are the difference between the dual (shadow) prices in the nodes and costs to supply gas to the nodes.

The GEAR model analyses the different scenarios to supply Mongolia with gas, namely, LNG import from Russia or China and the construction of the gas pipeline "Irkutsk-Ulaanbaatar-Beijing". The demand for gas is aggregated in Ulaanbaatar.

Analysing the role of Mongolia in the regional gas market described by the GEAR model is the first stage of the study. This model allows estimating the competitiveness of the supply sources and routes subject to limited capacities and provides with gas import costs estimations.

However, due to the fact that the country's demand is aggregated only in the single node, the necessity to build the national gas infrastructure, which would be different in the different import scenarios, is not taken into account.

That is why a special model of the national gas infrastructure creation is developed for Mongolia. The model considers the optimal directions of LNG or pipeline gas import and the construction of gas infrastructure facilities to satisfy the demand across the entire territory of Mongolia. The infrastructure facilities comprise pipelines, vehicles with a cryogenic cistern for LNG transportation, liquefaction plants and regasification facilities.

The GEAR model supplies the model of the national gas infrastructure with such parameters as import costs and maximum import volumes. Such a linkage between the models allows estimating the impact of the Northeast Asian gas market frameworks on the national gas supply system design.

Every infrastructure facility type is described by a financial model. The financial models evaluate the cumulative discounted cash outflows from operations and investing activities. These outflows are to be the objective function coefficients of the national gas infrastructure model.

The financial models of the gas infrastructure facilities investment projects can also be used to analyse the opportunities for increasing the competitiveness of the gas supply options and improving the performance indicators of the facilities.

The financial models calculate the main financial indicators from sales to net income and return ratios. These models estimate the minimum price, or tariff, to ensure the equivalence of the cumulative discounted revenues and the cumulative discounted cash outflows from operations and investing activities.

The financial models interact with the model of the national gas supply system of Mongolia. Firstly, the cash outflows from operations and investing activities are the main input parameters in the model of the national gas supply system of Mongolia. Secondly, the capacities of the gas infrastructure facilities are chosen taking into account gas demand profiles for typical consumers.

On the one hand, the interaction between the financial models and the model of gas supply system allows identifying the financial and performance parameters that are necessary to achieve a certain level of the competitiveness. On the other hand, it allows identifying the competitiveness level when the financial and performance parameters are given.

3 The model of gas supply infrastructure in Mongolia

Mathematically, the model of national gas supply infrastructure is a mixed integer linear problem.

The integer variables are the number of constructed infrastructure facilities and the number of infrastructure facilities at the beginning and at the end of the modelling interval (projected time period). The infrastructure facilities are gas pipelines between the nodes, LNG vehicles delivering LNG from one node to another, regasification and liquefaction facilities in the nodes.

The non-negative variables are the volumes of pipeline gas and LNG transported between the nodes and the regasification, liquefaction and import volumes in the nodes during the last year of the modelling interval.

The objective is to minimize the cumulative discounted cash outflows from investment and operating activities to create and operate gas infrastructure and to import LNG and pipeline gas during the modelling interval.

The model has three types of the constraints:

1) balance constraints,
2) capacity constraints,
3) existing infrastructure constraints.

The balance constraints are calculated for pipeline gas and LNG separately. They ensure that the sum of net inflow of gas to the node from the other nodes, net inflow from transformation processes and import is equal to the demand for gas in the node during the last year of the modelling interval.

The transformation processes are regasification and liquefaction. Regasification adds the volume of pipeline gas in the node and liquefaction reduces the volume of pipeline gas in the node. And vice versa, liquefaction adds the volume of LNG in the node and regasification reduces the volume of LNG in the node.

Transportation, regasification and liquefaction losses as well as facilities' own energy consumption are accounted for in the balance constraints.

In this version of the model, import of pipeline gas is possible only along the pipeline "Irkutsk-Ulaanbaatar-Beijing" and LNG import is possible only along the Trans–Mongolian Railway.

The capacity constraints ensure that the volumes of pipeline gas and LNG transported between the nodes, liquefaction and regasification volumes in the nodes do not exceed the total capacities of the corresponding gas infrastructure facilities. The cumulative capacities are calculated based on the quantity of the facilities and their capacities.

Existing infrastructure constraints link the number of the existing infrastructure facilities at the beginning of the modelling interval with the number of the facilities at the end of the modelling interval.

It is assumed that there is no infrastructure at the beginning of the first period. Decommission is not considered in this version of the model as the useful lifetime of the gas infrastructure facilities exceeds the period within the modelling interval when gas demand exists (2025-2040).

4 Demand projections

We use a two-stage approach when making energy demand projections for NEA. Firstly, we project the scales and structure of final energy consumption to satisfy the demand for useful energy. Secondly, we project energy transformation and energy carriers international transportation volumes to estimate total primary energy consumption.

When estimating final energy consumption projections, the following assumptions are used:

- estimations of the future social and economic development,
- cost-performance parameters for the different energy technologies included in the projections,
- the difference in energy carriers prices.

In the model of national gas supply system of Mongolia, gas demand at the end of period is aggregated in the 25 nodes. Natural gas flows in and out the nodes. Besides, regasification and liquefaction processes take place in the nodes.

Pipeline gas demand and LNG demand are accounted for separately, with LNG demand representing the demand from transport sector and autonomous consumers. Thus, it is assumed that natural gas is transported from the node to its autonomous final consumers, whose demand is aggregated, only in a liquid state due to long distances and low consumption volumes. At the same time, pipeline transport can be used between the nodes.

In the illustrative example provided in this paper, we assume total country's annual demand for gas during the period 2025-2040 at 6.6 billion cubic meters (the so-called "high gas" case), with the demand for pipeline gas accounting for 3.7 billion cubic meters.

5 Capacity of the infrastructure facilities

The infrastructure facilities vary by their capacity types. In this version of the model, we consider three types of pipeline capacities, two types of LNG vehicles capacities, which correspond to the volumes of cryogenic cisterns, two types of regasification facilities and four types of liquefaction facilities (Table 3).

Table 3. Capacity types.

Infrastructure facility	Capacity type	Unit
Pipelines	{0.4; 0.6; 1}	billion cubic meters per year
LNG vehicles	{15; 40}	cubic meters per truck/cistern
Regasification facilities	{8; 17}	million cubic meters per year
Liquefaction facilities	{0.1; 0.5; 1.5; 2.5}	million tons of LNG per year

It is important to note that including or excluding the capacity types is an iterative process. If the modelling results show that in the node or on the route, a large number of infrastructure facilities with maximum capacity are used or the facilities with minimum capacity are underused, new capacity types should be added to ensure more rational results. And vice versa, the unused capacities can be excluded to reduce the computational time.

6 Infrastructure facilities costs

The financial models of gas infrastructure facilities calculate the following types of cash outflows:

- cash outflows related to constriction investments,
- cash outflows related to maintenance investments,
- cash outflows from operations.

The cash outflows related to construction investments take place before commissioning the infrastructure facilities. It is assumed that the infrastructure should be commissioned at the beginning of the year 2025, i.e. actually, a static version of the model is described. These investments consist in the investments in the capital equipment, ancillary equipment and buildings as well as design, engineering and project management costs.

The maintenance investments take place when the useful life of the assets is less than the modelling interval of the national gas supply system model. In this case, new equipment should be commissioned in order to substitute the equipment that has been depreciated.

The cash outflows from operations consider personnel costs, maintenance services costs, consumables costs and taxes. They do not comprise the costs related to the energy losses and own energy facilities' consumption because these costs are accounted for in the national gas supply infrastructure model, i.e. in the financial models, variable operating costs are not included.

In this version of the model, the cash outflows for regasification and liquefaction facilities and for LNG vehicles do not vary with the nodes and routes, correspondingly. At the same time, the investments in pipeline construction per km are different for the each route, as some expert assessments of local geography and climate are taken into account.

Table 4 demonstrates the energy services tariffs, which would be set by the infrastructure facilities, that ensure the equality between the cumulative discounted cash inflows from sales and the cumulative discounted cash outflows during the modelling interval 2021-2040. In other words, the Net Present Value achieved at these tariffs is equal to zero.

All cash flows are real, i.e. net of inflation. The real discount rate is set at 9 percent.

These tariffs do not take into account the energy losses and own consumption components. Besides, it is assumed that the infrastructure facilities work at full capacity. Thus, the real tariffs should be higher.

Pipeline tariffs depend on the distance, diameter and local geography and climate. The other tariffs depend on infrastructure capacities, as the location factor is not considered. The higher the capacities, the lower the tariffs.

Table 4. Energy services tariffs.

Infrastructure facility	Tariff	Unit
Pipelines	9-17	2020 US$ per 1000 cubic meters per 100km
LNG vehicles	8-20	2020 US$ per tonne of LNG per 100km
Regasification facilities	16-35	2020 US$ per 1000 cubic meters
Liquefaction facilities	175-202	2020 US$ per tonne of LNG

Fig. 1. Modelling results.

7 Modelling results

Figure 1 demonstrates the results of illustrative modelling. It is important to note that this illustrative example does not consider the stages of gas infrastructure creation. This means that the results would be different if the model considered that the consumers were connected to the infrastructure stage-by-stage. In other words, it would probably be better to build several infrastructure facilities with smaller capacities during the different periods than to build one facility with bigger capacity because the facility was being underused while the costs were being incurred.

The modelling results indicate that

1) An optimal solution is to build a mid-scale liquefaction plant with the capacity of 2.5 million tons of LNG per year in Erdenet. The feed gas is to come from the gas pipeline "Irkutsk-Ulaanbaatar-Beijing".

2) A very small amount of LNG (0.5 percent of the imported gas) is to be imported in the border areas by rail transport.

3) The construction of the branches from the gas pipeline "Irkutsk-Ulaanbaatar-Beijing" is possible in some areas in the eastern parts of the country, while LNG supply is more feasible in the western parts.

Conclusions

Mongolia can play an important role in the process of the Northeast Asian gas market development. The participation of the country will ensure not only cost reduction effect when transporting gas from China to Russia but also the environment for the creation of the country's own gas industry contributing to sustainable economic, social and environmental development.

The proposed modelling tools can be used to estimate the role of national gas consumption patterns and the niches of pipeline gas and LNG exporters when developing national gas supply systems.

The development of the modelling tools should be directed to take into account the stages of gas infrastructure development and the demand dynamics.

The model of the national gas supply system will be expanded to include an optimal schedule of infrastructure facilities commissioning. This schedule could reflect long-term energy strategy goals and thereby support decision-making process.

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Increased Environmental Requirements for Energy Objects in the Central Ecological Area of the Baikal Natural Territory: Problems and Condition for Implementation

Elena P. Maysyuk [1,2,*] and *Boris G.* Saneev [1]

[1] Melentiev Energy Systems Institute SB RAS, 130 Lermontov, Irkutsk, Russia
[2] Irkutsk Scientific Center SB RAS, 134 Lermontov, Irkutsk, Russia

Abstract. The most important document regulating the use of natural resources in the territories adjacent to the lake Baikal in Russia became the federal law No. 94 "On the protection of the lake. Baikal" from 1 May 1999. A list of prohibited activities has been approved for the central ecological area which now again discuss. Taking into account the categorization of objects that have a negative impact on the environment, the energy objects of the central ecological area are assigned to categories II and III. And in case of changes concerning of categorization in the list of prohibited activities, it means that operation of energy objects will prohibited. The main environmental problem of the energy sector is the use of coal and the presence of a hazard class 1 substance in the emissions. To achievement environmental requirements, it is necessary to replace coal with alternative environmentally friendly types of energy carriers (natural gas and electricity). In order to implement the increased requirements for energy objects, it is necessary to develop a special package of normative legal acts and government support measures, including significant financial costs, focused on this territory.

1 Introduction

Currently for the protection of the lake. Lake Baikal along with the fundamental legislative acts (the UN Convention and The law "On the protection of the l Lake Baikal") [1, 2] the Governments of Russia and the subjects of the Russian Federation have developed a series of documents regulating the protection of lake Baikal and the socio-economic development of the adjacent territory.

According to the recommendations of the UNESCO Committee, along with the adoption of the law "On the protection of the Lake Baikal" (1999), the boundaries of the world heritage site with an area of 8.8 million hectares were established, the Baikal pulp and paper mill was closed (in 2013) and other activities were done.

One of the results of the adoption of the law "On the protection of the l Lake Baikal" was zoning with the formation of the Baikal natural territory and release three ecological areas: central, buffer and area of atmospheric influence.

Increased environmental requirements in the central ecological area are mostly associated with the presence of specially protected natural territories in this area: national parks, reserves, reserves, etc. Such restrictions are reflected in Federal law No. 33 of 14.03.1995 "On specially protected natural territories" [3]. Outside the boundaries of protected areas, a special mode of life and nature management is regulated by the law on the protection of the Lake Baikal.

It was determined that in the central ecological area it is necessary to reorient economic activities and existing infrastructure to ecologically acceptable types, which will ensure a harmonious combination of the life of the population and the functioning of economic objects with the environment.

It should be noted that the boundaries of the World Heritage Site do not include five urbanized, industrially developed territories (Baikalsk, Slyudyanka, Kultuk, Babushkin, Severobaikalsk). Moreover, these settlements include in central ecological area and it is in these territories that the largest industrial enterprises are located, where the most active economic activity is carried out.

2 Basis position

For the Central ecological zone by the Government of the Russian Federation in accordance with the Federal law "On the protection of the Lake. Baikal" was developed and approved by the Resolution of the Government of the Russian Federation No. 643 of August 30, 2001 [4] the list of prohibited activities, which eventually amounted to more than 50 types, and changes in this list are currently being discussed [5].

In the current Resolution No. 643, the list of activities prohibited in the central ecological area of the Baikal natural territory that relate directly or indirectly to energy systems includes the following [4]:

* Corresponding author: maysyuk@isem.irk.ru

- Extraction of crude oil and natural gas.
- Production of sources of autonomous power supply.
- Electricity production with a unit capacity of power plants over 100 MW, as well as activities for the supply of energy produced in the central ecological area of the Baikal natural territory, outside this area.
- Energy production at nuclear power plants.
- Construction of main oil pipelines, gas pipelines and other product pipelines, with the exception of gas pipelines for local gas supply.
- Construction of buildings and structures for metallurgical, chemical and petrochemical enterprises, coal-fired boiler houses and thermal power plants, with the exception of overhaul, reconstruction, modernization of coal-fired boiler houses and thermal power plants, as well as their distribution networks.
- Wholesale trade in solid, liquid and gaseous fuels and related products.
- Neutralization of production and consumption waste by incineration without purification of emissions to standard quality.
- Activities for the provision of housing and communal services during the operation of sanatorium and resort and recreational complexes without structures that provide wastewater treatment and emissions of harmful substances into the atmospheric air up to the approved standards.

The draft Resolution of the Government of the Russian Federation of 2020 “On Approving the List of Activities Prohibited in the central ecological area of the Baikal Natural Territory” is currently changes made, which are primarily related to the categorization of objects that have a negative impact on the environment. The criteria for assigning objects to different categories are determined by the Resolution of the Government of the Russian Federation No. 1029 of September 28, 2015 "On approval of criteria for classifying objects that have a negative impact on the environment as objects of categories I, II, III and IV" [6].

2.1. Problems

Research carried out at the Melentiev Energy Systems Institute SB RAS revealed that about 100 energy objects of various capacities currently operate in the central ecological area, which use coal, firewood, liquefied natural gas, fuel oil, as well as electricity for heating [7]. By classifying them based on categorization criteria, energy objects can be classified into categories II (large boiler houses, Baikal CHP) and III (the majority of low-power boiler houses).

At the same time, objects that have an insignificant negative impact on the environment and objects that are not included in group II or IV are classified as objects of category III. Thus, category IV includes [6] stationary sources of environmental pollution, the mass of pollutants in emissions into the atmosphere of which does not exceed 10 tons per year, in the absence of substances of hazard classes I and II, radioactive substances. Also, these sources should not discharge pollutants into centralized water disposal systems and the environment. In addition, category IV objects include facilities for providing electric energy, gas and steam (using equipment with a design heat capacity of less than 2 Gcal perhour when consuming gaseous fuel).

Taking into account the fact that the boiler houses of the central ecological area use mainly coal as fuel and even with small volumes of emissions, they emit benz(a)pyrene – a substance of the 1st hazard class, respectively, and belong to the III category. If a new Resolution on the list of prohibited activities in the central environmental area is approved, these objects will be banned not only for construction and reconstruction, but also for operation.

As a result, the increased environmental requirements for the central ecological area are mainly prohibitive and are determined by the list of prohibited economic activities and a special regime of environmental management for the population.

The main environmental problem in the energy sector of the central ecological area is the use of coal (70% of heat sources operate on coal). Under the current Resolution No. 643, even a ban on the construction of new coal-fired boiler houses will not solve this problem, and the allowed reconstruction and modernization of existing morally and technically out-dated energy objects (equipment wear reaches 80%) will not allow achieving the maximum effect on reducing emissions. In addition, up to 60% are emissions from low-power boiler houses without proper cleaning of particular matter.

In this regard, it should be noted that the regulation of permissible emissions at the level of the government of the Russian Federation, both in Order No. 63 of March 5, 2010 [8] and in Order No. 83 of February 21, 2020 [9] provides for only two pollutants: sulfur and nitrogen oxides. Permissible emissions of harmful substances into the atmosphere from objects of all types of economic activity (not only energy objects) are developed for three basins of Lake Baikal - in Table 1.

Table 1. Standards for permissible air emissions for three basins of the Lake. Baikal during the year, thousand tons

Territory	Pollutant	
	Sulphur oxides	Nitrogen oxides
Baikal natural territory, total	6.4	3.27
Southern basin of Lake Baikal	4.0	2.1
Middle basin of Lake Baikal	1.2	0.63
Northern basin of Lake Baikal	1.2	0.54

It should be noted that the standards for basins developed in Resolution No. 63 of March 5, 2010 require clarification in order to understand the permissible impact standards, for example, in the southern basin, the standards are provided for two ecological areas, while large industrial enterprises operate on the territory of the buffer ecological area in the southern part of Lake Baikal, and under certain meteorological conditions (as for the area of atmospheric influence), emissions can flow to the lake's water aquatory.

When coal is burned, the main impurity (80-90%) from the emission is particulate matter which directly enters in the surface layer and are washed out with precipitation (snow, rain) into the Lake Baikal. In fact, in the central ecological area, the emission of particulate matter from energy objects is predominant, and their rationing is absent.

At the same time, comparing the existing emission and standards, we can state the fact that only from energy objects to the Northern and Southern basins of the lake. Baikal receives more than 50% of emissions of sulfur oxides, and depending on the fuel burned and the winter period, this emission is close to or cab exceeds the norms [10].

In general, the environmental requirements for the central ecological area can be formulated as minimizing the impact on all elements of the environment.

2.2 Condition for implementation

To meet the environmental requirements for energy objects in the central ecological area, various measures and directions were developed to reduce emissions and waste generation [10, 11].

Among the possible directions are the modernization of coal-fired boiler houses; the replacement of coal with alternative environmentally friendly fuels (wood fuel, natural gas); the use of electricity for heating; and the use of renewable energy sources. For their implementation, there are certain conditions associated with the problems of legislation for a specially protected natural area or with high economic costs.

Modernization of coal-fired boiler houses, including cleaning equipment, will significantly reduce the load on the environment. However, taking into account the newly introduced restrictions on the categorization of energy objects (they will be assigned to categories II and III), their operation should be prohibited. In this case, the alternative to modernizing large coal-fired boiler houses will be to replace coal with environmentally friendly types of energy carriers (natural gas and electricity). Thus, there are all favourable conditions for replacing coal with natural gas, from the presence of a large gas condensate field of natural gas on the territory of the Irkutsk oblast, to qualified personnel for the use of gas fuel, etc. However, solving of this issue requires amendments to the legislation, including the list of prohibited activities, which includes "... the construction of main oil pipelines, gas pipelines and other product pipelines, with the exception of gas pipelines for local gas supply". In addition, the economic justification for the use of natural network gas with estimates of the rational volume of gas consumption in power objects (within the range of 175-190 thousand tons of fuel equivalent) and competitive prices for different categories of boiler houses, taking into account changes in efficiency, shows the need to use state support measures, since, in most cases, the implementation of such measures requires significant investment [12-13]. Small-capacity gas-fired boilers have great advantages, first of all, low emissions into the atmosphere, attributing them to category IV, which has its own preferences in terms of exemption from obligations to calculate emission standards and payments for emissions.

Another attractive and most feasible direction of reducing the anthropogenic load from energy objects to the environment is the use of electricity for heat supply. This direction is the most environmentally attractive, since the operation of such energy sources is completely no emissions, discharges and waste to the environment. Estimates of the potential amount of electricity to replace coal in boiler houses show that such measures are highly feasible. Competitive electricity tariffs for the implementation of this event are estimated at 1 RUB per kWh and the need for boiler houses in the central ecological area about 1300-1400 million kWh [11]. Currently, tariffs are significantly higher in the studying territory, especially within central ecological area of the Republic of Buryatia.

3 Conclusions

To meet the environmental requirements for energy objects in the central ecological area, it is preferable to use alternative energy carriers for heat energy production instead of coal.

The most preferable option is to replace coal with natural gas. The rational volume of gas consumption in power facilities is estimated at 175-190 thousand tons of fuel equivalent. The main condition for implementation is the construction of an export gas pipeline from Russia (through the territory of the Irkutsk oblast) to China via Mongolia and amendments to existing legislation or the organization of low-tonnage production of liquefied natural gas.

The most feasible currently is the use of electricity for heating purposes. According to the authors ' estimates, the potential volume of electricity for replacing coal in the Central ecological zone boilers is 1.3 billion kWh per year, but the competitive electricity tariff should be 1 RUB/kWh, which is several times lower than the current tariffs.

Thus, the functioning of energy objects in the central ecological area is spontaneous and does not correspond to the ecological significance of the territory. And, if the increased environmental requirements for energy objects in the existing legislation are formulated in the form of minimizing the impact on all elements of the environment, then the problems of meeting such requirements are associated with the need to develop a special package of normative legal acts, of state support measures focused on this territory, including significant financial costs.

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Demand of the Population on Heat and Electricity Markets of the Russian Far East: limitations and consequences

Svetlana Naiden [1,*], and *Olga* Dyomina[1]

[1]Economic Research Institute of Far Eastern Branch of the Russian Academy of Sciences, Khabarovsk, Russia

Abstract. The paper examines the specifics of organization of the electricity and heat energy markets depending on the population behavior in the Far East. The region maintains a regular monopoly, where vertically integrated companies provide services while keeping surplus supply; consumer has no ability to influence the demand in the conditions of imposed prices. The paper estimated the price elasticity of demand on electricity for the population of Khabarovsk Krai, which confirmed the low degree of dependency of consumption from either income or the scale of the tariff. Furthermore, the paper estimated the potential growth of population expenses on electricity in two scenarios: 1) keeping energy tariffs on inflation level and 2) keeping current average annual growth rates of tariffs. There is a differentiation of availability of services depending on the level of income. There is also a need for social support of population from budgets depending on the growth rates of tariffs on electricity and heat energy.

Introduction

The theoretical assumptions on effective functioning of the markets show that consumers receive price signals from manufacturers and suppliers, compare them with their own budget capacities, and make decisions over volume of demand on goods or services. However, there are such markets where consumers have no way of controlling their demand. For example, markets of electricity or heat energy, which satisfy basic needs, which affects the market mechanism of producing and supplying these services [1; 2]. The industry specifics of such markets are reflected in the lack of price elasticity of demand on energy for some consumers, for whom the economic incentive for decreasing energy consumption is weak. A good example are the isolated energy systems with surplus capacities, where decreasing consumption leads to increasing fixed costs, which leads to increase in tariffs and consumer's expenses on energy. This paper analyses such specifics of heat energy and electricity markets in the Russian Far East.

1 Specifics of organization of electricity and heat energy markets: consumers' behavior in the Far East

The classic economic theory states that effectively functioning competitive markets allow consumers to change their demand on goods and services depending on the changing prices. For electricity and heat energy markets this is not always true [3; 4]. The reasons are in creation of demand and supply of energy, mainly [5-8]:

– production and consumption of electrical and heat energy happens simultaneously;

– production of electricity and heat energy is highly concentrated, their distribution is highly centralized;

– the area of electricity consumption is limited by the boundaries of effective distribution of transmission network (up to several thousand kilometers);

– heat energy markets are localized, located in settlements and separate districts of large cities (maximal radius of distribution up to 50 kilometers);

– energy demand is seasonal, which requires maintaining surplus capacities for production.

These specifics presume the existence of increasing economy of scale, require significant investments into developing the infrastructure, including early contributions into creation and development of energy systems and systems of centralized heat supply. As such, for a long time heat and electricity markets remain regulated monopolies, where vertically integrated companies provide heat and energy supply services. In these conditions the balance between demand, supply, and prices on energy is set according to the producers' wishes and the ability of regulating bodies to keep them in check. The consumers are merely the recipients of these services and have no adequate tools of influencing the quality and the price of these services. This primarily concerns population and public organizations (education, healthcare), which objectively require state patronage.

Electricity and heat supply services are essential services that satisfy basic needs, which means everyone needs to have access to them regardless of location and income according to the concept of public utility [9-10]. As such, the producer is limited in the ability to cut off

* Corresponding author: naidensvetlana@mail.ru

consumers and suppliers of public (socially significant) sphere from these services, even if they are unable to pay. The consumer, faced with high prices on energy and limited budget, usually does not reduce consumption but instead stops paying, which creates financial debt to the producer of electricity or heat energy. This is explained by a simple fact that the consumer cannot stop using these services without reducing their quality of life. There are either no alternative ways of receiving these services at all, or they require complicated and expensive technological changes (for example, switching from centralized heat energy systems to individual heat units).

The climate conditions of the Far East make this situation more dire. Electricity and heat energy are not just essential, they are vital for survival in the harsh climate. The specifics of their production in the region is tied to significant costs. Tariffs on heat due to climatic and technological conditions of the region are traditionally the highest, 1.6 times the country average for industrial consumers, and 1.2 times the country average for general populace [1; 11]. Regional tariffs on electricity are also one of the highest in the country, despite intra-territorial cross subsidies, introduced in 2017.

Unlike the general Russian electricity market, which is competitive, where consumers sometimes can change the supply volume depending on electricity prices (price-dependent consumption was introduced in 2017), the Far East remains a regulated monopoly, where vertically integrated companies provide services and consumers are basically hostages of imposed prices. If energy saving policy were to be introduced, considering surplus energy system capacities, lack of new high-volume consumers – the decreasing demand in the region would cause increasing fixed costs and, most likely, increasing price for consumers in the Far East.

This means that consumers' behavior on the markets of electricity and heat is defined primarily by the specifics of market organization and energy qualities. In these conditions, price elasticity of demand on energy is unlikely to exist. The general empirical research that estimated coefficients of price elasticity of demand on fuel and energy showed that their values differ strongly depending on the country, industry, time period, and calculation method [10; 12-17]. Since the volume of heat consumption in most houses in the country is calculated with standards depending on the living area and its qualities, the analysis of price elasticity of demand is not expedient, unlike electricity, the consumption of which is estimated by meters.

2 Estimation of price elasticity of demand: Khabarovsk Krai

To analyze price elasticity of demand on electricity Khabarovsk Krai was chosen as a region most representative of the Far East. It has not only the typical spatial diversity of energy markets, but also a policy of regional patronage of essential goods and services, including investments into modernization of infrastructure of energy supply and a guarantee of social support of the population.

Looking at welfare the population of Khabarovsk Krai also represents a typical Far Easterner. There are 31.7 million square meters of housing (16.5% of total in the Far East), where 1315 thousand people reside (16% of total). By average nominal per capita income the population of Khabarovsk Krai is the first among the most economically developed in the south of the Far East, while having lower inequality level in income distribution (Gini coefficient of 0.388) – below average in Russia (0.401). The same can be said for the decile-dispersion ratio (income of 10% of the wealthiest to income of 10% of the poorest) of 13 against 15.5 average in the country.

The weighted share of poor population in Khabarovsk Krai is 12.2% of the total population in the region, which is comparable to the country average value. Despite growth of nominal income per capita in 2013-2019 (141.5%), its real volume has decreased and is even lower than it was in 2013 (only 95%). This is made worse by poverty reproduction in, for example, northern parts of Khabarovsk Krai, which have high tariffs on electricity and heat energy and there are few opportunities presented on local job markets unlike southern parts of the region (the range of variation in income between districts inside the region is 3.5 times on average). It is impossible to provide essential goods and services, including energy supply, without state support in such conditions.

To examine the dependence between electricity consumption per capita and the housing security (living area per person), the level of average income per capita, and electricity tariffs for urban population, several functions of demand on electricity were built for two income groups: with maximal and minimal income.

Currently the whole population of Khabarovsk Krai pays for electricity according to a unified tariff regardless of the supplier and energy consumption. The analysis was carried out using the data from 2000-2017. In general, the income (price) elasticity of demand is calculated as the ratio of the percentage change of demand to the percentage change of income (price). Calculating the coefficient of price elasticity of demand for electricity is calculated as the ratio of differential logarithm of demand to differential logarithm of price. The final model estimated the demand depending on income level and tariff. The calculations allowed to formulate the following conclusions [18]:

1) There is a direct relation between demand and income level, and it differs slightly between income groups. If income grows by 1% then electricity demand increases by 0.25% for low-income population and by 0.23% for high-income population. Electricity demand does not exhibit income elasticity. This is explained by the stable living conditions and quality of life, including accessibility of household appliances (and their characteristics, intensity of usage), which have extended usage time and are renewed seldomly. Which is why the volume of electricity consumption changes only so slightly despite the growing income.

2) The qualitative analysis has shown that population demand on electricity also does not exhibit price elasticity [3]. This is confirmed by empirical calculations done by other specialists [13]. This is explained by the fact that a certain degree of freedom in choosing an energy supplier creates only an illusion of competition, since it requires significant changes to a lifestyle from the population. Besides, in public utilities sphere (unlike manufacturing) energy has no real replacement. The lack of price elasticity of demand has its limits. It exists only when the share of expenses on electricity is no higher than 10% of income. For population of Khabarovsk Krai the share of expenses for the poorest group was 6.1%, and 0.8% for the high-income populace. The price elasticity of demand coefficient for electricity is estimated at 0.3 for the Khabarovsk Krai population.

Important to note that the lack of price elasticity of demand can be objectively influenced by subsidized tariffs that are actually below the real costs. But then the question is, how heavy would be the burden on households if the tariffs grew?

3 Estimating the consequences of tariffs growth for population: Khabarovsk Krai

The structure of payment redistribution is as follows: the population is pay for the majority of costs carried by the producers (65.2% for electricity and 49.1% for heat energy); the state compensates the loss of income experienced by the producers of energy due to welfare benefits and subsidies for socially vulnerable population: 25% for electricity and 43.6% for heat, which traditionally dominate among public utilities payments; the cross subsidies range between 7-10% [18, p. 22].

The However, the burden on households in Khabarovsk Krai is extremely unequal. When looking at the 20% groups of population depending on the volume of disposable income the first group with the lowest income spends 18.2% of that income on energy, the second group – 10.1%, etc., the fifth group with the highest income – no more than 2.5% of the average disposable income per capita. This means it is very important to monitor financial consequences for households in case of increasing tariffs on electricity and heat supply.

Two future scenarios are possible: (1) tariff increment matches inflation at 4% annually; (2) tariff increment is kept at the level of previous 5 years, 105.6% annually. For disposable income, the growth rates of the recent years for all five income groups were kept as is. Even if the quality of life changes for the better, in this case it is more important to establish a risk zone for solvency and potential need for state patronage over essential sphere for life and activity. The thresholds for this risk zone are the so-called "availability thresholds" established by Bashmakov I.A. [19] The "average availability threshold" denotes that the share of expenses on public utilities in population income is above 7-8%, of energy service – 3-4%, which leads to the loss of comfort and decreases payment discipline. The second, "marginal availability threshold", means that the share is 15% for public utilities and 6-8% for energy services. When this threshold is crossed, "no harsh measures in attempting to collect payments or supporting population will improve payment discipline. This threshold is the key in creating social support programs" [20].

The calculations show that (Table 1):

- In scenarios (1) and (2) the burden on households in the lowest-income group will cross the 20% threshold by 2025 and will be unbearable, causing lack of payments and high debt.

- For groups II and III both scenarios show burden reaching above 8% – the aforementioned "marginal availability threshold", which is followed by the decreasing payment discipline and the negative consequences for energy suppliers;

- For the most fortunate groups IV and V the high growth of tariffs will not increase the share of energy payments above critical levels, but this does not mean that their payment discipline would not change.

Table 1. The share of electricity and heat expenses in disposable income of the Khabarovsk Krai population divided into 20% groups, %

Group	2017	Estimate 2025	
		scenario (1)	scenario (2)
Group I (lowest income)	18.2	22.1	25.4
Group II	10.1	11.8	13.6
Group III	7.0	8.0	9.2
Group IV	4.8	5.4	6.2
Group V (highest income)	2.4	2.6	3.0

This means that if the tariffs on energy continue to advance rapidly, by 2025 the first three income groups in Khabarovsk Krai would cross the availability threshold, worsening their comfort level and becoming dependent, eventually transforming into insolvent.

Undoubtedly the state's involvement into this situation is necessary and is not just a goodwill act to support the poor, but the purposeful fulfillment of its social duties. In particular, supplying its citizens with social support (benefits) in paying for housing and public utilities.

The budget of Khabarovsk Krai in 2019 spent 3.2 billion rubles on compensating benefits, while subsidies for socially vulnerable population took only 770 thousand rubles. Where subsidizing correlates with the quality of life in the region, providing benefits depends on the goals and scale of the federal and regional social policy. This means that if the tariffs on energy grow (which occupy more than half of expenses on public utilities) and even if poverty decreases, the large share of state's financial burden would be devoted to fulfilling its social duties. The total expenses of Khabarovsk Krai budget on supporting its population by 2025 can reach:

a) in scenario 1 (tariffs match inflation) – 5.6 billion rubles annually,

b) in scenario 2 (maintaining tariff growth) – 6.3 billion rubles annually.

This presumes that the Far East maintains the existing patronage in setting tariffs below the level of real expenses. Cancelling it would decrease the quality of life, increase the level of non-payments, and increase the expenses of local budgets on compensating them.

Conclusions

This research has allowed to formulate the following conclusions. The estimations of price elasticity of demand on electricity in the conditions of surplus energy systems of the Far East confirm earlier assumptions of the lack of elasticity of demand on energy.

If the tariffs grow, the financial burden on household will significantly differ depending on the income levels of population of the Far East, especially Khabarovsk Krai, meaning: a) about two thirds of the population would experience a worsening quality of life; b) no less than 40% would become unable to pay; c) no less than 20% would cross the "marginal availability threshold", creating a category of stagnant poverty.

If energy costs were to increase, the subsidiary burden of territories of the Far East would increase 1.5 times, specifically in Khabarovsk Krai, which maintains a vast array of federal and regional benefits and a narrow window of work and increased income opportunities for the population, 20% of which require state support.

The correct choice of dominants of energy policy in the social sphere and public utilities sphere help foster favorable conditions in the society, because without a reliable electricity, heat and fuel supply not only do the economic, social, and political risks grow, but so do the costs of overcoming them.

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Contribution assessment of a technological factor to reducing CO_2 emissions in Russia

Vasily Nemov[1,2], *Irina* Filimonova[1,2,*], *Mikhail* Mishenin [1,2] and *Ekaterina* Zemnukhova [1,2]

[1]Trofimuk Institute of Petroleum Geology and Geophysics SB RAS, 3, Koptug, 630090, Novosibirsk, Russia
[2] Novosibirsk State University, 1, Pirogova, 630090, Novosibirsk, Russia

Abstract. Currently, the economy should develop along an innovative way of development with an increase in the efficiency of the use of natural resources and a decrease in negative impacts on the environment to ensure stable economic growth and improve the quality of life of the population. The purpose of the study is to assess the environmental and energy effects that affect the environment and energy intensity in the country. The dynamics of greenhouse gas emissions in Russia are contemporaneously influenced by many different factors, such as the industry structure of the economy, the structure of the fuel and energy balance, the level of technological equipment, and the situation in world markets. Our analysis showed that the dynamics of CO_2 emissions in Russia are determined primarily by the growth rates of the population's well-being and by the growth of industrial production. At the same time, in the period 2000-2012, the effect of welfare growth was partially offset by a decrease in the energy intensity of the economy, but then the potential for reducing energy intensity due to changes in the structure of the economy was exhausted. The contribution of the technological factor is also insufficient. So for the period 2000-2017, the improvement of technologies in the field of heat and electric energy production from fossil energy sources made it possible to reduce CO_2 emissions by only 33 million tons. Another significant constraint to the transition to a low-carbon trajectory of development is the low rate of implementation of energy-saving technologies in the production of energy-intensive industrial products, maintenance of residential and public buildings.

1 Introduction

Currently, the economy should develop along an innovative way of development with an increase in the efficiency of the use of natural resources and a decrease in negative impacts on the environment to ensure stable economic growth and improve the quality of life of the population.

The most intensive period of growth in emissions of pollutants into the atmosphere was from 1990 to 2010. During this period, carbon dioxide emissions increased by more than 45% (9.7 billion tons). The Asia-Pacific region and the countries of the Middle East accounted respectively for 76% and 9% of the increase in emissions. At the same time, during the same period, CO_2 emissions in European countries decreased by 13.6%, and in Russia and the CIS countries - by 32%. However, for the CIS countries, this is not caused by an increase in energy efficiency, but by a decline in industrial production.

The growth of greenhouse gas emissions at a high rate in 1990–2010 is associated with a high rate of growth in energy consumption (mainly coal consumption) in developing countries. The growth in the population and prosperity of developing countries has been significantly offset by the decrease in the energy intensity of the economy and by the change in the structure of consumed energy towards the consumption of natural gas and alternative energy sources since the 2010s. As a result, the average annual growth rate of CO_2 emissions in the APR countries decreased from 4.9% in 1990–2010 to 2.3% in 2010–2018 [1-3].

Over the past four years, there has been acceleration in the growth of greenhouse gas emissions. The growth rate of emissions increased from -0.1% in 2015 to 2% in 2018. This fact is associated with an increase in the share of energy-intensive industries in the economies of China and the United States, which has increased the demand for energy resources. Climatic factors also had a significant impact on the dynamics of greenhouse gas emissions in 2018. For example, cold winters in the United States have led to an increase in energy consumption in winter and summer. As a result, after a period of emission reductions in 2015-2017, in 2018, CO_2 emissions increased by 115 million tons. In European countries, on the contrary, milder climatic conditions in 2018 led to a reduction in energy consumption in the energy sector and a reduction in greenhouse gas emissions by 69 million tons.

The dynamics of greenhouse gas emissions in Russia is simultaneously influenced by many different factors, such as the industry structure of the economy, the

* Corresponding author: filimonovaiv@list.ru

structure of the fuel and energy balance, the level of technological equipment, and the situation on world markets [4, 5].

Thus, the purpose of the study is to assess the environmental and energy effects that affect the environment and energy intensity in the country.

2 Data

The sources presented in table 1 became the information base for statistical calculations and factor analysis in the framework of our study.

Table 1. Database formation.

Data	Data source
Population size	Rosstat
Consumption of fossil fuels	BP
Real GDP	Rosstat
CO_2 emissions in Russia	Rosstat
	Roshydromet
	BP
	IEA
CO_2 emissions from burning fossil fuels	IEA

The study also used national-level documents - strategic, programmatic, and official documents of the government and relevant ministries.

3 Methodology

The IPAT model is the basis for the factor analysis of this research work. Using this model, we assessed the factors causing changes in the analyzed indicator of emissions that pollute the atmosphere. This is an identity that determines three factors of anthropogenic impact on the environment, and according to which the impact of humanity (I) is expressed as the multiplication of population (P), affluence (A) and technology (T):

$$I = P \times A \times T \quad (1)$$

The use of this formulation makes it possible to structure the analysis of the driving forces that underlie the dynamics of harmful emissions. Further, this identity is transformed in the following form:

$$CO_2 = POP \times \frac{GDP}{POP} \times \frac{EC}{GDP} \times \frac{CO_2}{EC} = G \times E \times CI, \quad (2)$$

where CO_2 is carbon dioxide emissions; POP is population; GDP is Gross Domestic Product; EC is total energy consumption; G is GDP per capita; E is energy intensity of GDP, or in other words, the technology of using energy to produce GDP; CI is the carbon intensity of energy produced, energy production technology. The latter two factors determine two aspects of technological change: energy efficiency and energy production technology.

The subsequent development of the methodology for factor analysis of anthropogenic carbon dioxide emissions made it possible to include in the analysis of the influence of changes in the structure of fossil fuel consumption. Thus, the amount of carbon dioxide emissions from the combustion of each type of fossil fuel is different, i.e. they have different emission factors. The rapid development of alternative energy with zero carbon dioxide emissions and its increasing importance in the structure of energy balances has led to the need for further improvement of the methodology. As a result, in 2008, a model was proposed that allows one to assess the effect of changing the share of energy not related to CO_2 emissions, such as nuclear, hydroelectric, solar, etc.

$$CO_2 = \sum_i POP \times \frac{GDP}{POP} \times \frac{EC}{GDP} \times \frac{FE}{EC} \times \frac{FE_i}{FE} \times \frac{CO_{2i}}{FE_i} = \sum_i^k POP \times G \times I \times S_1 \times S_{2i} \times F_i, \quad (3)$$

where CO_2 is carbon dioxide emissions, the summation is performed by types of fossil fuels used (i = 1, .., 3: oil, coal, natural gas); POP is the country's population; GDP is a gross domestic product; EC is the energy consumption of all types; FE - consumption of all types of fossil fuels; FE_i - energy consumption of the i-th type of fossil fuel; CO_{2i} - emissions from combustion of the i-th type of fuel; G - GDP per capita; I - energy intensity of GDP; S_1 - share of fossil energy carriers in total consumption energy; S_{2i} is the share of the i-th type of fossil energy in the total consumption of fossil fuels; F_i is the emission factor of the i-th fuel.

Thus, within the framework of the applied method, the dynamics of carbon dioxide emission is explained by the cumulative influence of the following factors:

- population dynamics ΔC_{POP}, representing the change in carbon dioxide emissions due to a change in population;
- welfare change ΔC_{GDP}, showing the change in CO_2 emissions associated with an increase or decrease in income;
- change in the energy intensity of GDP ΔC_{enint}, which characterizes the change in the sectoral structure of the economy and the level of efficiency in the use of energy resources;
- change in the share of fossil energy carriers ΔC_{renew}, which characterizes the contribution of alternative and renewable energy to the reduction of carbon dioxide emissions;
- changes in the structure of consumption of fossil energy carriers ΔC_{FF}, which characterizes the impact of inter-fuel competition (for example, coal substitution with gas) on the volume of greenhouse gas emissions;
- a change in fossil fuel combustion technology $\Delta C_{carbint}$, which shows the change in the volume of carbon dioxide emissions due to a change in the specific carbon dioxide emissions when burning a kilogram of fossil fuels.

n this paper, the determination of the contribution of each factor to the dynamics of carbon dioxide emissions will be calculated based on the decomposition of changes using the log average of the Division's index.

$$\Delta C_{POP} = \sum_{i=1}^{3} \frac{CO_{2it} - CO_{2i0}}{\ln(CO_{2it}) - \ln(CO_{2i0})} \ln\left(POP_t / POP_0\right), \quad (4)$$

$$\Delta C_{GDP} = \sum_{i=1}^{3} \frac{CO_{2it} - CO_{2i0}}{\ln(CO_{2it}) - \ln(CO_{2i0})} \ln\left(\frac{GDP_t}{POP_t} \Big/ \frac{GDP_0}{POP_0}\right), \quad (5)$$

$$\Delta C_{enint} = \sum_{i=1}^{3} \frac{CO_{2it} - CO_{2i0}}{\ln(CO_{2it}) - \ln(CO_{2i0})} \ln\left(\frac{TPES_t}{GDP_t} \Big/ \frac{TPES_0}{GDP_0}\right), \quad (6)$$

$$\Delta C_{renew} = \sum_{i=1}^{3} \frac{CO_{2it} - CO_{2i0}}{\ln(CO_{2it}) - \ln(CO_{2i0})} \ln\left(\frac{FE_t}{TPES_t} \Big/ \frac{FE_0}{TPES_0}\right), \quad (7)$$

$$\Delta C_{FF} = \sum_{i=1}^{3} \frac{CO_{2it} - CO_{2i0}}{\ln(CO_{2it}) - \ln(CO_{2i0})} \ln\left(\frac{FE_{it}}{FE_t} \Big/ \frac{FE_{i0}}{FE_0}\right), \quad (8)$$

$$\Delta C_{emc} = \sum_{i=1}^{3} \frac{CO_{2it} - CO_{2i0}}{\ln(CO_{2it}) - \ln(CO_{2i0})} \ln\left(\frac{CO2_{it}}{FE_{it}} \Big/ \frac{CO2_{i0}}{FE_{i0}}\right), \quad (9)$$

where CO_2 is the total carbon emissions, the summation of which is carried out for three types of fuel (oil, coal and natural gas); POP is the population; TPES is the supply of primary energy of all types; FE is the supply of all types of fossil fuels; FE_i is the supply of the i-th fossil fuel; CO_{2i} - emission of carbon dioxide from combustion of the i-th fuel.

4 Results

The recovery of the Russian economy after the economic crises of the 1990s and the growth in the utilization of production capacities led to an increase in greenhouse gas emissions. However, the advancing development of the service sector and the change in the structure of the Russian economy in favor of less energy-intensive industries in the 2010s led to the stabilization of carbon dioxide emissions [6,7] (Figure 1).

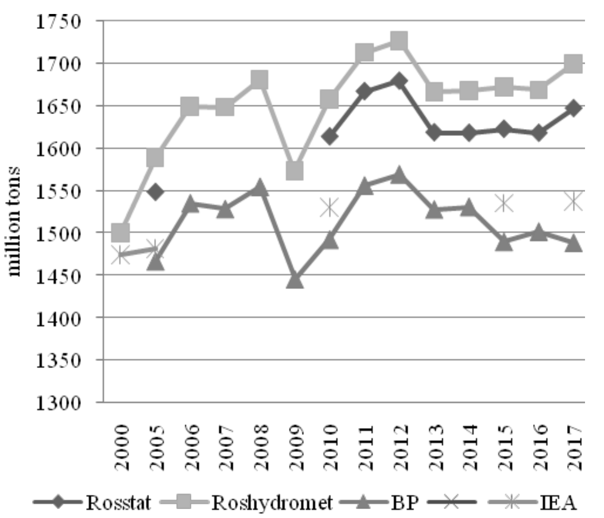

Fig. 1. Dynamics of CO2 emissions in Russia.

The analysis showed that the dynamics of CO_2 emissions in Russia is determined mainly by the growth rates of the population's well-being and the growth of industrial production. At the same time, in the period 2000-2012, the effect of welfare growth was partially offset by a decrease in the energy intensity of the economy, and in subsequent periods the potential for reducing energy intensity due to changes in the structure of the economy was exhausted. The contribution of the factor "growth of the welfare of society" to the increase in CO_2 emissions for the period 2000-2015 is estimated at 931.9 million tons. The contribution of the reduction in energy intensity to the dynamics of CO_2 emissions over the same period is estimated at -784.8 million tons.

The zero dynamics of CO_2 emissions in 2013-2017 is associated with a slowdown in economic growth. So the welfare (GDP per capita) of the population in 2017 decreased by 0.8% compared to the 2012 level. In the period 2015-2017, the contribution of this factor to the change in the volume of emissions amounted to 14.8 million tons. The stabilization, and in some years the growth of the energy intensity of the economy also provided a positive contribution to the dynamics of CO_2 emissions. Over the same period, the contribution of this factor is estimated at 21.3 million tons.

At the same time, the contribution of the technological factor is insufficient. So for the period 2000-2017, the improvement of technologies in the field of heat and electric energy production from fossil energy sources made it possible to reduce CO2 emissions by only 33 million tons. Another important constraint to the transition to a low-carbon trajectory of development is the low rate of implementation of energy-saving technologies in the production of energy-intensive industrial products, servicing residential and public buildings, which is reflected in the growth of energy intensity in recent years. In the production and distribution of electricity, gas, and water, the volume of pollutant emissions per ruble of value-added in 2017 increased by 2.8%, in manufacturing the value of the indicator remained at the level of the previous year. Thus, due to the exhaustion of the potential for reducing energy intensity due to structural changes in the economy, the energy intensity of GDP by 2018 increased by 2.6% compared to the 2015 level (Figure 2).

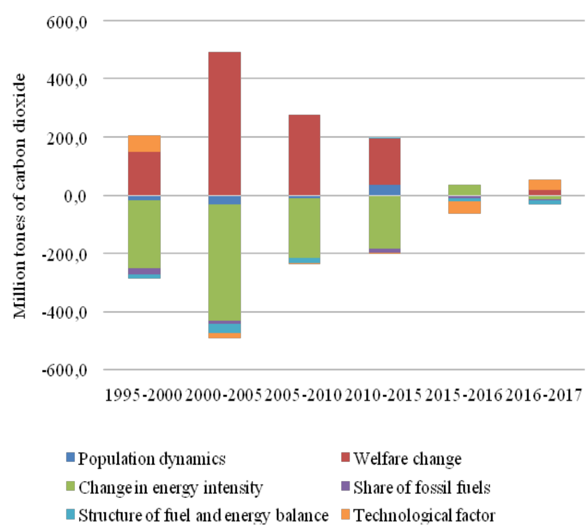

Fig. 2. Contribution of factors to changes in CO_2 emissions from fossil fuel combustion in Russia.

5 Discussion

Within the framework of the study, it is of particular interest to compare the ongoing changes in anthropogenic emissions of carbon dioxide in Russia and other countries of the world.

Calculations made based on this methodological approach for OECD countries showed a change in the structure of carbon dioxide emissions similar to Russia in the period 1990-2010. The main difference during this period was the impact of population dynamics on CO_2 emissions. For example, if a population decline was recorded in Russia, then the OECD population increased, which had a positive effect on CO_2 emissions [8-11] (Figure 3).

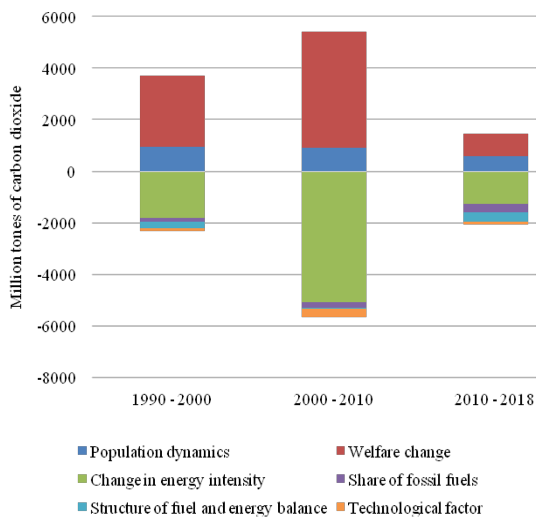

Fig. 3. Contribution of Factors to CO_2 Emissions from Fossil Fuel Combustion in OECD Countries.

However, in the last decade, Russia and the OECD countries are characterized by a significant difference in the structure of the increase in CO_2 emissions:

- Influence of energy intensity. In the previous decades, the decrease in the energy intensity of the Russian economy was mainly due to changes in the structure of the economy, but this potential has been practically exhausted. As a result, after 2015, this factor practically ceased to influence the dynamics of CO_2 emissions. In OECD countries, this factor continues to be a key factor in the process of reducing CO_2 emissions. In addition to structural changes, the introduction of modern energy-saving technologies contributes to a decrease in the energy intensity of the economy in the OECD countries;
- The growing influence of alternative energy in OECD countries on the reduction of CO_2 emissions. In Russia, alternative energy is developing at a slower pace than in the largest OECD countries and has a smaller impact on the dynamics of CO_2;
- Technological factor. During the past three decades, OECD countries have seen a steady decline in specific CO_2 emissions from burning a kilogram of fossil fuels. However, in Russia, the dynamics of specific emissions are unstable. At the same time, the volume of emissions from burning a kilogram of coal makes a negative contribution to this indicator, while specific emissions from burning gas and oil tend to decrease.

6 Conclusion

Over the past ten years, the annual volume of greenhouse gas emissions in Russia has remained at a relatively stable level. Taking into account the low rates of economic growth (since 2013, the average annual growth rate of Russia's GDP has decreased to 0.7%), this may indicate insufficient measures to reduce the energy intensity of the economy and reduce greenhouse gas emissions.

The analysis showed that the possibilities of reducing harmful effects on the environment due to factors such as changes in the structure of the economy have been mostly exhausted. To achieve the greenhouse gas emission indicators presented in the Strategy for the Long-Term Development of Russia with a Low Level of Greenhouse Gas Emissions until 2050, it is necessary to intensify the development of alternative energy, the introduction of digital and energy-saving technologies in industries, and the introduction of technologies for the capture, storage and processing of carbon dioxide.

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Hydro Power Plants in the Interconnected Power System of Siberia: Trends and Problems

V.M.Nikitin[1], E.N.Malinovskaya[2]

[1]D.Sc., Head of the Laboratory of Hydropower and Water Management Systems, Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences
[2]post-graduate student at Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences

Abstract. The paper discusses the trends, features, and current problems of the operation of hydro power plants in the interconnected power system (IPS) of Siberia. The main feature of the IPS of Siberia is a high proportion of hydro power plants and, as a result, a strong dependence of power generation on the natural fluctuations of water inflows into reservoirs. The problems affecting the power system efficiency arise when the inflows deviate from normal and close-to-normal values. The study indicates the need to improve the current system of managing and planning the operation of hydro power plants. The important factor that can increase the efficiency and reliability of the power system operation is bringing the permissible ranges of variations in reservoir levels in compliance with the design values. Planning the long-term power balances and increasing their validity should involve predictive scenarios of water inflows into reservoirs.

1. Introduction

In 2019, 60 years had passed since the establishment of the interconnected power system (IPS) of Siberia. Currently, it is one of the seven interconnected power systems of Russia. The main feature distinguishing it from other IPSs is a high proportion of hydro power plants (HPPs). In the IPS of Siberia, there are 112 power plants with a total capacity of 52.1 GW, including the Angara-Yenisei HPP cascade (one of the largest cascades in the world) with a total installed capacity of 24.7 GW [1]. Hydro power plants (given the Novosibirsk and Mamakan HPPs) generate about 50% of the total electricity produced in the IPS of Siberia, of which 80% is from the Irkutsk power system (the share of HPPs in the Russian Federation accounts for 18%). The Angara HPP cascade (Fig.1) plays an essential role in the operation of the IPS of Siberia. This system includes unique multi-year Irkutsk (Lake Baikal) and Bratsk reservoirs (with a total live capacity of 96 km3), which allows storage of up to 10-12% of the entire annual demand for electricity of the IPS. Together with the Ust-Ilimsk and Boguchany HPPs, the Angara cascade produces about 30% of the total electric power of the IPS of Siberia. At the same time, the Bratsk HPP performs the compensating function in the power system, being the regulator of the annual power balances, whereas the Bratsk reservoir provides a balanced water management system of the Angara and Yenisei basins.

The Angara and Yenisei hydro power cascades fulfill several other system-wide functions. For example, they cover the variable part of the load curve, including daily and weekly regulation, regulate frequency, and provide the major part of the load and emergency power reserves [2,3].

2. Trends

In 1959, when the IPS of Siberia was put into operation, the share of HPPs in the structure of its capacity was less than 16%. By this time, the Novosibirsk (1958) and Irkutsk (1959) HPPs with a total capacity of about 1 GW had been commissioned. The largest hydro power plants in Siberia were mainly constructed in the 1960s-80s. These were the Bratsk HPP (1967), Krasnoyarsk HPP (1971), Ust-Ilimsk HPP (1980), and the Sayano-Shushenskaya and Mainskaya HPPs (1985). By the mid-1980s, the total capacity of the Siberian HPPs had amounted to 22.3 GW or 52% of the total capacity of the IPS of Siberia [2] (Fig. 1).

The construction of hydro power plants became an important regional factor determining the accelerated development of the Siberian economy. That period saw the creation of large territorial production facilities, including the most electricity-intensive industries (aluminum plants, pulp and paper mills, etc.) that used the cheapest electricity in the Soviet Union.

Two different periods can be distinguished in the development and formation of the power system of Siberia. These periods coincide with the Soviet and post-Soviet stages of political and socio-economic development of the country. The Soviet period (1960-1990) was characterized by a sharp increase in electricity production and consumption. Electricity consumption increased by 6 times (about 20% per year), the total capacity of power plants - by 7 times, including that of hydro power plants - by 22 times, and thermal power plants (TPP) – by 3.9 times (Table 1).

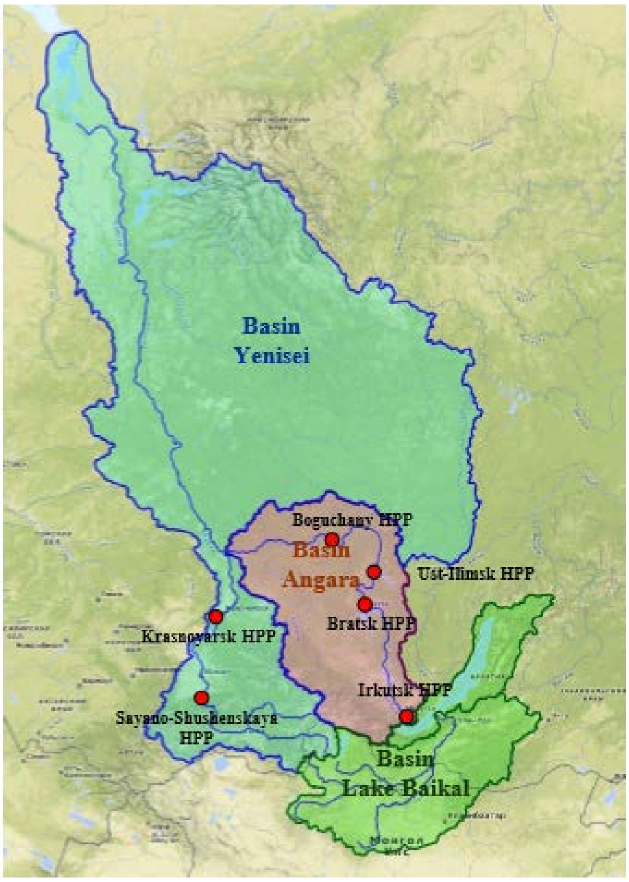

Fig. 1. The scheme of the Angara-Yenisei HPP cascade

The extremely low-water period of 1976-1982 showed a strong dependence of the IPS of Siberia on natural factors and, above all, on water inflows into the reservoirs of Siberian hydro power plants. This dependence was seen in the inability of hydro power plants to balance electricity generation and consumption in the power system in the dry period. For this reason, to improve the balance and reliability of the power system, in the second half of the 1980s, the country built several large heat generation facilities (three units of the Novosibirsk CHP-5, the first unit of the Berezovskaya GRES (condensing power plant), and several 500 kV transmission lines.

Such dynamics made it possible to balance the growth of electricity production and consumption in the power system. However, in some years, the uneven placement into the operation of units at HPPs and TPPs; commissioning of electrical networks and substations; and the emergence of energy-intensive consumers were accompanied by either shortage or surplus of electricity and power. Nevertheless, the modern structure of the IPS of Siberia was mostly shaped in the Soviet period.

There was a significant decline in electricity consumption due to the collapse of the USSR and the economic crisis from 1990 to the mid-2000s. During that period, the IPS of Siberia operated in isolation from the UPS of Russia. At the end of the 1990s, electricity consumption in the IPS of Siberia went down to 170 TWh (dropped approximately by 20% to the 1980 level), and only in recent years, it has returned to the 1990 level. Over those years, only one hydroelectric power plant, the Boguchany HPP, with a capacity of 3 GW was built (the construction was completed in 2015, 40 years after it started), and several new heat-generating plants and units at the existing plants with a total capacity of 6 GW were commissioned. Also, 28 new substations and about 5 thousand km of 500 and 220 kV overhead lines were put into operation [1]. The IPS of Siberia generated surplus capacity and, in some years, at the time of maximum load, the surplus was as high as 10 GW [4]. Over the past 15 years, the IPS of Siberia has been operating under the conditions of stable power consumption and still has available power surplus (power consumption has increased by an average of only 0.1% per year).

Table 1. The structure of the capacities in the IPS of Siberia in 1960-2020

Index	1960	1970	1980	1990	2000	2010	2020 (2019)
Electricity consumption TWh	34.6	101.6	167.7	205.6	172.5	202.7	211.4
Total installed capacity, GW, including:	6.3	22.7	35.1	43.0	45.5	47.3	52.1
HPPs	1.0	10.2	18.7	22.3	22.3	22.3	25.3
TPPs (CHP +CPP + others)	5.3	12.5	16.4	20.7	23.2	25.0	26.8
Capacity structure, %, including:	100	100	100	100	100	100	100
HPPs	15.9	44.9	53.3	51.9	49.0	47.1	48.6
TPPs (CHP +CPP + others)	84.1	55.1	46.7	48.1	51.0	52.9	51.4

Since the early 1990s, the country's economic system has radically changed. Most of the unified state property has become private and corporate. Generating companies, grid companies, and large energy-intensive electricity consumers have become joint-stock companies. The electric power industry has been restructured and a wholesale market for electricity and capacity has been created. Each joint-stock company has set its objectives, strategy, and performance criteria. As a consequence, it is difficult to make long-term planning and forecasting of power demand in the power system. The construction and commissioning of new large electricity consumers are determined, first of all, by the conditions of the Russian and World markets. A good example is a delay in the construction and commissioning of the Boguchany and Taishet aluminum plants with a total design capacity of 2640 MW planned to be launched 10 years ago, before the commissioning of the Boguchany hydro power plant. The implementation of these plans, due to the unfavorable situation in the world aluminum market, remains in question for an indefinite period. There are no other large new electricity consumers in the power system so far.

3. Specific features and problems

The main specific feature of a power system with a high proportion of HPPs is a strong dependence of power generation on a natural factor, i.e., the natural fluctuation in water inflows into reservoirs. The deviation of the power output of hydro power plants of the Angara-Yenisei cascade from the long-term average values can be as high as 30% or 31-36 billion kWh per year (Table 2).

Table 2. Fluctuations in annual electricity generation from HPPs of the IPS of Siberia

HPP	Installed capacity, MW	Annual electricity output, bn kWh		
		Maximum	Long-term average	Minimum
Irkutsk	662	5.16	4.13	2.86
Bratsk	4500	28.10	22.50	14.36
Ust-Ilimsk	3840	27.17	21.20	14.34
Boguchany	2997	22.90*	17.60*	11.40*
Angara Cascade **	11999	83.33	65.43	42.96
Sayano-Shushenskaya	6400	30.70	23.65	16.45
Mainskaya	321	2.00	1.71	1.35
Krasnoyarsk	6000	25.90	19.90	13.67
Yenisei cascade **	12721	58.60	45.26	31.47
Angara-Yenisei cascade**	24720	141.93	110.89	74.43
Novosibirsk	455	2.41	1.99	1.57
Mamakan	100	0.17	0.16	0.15
IPS of Siberia, total **	25268	144.51	112.84	76.15

Note: * – calculated values.

** – the aggregate indices for the HPP cascades and the entire IPS of Siberia did not take into account the asynchronous runoff in different river basins and individual reservoirs within one basin.

Problems in the IPS of Siberia and related water management and socio-economic systems arise when inflows deviate from normal and close-to-normal values. In low-water (extremely dry) periods, the electricity production at hydro power plants is significantly reduced, the power balance in some areas of the IPS of Siberia is disturbed, and hydropower reserves in the long-term storage reservoirs decline. In general, the overall reliability and stability of both the power system and the water management system are reduced.

Throughout the whole period of the Angara HPP cascade operation, there were two such periods: 1976-1982 and 2014-2017. The extremely dry years (1976-1982) coincided with reduced electricity production at thermal power plants in the IPS of Siberia, which was due to fuel undersupply and related electricity shortage in the system by the end of the low-water period. By 1979, to compensate for the decrease in electricity production at TPPs, long-term water reserves in the Irkutsk (Lake Baikal) and Bratsk reservoirs had been completely depleted. As a result, along with the failure of power supply to consumers, the requirements of other water users and water consumers were not fulfilled either [2]. The 2014–2017 years, which were even severer in terms of inflow volume, caused less damage: navigation period was shortened, long-term resources of the Bratsk reservoir were almost completely drawn down, electricity production at the Angara HPP cascade decreased by 15-20%. The insufficient electricity production from the HPPs during that period was compensated by the electricity generation from thermal power plants. The reason is the available sufficient reserves and surplus capacity in the power system, and the capability to maintain the maximum possible saving of water resources [5].

Problems arise in high-water years as well. Due to the limited need of the power system for electricity during flood periods (that usually occur in summer), as well as the insufficient transfer capability of intersystem and intra-system power lines, there are risks of overflowing reservoirs and idle discharges through the throughput facilities of HPPs, and flooding of territories located in the upper and lower pools. The latter relates primarily to Lake Baikal and the lower pool of the Irkutsk HPP.

A specific feature of the power system with a high proportion of HPPs is the structure and dynamics of the intra-annual load curve. Every year from March to October there is a seasonal decrease in power consumption. The same period (April-October) sees the maximum inflows into the reservoirs of HPPs and, consequently, the maximum generation of electricity from HPPs (Fig. 2).

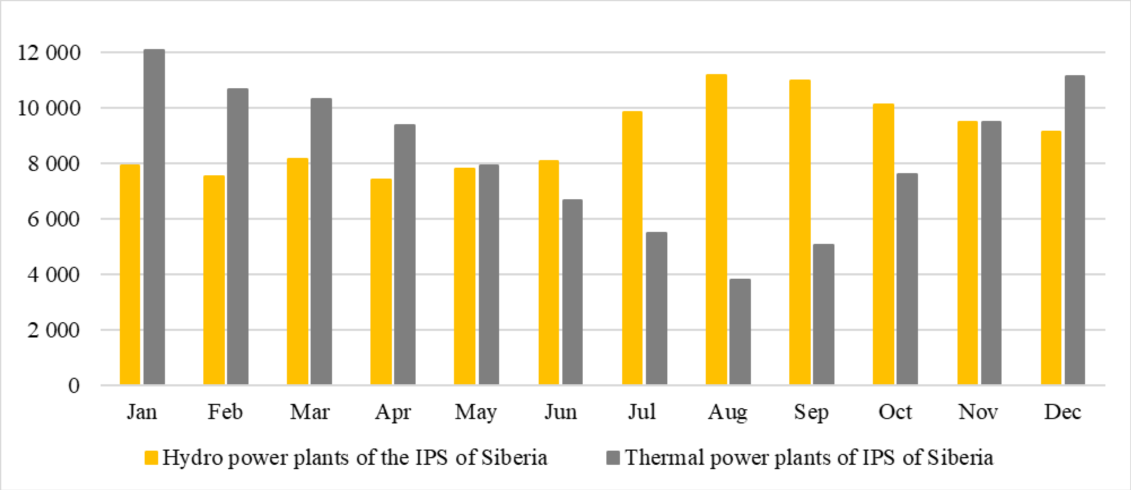

Fig. 2. Generation structure of the IPS of Siberia on the example of 2019, million kWh

Seasonal non-uniformity of electrical loads, with a limited variable part of the load curves, is compensated by unloading thermal power plants. In summer, some thermal power plants are unloaded to a minimum safe output, some are switched to heat generation only (Krasnoyarskaya GRES (CPP) 2 and CHP 1), or completely stop (Berezovskaya GRES (CPP) 1) (Fig. 3). This situation is repeated annually even in the average-water years, including 2019 (Fig. 4). In wet years, the HPP generation increases significantly. In this case, thermal power plants (including those the most efficient of them) are forced to unload (some of them are unloaded even below the minimum safe output), which complicates planned maintenance of energy equipment and electrical networks, carried out mainly in summer. As a result, the overall economic efficiency and reliability of the power system are reduced.

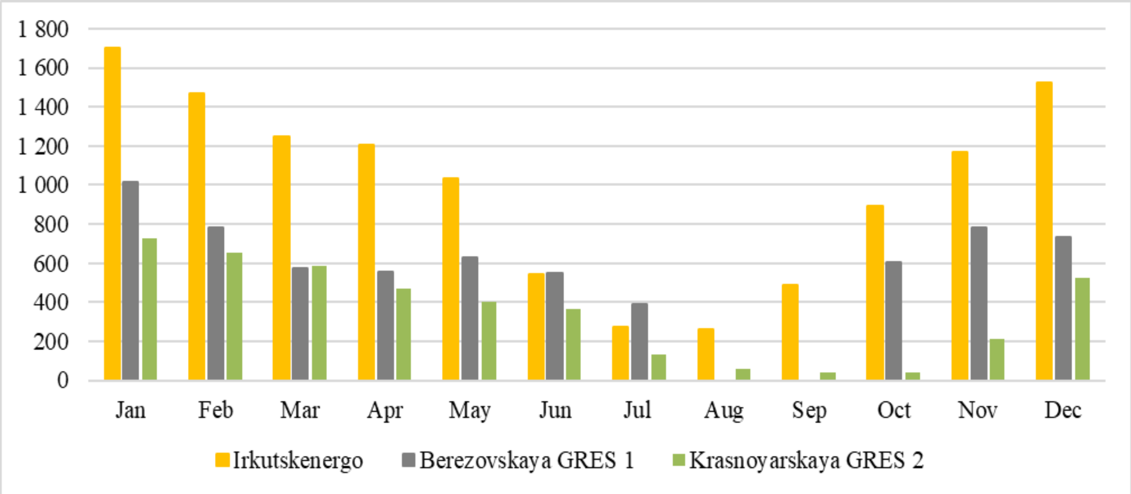

Fig. 3. Generation structure of the largest thermal power plants of the IPS of Siberia on the example of 2019, million kWh

The operating conditions of hydro power plants are also affected by intra-seasonal water management and environmental requirements, as well as daily regulation restrictions. In the summer-autumn period, these entail the requirements for navigation flows through HPPs and fishery restrictions during spawning periods. A significant limitation for the lower pools of the Krasnoyarsk HPP and, especially, the Irkutsk HPP, is the one on the flows through the HPPs aimed at preventing flooding of adjacent territories. In winter, there are restrictions on the maximum flow in the lower pools associated with ice conditions.

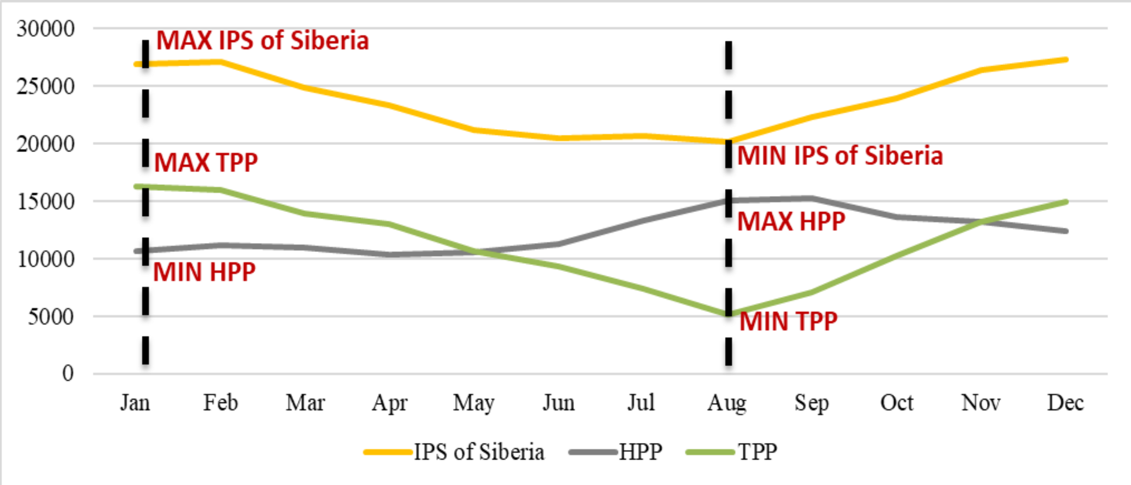

Fig. 4. The structure of the maximum and minimum generation in the IPS of Siberia on the example of 2019, MW

There is a problem related to the limitation of the transfer capability of intra-system and intersystem electrical networks. The IPS of Siberia is generally self-sufficient in terms of the electricity generation and consumption balance (power flow from other IPSs is about 1% of the total consumption). However, there are both power-surplus and power-deficient areas in the IPS of Siberia, which is due to the limited network transfer capabilities in critical cutsets.

An important factor that affects the operation of HPPs in the IPS of Siberia is the deviation of the permissible reservoir levels and flows through the hydraulic structures from design values, which is especially true for the HPPs and reservoirs of the Angara cascade, whose design characteristics are presented in Table 3.

Table 3. Design characteristics of the Angara HPP cascade

Characteristics	Irkutsk HPP	Bratsk HPP	Ust-Ilimsk HPP	Boguchany HPP	Angara cascade
Hydro power plant parameters:					
Commissioning year	1959	1967	1980	2015	
Installed capacity MW	662.4	4500	3840	2997	11999.4
Average long-term electricity generation, billion kWh / year	4.1	22.5	21.2	17.6	5.4
Average long-term water inflow into the reservoir, km^3	59.5	91.1	99.3	105.3	
Design head, m	26	101.5	85.5	70	
Reservoir parameters:					
Normal water surface (NWS), m	457.0	401.73	296.0	208.0	
Dead storage level (DSL), m	455.54	391.73	294.5	207.0	
Maximum water surface (MWS), m	458.2	402.5	296.6	209.5	
Reservoir surface area, km^2	33000	5470	1870	2320	42660
Total storage capacity, km^3	48.4	162.3	58.9	58.2	327.8
Live capacity, km^3	48.4	48.2	2.8	2.3	101.7

Irkutsk Hydro Power Plant (Lake Baikal). After the Resolution of the Government of the Russian Federation No. 234 of March 26, 2001 (herein referred to as the Resolution) on the necessity of compulsory fulfillment of the limited one-meter range when regulating the level of Lake Baikal (456 ÷ 457 m Pacific system (PS)) came into force [6], the permissible range halved relative to the design one (455.54 ÷ 457.50 m PS, (Table 3)). In 2015-2020, due to the extremely low water period that began in 2014, this Resolution was temporarily suspended. However, it will be brought into effect again in 2021. This Resolution changed the storage conditions not only for Lake Baikal but also for the entire Angara cascade since Lake Baikal provides more than 60% of the total inflow into the downstream reservoirs. Baikal has ceased to fulfill the functions of long-term runoff regulator, which is stipulated by the Rules for the Use of Water Resources of reservoirs (herein referred to as "RUWR") and the Technical Design of the Irkutsk HPP [7,8]. In the last 20 years, the Lake Baikal has only been providing seasonal regulation. The 2014-2017 period of extremely low water demonstrated the insufficient validity and impossibility of implementing the Resolution under the water conditions other than normal one [9].

Bratsk hydro power plant. The regulation range of the Bratsk reservoir also deviates from the design one. Even in the stage of the HPP construction, the benchmarks of water intakes and piers in the water area of the reservoir were set at 395 m PS, which is 3 m higher than the design dead surface level (Table 3). As a result, the ten-meter regulation range decreased to a seven-meter one.

In the Ust-Ilimsk and Boguchany reservoirs, the possibility of summer navigational drawdown to the dead storage level is also not provided for, and thus their design regulation capability is reduced.

Thus, the resources of long-term regulation of the entire Angara cascade have decreased by about half, which is equivalent to 10 billion kWh of annual electricity output. The principles of using long-term water resources of reservoirs are not regulated by law.

The current management and planning system can also be viewed as a problem. Energy and water management systems are closely interrelated through the operation of hydro power plants (cascades of hydro power plants). The reservoirs of the Angara-Yenisei HPP cascade are of a comprehensive and multipurpose nature. They are used not only for energy needs but also for water supply, water transport, fisheries, and other purposes. However, the operation of hydro power plants is managed and planned by different departments - the System Operator (SO) in the electric power industry and the Federal Agency of Water Resources (FAWR) in the water management systems, which use different approaches. After restructuring, the power industry switched to market conditions. Currently, there are wholesale and retail electricity and capacity markets, including a day-ahead market and a balancing market, where pricing is based on the balance between the demand of the consumer and supply of the generator, including hydro power plants [3]. At the same time, the water sector management relies on the administrative system. Water legislation on the use of water resources is currently regulated by the Water Code [10]. According to the Water Code, 100% of water bodies are in the state ownership, including 95% in the federal one. Economic management mechanisms imply payments for the use of water bodies under the water use agreements. Regulatory documents do not stipulate a management system corresponding to the conditions of a market economy that stimulates rational water use [11]. In practice, the management of hydropower resources under the Water Code and RUWR is confined to the situation where the regional division of Federal Agency of Water Resources, i.e., the Yenisei Basin Water Administration (YBWA) prescriptively sets the flows through the hydropower facilities for the coming month, taking into account the current hydrological conditions (the current state of reservoir levels and the expected inflow). At the same time, the proposals of power engineers, and other water users that are members of the advisory interregional working group at YBWA are only advisory in nature. The YBWA (FAWR) independently determines the flows (and, consequently, the electricity generation) of hydro power plants, and, hence, the operation of the IPS of Siberia. Economic criteria, including potential risks and damages, are not considered when distributing water resources between water users. In the context of limited water resources, this inevitably leads to their inefficient use and contradiction between the water sector participants, primarily between the energy industry and water transport.

Another management and legislation problem is the administrative principle of distributing water resources between water users and water consumers in the absence of economic criteria. Since the future water inflows into the reservoirs are uncertain and the water resources are used for many purposes, the standard calculated water availability is used as the main criterion of distribution and index of the reliability of meeting the water demand. This principle is legislatively enshrined in the current Methodological Guidelines [12], which serve as a basis for RUWR development. It is worth noting that these standards of calculated water availability were developed 60 years ago [13]. Moreover, they are the same for all reservoirs in the country, without exception. In this regard, it is necessary to conduct a feasibility study on the calculated water availability for each basin with its water users, given current conditions, features, requirements, and restrictions, and to periodically update these indices in the future.

In water management systems, the reservoir operational conditions are planned for 1-3 months. The monthly planning horizon for HPP operational conditions is associated with the extreme difficulty in the long-term forecasting of water inflows into reservoirs. At present, the Hydro Meteorological Center provides a probable (interval) forecast of inflows for the coming month at the end of the previous one (before the 25th day of month) and for three months - once a quarter. There are no forecasts for a longer period. At the same time, planning and forecasting in the electric power industry are carried out for the future up to 1 year or more, which is due to the need to build long-term planned balances of electricity and power in the power system. These balances allow planning the electricity and heat output from thermal power plants, building fuel reserves, planning repairs of power equipment and electrical networks, and solving other problems. In the absence of the forecasts on the water inflows into reservoirs for a period of more than three months, long-term forecasting and planning of power balances rely on statistics over the past period in the form of long-term and monthly averages. Such planning and forecasting give acceptable results for normal conditions (close to long-term average) but are not justified for the extremely high or low water periods. The statistics of observations of tributaries in the basins of Lake Baikal and the Angara river over the past 120 years show that the proportion of normal and close-to-normal water years is less than 50% of the total number of years. Besides, recent decades have seen significant global and regional climate changes that alter the prevailing trends, which also makes the use of long-term and monthly-average indicators for forecasting ineffective [14]. In this regard, it is advisable to use new approaches to building long-term power balances. For example, one can use prognostic scenarios of water inflows into reservoirs for a period of up to 1 year based on the data from global climate models and correct them monthly [15].

The discussed features and problems reduce the efficiency of using water resources in the IPS of Siberia. Taking them into account in long-term planning and solving individual problems (where it is economically and socially justified) create potential opportunities for its enhancement.

4. Conclusion

1. In recent years, the operation of the IPS of Siberia has been characterized by stable power consumption and surplus available power of power plants. In the coming years, the emergence of new large electricity consumers is not expected. In the medium term, the main objective of the power system expansion is not the commissioning of new generating capacities and an increase in electricity production, but rather the improvement in the reliability and efficiency of the existing energy facilities.

2. The main feature of the IPS of Siberia is a high proportion of hydro power plants and, as a result, a strong dependence of power generation on the natural fluctuations of water inflows into reservoirs. The problems affecting the power system efficiency arise when the inflows deviate from normal and close-to-normal values.

3. An important factor that can increase the efficiency and reliability of the power system operation is bringing the permissible ranges of variations in reservoir levels in compliance with the design values and introducing appropriate changes in legislation and regulatory framework. These will increase the regulation capabilities of the reservoirs and ensure the reliable operation of hydropower plants under extreme water conditions.

4. The study indicates the need to improve the current system of managing and planning the operation of hydro power plants within the interacting energy and water management systems, using the criteria of economic, social, and environmental efficiency.

5. Planning the long-term power balances and increasing their validity should involve predictive scenarios of water inflows into reservoirs for a period of up to 1 year, and their monthly adjustment.

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Modeling of Long-term Operating Regimes of Hydro Power Plants as Part of Energy and Water Systems in the Context of Uncertainty

Viacheslav Nikitin*, *Nikolay* Abasov, *Evgeny* Osipchuk, and *Dmitry* Krupenev

Melentiev Energy Systems Institute Siberian Branch of the Russian Academy of Sciences (ESI SB RAS), 134 Lermontov St., Irkutsk, 664033, Russia

Abstract. Energy and water management systems are closely interrelated through the operating regimes of Hydro Power Plants (HPP) or HPP cascades. This is first of all, characteristic of energy systems with a large share of HPP. One of such systems is the energy system of Siberia, which includes the Angara-Yenisei cascade of HPP, the largest in Russia and one of the largest in the world. The studies were carried out on the example of this energy system and the water management system of the Angara and Yenisei basins. A specific feature of the energy and water management systems of Siberia is a significant impact of stochastic factors on their operation. These factors include natural (water inflow in the reservoirs in the spring-summer period and outdoor temperature in the autumn-winter period), and also economic (demand for electric and thermal energy, electricity and heat prices) factors. The paper presents mathematical models for the joint study of energy and water systems. These models factor in the specifics of the systems during planning for a period of up to 1 year. Modeling of the interconnected operation of energy and water systems makes it possible to solve important problems. These are the improvement in the reliability and stability of the considered systems, increase in their economic efficiency (minimization of electricity prices for consumers), assessment and minimization of various risks, prevention from or reduction in possible damages, rational planning of repairs, the formation of fuel reserves at thermal power plants, and others.

1 Introduction

Energy and water systems are managed by various departments, as a rule, independently of each other. The legal and regulatory framework for these systems in the Russian Federation works also separately. Planning the operation of these systems focuses primarily on normal (average) operating conditions. Practical problems of studying the HPP operating regimes, however, are related to the periods of extreme conditions and the effect of these conditions on the stability and reliability of the systems. The extreme climatic situations in the water-energy systems lead to negative consequences, including significant socio-economic damages. Therefore, it is important to timely make management decisions to prevent (mitigate) the consequences of such events. By way of illustration, note the situation in the Angara basin and the Siberian energy system in recent years. In 2014–2018, an extreme water shortage was observed in the reservoirs of the Angara cascade. During this period, electricity generation from HPP decreased by 15–20%. All participants in the water management sector encountered problems, the overall reliability and stability of the water and energy systems significantly declined. The problem is compounded by the fact that the existing planning and management system in the electric power industry suggests the estimation of long-term energy system operating conditions and balances of electricity and power for a period of up to 1–5 years, while in water management, the forecasting horizon for water inflow into reservoirs and planning of HPP operating regimes is 1–3 months, and the forecasting period for air temperature is limited to 5–10 days.

The problem of modeling the operation of energy systems with HPP, including optimization of their operation, started evolving as soon as energy systems came into existence. Modeling methods developed alongside with the complication of the systems and the emergence of new mathematical and information technologies. A great number of effective algorithms, methods and models have been developed in recent years to study the operating regimes of HPP and the functioning of energy and water systems. Many of them were created in the 1960s and 1970s and were subsequently used in automated dispatch control systems for energy systems, to perform water-energy calculations, and manage water and energy systems. Simulation and mathematical methods found wide use in the optimization of operating conditions (linear, nonlinear, dynamic programming, including stochastic and multi-criteria optimization, etc.) [1–5]. Apart from Russia and USA, there is a great experience in modeling

* Corresponding author: nikitin1310@mail.ru

energy systems with high penetration of hydro in Norway, Canada, Brazil, and China [6–13].

Thus, to date, considerable experience has been gained in the practice of modeling energy systems with hydraulic and thermal power plants. Many issues, however, remain unsolved due to the complexity and versatility of the problem to be solved. Most models do not fully represent the constraints for hydroelectric power plants, such as the lack of data on the future hydrological regime of a probabilistic nature. This, in turn, leads to insufficient consideration of random nature-induced factors in planning the operating conditions of energy and water systems and ensuring their flexibility and reliability. This is especially true for long-term estimates of possible water inflows into HPP reservoirs and temperature changes.

Most modern methods and models for managing the long-term operating conditions of HPP, water and energy systems for a period of more than 3 months rely mainly on statistical information on long-term average changes in water inflows, and long-term average annual, monthly, summer and winter temperatures over past periods. Traditionally, the Monte Carlo method is most often used to generate forecast estimates of stochastic indicators. Some studies suggest the use of an integrated approach for managing cascades of reservoirs with the priorities of meeting either water system requirements or energy system requirements [14–16]. Joint long-term operation of the two systems (energy and water), as a rule, is not considered. This is especially true for climate factors.

Significant changes in socio-economic conditions, legislation, and regional climate changes in recent years associated with global processes require appropriate changes and additions to the methods and models of managing energy and water systems and their operation. The use of various prognostic methods and models is necessary to beforehand take account of possible changes in the indices of water content and temperature condition, including the data obtained with global climate models on the dynamics of the state of the atmosphere for a period of up to 1 year. Regular monitoring of such estimates and their refinement (at least 1 time per month) makes it possible to obtain more informed probabilistic scenarios of expected changes in natural factors for long-term planning of the energy and water systems. Their use allows increasing the efficiency of planning and management.

This paper presents an approach used at the Melentiev Energy Systems Institute SB RAS (ESI SB RAS) to jointly model long-term operating regimes of HPP and HPP cascades (for example, the Angara-Yenisei cascade) within energy and water systems, given climatic and other factors.

2 A system of models for the joint study of water and energy systems

A research team of ESI SB RAS has developed an approach [17–18] to comprehensively study the long-term operation of water and energy systems with a large share of HPP (Fig. 1).

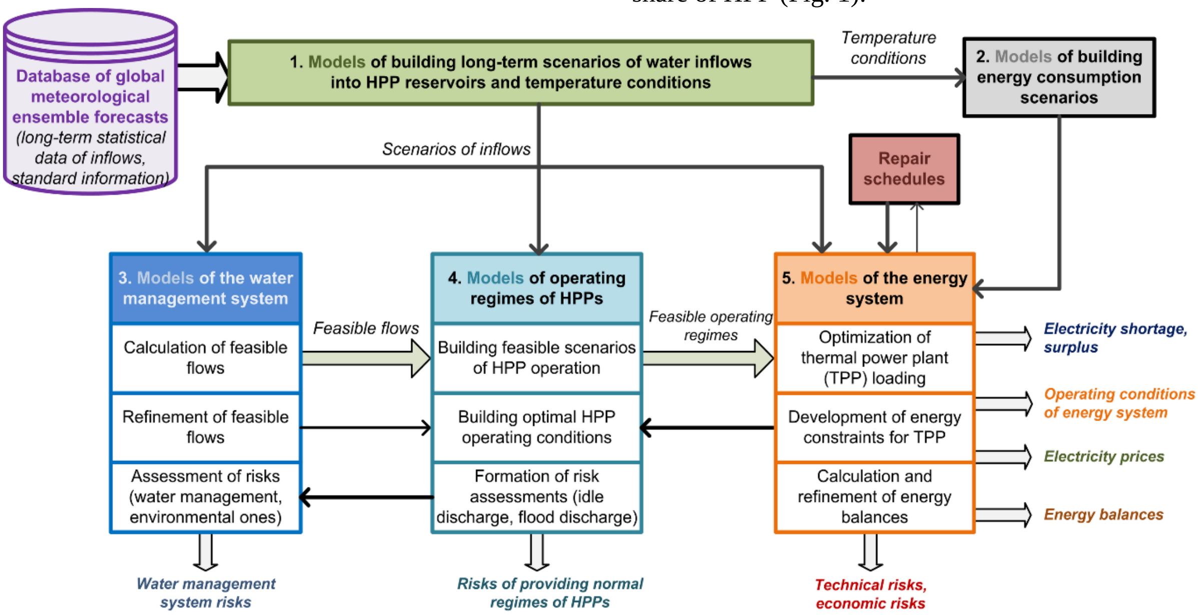


Fig. 1. The scheme of models for integrated studies of long-term operation of water and energy systems

This approach is implemented by 5 main blocks of the models:

1. Models of building long-term scenarios of water inflows into HPP reservoirs and temperature conditions in winter and summer in a probabilistic form;
2. Models of building energy consumption scenarios in a probabilistic form;
3. Models of the water management system;
4. Models of operating regimes of HPP and HPP cascades;
5. Models of the energy system.

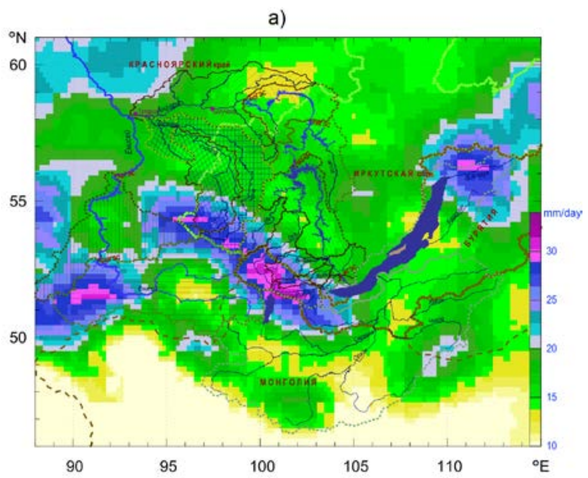
Each block includes several models (simulation, optimization, and multi-criteria) that solve various problems, given the uncertainty of water inflows into reservoirs, the amplitude and frequency of temperature anomalies in the studied regions, the requirements of water users, the amount of electricity consumption, forced and planned repairs of electrical equipment and electrical networks, constraints on maximum transfer capability of individual sections of the power grid in controlled cutsets, other factors, and limitations.

Based on probabilistic long-term scenarios of water inflows into reservoirs and expected temperature conditions, the proposed approach provides optimal balanced operation of water and energy systems while ensuring reliability and uninterrupted energy and water supply to consumers at any considered time interval.

2.1 Models for building long-term prognostic scenarios of water inflow into reservoirs

In the context of global and regional climate changes, the use of hydro-meteorological statistics alone becomes ineffective for forecast estimates of water content and temperatures. Given the significant advancements in the creation and development of global climate models over the past decades, it seems appropriate to use them for long-term estimates of water availability and other hydro-meteorological indices. One of such models is the global climate model CFS-2 (Climate Forecast System) [19]. The results obtained with this model are updated daily in the form of ensemble forecasts of the state of the atmosphere and ocean with a time interval ranging from several hours to 10 months for the entire globe. The ensemble approach used in the model allows the formation of probabilistic estimates of the state of the atmosphere for the long term.

To monitor, accumulate and process the results of modeling, we developed special components that can quickly generate long-term estimates of precipitation, temperature, pressure, and geopotential in the river basins of the studied energy system. Figure 2, for example, illustrates the forecast maps for analyzing the climatic situation in the basins of Lake Baikal and the Angara reservoirs for the summer period of 2020, as of January 2020.



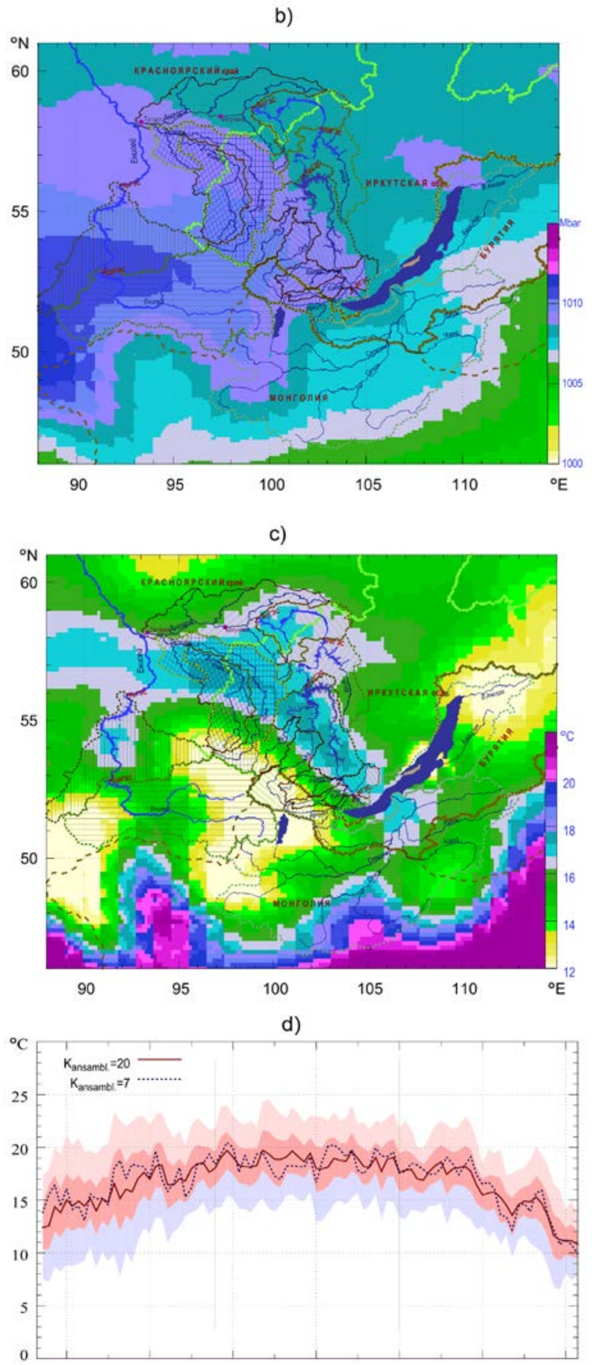


Fig. 2. An example of maps of prognostic indicators (average for the summer period of 2020): a) precipitation intensities; b) surface pressure at sea level; c) temperature conditions; d) dynamics of changes in surface temperatures in the area of the city of Irkutsk

Based on the processing of ensemble forecasts of meteorological indicators in the considered region, one determines analog years that are closest in atmospheric state characteristics. The found analogs are used to form estimates of inflows into the cascade reservoirs in the form of ranges of probability distributions. The period from April to October is the most important for planning the operating conditions of the water management system of Siberia. The final ensemble forecasts are generated by an automated procedure, which cuts off the unlikely events, processes regression relationships and relations between meteorological indices and river flows, and refines their boundaries based on expert estimates generated by other models [20, 21]. Temperature conditions are formed as anomalies of their spatial distributions. In Siberia, the temperature conditions are essential for planning the operation of the energy system in the winter heating period (from November to March), when possible generation and consumption of thermal energy varies widely [22–24].

2.2 Models for building long-term scenarios of electricity consumption in the energy system

Electricity consumption in the energy system is probabilistic in nature. It is characterized by daily, seasonal, and interannual variability associated with the intensity of the consumer load, temperature conditions in the served territories, which significantly affects the heat output, and also with a possible connection of additional planned and unplanned consumers.

Models for building long-term scenarios of electricity consumption are based on the accumulated statistical data for various temperature conditions, which make it possible to form regression relationships, with a focus on periods of maximum and minimum consumption in daily and seasonal resolutions. Available planned indices of demand for electricity and power, commissioning of new large electricity consumers are also used.

2.3 Water System Models

The system includes hydrological models based on water balance equations; hydraulic models for estimating the travel time of the water flow to different points of the river network; water management models to take into account the constraints of all water users and water consumers, as well as environmental and social constraints. For example, a hydrological model of a linear cascade or its part can be represented as:

$$\frac{dV_i}{dt} = P_i(t) - Q_i(t) + \overline{Q}_{i-1}(t) - \Lambda_i(t), \quad (1)$$

$$Q_B(t) = Q_4(t) + P_B(t),\ Q_T(t) = Q_B(t) + P_T(t), \quad (2)$$
$$Q_0(t) = 0,$$

$$\Lambda_i(t) = R_i^{isp}(t) + R_i^{filtr}(t) + R_i^{pz}(t) + R_i^{tr}(t), \quad (3)$$
$$t \in [t_0, T],\ i = \overline{1, N},$$

where i – HPP index; t – time within a set interval $[t_0, T]$; $V_i(t)$ – water volume in the reservoir; $P_i(t)$ – lateral (full) water inflow into reservoir; $Q_i(t)$ – flow rate through the HPP; $\overline{Q}_{i-1}(t)$ – flow rate of water of the upper stage of the HPP cascade, given water travel time; Q_B, Q_T, P_B, P_T – flow rates and lateral inflows in the areas below the last stage, where the river levels are monitored; $\Lambda_i(t)$ – function of additional effect of evaporation from the reservoir surface $R_i^{isp}(t)$, filtering through dam $R_i^{filtr}(t)$, changes in the underground component $R_i^{pz}(t)$, variations in the volume of water area between reservoir and upper stage of HPP. The values of functions $\Lambda_i(t)$, except for evaporation, can be neglected in practical calculations. This is due to the complexity of the estimates of these indices and their relatively small impact on the total inflow. The evaporation function plays a significant role in dry periods on Lake Baikal, therefore, its indices are included in the final available inflow to the Irkutsk reservoir.

For the specified time interval τ equation (1) can be approximately written in the finite difference form:

$$\Delta V_i^\tau(t) = [Q_{i-1}^\tau(t) + P_i^\tau(t) - Q_i^\tau(t) - R_i^{isp}(t)] \cdot \tau, \quad (4)$$
$$Q_0^\tau(t) = 0,\ i = \overline{1, N}.$$

Constraints for upstream reach:

$H_i^{UMO} \le H_i(t) \le H_i^{NPU}$ – for normal water content,

$H_i^{UMO-} \le H_i(t) \le H_i^{FPU}$ – for extreme water content.

Constraints on flow rates:

$$q_i^{turb}(t, j) \le q_i^{\max}(h_i),\ \ q_i^{hol}(t,k) \le q_i^{hol,\max}(h_i). \quad (5)$$

Statistical functions:

$$z_i = \varphi_i^z(Q_i, H_{i+1}^{vb}),\ E_i^{\max} = \varphi_i^E(Q_i, h_i), \quad (6)$$
$$H_i = \psi_i(V_i),\ V_i = \psi_i^{-1}(H_i),$$

where $\Delta V_i^\tau, P_i^\tau, Q_i^\tau, R_i^\tau$ are average values of the functions on the time interval.

Functions of water inflow $P_i^\tau(t)$ have large interannual and seasonal variations, which affects greatly both the water system and the energy system.

The hydraulic models of steady-state flow can provide an estimate of the average flow at the point X, located at a distance from the initial one:

$$Q^X = \frac{1}{T} \cdot [Q^- \Delta t + Q^+(T - \Delta t) + q^- \tau + q^+(T - \tau)], \quad (7)$$

where Q^-, Q^+ are flow rates at the initial cross-section for the previous and current ten days; q^-, q^+ – analogous lateral average ten-day inflows in the area; Δt, τ – travel time of the main and lateral inflows to point X; T – duration of ten days (c).

The reservoir operating curves intended to manage the operating conditions at levels and given scenarios of water inflows into the reservoirs are used to make forecast scenarios of flow rates through HPP. The range of limiting flows goes to the block of models of HPP regime management.

In addition to feasible flow rates through HPP according to the requirements of water users and water consumers, the models of water management system determine periods and assess probable water management, environmental, and social risks.

2.4 Models of operating conditions of HPP and HPP cascades

Power and electricity output at individual HPP varies widely, which is related to seasonal and interannual unevenness of water inflows into reservoirs and operation of the energy system at different time intervals according to load curves. For the HPP cascade, as a rule, the interannual unevenness of the inflows decreases, except for cases of global low-water and high-water periods, covering large river basins.

Modeling the operating regimes of HPP according to the generated scenarios of water inflows into reservoirs solves the following problems:

1. Specification of water flow rates by reservoir operating curves:

$$Q_t^g = D^g(H_t^g, P_t^g, \theta^g), \tag{8}$$

where D^g – reservoir operating curve of HPP with index g; θ^g – additional vector of the reservoir operating curve parameters; Q_t^g, H_t^g, P_t^g – flow rate, the upstream reach level, inflow into the reservoir at time t. With the sufficiently long hydrological statistics available, the reservoir operating curves allow building efficient operating conditions for any intra-annual and intra-month period for a given total inflow of water into the reservoir and the level of its upstream reach. The reservoir operating curves can be effectively used in simulation models for various studies. In the case of significant changes in hydrological characteristics compared to those observed previously, the effectiveness of their use in the calculation of flow rates decreases.

To determine the effective operating regimes of HPP to meet the set constraints on flow rates generated in the block of the water management system in the form of $Q_i^{\min}(t) \le Q_i(t) \le Q_i^{\max}(t)$, $i = \overline{1, N}$, the ranges of flow rates for each time interval (a day, ten days, a month, a quarter) are specified using the reservoir operating curves given planned repairs.

2. Determination of flow rates for cascade management according to the criterion of maximization of electricity output from the entire cascade:

$$\sum_{(t)} C_t \sum_{(g)} (E_t^g - E_t^{hol}) \to \max \tag{9}$$

with a set of constraints on flow rates, levels of upstream reach, power related to the type of loading the hydro units:

$$\begin{aligned} Q_{t,\min}^g &\le Q_t^g \le Q_{t,\max}^g \\ H_{\min}^g &\le H_t^g \le H_{\max}^t \\ W_{\min}^g &\le W_t^g \le W_{\max}^t \end{aligned} \tag{10}$$

Additional constraints are all water management constraints.

The optimization criterion may also be the maximum firm power of HPP in the winter period or for the entire water management year.

The output of this block is the feasible (possible) ranges of electricity output for each HPP, the entire HPP cascade, and indicators of used capacity in different periods.

For energy systems with a high share of hydropower plants, the main risks of operation management in the summer period are idle discharges through spillway structures of hydro systems, and an increased electricity output, when there is no corresponding demand and (or) it is impossible to fully use (transmit) it. The main risk in winter is the impossibility of providing firm power from HPP.

2.5 Model of energy system

Depending on the tasks being solved, which may include increasing the reliability and resilience of energy systems, increasing the economic efficiency of energy systems, assessing and minimizing various risks, preventing or reducing possible damage, rational planning of repairs, building up fuel reserves at Thermal Power Plants (TPP) and others, various formulations of the power system model are possible. In this case, the modeling of energy systems is reduced to solving the optimization problem, where the criterion for the efficiency of the energy system is reflected in the objective function, and the restrictions consist of balance restrictions and restrictions on variables. The main input parameters for the operation of the power system model block are: long-term energy consumption scenarios in annual, seasonal, monthly, weekly, daily and hourly sections; permissible operating modes of hydroelectric power stations taking into account all water management and energy restrictions, repair schedules for electrical equipment and electrical networks

One of the criterion of electricity generation cost minimization, the input data are flow characteristics of generating plants, the required levels of consumer loads in the territorial energy zones, transfer capabilities of tie lines, auxiliary power consumption, and factors of power losses in the transmission lines of the energy system. It is necessary to determine the optimal load of power plants given some technical limitations on the operation of the energy system and its facilities, and the potential surplus (shortage) of generating capacity.

The problem of planning the operation of the energy system for a period of up to 1 year is solved, the power balance is optimized for each hour of the calculation period.

Mathematically, the problem of optimizing the energy system operation is formulated as follows:

$$\sum_t \sum_i \sum_k C_{t,i,k} \to \min \tag{11}$$

subject to balance constraints:

$$P_{t,i} - W_{t,i} + \sum_{(j)} (1 - Z_{t,ji} \chi_{ji}) Z_{t,ji} - \sum_{(j)} Z_{t,ij} = 0 \tag{12}$$

also variable constraints:

$$\begin{aligned} &\underline{P}_{t,i} \le P_{t,i} \le \overline{P}_{t,i}, \\ &P_{t,i} = \sum_{(n)} P_{t,i,n} + \sum_{(k)} P_{t,i,k}, \\ &C_{t,i,k} = \alpha_{i,k} + \beta_{i,k} P_{t,i,k} + \tfrac{1}{2} \gamma_{i,k} P_{t,i,k}, \\ &0 \le Z_{t,ij} \le \overline{Z}_{t,ij},\ 0 \le Z_{t,ji} \le \overline{Z}_{t,ji}, \\ &t = 1, \dots, T,\ i = 1, \dots, I,\ k = 1, \dots, K, \\ &n = 1, \dots, N,\ j = 1, \dots, J, \end{aligned} \tag{13}$$

where $C_{t,i,k}$ – the cost of generating electricity per hour t at the k-th TPP in energy zone i; $P_{t,i}$ – generated power per hour t in energy zone i; $W_{t,i}$ – power consumption per hour t in energy zone i; $Z_{t,ji}$ – power flow over the connection between energy zones j and i per hour t; χ_{ji} – power loss coefficient; $Z_{t,ij}$ – power flow over the connection between energy zones i and j per hour t; $\underline{P}_{t,i}$ – the total value of the minimum load of power plants per hour t in the energy zone i; $\overline{P}_{t,i}$ – the total value of the maximum load of power plants per hour t in the energy zone i; $P_{t,i,n}$ – loading of the n-th HPP per hour t in the energy zone i; $P_{t,i,k}$ – loading of the k-th TPP per hour t in the energy zone i; $\alpha_{i,k}$, $\beta_{i,k}$, $\gamma_{i,k}$ – the coefficients forming the flow characteristic of the k-th TPP in the energy zone i; T – the number of hours of the calculating period; I – number of energy zones; K – number of thermal power plants; N – number of hydropower plants; J – number of energy zones.

Problem (11)–(13) is solved by nonlinear programming methods. $P_{t,i,n}$ is determined when modeling the regimes of HPP and their cascades, while $P_{t,i,n}$ can have a constant value or be in the range $\underline{P}_{t,i,n} \le P_{t,i} \le \overline{P}_{t,i,n}$, where $\underline{P}_{t,i,n}$ is the minimum load of the n-th HPP at hour t in the energy zone i; $\overline{P}_{t,i,n}$ is the value of the maximum load of the n-th HPP per hour t in the energy zone i.

After solving problem (11)–(13), an analysis is made of the results and modes in which no solution was found for various scenarios of water inflows and temperature conditions. As a result of several iterations according to model calculations with $P_{t,i,n}$ adjustment, the most optimal power system operating modes are selected according to the accepted criterion and electric power generation by the HPP of the power system.

3 Conclusion

The system of models presented in this paper allows studying the issues related to the management of HPP cascade operation within the water management and energy systems. It also enables us to formulate proposals for optimal long-term operating conditions, increase in stability, reliability, and efficiency of these systems while planning and managing them.

Long-term scenarios of changes in hydro-meteorological indices (water inflows into reservoirs, temperatures, precipitation), obtained using the processed data from global climate models, provide an opportunity to assess in advance the probable risks of the impact of stochastic factors on the operation of the water and energy systems with a large share of HPP.

Acknowledgements

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Prospects for the use of coal of the Republic of Sakha (Yakutia) for energy needs

Nikita Pavlov[1,*], *Liudmila* Takaishvili[2], and *Vasiliy* Zakharov[1]

[1]Larionov Institute of the Physical-Technical Problems of the North of Siberian Branch of the Russian Academy of Sciences, Energy Problems Department, Yakutsk, Russia
[2]Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Department of Complex and Regional Problems in Energy, Irkutsk, Russia

Abstract. The Republic has significant resources for the development of mining, export and domestic consumption, including the energy needs of the republic and neighboring regions. The article provides a retrospective analysis of the supply of Yakut coal for energy needs and the structure of capacities by energy resources. The estimation of power-generating coal resources, including low-grade products of coking coal processing of the Republic of Sakha (Yakutia), is given. Characteristics of coal deposits are presented, which are useful for energy needs. Projects for the development of coal-fired energy in the Republic of Sakha (Yakutia) are presented. The Republic of Sakha (Yakutia) has significant coal resources for the development of coal-fired power plants. Coal power facilities play a closing role in meeting the demand for electricity and heat. The use of coal for the development of coal-fired energy in the Republic of Sakha (Yakutia) can be determined by the development of mining industry, the construction of power plants of small capacity in isolated areas, as well as the possibility of exporting coal-fired power plants.

Keywords. Energy system, coal, balance reserves, the Republic of Sakha (Yakutia), consumption, projects, trends.

1 Introduction

The Republic of Sakha (Yakutia) is the world's largest administrative-territorial unit. Being the largest region of the Russian Federation in terms of area, it occupies 18% of its territory. The republic belongs to the territories of the Arctic zone of the Russian Federation and the Far East. The Republic of Sakha (Yakutia) has significant reserves of energy resources: water resources, coal, oil, gas. Currently, the main resources for generating electricity in the region are hydro resources, gas and coal. Coal, along with gas, is of paramount importance as a type of fuel consumed in the republic. South Yakutia coal power plants act an important role in the energy system of Russia's eastern regions. Coal mined in the republic is supplied to power plants in Yakutia and neighboring regions.

The program of development of the coal industry of Russia for the period up to 2030, involves the construction of coal power plant in the eastern regions of Russia, including the Republic of Sakha (Yakutia) to meet domestic demand and export electricity1,2. The development of coal generation is also considered in regional documents3,4. At the same time, program documents of the state and regional levels are often not coordinated with each other.

According to forecasts made by the U.S. Energy. Information Administration and International Energy Agency demand for electricity in Asia will increase, [1,2], which creates favorable conditions for the construction of export power plants oriented to the export of electricity.

The research of the prospects for the use of coals of the Republic of Sakha (Yakutia) for energy needs is relevant for a number of reasons:

- the presence of significant coal resources for the energy sector, including in isolated areas and low-grade products of coal processing at coal processing plants;
- high social significance of existing coal mining enterprises, not only for fuel supply, but also as city-forming enterprises.

2 The use of coals of the Republic of Sakha (Yakutia) for the energy needs – the current state

* Corresponding author: pavlov_nv@iptpn.ysn.ru

[1] Долгосрочная программа развития угольной промышленности России на период до 2030 года; утв. распоряжением Правительства Российской Федерации от 24.01.2012 г. № 14-р /.перевод
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[3] «О схеме и программе развития электроэнергетики Республики Саха (Якутия) на 2020-2024 годы». Утверждена указом Главы Республики Саха (Якутия) №1171 от 30 апреля 2020 года /перевод
[4] О проектной программе оптимизации локальной энергетики Республики Саха (Якутия) на период до 2017 года правительство Республики Саха (Якутия) постановление от 3 сентября 2011 года N 424 / перевод

Coals of the Republic of Sakha (Yakutia) are supplied to power plants and boiler houses of the Republic and to power plants of the Primorsky and Khabarovsk Territories (Table 1).

The supply of coal to the power system of the Republic is subject to fluctuations. This is due to the peculiarities of the energy system of the Republic.

A distinctive feature of the power system of the Republic of Sakha (Yakutia) is the presence of zones of centralized and decentralized power supply. The zone of decentralized energy supply includes the territories of the Arctic and northern regions of the Republic of Sakha (Yakutia). This zone accounts for 74% of the territory of the republic and 15% of the population. The centralized power supply zone includes three power regions - Western, Central and Yuzhno-Yakutsk. Centralized power supply covers only 36% of the territory, with 85% of the population. In 2019, the Central and Western energy regions became part of the Unified Energy System of Russia. Due to the isolation of the energy regions of the Republic of Sakha (Yakutia) until now, they have been characterized by an excessive balance of energy and electrical power. In the last decade, due to the adopted policy of eliminating the isolation of energy regions, additional overhead power transmission lines have been introduced.

Large generating companies operate on the territory of the republic, which provide over 95% of the total electricity generation and more than 45% of heat energy in the republic. There are also a large number of stand-alone energy sources. Thermal power plants (TPPs) and hydroelectric power plants (HPPs) form the basis of the electric power industry. Their share in the total capacity of power plants is estimated at 43 and 30.6%, respectively (Fig. 1).

Diesel power plants (DPP) are stationary and mobile, occupy 25% of the installed capacity. Renewable energy sources (RES) account for an insignificant share in the capacity structure - 0.05%. In retrospect, the installed capacity at power plants of the power system of the Republic of Sakha (Yakutia) from 2014 to 2018 increased by 262.7 MW from 2861.6 MW to 3124.3 MW. The installed capacity of HPPs remained unchanged, TPPs and DPPs - increased by 97.2 MW and by 131.4 MW. The installed capacity of solar power plants (SPP) increased from 0.225 MW to 1.617 MW, with a 6-fold reduction in the installed capacity of wind power plants (WPP).

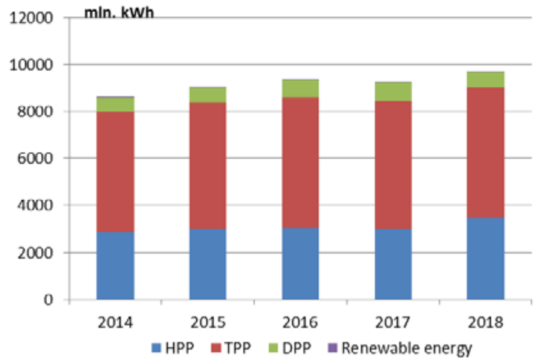

Fig. 1. Electricity production by the power system of the Republic of Sakha (Yakutia), million kWh

Table 1. Coal supplies of the Republic of Sakha Yakutia, million tons

Index		2013	2014	2015	2016	2017	2018	2019
Mining		11,9	12	15,3	17	16,8	17,5	19,2
Export		6,2	6,7	6,3	7,9	7,4	6,6	8,6
By-product coke plants		0,5	0,6	1,9	2,2	2,6	2,7	2,1
For energy needs		3,2	2,9	3,3	3,1	2,8	3,3	2,4
At the power plant of the Republic		1,7	1,5	1,7	1,8	1,7	1,7	1,6
At the power plants of neighboring regions		1,5	1,4	1,6	1,3	1,1	1,6	0,9

Source: statistical data of FGBU “CDU TEK”, forms 6-TP

Electricity is also supplied from the energy system of the republic to the IES of the East and the Irkutsk region. The share of coal generation in electricity supplies to neighboring regions is 96%. At the same time, the settlements of two districts - Nizhnekolymsky and Oymyakonsky, located in the zone of decentralized energy supply, are supplied with electricity from the Magadan Region and the Chukotka Autonomous Region.

The total volume of fuel consumption by power plants and boiler houses in 2019 amounted to about 5.0 million tons of fuel equivalent, including 2.4 million tons of fuel equivalent of coal. (45.6%), natural and associated gas - about 2.4 million tons of fuel equivalent. (46.8%).

In 2019, thermal power plants consumed 3.2 million tons of fuel equivalent, of which 51.4% was gas (natural and associated), 43.1% - coal. Diesel fuel accounts for 4.6% in the structure of fuel consumption by power plants. In 2019, boiler houses consumed 1.8 million tons of fuel equivalent. fuel, of which 52.7% is coal, 38.8% is gas (natural and associated) (Table 2).

Table 2. Fuel consumption by power system objects, 2019, t.o.e.

Type of fuel	Total (% of consumption)	TPP	boiler house
Total	5048	3189	1859
Coal	2354	1375	979
Oil (including gas condensate) and oil products (except diesel fuel)	182	27	155
Diesel fuel	151	148	3
Natural gas	2006	1301	705
Associated gas	355	338	17
Wood	0,6	0	0,6

Source: [3]

The program for the development of gas supply and gasification of the Republic of Sakha (Yakutia) for the period from 2021 to 2025, adopted in 2020, is focused on transferring 21 settlements to gas in the Aldan, Lensky, Neryungri and Olekminsky regions of the republic.

Despite the conversion of individual energy facilities to gas, coal consumption is relatively stable. According to the statistics of the FGBU "CDU TEK", the supply of Yakut coals in the country as a whole from 2014 to 2018 increased from 4.56 million tons to 7.34 million tons with a relatively stable dynamics of coal consumption at power plants. On the domestic market, coals of the Republic of Sakha (Yakutia) are supplied to coke plants, power plants, for use in the household sector and other consumers. At power plants, in addition to raw coal, low-grade products of coking and thermal coal processing are consumed.

Boilers of the republic mainly use low-capacity boilers, as a rule, designed for burning sorted and refined coal. However, at present, all burned coals are used without any cleaning, enrichment, after repeated reloading, transshipment and long-term storage. When operating boilers on such raw coals, a layer of contamination on the heating surfaces increases, labor costs for servicing boiler houses, and their efficiency significantly decreases. The supply of low-grade fuel, the operation of boilers at an insufficiently high level leads to low efficiency of use and an annual excessive consumption of fuel.

3 Balance reserves of coal

The Republic of Sakha (Yakutia) has significant resources and reserves of power and coking coals. The largest coal basins of Russia are located on the territory of the republic: Lensky, South Yakutsky, Zyryansky, the eastern part of the Tunguska basin and also in the northern and northeastern parts of Yakutia - separate scattered deposits. Explored balance reserves of coal in categories A + B + C1 + C2 amount to 14.3 billion tons, or almost 50% of the balance reserves of the Far Eastern Federal District. In terms of geological reserves of coal, the Republic is one of the main subjects of the Russian Federation [3,4]. (Table 3).

Table 3. Reserves of coal of the Sakha Republic (Yakutia) by types of coal and method of mining, bln t

Coal type, mining method	Stock category		
	$A+B+C_1$	C_2	$A+B+C_1+C_2$
Total, including	9,7	4,6	14,3
Coking	4,1	2,6	6,7
Thermal coal, of them	5,6	2	7,6
Brown	4,4	1,5	6
Hard	1,2	0,5	1,6
For open source development, including	6,5	2,1	8,5
Coking	1,4	0,3	1,8
Thermal coal,of them	5,1	1,8	6,7
Brown	4,4	1,6	6

Source: [3,4]

in the republic is 1.1%. In the South Yakutsk basin, the coal resource potential is most significantly realized - 19.2%. For the Lena basin and others, this ratio is less than 1%. This indicates great prospects for the development of coal mining due to the development of not yet developed predicted resources. Prepared for development and is being developed and 4.53 billion tons, which is 46.7% of the volume of reserves of categories A + B + C1.

59.4% of coal reserves are suitable for open pit mining. Thermal coals account for 7.6 billion tons of reserves of categories A + B + C1 + C2 slightly more than 50% of the balance reserves. And from the balance reserves suitable for open-pit mining, power-generating coals account for 79%.

4 Coal resources for the development of coal energy

Coal resources for power generation are significantly higher than the balance reserves of steam coal and consist of steam coal and low-grade products of processing of hard and coking coals. With possible production levels in the republic of 45-50 million tons, the resources of coal for the power industry can reach up to 19-22 million tons, including energy concentrate, raw energy coal and industrial products. The volumes of low-grade processed products suitable for the needs of the energy sector can make up from 23 to 42% of the processing volumes

The provision of coal reserves in the Republic of Sakha (Yakutia) at the level of production in 2018 is more than 550 years, and in energy reserves at the level of supplies to the power plants in 2018 for more than 2000 years..

Coking coal deposits of the South Yakutsk coal basin are promising for development: Elginskoe, Denisovskoe, Chulmakanskoe, Kabaktinskoe. Low-grade products after the processing of the coal from these deposits, suitable for combustion at power plants, can amount to up to 8 million tons. Development projects of the deposits presented are in varying degrees of implementation. The largest production volumes under the projects are being considered at the Elginskoye field.

The Elginskoye field is the largest in Russia and one of the world's largest deposits of high quality coking coal. Coal reserves of the Elginsky deposit amount to 2.2 billion tons, including balance categories A + B + C1 - 1599.4 million tons. with a production volume of 27 million tons of coal per year, an enrichment plant with a production output of up to 23 million tons per year and the Elginskaya CHPP has been under way since 2010. In 2018, coal production at the Elga open-pit mine amounted to 4.92 million tons, and exports - 1.74 million tons. When the open-pit mine and the processing plant reach their full capacity, resources for the energy sector can range from 8.5 to 10.6 million tons. The project is constrained by financial problems..

In decentralized energy supply areas, the proven balance reserves of coal deposits suitable for use at energy facilities do not always correspond to real reserves. Additional geological exploration is needed to clarify coal reserves.

In the Lensky coal basin, the most promising deposit for supplying the Arctic regions due to its geographical location is the Belogorsk brown coal deposit, located on the right bank of the river. Lena is 20 km away. from the village Sangar in Kobyayskiy ulus.

In the Zyryansk coal basin, the development of the Nadezhdinsky deposit is of great strategic and socio-economic importance for enterprises and the population of the northern group of regions of the republic and neighboring regions.

The Nadezhdinskoye coal deposit is located 48 km from the village of Zyryanka and 12 km from the village of Ugolnoye.

In the zone of decentralized energy, coal deposits can be promising for energy supply to consumers: Krasnorechenskoye, Kularskoye, Taimylyrskoye coal deposits and bogheads, etc.

Krasnorechenskoye coal deposit is located on the left bank of the middle reaches of the river. Indigirka, 160 km. upstream from the village of Druzhina. The Sogolokh section is remote from the navigable part of the river. Indigirki 1.5-4 km. The deposit is characterized by “heterogeneity of the distribution of the ash content of coal and the heat of its combustion in certain areas” [6].

The Kular brown coal deposit is located in the basin of the lower reaches of the river. Kuchuguy Kuegyulyur. The deposit belongs to the Ust-Yansky ulus of the Republic of Sakha (Yakutia). Coal of the Kular deposit belongs to brown humus coals of B1 group of low degree of coalification (ash - 7.00-50.00%, sulfur - 0.30-0.40%).

The Taimylyr field is located in the Bulunsky district, 15 km west of the village of Taimylyr and 260 km from the village of Tiksi

The resources of thermal coal, including low-grade products from processing plants, significantly exceed the demand.

5 Projects for the development of coal energy in the Republic of Sakha (Yakutia)

The Republic of Sakha (Yakutia) has sufficient coal resources for the development of energy, including coal for supplying its own consumers and for the supply of electricity and energy resources to neighboring regions [7, 8].

Various state federal and regional strategies and programs consider the construction of coal power plants in the Republic of Sakha (Yakutia) (Table 4).

Table 4. Proposed coal power plants in the Sakha Republic (Yakutia)

Name	Capacity, MW	Years of construction
Elginskaya GRES*	1800	2025-2030
Dzhebariki-Khaiskaya TPP*	150	2020-2030
Expansion of Neryungrinskaya GRES (block 4)**	225	2026-2030

* Energy Strategy of the Republic of Sakha (Yakutia) for the period up to 2030

** General layout of power facilities until 2035, Program for the development of the coal industry until 2035, program for comprehensive modernization of PJSC RusHydro

The program for the long-term development of the coal industry provides for the construction of the Elginskaya CHPP and the expansion of the Neryungrinskaya TPP.

Three power units with a total electric capacity of 570 MW and a thermal capacity of 1120 Gcal / h are installed at the Neryungrinskaya GRES. The fuel for the power plant is an industrial product obtained during the enrichment of coking coal from the Neryungrinskoye deposit. The average annual demand for solid fuel at full load is 1.6 million tons per year..

Until 2030, it is planned to expand the Neryungrinskaya SDPP by commissioning the fourth unit with a capacity of 225 MW, the installed electric capacity will be 795 MW, the average annual demand for solid fuel will increase to 2.2 million tons per year.

In reality, projects for the construction of coal-fired thermal power plants are often in the initial stage of development or implementation, and the implementation of projects can often be significantly delayed or become unattainable for various reasons.

In the Arctic zone in the village of Zyryanka, the construction of a mini-CHP with electric capacity is underway to supply power to nearby settlements. Coals of the Zyryansk deposit are supposed to be used as fuel. Currently, due to lack of funding for the completion of construction, a decision has been made to mothball the installed equipment.

6 Options for the development of coal energy

Possible options for the development of coal energy:

1) Basic scenario of economic development with the implementation of energy-intensive industrial development projects;

2) Optimistic scenario: construction of a thermal power plant to join the super-Asian ring through the IES of the East.

The optimistic scenario is a low probability scenario due to the high risks associated with the implementation of its highly capital intensive projects. Yakutsk high-quality coal is in demand on the world and Russian coal markets. For export and coke-chemical plants in Russia, mainly coal concentrate is supplied from concentration plants. The lack of demand for low-grade coal processing products suitable for the needs of the energy sector may restrain the development of coal exports.

Basic scenario. The internal potential for the development of coal-fired energy is undoubtedly associated with the further operation and modernization of the Neryungrinskaya SDPP (570 MW). There are also two low-capacity coal-fired CHPPs in operation in the republic: Deputatskaya - 7.5 MW (owner of Sakhaenergo JSC, commissioned in 2011) and CHP of the Gross mine - 16 MW (owner of Neryungri-Metallic LLC). Start-up and adjustment works are currently being completed.

Optimistic scenario. A significant change in the share of coal generation in the electric balance of the region is associated with promising projects for the construction of export-oriented generation, primarily at the Elginskoye field, as well as the further development of the IES East towards connection to the isolated Magadan energy system [9, 10]. Approximate technical and economic parameters of Elginskaya GRES were reflected in the Energy Strategy of the Republic of Sakha (Yakutia) until 2030. approved by the Resolution of the Government of the Republic of Sakha (Yakutia) on October 29, 2009 No. 441 [11]. Within this document large-scale export of electricity offered to be realized from the newly built Elga (1.8 GW) and Urgal (2.4 GW) TPP to Shenyang (China). The competitor to this proposal was the construction of a cascade of hydroelectric power plants on the Timpton River with a capacity of more than 1 GW. At the moment, after the design and survey work at the site of the alignment, the hydropower plant construction project is mothballed.

It is planned to form a connection with the Magadan power system between the power plants of the central power district of the Yakut power system and the Magadan power system. The line (about 1000 km) will pass through the administrative center of the Tomponsky municipal district, Khandyga settlement in the immediate vicinity of the Dzhebariki-Khai coal deposit. The construction of a thermal power plant in this section can significantly increase the stability of the power system, as well as the reliability of power supply to the central energy district. An additional factor in favor of construction is the possibility, at the same time, of guaranteed sales of the products of the Dzhebariki-Khaiskiy open-pit mine.

The high fuel component in the cost of municipal energy in the republic forces the utilities to initiate the issues of opening additional small open-pit mines located in more convenient transport locations and in close proximity to hard-to-reach consumers. At the same time, the emergence of several mining enterprises balancing on the brink of profitability poses a threat to energy security. Consequently, the task of expanding the sales market for thermal coal in the central and northern regions is of great importance.

Potential points of expansion of coal generation in the region are associated with a long-term perspective and have strong competitive projects on the part of gas and hydro generation, which have more attractive technical and economic parameters.

The forecast of fuel consumption was made on the basis of forecasts for the generation of electric and thermal energy by power plants, taking into account the peak boiler houses in their composition provided by generating companies, as well as under conditions of maximum utilization of generating capacities. The expected volume of coal consumption at power plants is estimated at 2.7 - 6.8 million tons per year, the maximum consumption in boiler houses is estimated at 1.2 million tons (Fig. 2.). In the forecast period, an increase in natural gas consumption is expected due to an increase in heat loads and an expansion of the service area of heating networks of power plants in Yakutsk, gasification of municipalities adjacent to the Power of Siberia gas pipeline (21 settlements in Aldan, Lensky, Neryungrinsky and Olekminsky regions of the republic).

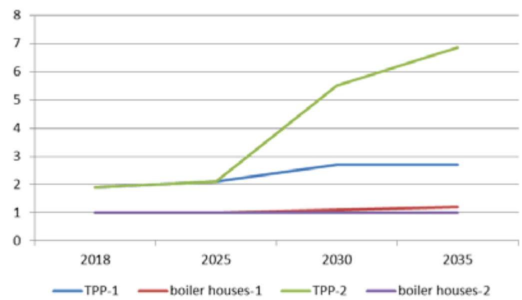

Fig. 2. The forecasted demand for coal, mln.t.
1 - baseline scenario, 2 - optimistic scenario

Table 5. Coal balance, million tons

Balance item	Years			
	2018	2025	2030	2035
Incoming part, total	17,6	39-51	41-55	42-56
including:				
- production, total	17,5	39-51	41-55	42-56
- import	0,1	0,1-0,1	0,1-0,1	0,1-0,1
Consumable part, total	17,6	39-51	41-55	42-56
including:				
- domestic consumption, total	3,7	4-4	4 -7	5-9
- processing losses	2,3	5-6	5-7	5-7
- coming out, total	11,6	30-41	32-41	32-40
including:				
- to regions of Russia, total	4,2	4-4	4-4	4-4
- export, total	7,4	26-37	28-37	28-36

Sources: author's calculations

7 Conclusion

Coal in the Republic of Sakha (Yakutia) is the most reliable source of fuel for the long term. This is due not only to the presence of significant coal reserves, including in the area of decentralized energy, but also in the long term, the growth in the processing of high-quality coals in demand on the world market.

At the same time, there are the following main problems and limitations for the group of northern enterprises:

- poor technical equipment, deterioration of conditions for the development of coal deposits;

- low level of coal processing and upgrading in the northern group of enterprises;

- complex transport scheme of delivery with several transshipments to various types of transport (sea, river, road);

- restrictions related to the financial support of the work and development of enterprises.

For the group of southern companies:

- the displacement of republican thermal coal in the Far East;

- deficit of the railway transportation capacity, the capacity of the Far Eastern ports;

- issues related to the demand for low-grade products from processing plants.

The development of energy in the Republic of Sakha (Yakutia) should be aimed at eliminating energy-deficient territories as well as with the great potential of industrial development, as well as isolated areas with the possibility of using local raw materials.

The growth of energy consumption in the republic is possible only at the expense of the development of coal generation in the republic. Unstable quality of coal in small areas in the zone of decentralized energy and competition from other energy carriers creates complexity in the implementation of coal development projects.

Consumption of Yakut energy coal in the neighboring regions of Khabarovsk and Primorsky Krai can be quite stable.

There is a promising introduction of standardization of coal fuel, which will allow to reduce the negative impact of coal energy [12]. The question of the reality of such standardization in the zone of decentralized energy supply is obvious.

Demand for electricity and heat from coal-fired power plants in the Republic of Sakha (Yakutia) is possible thanks to the development of mining industry, construction of new residential complexes and the development of energy security of the population of the republic. Implementation of projects for the construction of power plants on carbon for the export of electricity or the addition of a super-Asian ring in the near future is unlikely. Environmental and economic aspects of large-scale development of coal and the export of electricity require basic processing.

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"World crisis (2020): Plans and Reality for Implementation of the "Program of Development of the Coal Industry for the Period up to 2035"

Liudmila Plakitkina *[1]
[1] Energy Research Institute of the Russian Academy of Sciences (ERI RAS), Moscow, Russia

Abstract. The macroeconomic situation, both in the world and in Russia, is considered, which developed in 2020. COVID-19 made significant adjustments to the previously developed forecasts for the development of coal production and export. The results of calculations on the dynamics of coal production and export in the main countries of the world and in Russia are presented. The global crisis of 2020 forces us to revise (adjust) the "Program for the development of the coal industry in Russia for the period up to 2035" adopted in June 2020 (Program) [1], including coal export.

Keywords. Global crisis in 2020, Program for the development of the coal industry in Russia for the period up to 2035, forecasts of coal production and export in the world and the Russian Federation until 2040.

Introduction

The macroeconomic situation in the world has deteriorated significantly: oil prices, and then coal prices, began to fall, which leads to a decrease in coal production and consumption. COVID-19 has made significant adjustments to the previously developed forecasts for the development of coal mining and export. The research in this article is devoted to the answer to the question: what is the reality of the implementation of the "Program for the development of the coal industry in Russia for the period up to 2035", including the export of coal.

Macroeconomic situation and state of the coal industry in 2020

Starting in 2019, and especially in 2020, the macroeconomic situation both in the world and in Russia has changed significantly [2-6]. COVID-19 has led to the fact that the decline in global GDP in 2020, according to forecasts of the World Bank, may be about 5.2% compared with the level of 2019. The average world price of Brent oil in 2020 may "fall" by half compared to the level of 2019 - up to 32 dollars. US / bbl.

Coal production in the world in 2019 amounted to about 7.9 billion tons (+ 4.1% to the level of 2018), incl. in China - about 3.7 billion tons (- 5.3% by 2018), India - 769 million tons (- 0.9% by 2018), USA - 640 million tons (- 6.7% to 2018), Australia - 503 million tons (+ 3.7% by 2018), Indonesia - 616 million tons (+ 12.4% by 2018), Russia - 441.3 million tons (- 0.6 million tons by 2018) [2, 3]. In 2020, according to the forecast МЭА, world coal production may decrease by 8%, incl. in China - by 9%, in the USA - 25%, Japan and South Korea - by 5-10%, EU countries - by 20%.

The drop in oil prices, characteristic of 2019 and 2020 [2, 3], led, respec-tively, to a drop in world coal prices and a decrease in the average annual prices of Russian coal producers, and hence to a decrease in demand for coal and its production ... In the period from the second half of 2016 to 2018, oil prices increased, followed by an increase in gas and coal prices, and the growth of global coal production resumed. This allowed Russian producers to accelerate their production and export of coal. However, in 2019 the macroeconomic situation on the market changed: oil prices began to fall, while the average world prices of 1 ton of thermal coal on the world market decreased by 7.9%, to 108.6 USD. US / t, incl. in Europe - by 33.8%, to 60.9 dollars. USA. In turn, the average world prices for 1 ton of coking coal in 2019 decreased by 6.3% compared to the level of 2018 and amounted to $ 148.5. USA / t. These prices, in fact, balanced at the self-sufficiency mark. Nevertheless, from January to July 2020, coal prices on the European market were in the range of $ 54-59. USA for 1 ton at the port of importers, depending on contracts and delivery times. Prices in the Asia-Pacific market (APR market) also remain low. Contracts for the shipment of thermal coal (with a calorific value of 6300 kcal per 1 kg) in the Australian port of Newcastle were concluded at a price of $ 50. USA / t.

In the period from 2000 to 2019. the average annual prices for coking coal increased 6.2 times, for thermal coals - 6.7 times. Some price dips in 2009 and 2014 can be explained by the financial and economic crisis and the

* Corresponding author: luplak@rambler.ru

fall in oil prices, which, in turn, "pulled" the price of coal.

n December 2019, average producer prices for 1 ton of Russian coal amounted to $ 46.5. USA / t, including coking - 77.3 USD USA / t, energy - 36.0 USD. US / t, which is significantly less than in 2018.

High rates of growth in the prices of Russian coal producers “stimulated” the growth of the volumes of mined coal, especially coking coal, which were then exported in large volumes, given the need for high-quality coking coal. However, since the beginning of 2020, coal prices have dropped by 22%.

The drop in oil prices, characteristic of the second half of 2008, 2013, 2014, 2019 and 2020, led, respectively, to a decrease in the average annual prices of Russian coal producers, and hence to a drop in demand and volumes of production and supplies of Russian coal.

Coal supplies to the domestic Russian market continued their downward trend, and in January-August 2020 they decreased by 10.6% - to 103.6 million tons compared to the same period in 2019.

Nevertheless, despite the decline in coal production in Russia, Colombia and other countries, the supply of coal in the global market remains excessive, and weak competitiveness with gas also puts downward pressure on coal demand.

Global challenges generating a number of systemic problems and consequences for the coal industry in Russia

For the period 2011–2019 some financial performance indicators of the industry worsened: the debt on loans and credits received increased 3.3 times (from 243.4 to 810.8 billion rubles); the share of unprofitable enter-prises in the total volume of mined coal increased from 3.5 to 8.2% [5]. In the context of stagnation of domestic coal consumption in Russia, an increase in the supply of coal for export has been the main driver of growth in coal production for many years [6]. In 2019, Russia exported 192.3 million tons of coal, of which over 57% was supplied to the west. Compared to the level of 2010 in absolute terms, although they increased by 35.2%, the share of Russian coal supplied for export in the western direction fell from 84.3% in 2010 to 57.1% in 2019. of coal in the eastward direction in 2019 increased to 82.5 million tons (5.5 times more than in 2010), their share in the total volume of coal supplied for export in 2019 increased 2.7 times, amounting to 42.9%. Export prices of Russian coal supplied in the western direction in the period from 2010 to 2019 "Fell" to 60.9 dollars. US / t, or 34.1%, incl. coking - up to 59 dollars. US / t (- 38.8%), energy - up to 80.7 dollars. US / t (-32.4%). Export prices of Russian coal supplied to the east in the period from 2010 to 2019 decreased to 80.8 dollars. USA / t, or by 23.3%, incl. coking - up to 105.9 dollars. US / t (- 28%), energy - up to 77.5 dollars. US / t (-20.3%).

Revenue from coal exports in the industry as a whole in 2019 amounted to about $ 13.4 billion. USA (+ 46.8% to the level of 2010), incl. in the western direction - about 6.7 billion dollars. USA (- 10.9% to the level of 2010). To the east, revenue from coal exports increased 4.2 times compared to 2010. This indicates a reorientation of Russian coal supplies from West to East. Nevertheless, in January-August 2020, export supplies of Russian coal fell to 126.1 million tons, or 2.7% compared to the same period in 2019.

The main countries are consumers of Russian coal and factors that can lead to a drop in demand for coal

The main consumers of Russian coal in recent years have been: China, Japan, South Korea, EU countries and Ukraine. The situation in these countries with the consumption of coal testifies to the beginning of its decline and the transition to other energy sources. For example, China is cutting coal consumption due to a gradual reorientation from coal to natural gas and green energy. Due to Covid-19, coal consumption in China fell by 8% in May 2020, while coal consumption fell by 9%. In the EU countries, the decline in coal and hydro generation is taking place against the backdrop of an increase in gas, solar and wind generation. This has been fueled by the rise in the price of carbon emissions and the decline in gas prices, as a result of which gas generation has become cheaper than coal.

Coal consumption in Japan is planned to be reduced, and 110 out of 140 coal-fired power plants will be closed by 2030, which will “hit” the traditional suppliers of thermal coal to the country - Australia, Indonesia and Russia. Therefore, Russia in the next 10 years may lose another of the significant Asian markets for coal.

For many years Russia remained the largest supplier of coal to Ukraine. In 2019, according to the Ukrainian State Statistics Service, 58% of the total volume of coal supplied to the territory of Ukraine accounted for Russian hard coal and anthracite. However, in May 2020, Ukraine imposed duties on coal imports from Russia (at 65%) to protect its domestic market.

All of the above indicates that the demand for coal in the prospective period will significantly decrease. Russian coal supplies, both to the west and to the east, may decline.

Changes in the volumes of coal production and supplies are significantly influenced by the following factors: changes in the conjuncture for energy resources on the global and domestic markets, which in turn leads to a drop (or growth) in demand for coal, as well as the devaluation of the ruble. So, if in 2012 for 1 US dollar on average they "gave" 31.07 rubles, then in 2019 - 64.97 dollars. USA. At the same time, investments in fixed assets of Russian coal enterprises, which in 2019 amounted to $ 3,010.6 million. The US may also fall. In the current macroeconomic situation, Russia's GDP in 2020, according to experts' estimates, may decrease by 4-7% compared to the level of 2019.

Plans for the implementation of the "Program for the development of the coal industry in Russia for the period up to 2035"

In such a difficult macroeconomic situation, in June 2020, the Program for the Development of the Russian Coal Industry for the Period up to 2035 was adopted. (approved by the order of the Government of the Russian Federation dated June 13, 2020 No. 1582-r.) (Table 1).

Table 1. Forecast of production and export of Russian coal until 2035

	2019	2020		2025		2030		2035	
		I	II	I	II	I	II	I	II
Coal production, total, mln t	441	435	466	459	593	476	659	485	668
incl. coking	99	102	107	120	145	136	149	140	150
energetic	343	333	359	339	449	341	510	345	518
Coal exports, total, mln t	192	195	215	218	297	228	341	241	349

The question arises: how realistic are the plans for the implementation of the "Program for the development of the coal industry in Russia for the period until 2035" As mentioned earlier, an increase in coal production in the Russian Federation is possible only through an increase in the volume of coal supplied for export, due to the stagnation of the domestic market. In this regard, an assessment was made of the possibilities for increasing the export supplies of Russian coal in the period up to 2040 for the main coal-consuming countries of the world.

Scenario options for economic development in the post-crisis period

Two scenarios for the development of the world economy, widely discussed in the expert community, were analyzed.

Option I, providing for a rapid "V-shaped recovery of the world economy" within one - maximum two years with the achievement of the growth rate of the world's gross domestic product (GDP) at the level of the pre-crisis period (2020) and equal to about 3 -3.5% per year. Option I is the trajectory of continued sustainable global GDP growth. At the same time, the depth of the fall in the world's GDP in 2020 in this variant is taken, in accordance with the estimates of the World Bank, equal to approximately 5.0-5.5%.

Alternative to the above option I is option II, which provides for a slow "L-shaped recovery of the world economy." In option II, the world GDP growth rates are taken at the level of the pre-crisis period (2020) - about 3-3.5% per year. Option II is a trajectory that implements stabilization trends in develop-ment, based on innovative development of the economy. The depth of the fall in the world's GDP in 2020 is taken according to the World Bank estimates - 5.0-5.5%. The decline in the world's GDP, starting from 2020, will continue until 2024, after which the GDP will first reach a stabilization level, and then move to a systematic growth with its low rates.

Forecasts of oil prices until 2040 in scenario scenarios for the development of the world economy

In option I, the tendencies formed in the pre-crisis period will, in fact, scale. The world oil price, after falling to $ 32 in 2020. US / bar., According to the World Bank, will recover to the maximum levels of 2011-2012. in 2040 and will be about 115-120 dollars. US / bar.

In option II, these tendencies will be broken, as a result, the economy will switch to global resource conservation, including energy conservation. The world oil price will fall to $ 21-22. US / bar.

Possibilities for the implementation of scenario options in individual countries of the world

To answer the question about the implementation of the considered scenario options, forecasts were developed until 2040 for two scenario options for individual countries (China, India, Japan, South Korea, EU countries, USA, Russia, countries of the western direction and countries of the eastern direction -ni) the following indicators: average annual GDP growth rates; GDP dynamics; share of the GDP of each of the above countries in the world's GDP.

As shown by the calculations, the growth rate of China's GDP by 2040 is almost 2 times higher than the corresponding growth rate of world GDP. This largely determines the growth of China's share in the world economy. In accordance with forecast calculations, China's share in the world economy over a 20-year period will increase 1.7 times in option I, and 1.5 times in option II. By 2040, China will occupy about 20-24% of the global economy. Therefore, there will be a fairly high impact of China on the export of Russian coal.

India's GDP growth rates by 2040 in the options under consideration are also almost 2 times higher than the same world GDP growth rates, which will ultimately lead to an increase in India's share in the world economy. In option I, over a 20-year period of time, India's share in the world economy will increase 1.7 times and will be approximately 6%, and in option II, accordingly, the share will increase 1.4 times and will be 5% in the world GDP. This determines a rather significant potential of India's influence on the export of Russian coal.

In accordance with the forecast calculations, the growth of the Japanese economy by 2040 in the two considered options is significantly lower than in China and India. Thus, in option I of the “V-shaped economic recovery”, the growth rates of Japan's GDP are almost 2 times lower than the rates of world GDP, and in option II, the L-shaped economic recovery, they are comparable to the same rates of world GDP. A more restrained development of the Japanese economy in the options under consideration, in comparison with China and India, will lead either to stabilization or to a drop in its share in world GDP.

Forecast calculations point to high average annual GDP growth rates in South Korea under option I "V-shaped economic recovery", averaging 5.6%. In option II "L-shaped economic recovery" South Korea's GDP will grow at a rate of approximately 2.2-3.5% per year. Such average annual growth rates ensure an increase in South Korea's GDP over the 20 years of the coming period in option I by 1.6 times, and in option II - 1.4 times.

In option I, the share of South Korea in the world's GDP for the upcoming forecast period increases from 1.7% to 2.8%, and in option II - to 2.4%. Such an increase in indicators positions South Korea as a country that ensures the growth of the export potential of the Russian coal market GDP of the Eastern Direction countries in option I, in accordance with the calculations, will grow at an average rate of 5% per year, and in option II, respectively , 1.9-3% per year.

Such growth rates ensure an increase in the GDP of the Eastern Direction countries in the 20-year forecast period in option I by 2.8 times, and in option II - by 1.5 times. In accordance with the accepted scenario options, the share of the Eastern Direction countries increases from 26 to 34-38%. This is a very significant share, which determines the development potential of the Russian coal industry in the Eastern direction.

In the Western direction, the demand for Russian export coal is formed mainly by the EU countries. The projection of scenarios for the development of the world economy testifies to the actual identity of the dynamics of the GDP growth rates of the EU countries and the world as a whole. Both the depth and the average GDP growth rates of the EU countries in the post-crisis period have a slight discrepancy with the values adopted in the whole world in options I of the "V-shaped economic recovery". Similarly, for option II of "L-shaped economic recovery" such an identity is characteristic. The active recovery of the EU economy in option II begins in 2025. The GDP growth rates of the EU countries adopted in the scenario options determined the volume values of this indicator achieved in the forecast period. The average annual GDP growth rate of the EU countries in the forecast period, averaging 3%, makes it possible to increase the absolute value of this indicator by 2040 by 1.8 times (relative to 2019). In option 2, the average annual GDP growth rate of the EU countries is 0.5-1.5%. Such rates ensure the recovery of GDP volumes only by 2040. In fact, option 2 is an option for the stabilization development of the EU countries. It is obvious that under these conditions one cannot expect an increase in the share of EU countries in the world economy. Moreover, in accordance with forecast calculations, the share of EU countries in the world's GDP even slightly decreases to 19.2 - 19.5%. In contrast to the Eastern direction of development of Russian coal exports, the Western direction is gradually reducing its growth potential for Russian coal supplies.

The USA in option I of "V-shaped economic recovery" almost completely repeats the accepted profile of changes in the world economy. The depth of the decline in US GDP, as well as the rate of its recovery, is about the same as in the whole world. The dynamics of the US GDP in option II "L-shaped slow economic recovery" is projected in a similar way. This recovery, in accordance with forecast calculations, in option II should be carried out no earlier than 2025. In option I, with an average annual GDP growth rate of 3.1% for the forecast period, US GDP will increase by 2040 . (relative to 2019) almost 1.9 times. In Option II, the average rate of GDP growth in the post-crisis period is 0.5-1.5% per year, which will increase the absolute level of US GDP by 2040 - by only 1.1 times. Despite the large difference in the values of the US GDP by the options reached by the end of the forecast period, the share of the US economy in these options will practically not increase. The share of the United States in the world economy will be at the level of no more than 21-22%.

Forecast estimates of world coal production and export

The scenario parameters of the development of the world economy, adopted in the considered options, made it possible to develop forecasts of world volumes of coal production until 2040. The assessment at the first stage of calculations provides for forecast calculations of the coal intensity of the world's GDP. In 2010-2013. the coal content of the world's GDP reached its “peak”, after which the process of its systemic decline began. By 2019, the coal content, compared to the maximum levels of the period 2010-2013, decreased by 17%. Further decrease in coal capacity, in accordance with the scenario options, will be carried out in two ways:

- the first (option I), assumes a low rate of decline, approximately until 2030-2052. and more intense decline after this period;
- the second (option II), assumes a more intensive decrease in carbon intensity at the first stage.

Despite the reduction options of different intensity, the carbon intensity of GDP in both options will fall by 38% by 2040 (compared to 2019). Different trajectories of a decrease in the coal intensity of the world's GDP, envisaged in the scenario options, determined the opposite dynamics of changes in the volumes of world coal production - by 2035 - 5.2-9.7 billion tons, by 2040 - 4.4-9.4 billion tons. Forecast dynamics of coal intensity of the world's GDP (for thermal coals) is practically identical to the dynamics for the accepted scenario options. In general, by 2040, the coal intensity of the world's GDP will decrease by 38% compared to 2019.

According to calculations, the global production of steam coal will increase by 17% by 2040 under Option I, to 8020 million tonnes. Under Option II, on the contrary, the production of steam coal will decrease by 30% by 2040, to 4,820 million tonnes.

The dynamics of the coal intensity of the world's GDP (for coking coal) has a high differentiation according to scenario options. In option I, the coal content by 2040 (for coking coal) should decrease by 30% by 2040, and in option II - by almost 50% (relative to 2019). In option I, by 2035, the stabilization of coking coal production at the level of 1470 million tons is achieved.Outside this period, the world production of coking coal slightly decreases, reaching values equal to 1390 million tons by 2040.

Option I provides for a further increase in the capacity of ferrous metallurgy for smelting metal used in the economy. The metal intensity of the economy is increasing. Option II is characterized by a systemic decrease in the production of coking coal, reaching 580 million tons by 2040. In option II, the opposite trend of a decrease in coke consumption and, consequently, a decrease in the volume of metal used in the economy is set. In this variant, the use of metal is replaced by the use of more advanced materials used in various machines and structures. This option is more innovatively focused. It is carrying out an intensive withdrawal from the economic turnover of the economy of coking coal and metals.

With a favorable price environment for energy resources (option I, the vol-ume of coal exports is growing: from 1,420 million tons in 2019 to 1990 million tons in 2035, with a slight decrease by 2040 to the level of 1,880 million tons.

The overall growth of coal exports by 2040 is 32% (relative to 2019). Such volumes can only be achieved with a 4-fold increase in energy prices. At the same time, it is assumed that by 2040 the world oil price should recover to $ 120 / bbl. (2020 estimate - 38 USD / bbl.). In option II, with an unfavorable situation on the energy market and an almost 2-fold decrease in prices for them by 2040, the volume of coal exports will systematically decrease: from 1,420 million tons (2019) to 790-795 million tons (2040).), i.e. on average by 44%.

Global exports of thermal coal under Option I (favorable energy market conditions) will increase from 1,090 million tons (2019) to 1,580 million tons in 2035 and 1,486 million tons in 2040. Growth in the volume of energy coal exports over the entire forecast period will amount to 36%.

In option II (unfavorable conditions on the energy market), the volume of thermal coal exports will systematically decrease to the level of 580-585 million tons. The overall decline over the entire period will be 46% on average.

The dynamics obtained indicates that the drop in exports in option II is to a greater extent associated with thermal coals than with coking ones. With a more intensive reduction in consumption of the latter, most likely, this indicates the direction of the export of coking coal, to a greater extent, to developing countries.

Developed countries are likely to move their coking coal off the market. The forecast dynamics of export volumes of coking coal also significantly depends on the price environment and parameters of the world economy. In option I, the export volumes of coking coal increase from 330 million tons (2019) to 404 million tons in 2035 and 390–395 in 2040. The average growth in export volumes in this option for the entire forecast period is 19%. In Option II, the average GDP growth rate in the post-crisis period is 0.5-1.5% per year, which will increase the absolute level of US GDP by 2040 - by only 1.1 times. Despite the large difference in the values of the US GDP by the options reached by the end of the forecast period, the share of the US economy in these options will practically not increase. The share of the United States in the world economy will be no more than 21-22%.

Coal consumption in the countries of the western and eastern directions

To assess the possible volumes of coal consumption by the countries importing Russian coal, calculations were also carried out on the predictive estimate of the coal capacity of China, India, Japan and South Korea. The higher rates of decline in the coal intensity of the GDP of China and India indicate that coal consumption in these countries, at the same rate of GDP growth, will decline more intensively than in Japan and South Korea, which are advanced economies. Coal consumption under option 1 in South Korea in the forecast period may increase by almost 2.5 times, and in option 2 - by 14%. South Korea is quite a promising consumer of Russian coal.

In general, the countries of the Eastern vector may increase their coal con-sumption (option 1). However, due to the decrease in coal consumption (option 2), one can expect, at best, a stabilization or even a decrease in Russian export supplies, especially for coking coal.

The coal intensity of the EU countries has a higher rate of decline than the countries of the Eastern vector. In option 1, coal consumption in the EU countries by 2040, under the most favorable conditions, may increase by a maximum of 11%. In option 2, coal consumption in the EU countries will fall at a significant rate and by 2040 will decrease (compared to 2019) by 83%.

Considering that the total consumption of coal determines the volumes of Russian coal exports, it should be noted that the potential of Russian exports to the West has decreased. In the forecast period, it is more likely that the potential of Russian exports will be determined by the consumption of coal by the countries of the Eastern vector. In option 1, despite the decrease in coal content, the volume of coal consumption, in the context of intensive economic development and favorable conditions on the energy carriers market, may increase by 2040 by a maximum of 18%. If option 2 is implemented, which provides for the intensive development of the economy, in the face of unfavorable conditions on the primary energy market, the volume of coal consumption in the economy by 2040 may decrease.

With a high probability, in the forecast period, option 2 will be implemented - intensive development of the economy, significantly increasing labor productivity. The development of the world economy according to this option can lead to a reduction in coal consumption, which can significantly reduce the development potential of Russian coal exports.

Over the entire forecast period, the coal intensity of Russia's GDP may decrease by 48-52% by 2040. In accordance with the forecast calculations, the volumes of coal consumption in Russia under Option 1 are practically stabilizing in nature. If in 2019 the volume of consumption was 249 million tons, then by the end of the forecast period (2040) - 250-255 million tons. The average growth in consumption volumes is about 1.8%. According to option 2, the consumption of coal is systemically decreasing. most likely due to its "squeezing out" by gas and non-traditional energy sources.

In general, for the entire period (2019-2040), the volumes of coal consump-tion may decrease according to option 2 from 249 million tons to 160 million tons. Therefore, the volumes of coal production in the forecast period will largely be determined not by the domestic Russian market, and the export coal market.

According to Option 1, the export of Russian coal may increase from 192 million tons in 2019 to 283 million tons in 2040, i.e., by 47%. Option I aims at further increasing the export of natural resources in the Russian economy. Option 2 is aimed at reducing the dependence of the Russian economy on the export of natural resources.

Thus, based on the scenario scenarios of the development of the world economy, the possible volumes of Russian coal production were obtained: 2035 - 285-498 million tons; 2040 - 271-536 million tons. Calculations showed that even in the most favorable conditions (option I), coal production in Russia can be 498 million tons in 2035, and 536 million tons in 2040 (2019 - 441 million tons). For the entire forecast period, its growth will not exceed 20-22%. In option II, with a drop in global coal consumption, the production of Russian coal may decrease from 441 million tons in 2019 to 285 million tons in 2035 and to 271 million tons in 2040. Over the entire forecast period, the total decrease may amount to 38- 39%.

Conclusion

Based on the scenario options for the development of the world economy and taking into account the intentions of coal companies, the following possible volumes were obtained:

Russian coal production: 2035 - 328-365 million tons (at best);

Russian coal exports: 2035 - 145-168 million tons.

At the same time, according to the "Program for the development of the coal industry in Russia for the period up to 2035" Possible coal production volumes: 2035 - 485-668 million tons; exports: 2035 - 324-370 million tons.

Achievement of high volumes of coal production in Russia for the period up to 2035, provided for in the Program, seems unlikely. The global crisis in 2020 requires government bodies to significantly adjust the long-term guidelines for the development of the industry adopted in the Program.

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Hydrogen Energy: a New Dimension for the Energy Cooperation in the Northeast Asian Region

Sergei Popov[1,*], *Darya* Maksakova[1], *Oleg* Baldynov[1], *Konstantin* Korneev[2]

[1]Department of Complex and Regional Problems in Energy, Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences (ESI SB RAS), 664033, 130 Lermontov st. 130, Irkutsk, Russia
[2]Center for Japanese studies, Institute of the Far East of the Russian Academy of Sciences (IFE RAS), 117997, 32 Nakhimovsky Av., Moscow, Russia

Abstract. The Northeast Asian Region is a home for the major world's energy importers and Russia – the top energy exporter. Due to the depletion of national fossil energy resources, the industrialised East Asian economies are facing serious energy security issues. The snapshot of the intraregional energy trade in 2019 was analysed in terms of development potential. Japan, Korea and China are at the frontline of hydrogen energy technologies commercialisation and hydrogen energy infrastructure development. The drivers for such endeavours are listed and national institutions for hydrogen energy development are characterised. The priorities related to regional cooperation on hydrogen energy in Northeast Asia were derived on the basis of hydrogen production cost estimations. These priorities include steady development of international natural gas and power infrastructure. The shared process will lead to the synergy of regional fossil and renewable resources within combined power and hydrogen infrastructure.

1 Introduction

Hydrogen energy is one of the key components in the energy transition paradigm, which implies energy systems transformation. The hydrogen role in this process is to replace traditional internal combustion powertrains with fuel cells and provide opportunities for power grid regulation. The former means electrification of transportation, which will eventually complete a substitution of fossil energy for renewable energy in transportation vehicles. The latter allows daily and seasonal regulation of electric power systems on a large scale. Thus, the drivers to develop hydrogen energy in the Northeast Asian (NEA) region comprise the following:

- decreasing import dependency on fossil energy,
- preventing air pollutions and improving environmental quality,
- siting energy value chain in the domestic market,
- stimulating innovations,
- reshaping the structure of energy services costs,
- opening new opportunities to expand the countries' presence in the innovative global and regional markets,
- keeping up with the Paris agreement and global climate mitigation initiatives.

The implementation of the energy transition paradigm in the NEA economies will lead to the transformation of the traditional global energy markets and discoveries of new patterns of regional cooperation.

The purpose of the study is to identify new opportunities that are opening up with the development of hydrogen energy in the NEA region. The objectives include analysing the current state of energy cooperation in the region, assessing the possibilities of hydrogen production technologies in the long term, and making the implications about hydrogen energy influence on regional energy cooperation.

2 The current status of the energy cooperation within the NEA region

The region is a net energy importer, with the combined share of China, Japan, R.Korea and Taiwan comprising almost half of the global energy import in energy terms. The resource factor in the NEA region provides favourable environment for the regional primary energy exporters to access the largest energy market. The geographical factor favours maritime trade, which is usually more competitive than the trade based on stationary infrastructure such as railways and pipelines. Major indicators of intraregional energy trade for the year 2019 are presented in Table 1, including total import and export volumes for coal, natural gas, crude oil, petroleum products, and electricity trade, as well as the respective shares for intraregional trade. Finally, energy carriers (HS 27)[a] trade values are indicated for all the seven regional economies.

[a] The Harmonized System (HS) is international nomenclature defined by the World Customs Organisation (WCO) for the classification of products, to establish common basis for custom purposes.

* Corresponding author: popovsp@isem.irk.ru

In 2019 total energy import to the NEA economies exceeded 370 bln international dollars, and intraregional energy turnover was estimated at 190 bln international dollars. Russia is a major regional energy donor with 66 bln dollar export to the East Asian economies, and export to import ratio exceeding 110 times. Mongolia is next with 2.5 times indicator, and lastly, R. Korea presents some 10 percent excess of regional energy export over regional energy import in monetary terms.

The Korean phenomenon arises from crude oil, coal and natural gas imports outside of the NEA region and petroleum products export to the neighbouring East Asian economies. China is adjacent to Russia in terms of mutual energy turnover within the NEA region (some 63 bln), followed by R.Korea (31 bln.), Japan (20 bln.), Taiwan (7 bln.), and Mongolia with the turnover of 4.5 bln international dollars.

The major intraregional energy flows are mutual deliveries of petroleum products (HS 2710, mostly petrochemicals).

China is highly dependent on intraregional energy bi-directional flows of electricity and coal (between 33 and 83 percent), and petroleum products import (41 percent).

Table 1. Major indicators of the Northeast Asia economies' energy trade in 2019.

Indicators \ Economies	Russia	China	Japan	R.Korea	Taiwan	DPRK	Mongolia
Coal (HS 2701)							
Total import (export), mln ton	21 (205)	198 (6)	186 (–)	141 (–)	67 (–)	– (–)	– (36)
The share of NEA, percent	– (39)	33 (83)	12 (–)	22 (–)	14 (–)	– (–)	– (99)
Natural Gas (HS 271111 + HS 271121)							
Total import (export), mln ton	.. (189)	97 (0.07)	77 (–)	41 (–)	17 (–)	– (–)	.. (–)
The NEA share, percent	– (15)	2.6 (100)	8 (–)	6 (–)	9 (–)	– (–)	100 (–)
Crude Oil (HS 2709)							
Total import (export), mln ton	.. (269)	239 (0.8)	147 (–)	143.1 (–)	44 (–)	– (–)	–0.8
The NEA share, percent	– (34)	15 (38)	5 (–)	6 (–)	– (–)	– (–)	– (–)
Petroleum Products (HS 2710)							
Total import (export), mln ton	0.6 (143)	30.6 (55)	23 (19)	32 (65.8)	13 (22)	0.0 (0.0)	1.8 (–)
The NEA share, percent	17 (15)	41 (9)	36 (32)	24 (38)	26 (6)	100 (–)	100 (–)
Electricity (HS 2716)							
Total import (export), TWh	1.6 (3.5)	5.3 (1.4)	– (–)	– (–)	– (–)	0.03 (0.3)	1.7 (0.03)
The NEA share, percent	2 (17)	72 (33)	– (–)	– (–)	– (–)	100 (100)	100 (100)
Energy (HS 27)							
Total import (export), bln int. dol	1.9 (221)	344 (37)	156 (14)	127 (42)	44 (13)	0.06 (..)	1.3 (3.2)
The NEA share, percent	30 (30)	17 (11)	10 (35)	12 (38)	11 (14)	100 (100)	100 (100)

0.0 – less then 100 000 ton; ..– less then 10 000 ton

Source: author's estimations based on castom statistics from trademap.org

Mongolia and DPRK have critical dependence on regional energy supply, particularly, on electricity import and export. Almost all Mongolian coal export is swallowed by China. The DPRK's energy export and import are extremely low due to the sanctions of the UN

Security Council, so the regional energy cooperation is under the great stress for this economy.

Russia seems to be significantly involved in the NEA regional energy market. The share of East Asian economies reached 30 percent both in total Russia's energy export and import in 2019. In the same year the share of Northeast Asia in total Russia's export accounted for 39 percent for coal, 34 percent for oil, 17 percent for electricity, and 15 percent both for natural gas and petroleum products.

For Japan, R.Korea and Taiwan, regional energy cooperation is important in terms of petroleum, coal and natural gas imports. Regional import of crude oil for Japan and R.Korea are marginal between 5-6 percent, while it is equal to zero for Taiwan.

Recent transformations of the national gas and electricity market institutions in Japan and China, coupled with the regional and global natural gas market developments, give some hope to expect more active regional cooperation on natural gas and electricity. Considering the perspectives for natural gas demand growth in China and the resource potential in Russia, the development of gas infrastructure will be one of the most perspective objectives for energy cooperation in the NEA region in the coming decades.

3 The Hydrogen National Institutions in the NEA region

Hydrogen technologies development is one of the most important issues within the energy transition framework, when energy strategy is considered in the energy-deficient industrial economies of East Asia. This section presents a short scope of the national-scale hydrogen institutions in the each NEA economy.

3.1 The case of China

The energy development strategy action plan for the period 2014-2020 adopted by the State Council in 2014 [1] highlights the transition to low carbon energy as one of the key strategic guiding principles. The document prioritises the increasing role of natural gas, renewable energy (wind, solar and geothermal) and nuclear energy. Besides, the document includes hydrogen energy and fuel cell (FC) in the 20 key technologies to be developed.

The issue of a national hydrogen strategy was raised at the third session of the 13th National People's Congress in May 2020 [2]. However, several provinces and cities have already issued hydrogen energy development plans.

In 2018 China Hydrogen Alliance was established by state-owned China Energy Investment Corporation and the other 17 sponsors. The aim is to enhance the development of China's hydrogen sector by providing policy advice and serving as a platform to coordinate efforts for the development and commercialisation of hydrogen technologies. The alliance is supported and supervised by the Ministry of Science and Technology and other government bodies [3].

According to the White paper [4] prepared by the Alliance, hydrogen consumption in China will have risen up to 35 million tons or 5 percent of the final energy demand by 2030. By 2050 the figures should achieve 60 million tons and 10 percent, correspondingly. The number of fuel cell vehicles (FCV) will have grown to 50 thousand by 2025, 1.3 million by 2035 and 5 million by 2050.

It is worth noting that the White paper sets ambitious targets for renewable energy. The share of water electrolysis using renewables in hydrogen supply should achieve 15 percent by 2030, 45 percent by 2040 and 70 percent by 2050, in comparison with 3 percent in 2020.

3.2 The case of Japan

Japan is at the third wave of hydrogen technologies development now. The first one was in the early 1990s, the second one followed in a decade, and the third wave started around 2015.

In 2014 the Ministry of Economy, Trade and Industry provided a new Basic Plan for sustainable energy transition under the "3E+S" motto. It is interpreted as Energy security, Environment (emissions reduction), Economic affordability (competitive cost) and [inherited] Safety. Hydrogen's contribution to the Basic Plan looked undoubted because of four effects: decarbonisation, mitigation of the dependence on particular fossil fuel exporters, ability to utilize low cost feedstock and new opportunities for innovative developments. As a further step, the Basic Hydrogen Strategy (world's first national strategy of such a type) was adopted in 2017. The idea was to make Japan a "hydrogen nation" with a wide range of new industries, including transportation and digital devices, which use hydrogen for power generation [5].

In May 2018 the Non-fossil Fuel Energy Value Trading Market was established at the Japan Electric Power Exchange. This is a *green* certificates market where non-fossil fuel energy power producers sell "non-fossil fuel energy certificates", which evidence to energy retailers that electricity is *green*, i.e. it was originated exclusively from renewable primary energy. The certificates can be traded separately from actual electricity [6].

Japan aims to use *green* hydrogen in power generation and other industries in the future. At present, the government is examining the replacement of existing fuels and raw materials with *green* hydrogen and the associated costs for various industrial processes. The combination with carbon capture, utilisation and sequestration (CCUS) is necessary in order to produce *blue* hydrogen from natural gas or coal.

Considering insufficiency of the domestic renewable energy resources, Japan looks for hydrogen supply chains from overseas, in addition to Australia and Brunei, where demonstration experiments are ongoing.

3.3 The case of R.Korea

In January 2019 the R.Korea adopted a Hydrogen Roadmap [7]. The major goal is to shift the demand from transport sector from oil-based fuels to electricity, including FCV. It is projected to consume more than 5.2

million tons of hydrogen to power up to 6 million FCVs, 2 GW of decentralised and 15 GW of grid-operated FC generators by 2040 [8].

In addition to the Hydrogen Roadmap, some basic laws related to hydrogen economy and energy were drafted:

• The Hydrogen Act (will come into force on February 5th, 2021). It is expected that the Hydrogen Act will become the central legislation regulating the hydrogen industry, while the Renewable Energy Act will be used where an issue is not covered;

• The Hydrogen Economy Promotion and Hydrogen Safety Management Law (came into force in 2020). It consider the measures to create favourable environment for a hydrogen economy: the adoption of hydrogen programs by regional governments; support and subsidies for hydrogen companies engaged in the development of hydrogen technologies; the creation of the Hydrogen Economy Committee to facilitate the cooperation among the government, industry, academic, and civil experts on national and international stages [9].

The Ministry of Energy is primarily responsible for regulating the hydrogen industry. The promotion of the hydrogen industry will be carried out by the Hydrogen Convergence Alliance, a private organisation that aims to improve the competitiveness of hydrogen specialised companies.

The Korea Gas Corporation, a state enterprise, will establish a system for the distribution and transaction of hydrogen, and manage pricing for hydrogen. The Korea Gas Safety Corporation, a state enterprise, will oversee safety management, inspect safety standards for hydrogen related components and facilities, and support education, advertisement and international cooperation relating to hydrogen safety.

To provide *green* hydrogen, domestic and imported renewables are considered. The import of hydrogen related components will be regulated by the Hydrogen Act, which states that such components can be inspected by the Ministry of Energy or the local authority of the relevant city or district. The government will establish the Foreign Marketing Support Centre to assist with the export of hydrogen specialized companies [10].

Korean companies by their own initiatives participate in international organisations for hydrogen technologies development, like Hydrogen council, Fuel cell and hydrogen energy association, International association for hydrogen energy, *etc*.

3.4 The cases of Taiwan, Mongolia and DPRK

The policy towards hydrogen energy it this economies is still sporadic and non-systemic, and there are no special institutions established for hydrogen technologies and infrastructure development.

3.5 The case of Russia

The Energy Strategy of the Russian Federation up to 2035 was approved in June 2020 [11] Hydrogen technologies are considered as important means for energy storage and niche applications, mainly for transportation and autonomous energy supply. Importantly, hydrogen technologies for energy storage and conversion should be implemented to increase efficiency of power grid operations.

Export targets for hydrogen were set as a major indicator of the progress in hydrogen energy developments. In 2024 Russia is expected to export 0.2 million tonnes of hydrogen, and 2 million tonnes in 2035. However, the primary technologies for hydrogen export are supposed to be electrolysis powered by nuclear energy, or natural gas pyrolysis.

A Working Group on the development of hydrogen energy was established under the Ministry of Energy in November 2019. It includes Gazprom, Sberbank, Rosatom, academic and expert community representatives. The objectives of the WG are to develop support measures, review pilot projects, remove regulatory barriers, and create a road map for hydrogen technology development [12].

3.6 The Section's Summary

The lessons learned from the studies of the hydrogen national institutions in the NEA economies suggest that fuel switching from fossil to renewable energy for transportation, industrial and building energy services is considered as an important pattern for the long-term energy transition strategy.

Hydrogen technologies are pivotal for renewable energy based on the so-called "New Green Deal", designed to repower economies and reindustrialise global transportation sectors on innovative technological basis. Additionally, hydrogen energy is supposed to contribute significantly to securing energy supply and energy efficiency.

However, in order to build up hydrogen infrastructure at the first stage of the hydrogen energy development, hydrogen production from fossil energy (natural gas, coal, and petroleum products) will have a priority.

4 Cooperation patterns: resources, infrastructure and hydrogen value chain

When moving towards hydrogen energy, the cooperation patterns reflect the structure of hydrogen value chain. The chain links are hydrogen production, storage, transportation and distribution. Hydrogen production costs vary with energy sources and production methods, while hydrogen storage, transportation and distribution do not depend on primary energy sources.

Steam methane reforming, coal gasification and water electrolysis are the most widespread among the various hydrogen production methods. In steam methane reforming, natural gas (or another source of methane) reacts with steam to produce hydrogen and carbon dioxide. In coal gasification, coal is converted into a synthesis gas that is then transformed into hydrogen and carbon dioxide. Carbon capture, utilisation and storage can be applied to the both processes. Water electrolysis is an electrochemical process that splits water into hydrogen and oxygen. The process requires water as well as electricity [13].

IEA's estimations suggest that hydrogen production by water electrolysis using renewable energy can be competitive with hydrogen production from fossil fuels, including carbon capture and storage costs, in the long term (figure 1).

The main drivers are a significant drop in capital expenditures in water electrolysis in 2050 by a factor of 3.2 and a decrease in renewable electricity prices from USD 36-116 per MWh to USD 20-60 per MWh.

According to IEA’s data [14], if *blue* and *green* hydrogen production are considered and resource prices and efficiency assumptions are not taken into account, then steam methane reforming is the cheapest process followed by water electrolysis and coal gasification. In the long term, water electrolysis can become more cost-effective solution, competitive to steam methane reforming and coal gasification with CCUS. However, it is worth noting that a large reduction in capital expenses in water electrolysis is necessary to achieve such a competitiveness level.

Besides, the location of water resources and renewable energy potential should be considered when planning international power interconnections. Water scarcity in the arid areas with high wind and solar energy potential in Mongolia and China can be an important driver to create power interconnections in the NEA region allowing producing hydrogen in the eastern regions of Russia with sufficient water resources.

Thereby, efficient gas and electricity trade is the main prerequisite for hydrogen production in the NEA region in the middle and long term. This means that international gas and electricity infrastructure and favourable institutional frameworks are required to support gas and electricity trade and overall Energy Transition process in the region.

5 Implications

The Energy Transition process in the highly energy import dependent East Asian countries is led by hydrogen technologies. Hydrogen energy is considered as a major tool for dealing with complex issues focused on energy supply chains in industrialised, export-oriented, and environmentally-concerned economies. Remastering energy services for transportation sector through electrification, partly based on fuel cells technologies, will have numerous consequences in terms of energy security, environmental quality improvements, innovative developments, and new value chains creation.

In addition to their inherited low-carbon feature, hydrogen technologies are important for power grid regulation and decentralisation of building’s energy services.

The national hydrogen strategies in the major East Asian economies are focused more on hydrogen consumption and transportation than hydrogen production. However, hydrogen itself is just an energy carrier, not a primary energy resource. We are entering on a long transition period, when hydrogen production derived from fossil fuels will be more economically feasible than *green* hydrogen (based on renewable energy).

Considering the stabilisation of primary energy demand in coming decades, descending demand for coal and oil, remaining superior efficiency for hydrogen production from natural gas, we expect the growth in natural gas regional trade and cooperation in natural gas infrastructure development.

Additionally, with the rapidly declining costs of renewable energy, *green* hydrogen production and seasonal hydrogen storage will end up in fusion of power grid and hydrogen energy infrastructure on regional scale.

Such electro-hydrogen infrastructure will be an ultimate energy system with 100 percent renewable primary energy supply. The task for energy researchers is to demonstrate the feasibility of such a system in Northeast Asia.

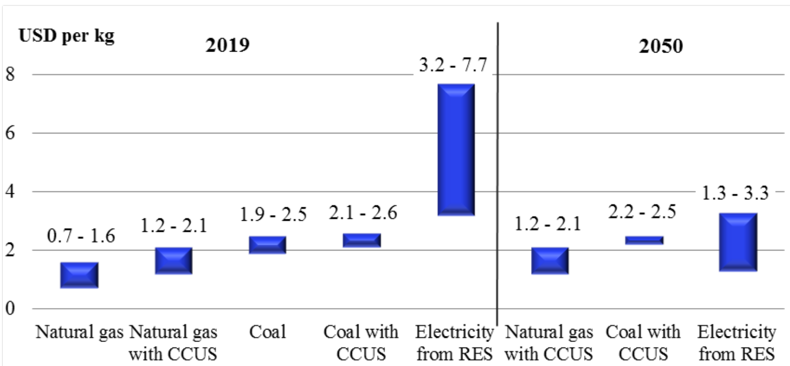

Fig.1. Hydrogen production costs.
Source: [14]

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CONCEPTUAL APPROACHES IN THE REGIONAL SEGMENT ASSESSMENT THE ENERGY SECURITY STATE OF DECENTRALIZED TERRITORIES OF THE NORTHEAST OF RUSSIA

Stepan Reev[1], *Violetta* Kiushkina[2], *Boris* Lukutin[3]

[1] *Department of State Energy Policy Ministry of Energy of Russia*
[2]*Chukotsk branch of the North-Eastern Federal University Scientific, Anadyr, Russia*
[2]*Technical Institute (branch) of North-Eastern Federal University Scientific named after M.K. Ammosov, Neryungri, Russia*
[3]*National Research Tomsk Polytechnic University Energy Engineering School, Tomsk, Russia*

Abstract. In order to timely identify threats and risks to energy security and promptly respond to them and the dynamics of their change, the Energy Security Doctrine provides for the formation of a risk management system. The significant heterogeneity of the regions of the Russian Federation, including with a special specificity of the territories of the North and the Arctic zones and the predominance of decentralized energy supply in them, justifies the need for the formation of a regional segment of the assessment that provides for and takes into account these differences in detailing the sphere and the monitoring process itself. The paper presents proposals on the formation of the structure of a separate module of the regional segment for assessing the energy security of isolated areas, separate research modules and indicators for assessing decentralized power supply systems from the standpoint of ensuring energy security. One of the approaches to the formation of the structure of a single information space of the regional segment of the risk management system is proposed.

Regions of "Severny Zavoz", attributed to the North, differ significantly in terms of comfort of life and conditions of management. For these reasons, the zone is very heterogeneous in terms of economic and social development. The heterogeneity of the territories of the Far North regions, in particular the Far East region, from an energy point of view, characterizes a different degree and unevenness of the supply of fuel resources and a wide range of the level of energy security.

Analysis of energy supply in technologically isolated and remote territories of Russia is characterized by a number of negative indicators and trends that can provoke emergencies in fuel and energy supply systems. In such territories, with more than 100 thousand isolated settlements, the state of energy security is ensured by the proper functioning of decentralized energy supply complexes in conjunction with interconnected accompanying systems.

Based on the provisions of the Doctrine of Energy Security (DES) of the Russian Federation regarding decentralized territories, mainly located in the regions of the Russian North, a number of urgent tasks in terms of energy can be identified:

- ensuring reliable and sustainable provision of Russian consumers with energy resources of standard quality and services in the energy sector;
- ensuring the technical accessibility of the infrastructure of the fuel and energy complex for various groups of consumers and the possibility of providing them with services in the energy sector.

The territorial level comprehensively characterizes the state of energy supply to consumers on the territory of a subject or a federal district of the Russian Federation. The importance of interests and the weight of the characteristics of local energy zones and autonomous objects of electrification of the territories of the North makes it possible to single out the regional segment as a separate monitoring object with its own unified indicators (Figure 1, 2) of the energy security assessment system.

In this regard, the task is to form a regional segment within the framework of the formation of a risk management system for the energy security of the Russian Federation (the creation of which is envisaged by the DES), providing for a significant socio-economic, climatic and other heterogeneity.

The degree of difference between the decentralized territories of the North-East and other territorial entities is great. The specificity of autonomous energy, leaving its mark, loses the possibility of reliable functioning in situations in which centralized energy remains survivable. They are not characterized by such indicators as the presence of unlimited transport links between energy zones for emergency mutual provision of fuel resources, electrical connections between decentralized power supply complexes (DECPS) within one zone and intersystem connections between zones, etc. At the same time, the influence of factors and conditions is maximized by extreme weather events and infrastructural isolation in the permafrost zone. The degree of detailed consideration of the peculiarities uncharacteristic for the rest of the territories of the Russian Federation in the choice of criteria for assessing the state, the direction of measures to improve energy security is relevant.

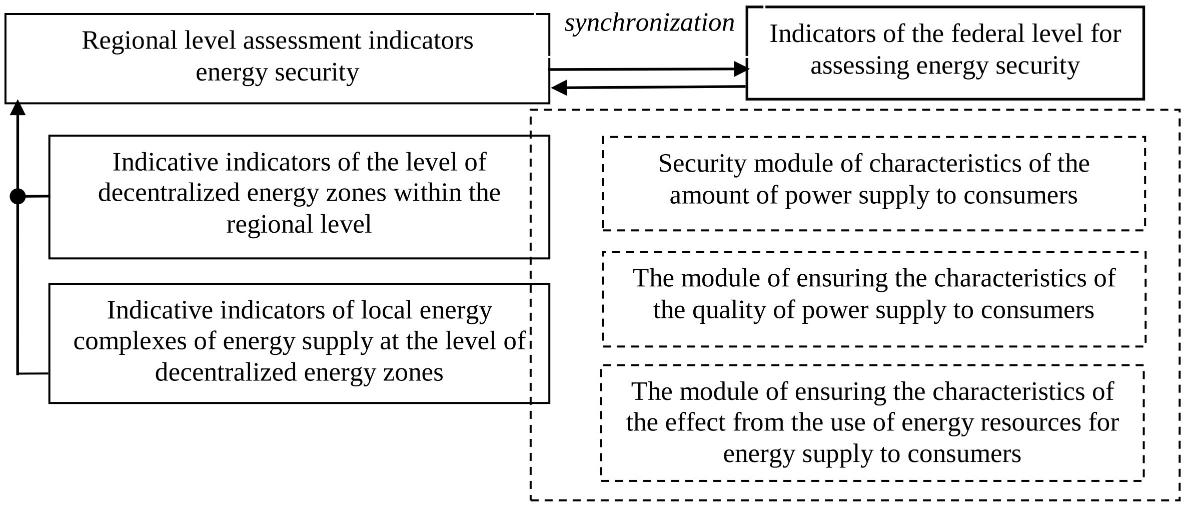

Fig 1. Proposals for the formation of a separate module of the regional segment for assessing the energy security of isolated territories

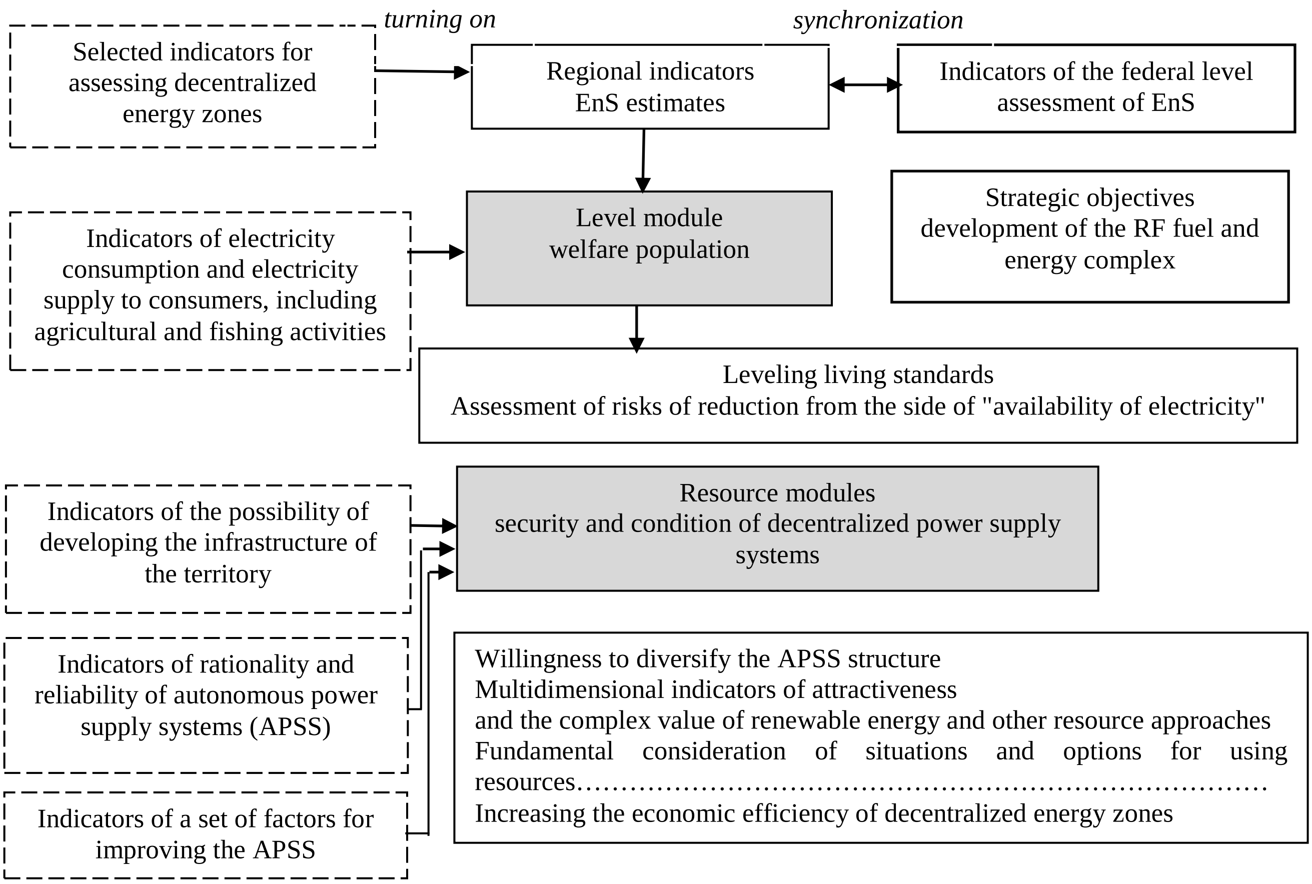

Fig 2. Proposals for individual study modules and indicators for assessing decentralized power supply systems from the perspective of ensuring energy security

For a timely and adequate response to emerging challenges and threats to energy security, improving the reliability and sustainability of the energy infrastructure, it is necessary to improve the quality, efficiency and expand monitoring aimed not only at identifying challenges, threats and risks to energy security, but also at their trends.

To this end, the Doctrine provides for the formation of an energy security risk management system (hereinafter - RMS). The RMS provides for the participation of public authorities of the constituent entities of the Russian Federation within its competence. The inclusion of regional executive authorities in the composition of RMS subjects makes it possible to ensure a high-quality account of the regional peculiarities of the EnS, improve the quality of the information provided in the regional context and analyze the responsibility of the situation in the region within the framework of the distribution of powers. The consistency and harmonious balance of strategic planning documents in the energy sector makes it possible to quite clearly build the relationship between the basic principles of the nature of state activity and the mechanisms for implementing state policy in the field of ensuring energy and economic security with the allocation of guidelines for the regional component.

In accordance with this, the main tasks of the RMS at all levels are: monitoring, assessing and forecasting the state of energy security, as well as determining the resources necessary to prevent threats to energy security, reduce the likelihood of their implementation, as well as to minimize the consequences of their implementation. In addition, the RMS is a tool that allows you to determine or clarify the tasks of the subjects of energy security, as well as planning measures to ensure energy security. To solve each task, the System must perform a number of functions according to its procedural structure. Energy security risk management is an integral part of government policy.

The specific feature of the characteristic threats of the territories under consideration necessitates a systematic analysis and, if necessary, adjustments to the components of the assessment of regional energy security. One of the key factors requiring close attention and detailed study is the strong relationship between energy and the economy of local energy supply systems in isolated remote areas of the North.

One of the basic modules of segments of any level is the process of collecting, processing, organizing and storing information about the current state of objects in the monitoring sphere and the dynamics of changes in events that affect the state of energy security.

These measurements must be synchronized with monitoring processes in the main areas of energy security, which cover 14 critical areas. These directions set its normative level. The values of the parameters are determined by the provisions of legislative and regulatory legal acts regarding these areas. Measurements include quantitative and qualitative characteristics of energy security and include both traditional energy security problems and environmental, socio-cultural and technological factors.

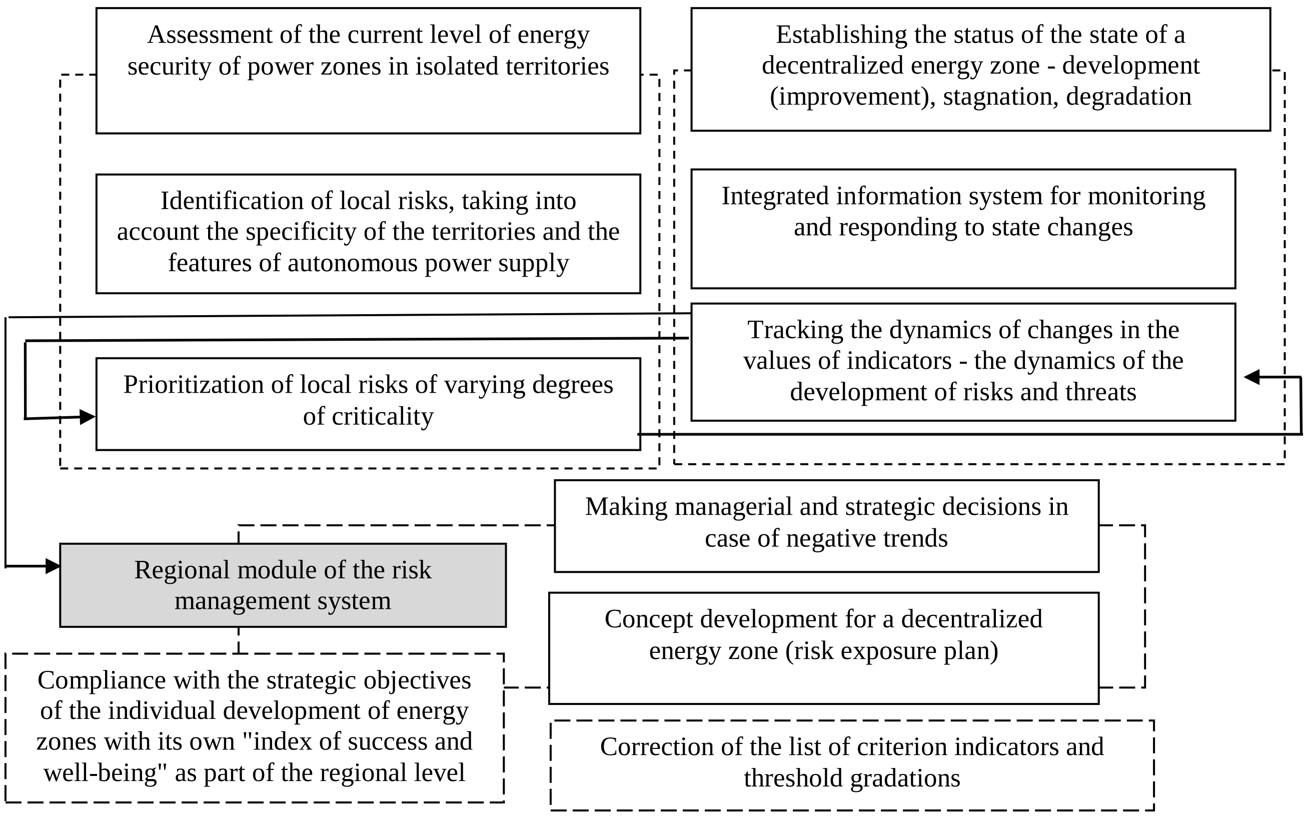

Fig 3. One of the approaches to the formation of the structure of a single information space of the regional segment of the RMS system

The susceptibility of territories and objects of analysis (territorial or sectoral component of the structure) to energy security risks is realized in the characteristics of criterion indicators reflecting the degree of impact of threats inherent in each region.

Identification of local risks, taking into account the specificity of the territories and the features of autonomous power supply of decentralized areas (Figure 3). The study proposes a possible group of criterion indicators for assessing the regional level of energy security in decentralized areas, reflecting the degree of action of inherent and identified threats to the development and functioning of the energy sector, its subsystems and objects of the territories under consideration.

Continuous monitoring of the effectiveness of energy security management ways should be correlated with the actualization of the tasks of the strategic directions of the region's development, with the internal goals of socio-economic development and indicators of the federal level in general and at the level of the constituent entities of the Russian Federation.

The implementation of the task will allow not only to solve the designated tasks, but also to create conditions for the growth of investments, technological renewal of the fuel and energy complex, the introduction of modern domestic technologies and equipment, as well as to train highly qualified personnel.

Energy cooperation between Russia and Mongolia: priority areas and mechanisms to pursue them

Boris Saneev[1*], *Anatoly* Korneev[1], *Sereeter* Batmunkh[2] and *Sodovin* Bathuyag[2]

[1]Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences, Irkutsk, Russia
[2]Mongolian State University of Science and Technology, Ulan Bator, Mongolia

Abstract. The study examines the directions of Russian-Mongolian energy co-operation. The focus is on an analysis of internal and external factors that negatively affect the implementation of the current inter-country energy projects. The mechanisms are proposed to cope with the factors limiting energy cooperation.

1 Introduction

Interstate cooperation between Russia and Mongolia has a long history. During the Soviet period, it was characterized by close economic, energy, cultural, and many other ties. The transition to a market economy has significantly changed Mongolia's inter-country relations, which have become multi-vector ones. The country has intensified relations with China, with developed European countries, with the United States, and others. Although the cooperation between Russia and Mongolia has weakened over the past 25 years, it has not lost its importance, and, first of all, for the energy sector. Mongolia has rich mineral resources [1], and their development requires huge investments and a powerful energy supply system [2]. Mongolia has a long border with Russia, which has a developed fuel and energy resources and surplus energy power in the regions bordering Mongolia. Currently, Russia is rendering all possible assistance in providing reliable energy and fuel supply to Mongolian consumers, which can have a significant impact on the economic development of Mongolia and mutually beneficial cooperation between the two countries in the future.

The primary internal and external challenges and problems facing today's energy projects implemented in Russia and Mongolia with the NEA countries include [3, 4]:

- high investment, production, social and labor costs of the extraction, production, and transportation of energy products, which ultimately reduce their price competitiveness in the world energy market, including that in the neighboring countries of NEA;
- limited public investment in the development of infrastructure projects;
- high tariffs in electricity and heat supply for the production of energy products and their transportation (transmission) by various modes of transport, which significantly increase their domestic and export prices;
- poorly developed domestic innovation and technology base, which prevents a timely (synchronous with developed countries) transition to new efficient high-tech production levels;
- increasing competition in the global energy market (dumping pricing policy, collusion for the imposition of financial, technological, and various economic sanctions, and others);
- unknown demand for energy resources due to the uncertainty of the world economy development and its structural transformations;
- restrictive measures related to the spread of coronavirus in the world and a downturn in business activity, and others.

Overcoming these unfavorable factors and increasing the possibilities for the implementation of inter-country energy projects require the flexible application of various mechanisms, both at the state and corporate levels.

The paper examines a wide range of mechanisms to be used, with the focus on the most important ones for specific areas and conditions of interstate energy cooperation between Russia and Mongolia.

2 Priority areas of energy cooperation between Russia and Mongolia

According to the state policy documents, the priority direction of the strategic development of the Mongolian energy sector is the improvement of its territorial-production structure based on internal capabilities and mutually beneficial international energy cooperation with Russia and the NEA countries [4]. Russia's energy policy is also aimed at cooperation with the NEA countries. The Energy Strategy of the Russian Federation until 2035, adopted by the Government of the Russian Federation in 2020, pays special attention to the energy development and the creation of a developed energy infrastructure in the eastern regions, which will increase the national energy security, strengthen fuel and energy ties between the countries and provide Russia's access to the energy markets of China, Japan, Mongolia and other countries of Northeast Asia and the Asia-Pacific region [3].

At present, the areas which are considered by the government, scientific, and business communities to be of

* Corresponding author: saneev@isem.irk.ru

priority for the Russian-Mongolian energy cooperation include the following:

1. Supplying Russian natural gas to Mongolia. This goal can be achieved by constructing a gas pipeline to China through the territory of Mongolia. The PJSC Gazprom considers it possible to implement the new project of the Power of Siberia-2 gas pipeline with a capacity of 50 billion cubic meters of gas annually. Now it is being discussed at the intergovernmental level [5]. The implementation of this project will both provide large gas supplies to China, and increase the number of gas consumers along the route of the pipeline in the Irkutsk region, the Republic of Buryatia, the Trans-Baikal Territory, and Mongolia [6]. In this case, Mongolia will have to invest only in gas distribution pipeline networks, excluding the main gas pipeline and branches. At the same time, Mongolia's revenues from gas transit through its territory to China can be used for the development of gas distribution networks.
2. Providing Mongolian consumers with petroleum products. Two options are considered: the existing one, through an increase in the supply of petroleum products from Russia and the construction of the Darkhan refinery with a capacity of 2–3 million tons per year in Mongolia, and the supply of Russian oil by oil pipeline or railway transport.
3. Increasing direct supplies of electricity from Russia and building Asian Energy Super Ring in the distant future, which will interconnect the power systems of Russia, China, Japan, South Korea, and Mongolia. The second option suggests the construction and reconstruction of thermal power plants with a capacity of more than 6000 MW in Mongolia, and their connection to the interstate electric power system [7, 8].
4. Developing the world's largest Tavan Tolgoy deposit of coking coal with the participation of Russia and the supply of this coal to the NEA countries [9].
5. Constructing railways to transport large volumes of mined coal to external consumers and others, in the future. [10, 11].

The feasibility of the inter-country energy projects under consideration will, first of all, be determined by the rates of economic development of China and Mongolia, given the development of Mongolia’s mineral resources, competitive (price) advantages of Russian energy resources, and the possibilities of overcoming some other internal and external limiting factors described above.

3 Requirements for mechanisms to implement inter-country projects

In the practice of promoting and supporting the projects planned for implementation, there are many organizational, economic, and legislative mechanisms [12, 13]. In the context of energy cooperation with Mongolia, the most important of them include organizational and economic ones. Figure 1 presents an extended list of organizational measures designed for the countries to jointly develop coordinated proposals for energy cooperation projects, to work out interstate target programs for the economic development of individual territories and industries in conjunction with the implementation of inter-country energy projects, and others.

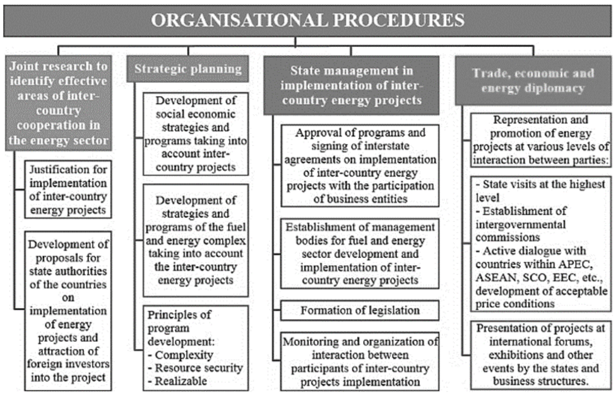

Fig. 1. Organizational mechanisms for the implementation of inter-country energy projects

In the stage of project implementation, an important role is played by the interstate government monitoring of the work progress and the timely elimination of obstacles by organizing coordinated actions of project participants, eliminating bottlenecks, and adjusting various project parameters.

The central point of substantiating the effectiveness of inter-country projects and their feasibility is the high competitiveness of energy products in terms of quality and price characteristics. Here economic mechanisms are of decisive importance. A list of them is shown in Figure 2.

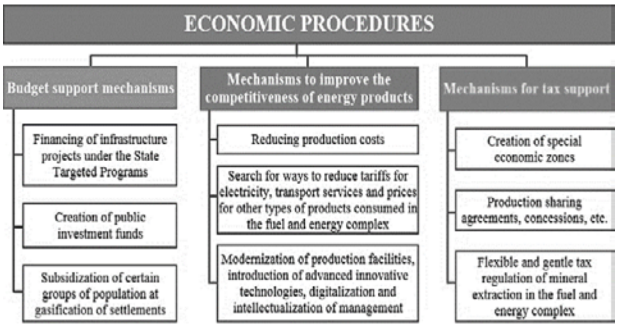

Fig. 2. The economic mechanisms to implement inter-country energy projects

At the present stage, the corporations should pay special attention to such economic mechanisms as the reduction in the costs of extraction, processing, production, and transportation of energy products based on the modernization of production facilities, the adoption of advanced innovative technologies, digitalization, and smartization of management. At the same time, the states should make maximum use of the mechanisms of budget-based financial support for infrastructure projects within the framework of targeted state programs, and apply flexible and tax sparing regulation to the extraction of minerals in the energy sector.

Almost all economic mechanisms aimed at implementing inter-country projects are directly or indirectly related to the formation of sources and attraction of investments. The primary investment mechanisms are shown in Figure 3.

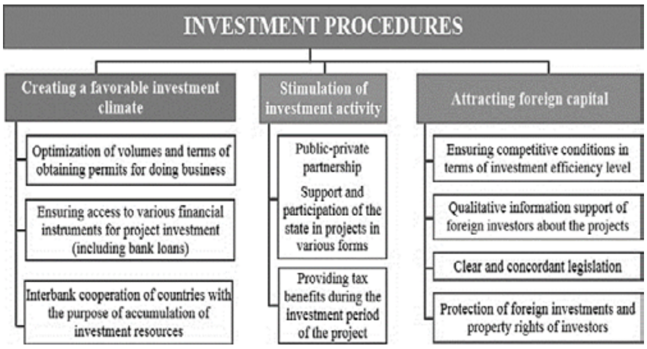

Fig. 3. Investment mechanisms to implement inter-country energy projects.

In the context of sanctions imposed by the Western countries on Russia and the restriction of access to credit resources of foreign banks, funding based on organizational and legislative mechanisms is becoming especially relevant:

- accessibility to various domestic financial tools for project investment, including bank loans, with interest rates not exceeding those of leading Western European banks;
- competitive conditions in terms of the efficiency of investment by domestic and foreign investors in the projects at issue compared to possible alternative projects;
- interbank cooperation of states implementing interstate energy projects to accumulate investment resources, and others.

Despite the existing experience in the implementation of inter-country projects for the supply of energy resources from the eastern regions of Russia to Japan, China, and other NEA countries, the existing mechanisms for the implementation of inter-country projects do not yet have a systemic (interconnected) nature of their use and require further improvement.

4 Conclusion

Energy cooperation between Russia and Mongolia, and the implementation of inter-country energy projects should be based on comprehensive program-targeted planning of economic development of the respective territories and leading industries of the parties involved, i.e. within the framework of programs agreed with investors and approved by governments. At present, the research teams of the Academies of Sciences of Russia and Mongolia systemically conduct studies to substantiate the directions of energy cooperation between the two countries for the time horizon until 2035. At the same time, they consider the Baikal region (Irkutsk region, the Republic of Buryatia, and the Trans-Baikal Territory) to be the base area for cooperation with Mongolia.

To ensure the competitiveness of export energy products produced within the framework of inter-country projects, corporations must focus on the most advanced technologies, have flexible, sparing taxation, acceptable tariffs for the energy supply within projects to be implemented and the transportation of energy products, which in general significantly reduces costs and increases the flexibility of export prices.

Another crucial factor in reducing investor costs and increasing the efficiency of inter-country energy projects is active, multilateral, and systematic state infrastructure support for the projects.

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Trends in the energy development of the Russian Federation and its Asian regions in the first half of the 21st century in the context of Russia's energy ties with the countries of northeast Asia

Boris Saneev[1], *Anatoly* Lagerev[1*] and *Valentina* Khanaeva[1]

[1]Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences, Irkutsk, Russia

Abstract. The present paper deals with the role of the Asian regions of Russia (Siberia and the Russian Far East) in the production and consumption of energy resources in the country for the period up to 2050. The focus is on the dynamics and structure of energy resources outflows from the Asian regions of the country to the European part of the country and for exports to European and Asian destinations.

Keywords: energy sector, Asian regions of Russia, Northeast Asian (NEA) countries, energy resources, projection, scenarios, production, consumption, exports, prices

1 Introduction

The Asian regions of Russia (Siberia and the Russian Far East) have unique reserves of energy resources of all-Russian and international importance.

Currently, more than 80% of Russia's energy resources are produced in its Asian regions, including 71% of the country's oil, 97% of natural gas, more than 95% of coal; more than 30% of the country's electricity is produced there as well.

In recent years, a lot of work has been done in Russia to create a list of policy documents that define the strategic development of the energy industry in the East of the country so as to take into account mutually beneficial energy cooperation between Russia and the NEA countries in the energy sector [1–4].

The Melentiev Energy Systems Institute SB RAS, also makes a certain contribution to shaping the Eastern Energy Policy, see, for example, [5].

In the materials of the program documents, much attention is paid to the Asian regions, the development of which can give an additional impetus to the development of the energy sector of the country. The Energy Strategy notes that a more dynamic growth of consumption and production of energy resources is expected in these regions, given that they are associated with the main prospects for increasing Russian energy supplies to the countries of Northeast Asia.

The development of the energy sector of Russia and its Asian regions in the long term will depend on a number of factors, among which it is important to be aware of the changes in the projection of economic development and energy consumption levels in the country and its Asian regions; in the development of the resource and raw material base of the energy sector; in the pace of scientific and technological advances in the energy sector; in the dynamics of fuel and energy prices in domestic markets of Russia; in the international energy markets situation.

2 Modelling tools

To estimate the effect of prospective factors on the development of the energy sector of the Asian regions we employed the basic scheme of hierarchical modelling developed at the Melentiev Energy Systems Institute, SB RAS [6], at the core of which is the dynamic model of optimization of the territorial and production structure of the country's energy sector (Figure 1), [7].

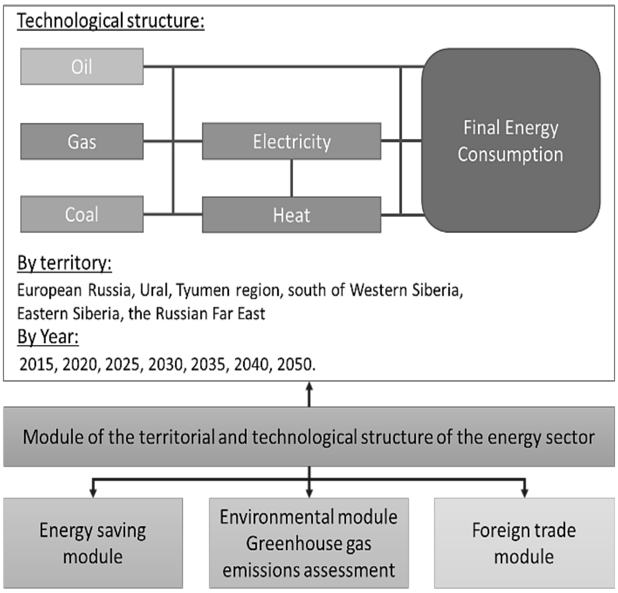

Fig. 1. Structure of the dynamic optimization model of the country's energy sector

* Corresponding author: lagerev@isem.irk.ru

The model describes the process of development of the territorial and production structure of the energy sector up to 2050 in dynamics (modelled in five-year increments) as applied to large aggregated regions defined based on their geographical location.

3 Research findings

The model-based studies enabled us to form a well-balanced rational structure of regional energy sector development for the country as a whole and for each of the Asian regions (Western and Eastern Siberia, the Russian Far East) and outline their role in the energy sector of the country.

Backed by the program documents [1–4, 8] and other materials [9–11], as well as by the authors' previous research [12–15], we are able to identify a number of trends in the development of the energy sector of the country and its Asian regions to 2035 and with a view to 2050.

Below we study two scenarios of Russia's energy sector development to 2050: the conservative scenario and the more optimistic target scenario. The aggregated macroeconomic indicators of the country's economic development and corresponding energy consumption levels are shown in Table 1. The lower boundary of the indicator change range corresponds to the conservative scenario, while the upper boundary corresponds to the target scenario.

Table 1. Projection of economic development and energy consumption in Russia

Indicator	2015	Projection		
		2025	2035	2050
GDP*, bln. USD	1.555	1.850-2.105	2.300-2.960	3.160- 4.610
GDP growth rate as compared to 2015, %	100	119-135	148-190	196-286
Average annual GDP growth rate, %	-	1.7-3.1	2.2-3.5	2.1-3.0
Population, mln. people	146	146	145-146	145-147
GDP per capita, thous. USD per person	10.7	12-14	16-20	22-31
Domestic primary energy consumption, mln. tce	964	1.073-1.091	1.143-1.174	1.144-1.190
Primary energy consumption growth rates as compared to 2015, %	100	111-113	118-122	119-123
GDP energy intensity, tce per thous. USD	0.62	0.56-0.53	0.5-0.4	0.4-0.3
Energy intensity decrease rate as compared to 2015, %	100	92-87	79-66	59-43

Note: reported in constant 2015 prices.
Sources: [1,8], estimates by the authors

Average annual GDP growth rates for assumed scenarios were covered within the following ranges: 1.7–3.1% for the period between 2015 and 2025 and 2.2–3.5% for the period between 2026 and 2035. It is assumed that in the years to come (2036 to 2050) the GDP growth rate will drop to 2.1% under the conservative scenario, and to 3.0% under the target scenario.

One of the prerequisites for the assumed scenarios of economic development of Russia to materialize is the growth (as compared to 2015) of domestic primary energy consumption: by 11–13% by 2025, and by 19–23% – by 2035-2050.

To this end, the consumption of petroleum products in the period between 2015 and 2050 should increase by 15–17% and that of natural gas – by 23–28%, while the consumption of coal and other solid fuels should decrease by 5% under the conservative scenario and should increase by 1.5% under the target scenario. The consumption of non-carbon energy resources (HPPs, NPPs, non-conventional renewables) should increase by 33–43%.

The resulting energy consumption structure in Russia is shown in Figure 2.

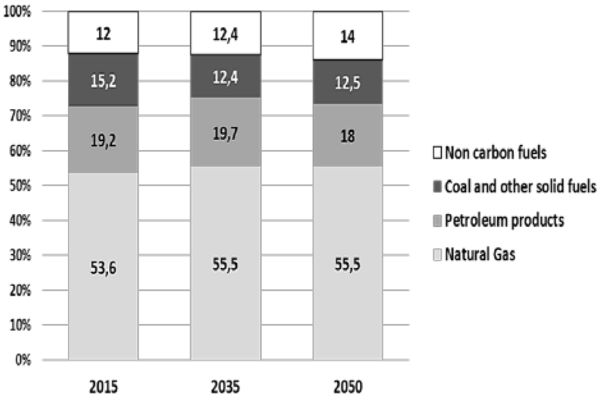

Fig. 2. Projected structure of energy consumption in Russia, %

As shown in Figure 2, natural gas will remain the dominant resource in primary energy consumption in Russia throughout the period under review: its share in the demand structure will increase from 53.6% in 2015 to 55–56% by 2050.

The share of petroleum products in the structure of primary energy consumption by 2050 under the conservative scenario will decrease to 18.5% (as compared to 19.2% in 2015), and, under the target scenario, to 18%, while the share of coal and other solid fuels will decrease from 15% to 12–12.5%.

The share of non-carbon energy sources in domestic consumption will remain at about 12% until 2035 and only by 2050 will it increase to 13.5–14%.

The results of the study show that after 2035 the consumption of energy resources in the Asian regions of the country will grow faster than before. Over the period under review (2015–2050) energy consumption in the Asian regions may increase by 28–35% (in the country as a whole – by 19–23%).

At present, Russia enjoys the status of the world's largest exporter of energy resources, the sales volume of which is slightly less (by 3%) than their domestic consumption in the country.

Within the given timeframe, export volumes and structure will be mainly determined by the factors of economic feasibility and will depend not only on fuel prices in the international energy markets but also on prices and production volumes of Russian producers.

At the same time, the political component will also play an important role.

The dynamics of international fuel prices assumed for modelled calculations is given in Table 2, while that of domestic prices is given in Table 3.

Table 2. Projection of fuel prices* in international markets

Indicator	2015	Projection		
		2025	2035	2050
Oil, USD per barrel	45	50-65	50-65	65-80
Natural gas, USD per 1,000 m^3				
Europe	240	250-290	250-290	300-350
Countries of Northeast Asia:				
China (pipeline gas)	250	275-290	300-345	330-380
Japan (LNG)	310	340-380	380-450	430-500
Steam coal, USD per ton	63	65-70	60-75	60-80

Note: *reported in constant 2015 prices.
Source: documents of strategic development of the Russian energy sector to 2035 and authors' estimates.

Table 3. Projection of fuel prices* in Russian markets

Indicator	2015	Projection		
		2025	2035	2050
European market				
Natural gas, USD per 1,000 m^3	90-105	120-130	120-150	125-185
Steam coal, USD per tce	45-50	50-60	50-75	65-80
Asian market				
Natural gas, USD per 1,000 m^3	95-100	120-135	145-170	170-200
Steam coal, USD per tce	35-45	50-60	50-60	55-65

Note: *reported in constant 2015 prices.
Source: documents of strategic development of the Russian energy sector to 2035 and authors' estimates.

The projected exports of Russian energy resources that we arrived at given international and domestic prices of fuel and energy supplies as assumed in calculations are shown in Table 4.

Table 4. Projection of exports of Russia's energy resources

Indicator	2015	Projection		
		2025	2035	2050
Exports, total, mln. tce/%,	925	1,050-1,090	1,010-1,070	915-1,060
Inclusive of the following:	100	114-118	96-98	87-97
Oil and petroleum products, mln. tons	406	377-390	321-338	276-312
Natural gas, bln. m^3	204	290-294	308-323	272-327
Coal, mln. tce	115	180-194	200 -215	200-230
Electricity (balance), billion kWh	7	21-22	22-28	62-67

It follows from the above that in 10 years (i.e., by 2025) the exports of Russian energy resources will increase by 14–18%, and then decline by 2050: under the conservative scenario – by 13%, under the target scenario – by 3%.

As is evidenced from Figure 3, oil exports will dominate in the structure of energy resources exports from Russia in the period under review, while its share in the structure of exports will gradually decrease: from 62% in 2015 to 45% by 2035 and to 42–43% by 2050.

Within the given timeframe, the European export destinations will remain the dominant ones for Russia, but their share in total exports will decrease and by 2050 it will amount to 55–62% (as compared to 80% in 2015).

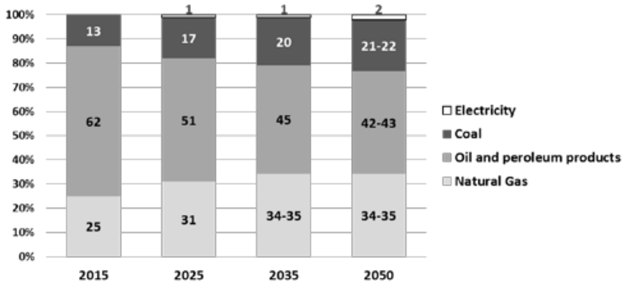

Fig. 3. Structure of Russian energy resources exports, %

The decline in the share of oil exports will be substituted mainly with natural gas and coal. At the same time, the share of natural gas in the structure of exports will increase from 25% in 2015 to 34–35% by 2035 and will remain at this level until 2050.

The share of coal will grow from 13% in 2015 to 21–22% by 2050.

Figure 4 shows the structure of Russian energy resources exports by export destinations.

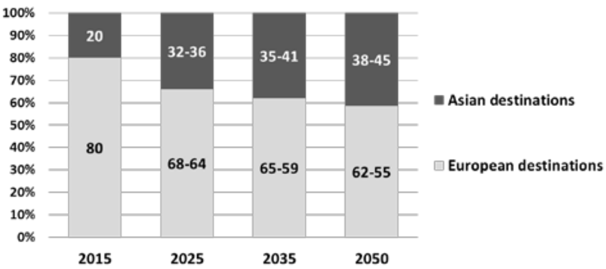

Fig. 4. Structure of Russian energy resources exports by destinations

At the same time, the availability of economically viable energy resources in the Asian regions of Russia and the growing demand for them in the NEA countries make Asian destinations of energy exports from Russia more promising. It is estimated that by 2050 the share of energy exports to Asian destinations in total energy exports may increase to 38–45% as compared to 20% in 2015.

The volume of energy resources production in Russia resulting from our modelled calculations is shown in Table 5.

Table 5. Energy production in Russia to 2050

Indicator	2015*	Projection		
		2025	2035	2050
Production, total, mln tce/%, inclusive of:	1886 *100*	2.117-2.173 *112-115*	2.170-2.257 *115-120*	2094-2284 *111-121*
Oil and gas condensate, mln. tons	534	526-542	428-502	428-466
Natural gas, bln. m^3	635	784-799	855-878	832 - 907
Coal, mln. tons	374	447-470	477-510	485 - 539
Other solid fuels, mln. tce	32	32	38	44
Hydropower, TW·h	170	207-208	215-221	251-260
Nuclear power, TW·h	195	222	256-263	330-361
Non-conventional renewable energy, TW·h	2.4	9-10	28-36	55-60

Note: *2015=100%

Our studies attest to the need to increase energy production in Russia by 11-21% by 2050 (as compared to 2015) to meet the country's projected domestic demand for energy resources and their exports.

It is estimated that oil and gas condensate production in the country will decrease by 2050 (as compared to 2015) by 20% under the conservative scenario and by 13% under the target scenario.

Natural gas production will increase (as compared to 2015) by 35–38% by 2035 and by 31–43% by 2050.

Table 6 shows the share of the Asian regions in the projected energy resources production in Russia.

Table 6. Share of Asian regions in energy resources extraction (production) in the country, %

Indicator	2015	Projection		
		2025	2035	2050
Energy, total, including:	79	82	83	81
Oil and gas condensate	70	73	75-84	78-79
Natural gas	92,5	93-94	94-95	89-87
Coal	94	96-97	96-97	97-98

Note: *2015=100%

According to the authors' estimates, by 2050 the Asian regions of Russia will account for 78–79% of oil production in the country (70% in 2015), 87-89% of gas production (92.5% in 2015), and 97–98% of coal production (94% in 2015).

Table 7 shows the dynamics of energy resources production in the Asian regions of Russia.

Table 7. Energy resources production in the Asian regions of Russia

Indicator	2015	Projection		
		2025	2035	2050
Production, total, mln tce/%, inclusive of:	1,493 *100**	1,736-1,790 *105-112*	1,812-1,890 *121-127*	1,708-1,848 114-124
Oil and gas condensate, mln. tons	375	383-397	359-377	333-366
Natural gas, bln. m^3	588	734-748	807 -832	741-787
Coal, mln. tons	351	431-454	460-494	473-528
Other solid fuels, mln. tce	9	8	8,6	9,4
Hydropower, TW·h	108	137	145-148	170-175
Nuclear power, TW·h	0,2	0,5	0,5	0,6
Non-conventional renewable energy, TW·h	0,8	2,5-3,8	9-13	18-20

Note: *2015=100%;

At present, the main oil production area is Western Siberia. It is projected that oil production in Western Siberia (as compared to 2015) may decline by 25% (by 80 million tons) under the conservative scenario by 2050, and by 17% (by 55 million tons) under the target scenario.

In the period under review, East Siberian and Russian Far Eastern fields may make a significant contribution to oil production, with production growth by 2050 to 55–60 million tons in East Siberia and 45-48 million tons in the Russian Far East.

Western Siberia where gas production may grow by 2035 and then decline by 2050 remains the main gas-producing region within the given time frame.

Eastern Siberia and the Russian Far East will become promising gas production regions in the period under review. Given the favourable market conditions in the Asian export destinations, gas production in Eastern Siberia will increase to 50–65 billion cubic meters by 2050 and to 72–77 billion cubic meters in the Russian Far East.

Coal production in Western Siberia is projected to grow by 2050 to 275–315 million tons (as compared to 215 million tons in 2015).

Significant growth in coal production will be provided by Eastern Siberia and the Russian Far East. According to the authors' estimates, coal production may grow by 30–42% by 2050 in Eastern Siberia, while increasing 1.8–1.9 times in the Russian Far East.

Production of non-carbon electric power sources in the Asian regions of the country (nuclear power, hydropower, non-conventional renewable sources) will increase by 23–28% by 2035 and by 34–39% by 2050.

That having been said, their share in the country's energy production will increase insignificantly: from 6.1% in 2015 to 6.3% by 2035 and to 7.5% by 2050.

Figure 5 shows the projected dynamics of energy resources exports from the Asian regions of Russia.

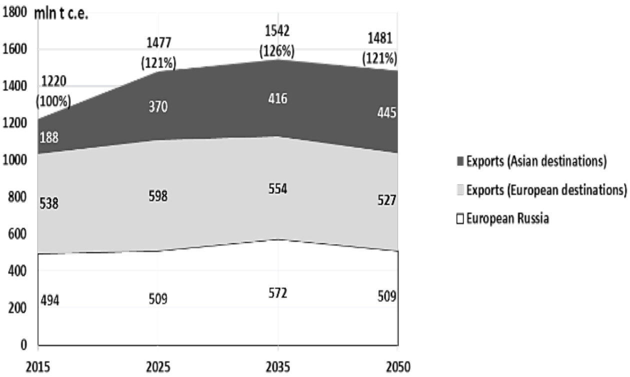

Fig. 5. Exports of energy resources from the Asian regions (target scenario)

In 2015, 1,220 million tce of energy resources (or 82% of their total production) were exported from the Asian regions of Russia, 41% of which were for the needs of the European part of the country and 59% were for exports.

According to the authors' estimates, the exports of energy resources from the Asian regions will increase by 21–26% by 2035, and then will decrease by 4–8% by 2050.

Figure 6 shows how the percentage ratio with respect to the destinations of energy resources exports from the Asian regions of Russia may change:

- the share of energy resources exported to the European part of the country in total exports will decrease and by 2050 will amount to 37–34% (as compared to 41% in 2015).

- the share of Asian energy resources exported to European destinations will decrease from 44% in 2015 to 39–36% by 2050.

- the share of Asian energy resources exported to Asian destinations will increase from 15% in 2015 to 24–30% by 2050.

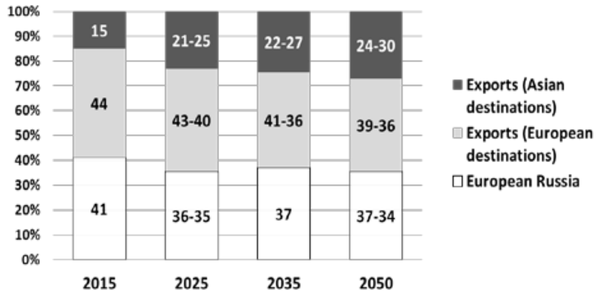

Fig. 6. Structure (by destination) of energy resources exports from the Asian regions

4 Conclusion

1. Under the considered scenarios of Russia's economic development, energy consumption in the country (in the period from 2015 to 2050) should increase by 19-23%, with energy consumption in Asian regions increasing by 28-35%. As a result, the share of Asian regions in the total energy consumption of the country will increase from 29% in 2015 to 31–32% by 2050.

2. Within the timeframe under review the Asian regions will still remain the main suppliers of energy resources, both to the domestic market of the country and for exports.

3. According to the authors' estimates, the exports of energy resources from Asian regions may increase by 21–26% by 2035 and then decrease by 4–8% by 2050.

At the same time, the proportion of exports of energy originating from Asia will also change in terms of their destinations:

- exports to European Russia will decrease from 41% in 2015 to 34–37% by 2050;

- exports to European destinations will decrease from 44% to 36-39%;

- exports to Asian destinations (Northeast Asian countries) will increase from 15% to 24–30%.

4. To meet domestic demand for energy resources and their exports, energy production in Russia's Asian regions should grow by 21–27% by 2035 (as compared to 2015), and then decline by 6–2% by 2050.

By 2050, Asian regions are expected to account for 78–79% of the country's oil production (70% in 2015), 87–89% of natural gas production (92.5% in 2015), 97–98% of coal (94% in 2015), 67–68% of electricity produced by HPPs (64% in 2015).

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Innovative development of the fuel and energy complex in the eastern regions of Russia

Alexander Sokolov[1,*], *Svetlana* Muzychuk[1], and *Roman* Muzychuk[1]

[1]Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences, Irkutsk, Russia

Abstract. The most important direction of the current stage of Russia's development is the growth of its energy efficiency associated with the transition to innovative energy. The use of innovative technologies is an important factor influencing long-term forecasts of economic development and the fuel and energy complex (FEC), which necessitates the development of new approaches to justify the forecasts of the FEC development in Russia and its regions. Innovative development of the FEC will increase energy efficiency of the economy and improve the environment as fuel consumption will be reduced and emissions of harmful substances into the environment will be reduced. Solving this problem is important for Eastern regions, which are the most environmentally disadvantaged economic regions of Russia. This has determined the relevance of the study. The goal of the study is to determine the impact of innovative development of the fuel and energy complex on the economy of Eastern regions. Methods of research - system analysis, balance sheet, statistical methods. The authors developed a method to assess the impact of innovative development of the fuel and energy complex on the economy of the regions, created a model and computer tools.

Keywords. Fuel and energy complex, Eastern regions, innovation, economy, energy efficiency, best available technologies.

1 Introduction

Changes in the country's economy associated with the transition to intellectual energy make it necessary to develop new approaches to justify the forecasts of innovative development of the Russian fuel and energy complex and its regions. Application of innovative energy technologies leads to changes in the structure of supply and consumption of fuel and energy resources (FER). Such changes should be taken into account in the analysis and long-term forecasting of the innovative development of the FEC of Russia and its eastern regions. The use of innovation technologies has a great impact on such tasks as improving energy efficiency, increasing energy security, increasing competitiveness of the country and its regions, reducing environmental problems. Therefore, taking into account the possible use of innovative technologies becomes an important factor affecting long-term forecasts of economic and fuel and energy sector development.

Eastern regions have significant potential in application of innovations in the fuel and energy complex. Figure 1 shows the role of Eastern regions of Russia in FER production A large number of power generating enterprises for the development of fuel and energy industries on a new technological basis. Implementation of large investment projects for the renewal and modernization of production equipment. The presence of a large number of isolated from centralized energy for the use of advanced technological solutions in the creation of new power generating enterprises.

Efficiency of FER utilization is one of the important tasks in realization of national fuel and energy resources, interests of both the region and the country as a whole. Implementation of innovative development of the Fuel and Energy Complex, which promotes energy saving, will significantly improve energy efficiency of the economy and increase environmental safety of the eastern regions, since reduction of fuel consumption will significantly reduce harmful emissions into the environment.

In order to conduct research based on materials from foreign and Russian sources, an information and analytical base of innovative technologies in the FEC was created and a model and computer toolkit was developed to assess the impact of the innovative development of the fuel and energy complex in Eastern regions on the economy.

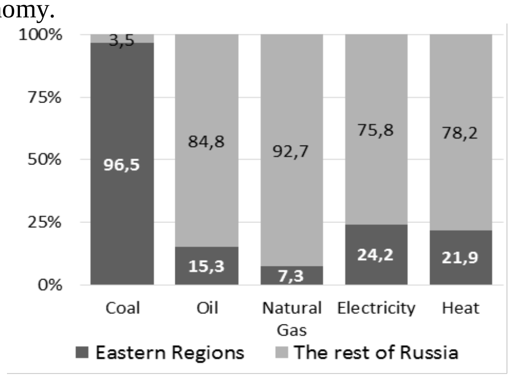

Fig. 1. The role of Eastern regions of Russia in FER production

* Corresponding author: sokolov@isem.irk.ru

2 Review of innovative energy technologies

In the world one of the most authoritative organizations in the field of innovation development for the fuel and energy complex is the International Energy Agency (IEA), which helps to ensure uninterrupted and affordable energy supply to consumers in OECD member countries while preserving the environment [1]. The IEA has an Energy Technology Outlook project that introduces stakeholders to the world's promising energy technologies. The IEA has the following interests in the field of energy technologies: fossil fuel use, efficient final energy use, fusion, electric power industry. The main result of the project is the report "Prospects of energy technologies", which is published every two years. The Energy Technology Outlook 2017 report presents the results of a study of the impact of scientific and technological progress on the dynamics of the fuel and energy complex, on which energy and environmental security, as well as economic stability of OECD countries in the next decades will depend. According to the IEA, the introduction of innovative technologies in the power industry on a global scale will ensure annual fossil fuel savings of about 950-1100 million t c. e. (which corresponds to the average annual consumption of natural fuel in Russia).

Japanese Business Alliance for Smart Energy Worldwide (JASE-W) is an organization established in 2008 to distribute Japan's advanced energy-saving developments. In "Japanese Smart Energy Products & Technologies", released in 2017. [2], presents a large number of innovations (with a detailed description of their principle of operation and advantages over traditional technologies) that are used in various fields (including the fuel and energy sector) in Japan.

A few examples of innovations used in the Japanese electric power industry that can be successfully used in Russia.

1. A high performance thermal power plant with supercritical pressure. Steam turbines use the most optimal high-strength materials and designs suitable for high pressure and temperature conditions. In comparison with similar equipment (steam turbines of pre-critical pressure), this equipment has 5.5% and higher efficiency factor.
2. Thermal gas turbine unit is an energy system with total efficiency of more than 80% (Power generation efficiency - about 30%, steam heat recovery efficiency - about 50%) based on an electric generator turbine using natural gas as fuel with heat recovery of waste gases. This system is economical due to the lack of special high-voltage power supply systems from the power grid, energy-saving and environmentally friendly due to reduced CO2 emissions.
3. New generation of solar thermal power plants - technology of molten salt parabolic trough (MSPT), the advantage of which (in comparison with other types of renewable energy sources) is convenience in energy storage and supply. Heliothermal energy can be stored in a reservoir and supplied to consumers regardless of the weather. The cost of energy storage is comparable to the cost of a battery. In the MSPT, synthetic oil is replaced by molten salt, which is used as a heat transfer fluid and can raise the operating temperature to 550°C. Advantages of this system in comparison with the technology on synthetic oil: increased efficiency of steam turbines; convenience in energy storage; smaller size of the unit.

Japan is the world leader in thermal power plants that use coal as fuel (the highest efficiency among developed countries). Introduction of advanced high-efficiency Japanese technologies at coal-fired power plants, equipment replacement and a number of other innovations in Russia can give a great energy-saving effect: reduction of new power plant commissioning, reduction of coal and other fuel consumption.

Therefore, studying the experience of innovative technologies in developed countries is very important for Russia, which is developing its own domestic innovations in various areas (which is especially important under the conditions of ongoing anti-Russian sanctions and import substitution policy). The strategic task facing the Russian fuel and energy complex is the innovative development of its industries, which requires technological innovations.

At present, the innovative development in the Russian fuel and energy complex is being implemented in accordance with the policy documents developed by the Ministry of Energy of the Russian Federation: "Forecast of scientific and technological development of the Russian Fuel and Energy Complex sectors for the period up to 2035". (hereinafter referred to as STD Forecast); Road Map "Implementation of innovative technologies and modern materials in the fuel and energy sector"; Road Map "Energynet" of the National Technological Initiative; National Project "Intellectual Energy System of Russia".

The STD forecast lists the advanced technologies that can have the greatest effect on the development of the Russian economy. The most promising areas of development in the oil and gas sector include the introduction of technologies to increase oil recovery and oil recovery factor, development of hard-to-recover oil and offshore fields, LNG production and transportation [3]. The most promising innovations in the electric power industry include: "digitalization of power engineering" - implementation of automated protection and control systems for power substations, development of technologies for active and adaptive power networks, technological concepts "SmartGrid" and "Energynet", introduction of new electrical, electromechanical and electronic equipment. In the coal industry, the most promising directions of technological development are considered to be: growth of technical level of coal mining by underground method and improvement of coal preparation technologies.

The STD forecast for the Russian Fuel and Energy Complex lists 24 main sectoral technologies, the introduction and diffusion of which can provide large-scale economic effect, prevent threats to energy security and ensure technological independence of the country [3]. The largest number of these technologies (11) is in the oil and gas sector, of which three - in oil refining and oil and

gas chemistry, ten innovative technologies are proposed for electric power industry and three - for coal industry.
The following innovative technologies are listed in the STD forecast for the development of Russia's oil and gas sector [3]: production of hard-to-recover and unconventional hydrocarbon reserves, including those offshore the Arctic and Far Eastern seas; hydraulic fracturing; drilling and construction of wells with complex profiles; production of coiled tubing for well intervention; enhanced oil recovery; integrated exploration of hydrocarbon deposits; production of catalysts for oil refining and petrochemical industries; and processing of hydrocarbons.
In the Russian electric power industry, according to the STD forecast, the following technologies are among the innovative ones [3]: production of large capacity gas turbine units (GTUs) with high efficiency; electrochemical, including fuel cells and accumulators of large capacity and capacity; environmentally friendly use of solid fuel in the power industry (include power units for super supercritical steam parameters, power units with coal combustion in a circulating fluidized bed; technologies of coal gasification with subsequent use of synthesis gas in a steam-gas cavity); technologies for gasification of coal.
The critical technologies proposed for the innovative development of the coal industry and listed in the STD forecast include: robotic coal mining technologies without permanent human presence in the working space; technologies for coal bed degassing and utilization of coal mine methane; coal preparation and deep processing [3].
Hydrogen energy, small distributed generation using renewable energy sources, photovoltaic converters, network drives are also included in the STD forecast [3].
In the framework of the National Technology Initiative (NTI), identified one of the important priorities of the state policy for the development of industries in the new technological mode and for the country's entry into the markets of the future, and has developed a roadmap "Energynet" [4], according to which it is planned to implement a number of technical pilot projects in the areas of increasing reliability and flexibility of power transmission networks for the development of intelligent distributed power generation and consumer services necessary for the implementation of solutions for active energy. The Russian Ministry of Energy is overseeing the implementation of the "Energynet" Road Map in terms of adjusting the regulatory framework, pilot technical projects, coordination of innovation policy within the power industry and at the level of power companies, and coordination of actions of all stakeholders.
The next policy document of the Ministry of Energy of the Russian Federation, according to which the innovative development of the electric power industry is currently being carried out, is the National Project "Intellectual Power System of Russia", the purpose of which is to create the necessary conditions for the transition to the intellectual power industry of the country through the formation of the relevant regulatory and normative-technical base, including the improvement of the retail and wholesale electricity market, as well as through the creation of the necessary infrastructure and the creation of the necessary infrastructure [5].

3 Innovative development scenario

The information and analytical base of innovative technologies in the fuel and energy complex, designed for complex analysis and long-term forecasting of the innovative development of the fuel and energy complex of the eastern regions, was formed in accordance with the directives of the Ministry of Energy of the Russian Federation. It's most part was made up of the innovative technologies listed in the STD Forecast, and also takes into account a number of the most promising technological solutions and developments implemented in Russia and economically developed countries of the world. The forecast of innovative development of the fuel and energy complex of eastern regions should be based on the above mentioned technologies.
The innovative scenario of development of the FEC of Eastern regions is presented in Table 1.

Table 1. Innovation scenario indicators for the fuel and energy sector in Eastern regions of Russia

Indicator	2019	2026-2030	2031-2035
GRP energy capacity, kg c.e./ thousand rubles	14	12,5-13,7	11,8-12,4
FER production:			
- coal, mln t	423	450-480	465-495
- oil, mln t	86	110-122	117-126
- natural gas, bln m^3	54	100-115	120-135
- electricity, bln kWh	275	318-335	332-366
- termal energy, mln Gcal	278	273-283	280-293
FER consumption:			
- coal, mln t	123	134-135	134-138
- oil & petroleum products, mln t c.e.	45	55-59	61-64
- natural gas, bln m^3	30	30-31	30-32
- electricity, bln kWh	276	305-320	320-350

The most significant factors affecting the energy efficiency of the economy of Eastern regions are as follows: reduction of specific FER costs for production, especially in the most energy-intensive economic activities (metallurgy, timber processing, petrochemicals, etc.); reduction of energy consumption in the public sector, housing and utilities sector, and among the population through more rational consumption of energy resources; reduction of FER losses during their extraction, processing, transportation; and reduction of specific FER costs for energy production.
Mechanisms for implementing technological factors to improve energy efficiency in the economy of Eastern regions in the fuel and energy sector are as follows:
- decommissioning morally and physically obsolete equipment with low parameters of coal-fired thermal power plants; accelerating technical re-equipment and reconstruction of existing thermal power plants based on environmentally friendly technologies;

- commissioning of highly efficient power generating capacities with minimal fuel consumption for power and heat generation (e.g., mini-CHPs, heat pumps, modern modular gas-fired boiler houses, wood processing waste, wood pellets, etc.) for isolated consumers;
- implementing energy-saving technologies and innovative equipment in the oil and gas coal industry, as well as in the processes of fuel and energy supply and distribution;
- reduction of FER losses in the oil and gas complex: according to the requirements of the Russian legislation, oil companies need to bring the utilization of associated petroleum gas up to 95% by either reinjection or application of innovative technologies. For example, fuel cell heat units (with efficiency up to 85% in combined production of electricity and heat), heat units based on external combustion engines, etc., which use associated petroleum gas as fuel;
- heat loss reduction: timely control and monitoring of technical condition of heat networks, diagnostics, analysis, operative repair, application of new heat protection materials, composite pipes, more complete use of secondary heat energy resources (including heat recovery units, recuperators, etc.).
Mechanisms for implementing technological factors in non-energy sectors of economic activity are:
- implementing of innovative technological processes and energy-saving equipment that allow rational reduction of fuel and energy consumption. For example, for electrical equipment, the use of capacitor units and frequency-controlled electric drives, which allow saving up to 30-50% of the energy consumed; in the housing and utilities sector, the use of "smart lighting systems" of automatic lighting control systems and energy-efficient lighting devices;
- systematic implementation of resource-saving measures in accordance with the regional energy saving program. In existing buildings - sealing and elimination of heat loss through windows, doors, ventilation communications; in buildings under construction - wall insulation, installation of modern double-glazed windows, energy-saving roofs, economical heating systems, etc.

4 Conclusion

In the course of the research the following results were obtained. The information-analytical base of innovative technologies for complex analysis and long-term forecasting of innovative development of the fuel and energy complex was developed. The review of foreign and Russian sources on the application of innovative technologies in the fuel and energy complex industries was carried out. The implementation of innovations in the eastern regions was monitored. The impact of innovative development of the fuel and energy complex on the economy was assessed.

The introduction of innovative technologies has a significant impact on energy efficiency in the economy of Eastern regions, increasing their competitiveness and reducing environmental problems. The article shows the main directions of innovation and technological development of the fuel and energy complex in the eastern regions, and gives an economic assessment of this process.

Innovative development of the fuel and energy complex will have a positive impact on the economy and the environment, which will improve the quality of life of the population of eastern regions of Russia.

The results will be used in further studies to forecast the innovative development of the fuel and energy complex of the country and its Eastern regions and to develop recommendations on the use of effective innovative technologies in energy supply schemes for the development of regional energy strategies.

The scientific developments can be used by federal and regional authorities and energy companies to implement innovative technologies in the energy sector for reliable and efficient energy supply to consumers.

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Infrastructure Risk-Oriented Advantages of Low-Power Nuclear Power Plants

Udyanskiy Yu. N., Shchepetina T. D.[*]

NRC "Kurchatov Institut", Moscow, Russia

Abstract. Variants of classification of risks of NPP design over the entire life cycle are proposed. The concept of integral risk is introduced and, on its basis, approaches to the creation of a low-risk nuclear power system based on small and medium power units are formulated. The key role of the human factor in the formation of risks is reflected. Comparison of the risks of NPPs of large and small capacity is carried out.

1 Introduction

Absolute safety cannot exist in principle. There is always some level of danger. The measure of the hazard level is the risk. There are many ways to assess it in various areas of human activity. Based on the many publications in the media, it can be concluded that, no matter how accurate the risk assessments are, they are not very convincing to the population.

If we begin to analyze the origin of the "risk" and then the reaction to its prevention, then involuntarily we are faced with a key point: "Human factor". It is believed that all adverse events are of an uncertain, random nature. From the point of view of the laws of nature, one cannot but agree with this. But where there is a person with his own free will in decision-making, there is soil for the "human factor" (HF) - and there will always be risk. And usually people look for ways to minimize it in one way or another. The research question, which the authors put before themselves, is the opposite: is it possible to find ways or methods of nuclear energy development, in which the HF, even being maximally "negatively implemented", will lead to the least adverse consequences.

Anthropogenic risk - the human factor - is not specific to the nuclear industry, but due to the possibility of a multiplying effect and the special danger of the industry as a whole, it deserves to pay attention to it and try to find any radical ways to neutralize it.

Man (personality), nature (environment), state (social society) are interconnected parts, subsystems of a single system, which are in synergistic interaction. The safety of any of these subsystems cannot be considered in isolation from the safety of other parts and outside the system as a whole, without taking into account such properties as the synergistic sum of the system. Sources of risks (hazards) are unevenly located in space and time and can synergistically interact with each other (domino effect).

To limit the danger and ensure the safety of project execution in the energy sector, all types of threats and risks in the preparation and implementation of projects should be taken into account and, if possible, minimized. At present, it is considered a generally accepted conclusion about the leading role of the human factor in ensuring the reliability of NPP operation. On this issue, scientists were divided into two categories: those who believe that all accidents, disasters, adverse events, etc. are of a random, stochastic nature, and those who see anthropogenic influence and the human factor to blame for all events.

2 Approach to nuclear power plant risk classification

There are many ways to classify risks and their sources (including in nuclear power). In this work, as a base, the analysis of risks by the stages of the NPP project life cycle is taken: strategic concept, research and development, development, design, construction, operation, decommissioning [1, 2].

Figures 1-5 shows one of the many possible ways of general classification of risks. It can be seen that there are groups of risks of a limited sphere of influence, there are "multi-group" (corruption, reputational) risks, but the "human factor" can become a source of trouble in all areas of the life cycle (LC) of the project.

If we accept the "human factor" as characterizing the quality of decision-making and execution, then although this phenomenon deserves a separate and comprehensive study, in this context it can be "rounded up" to a role in risk management in terms of the adequacy of competencies (experience and qualifications) at all stages of the life cycle of the project.

The following are approximate "risk maps" for all stages of the NPP project life cycle.

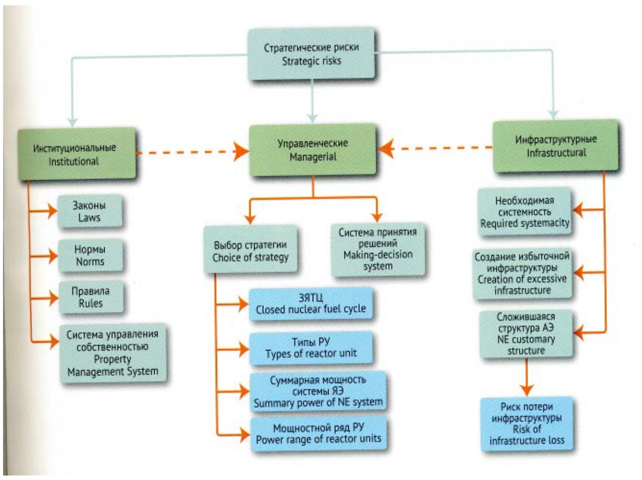

Fig. 1. Risks and their sources at the stage of strategic design

[*] Corresponding author: Schepetina_TD@nrcki.ru

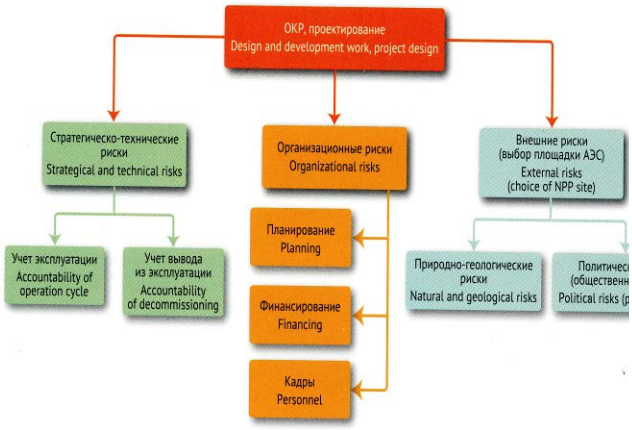

Fig. 2. Risks and their sources at the stages of research, development and design

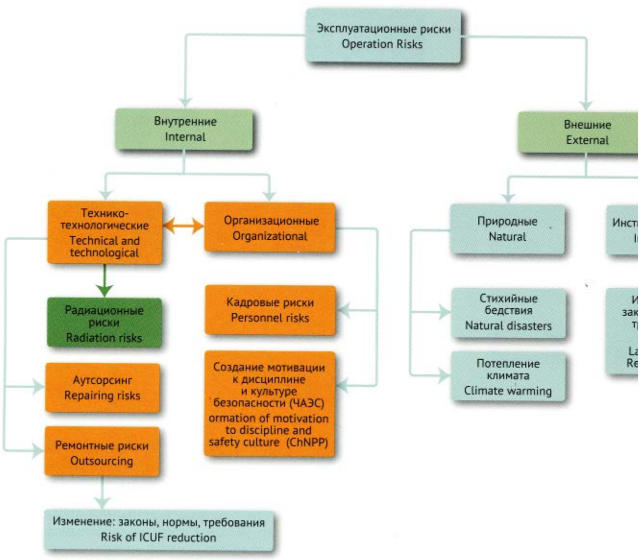

Fig. 3. Risks and their sources at the stage of power unit operation.

The presented options for the classification of risks are far from being complete and final, since, in fact, risks can be both simple and combining multidirectional effects. Simple risks are determined by a complete list of non-overlapping events, i.e. each of them is viewed as independent of the others. Complex risks, as a rule, have intergroup links according to sources of occurrence and consequences.

Only a small fraction of the risks discussed here can be considered “simple” in composition. For the most part, each "square" in the diagrams given in more detail will contain an equally complex nested structure.

As a result, it is possible to introduce the concept of integral risk of a nuclear power plant project, as the sum of the “spatial and temporal components” of risks accompanying the project from conception to liquidation (Fig. 6).

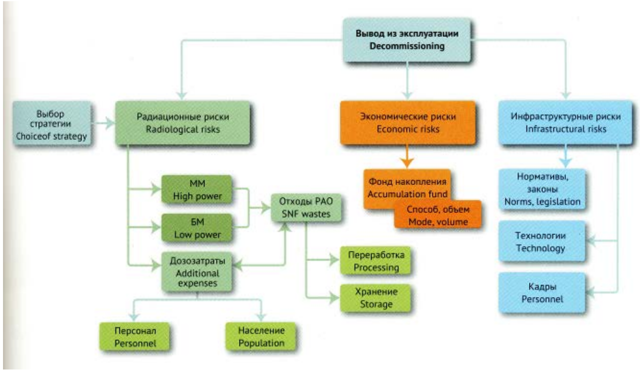

Fig. 4. Risks and their sources at the stage of decommissioning a power unit

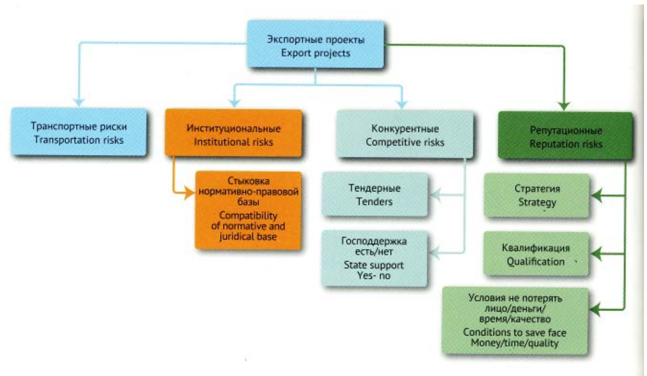

Fig. 5. Risks and their sources at the export

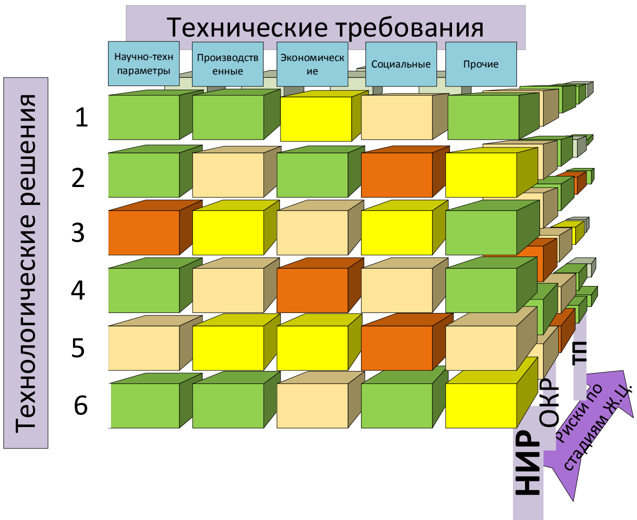

Fig. 6 Visualization of the integral risk of the NPP. Multidimensional risk matrix - Risk knowledge base.

Therefore, each group and subgroup of risks or their sources, indicated in the diagrams, and which are inherently complex, can be expanded / deciphered to the "elementary level" of simple risks. But this work will take a lot of time, knowledge of interdisciplinary technologies and connections, interdisciplinary definitions and interactions. And not all of them can be “digitized” or controllably minimized.

The need for classification stems from the fact that risks of different categories / hierarchies can only be managed from the appropriate levels. If at the stages of construction, operation, the "ancient method" - insurance is possible and appropriate, then at the level of developing a project or organization's strategy, it is already necessary to develop "directors' liability insurance" [3]. At present, mistakes can be avoided only by managing such risks in the categories of experience, collegiality, and a competent choice of goals when formulating strategic and systemic tasks, using systemic research and development.

3 Human factor and risk

But the most important thing is that in the overwhelming majority of the given “squares” the main source of risks can be considered the HF or its exposure. The essence of this influence of the HF lies in the need for human participation in decision-making, both key strategic and working tactical; in his possession at the same time a systematic approach (the ability to trace the connection "everything with everything", foresight); in psychological (un) stability against ambition and / or self-confidence, etc., etc.

For example, even possible “natural factors” and “climatic changes” can be foreseen when organizing security systems and diversifying technical water supply systems.

Regarding the Fukushima NPP: there was an earthquake, a tsunami, it would seem, what does the human factor have to do with it, where is its role in the accident or its consequences? The mistake was in the design solution for the placement of security systems (diesel generators). All this could have been foreseen and prevented, this, of course, is a human error.

A man with his decisions and actions found himself on the path of the natural disaster, but the human factor took part in this event much earlier. The greatest role of the Black Sea Fleet takes place at the very beginning of the life cycle of projects, at the level of making a strategic management decision, and it is not for nothing that the classification “Strategic risks” is put first. Miscalculation is also a human error. This means that at the time of the occurrence of an adverse event, accident, catastrophe, this notorious human factor was transferred through the previously adopted constructive and / or layout solutions.

A person is a connecting link in a technical system, but human nature has the right to make mistakes, since a person is not an automaton, and you cannot turn off emotions, temperament, different upbringing, preferences, environmental influences, etc. The influence of the human factor is inherent in all stages of the life cycle of a nuclear power plant and begins with an idea, when goals are set and arguments are made for their implementation in one way or another.

At the design stage, at the highest level of the life cycle stage hierarchy, there is a risk **of goal-setting error.** The damage from such mistakes is difficult to predict. From this level the largest consequences of the human factor arise. Therefore, it is much more “strategic” to identify the sources of risks and manage them (it is better to prevent them), rather than the risk itself or the developing risk situation.

Errors in regulatory documents can be ranked second in importance. It is known that the entire maritime code is written on the bones of sailors. There is a rule that says that there is no positive experience, all experience is based on mistakes. Everyone remembers that a fundamental revision of the US Nuclear Regulatory Commission (NRC) regulatory documents took place after the accident at the Three Mile Island nuclear power plant. The operator's mistake led to the curtailment of the US atomic program, and to the stagnation of nuclear power throughout the world. The entire approach to ensuring safety in nuclear power was reassessed, and probabilistic methods of safety assessment were introduced, including the human factor and common cause failures. How can you assess the degree of guilt of an American nuclear power plant operator, because he acted strictly according to the instructions? An operator error leads to an accident at one power unit or node, and an error in the regulatory documentation creates the preconditions for massive accidents. These are risks from the institutional environment as part of the infrastructure of the entire AE system.

In third place, you can put **errors in the formulation of the problem at the stage of product design and design.** Direct lobbying for types of installations without comprehensive expertise and comparative analyzes, taking into account consumer requirements, limiting innovative developments to the well-known formula “reference solutions”, which simply leads to stagnation of promising developments, belongs to the same type of errors.

Further, in terms of the degree of risk, there are **errors of designers and designers in implementation**, when all possible scenarios are not taken into account or the requirements of regulatory documents are violated. A typical example would be the accident at the Chernobyl nuclear power plant. Many would very much like to make the operator a "switchman", it cannot be considered a normal design that worsens the scenario of the process when the emergency protection button is pressed. It is impossible to shift problems and design flaws onto the operating personnel.

Only on March 29, 2013, the Japanese energy company Tokyo electric power (TEPCO) acknowledged its responsibility for the accident at the Fukushima-1 nuclear power plant. The company admitted that "due to human error, the nuclear power plant was not ready for a serious accident." "Among the mistakes made, in particular, is the incorrect location of the backup power supply systems, which almost immediately went out of order and made a nuclear crisis almost inevitable" [4]. Before that, they stubbornly nodded to the tsunami, forgetting that the analysis of the safety case must take into account all external factors.

Errors in the organization of design and construction work can be attributed to the same class of errors. Such errors include, first of all, the inability of managers due to low technical knowledge to identify key problems and challenges, errors in concentrating resources on insignificant research and ignoring urgently needed R&D, errors in developing criteria for competitive procedures, for example, the exaltation of economic criteria over quality indicators, organizational competence and experience, etc.

At the stage of construction and installation, the main HF is the failure to comply with the construction and installation technology and the violation of norms. Currently, such a risk of the human factor is associated with a lack of qualified personnel, constant violation of the work schedule, erroneous planning, irregularity of supplies, a complicated competitive procedure for concluding supply contracts, with the desire of managers to save on time, money, etc.

And finally, the **mistakes of the operating and maintenance personnel**, that "switchman" who is so fond of immediately identifying in the event of an emergency or equipment failure. The case of a generator rotor failure at one of our nuclear power plants is very eloquent: a small forgetfulness of a repairman with a plug in the oil system led to multi-million dollar losses and downtime of the power unit. But again the question arises, is a particular person really so guilty? Does the entire system not lead to such cases? Why was there no device in the design of the plug that made the next operation impossible without removing it; the usual "protection from the fool"? In aviation, similar techniques have long been used. But the designers or specialists of the service organization should think about this, and not the repairman who directly performs the work [5].

From all of the above, we can conclude that human errors are usually not limited to one level of organization structure, but affect the entire chain of organization/corporation structure (Fig. 7). I.e. error, originating in one link, manifests itself not in one link, but in a whole chain at the same time, otherwise it would be easy to prevent, localize and ultimately avoid.

So we need to look at the problem systematically, i.e. apply a Systematic approach, and try to **create a project that minimizes anthropogenic risks, or even insensitive to them.**

4 Ways to overcome the influence of the HF

It is possible to talk for a long time about using methods of psychology, psychiatry, philosophy, unmanned technologies to reduce the PF, but all of them will not give a deterministically stable result [6]. While there is one way that will allow not only to mitigate the risks associated with the HF, but to minimize other risks of nuclear energy, both based on natural physical laws and arising from the economic system.

There is nothing we can do about human nature, but we can change technical solutions.

A “perpendicular” approach to the problems of risk reduction from the Black Sea Fleet is proposed. We will not talk about automation and automation, which will not be reliable solutions (hopes for automation are futile, since there are effects of complicating systems, aging and wear of element materials, which are often of a threshold nature). The essence of the proposal is to switch to the introduction of small and medium-sized power units (NPP MSM) instead of units of large unit capacity.

Fig. 7 Distribution of causes of accidents at high-risk facilities

In this subsection, it is proposed to consider the possibilities of a "low-risk" approach to the design of large energy facilities - to construct on the site (or in the region) several units of modular nuclear power plants of low or medium power instead of one “large” unit of a nuclear power plant, but with the same total power indicators, thereby reducing the proportion of each possible adverse event at all stages of the life cycle of a separate project/power unit (during construction, operation and decommissioning of a nuclear power plant).

What this transition gives:

1) First, the “Hattori principle” comes into operation - reducing the unit capacity by a factor of 10, for example, from 1000 MW to 100 MW, **leads to an improvement in integral safety by a factor of 1000** [7];

2) The lower capital intensity of the AS MSM units makes it easier to find an investor (investing in "small portions", reducing financial risk);

3) the possibility of a phased commissioning of power units in phases with a stepwise increase in capacity as the installation and commissioning of a group of modules is completed, which makes it possible to reduce the payback period of investments due to earlier issuance of marketable products and the beginning of loan repayment in comparison with a power unit based on a reactor large unit capacity;

4) Allows the placement of modular NPPs of low and medium power in energy consumption centers, which eliminates the cost of constructing powerful power transmission lines;

5) The possibilities of applying insurance are expanding;

6) An efficient approach would be to use modular designs;

7) Seriality will reduce capital costs.

The modularity NPP of small and medium power implies the installation of an assembled reactor block already manufactured at the plant, or the entire NPP (module) at the site. In contrast to the usual practice, when a reactor, a power unit is completely assembled on the site, this approach provides the possibility of organizing large-scale (conveyor) production of reactor monoblocks (tens of units per year) and a stable load of machine-building plants, which significantly reduces manufacturing costs [8]. The ultimate in utility option will be the project of "atomic battery" - a ready-made mini-NPP.

Due to the fact that several blocks of modular plants can be built simultaneously and put into operation as soon as they are ready, in a shorter time frame than large NPPs, it should be concluded that the risk of cost increases from an increase in the construction period of NPPs is reduced. First, the design features of modular nuclear power plants of low and medium power, assembled at the factory, allow the installation of the reactor plant on the site already ready for operation, which reduces the time for construction, transportation and commissioning of nuclear power plants, in contrast to high power nuclear power plants mounted directly on the site. We bypass such risks as the risks of interruptions in the supply of electricity, first of all, because (n-1) blocks / modules remain in operation if there is any emergency stop of one module or fuel overload.

In particular, Rod Adams (USA), actively promoting the idea of switching a small reactor in large power systems, argues that low-power NPPs will reduce capital costs, contrary to the popular belief that the installed kilowatt will become cheaper with an increase in the capacity of a single unit. The fact is that many small reactors will be produced, and this, willy-nilly, will require serial production of equipment and components. For the large nuclear power industry, all attempts to talk about serial production invariably ended in failure. For the United States, the option of using IMS NPPs in large centralized power systems [9] is considered as an alternative to units of large unit capacity, combining the advantages of reducing both economic and nuclear-radiation risks.

5 Economic aspects of the transition to small nuclear power plants

Conceptually, the ECONOMIC EFFICIENCY of NPPs with SMR is relatively easy to justify. Rather, it is quite easy to prove that with an equal total power of AE systems with SMR and NPP of large power, the SMR system can have clear advantages of flexibility and safety. But the realization of these advantages will require serious work and serious financial, resource and intellectual investments, which are possible only with the use of the experience of developing NPP of large power, as well as nuclear power plants for space, aviation and the navy.

At present, when choosing a project, comparing and considering different alternatives, first of all, they pay attention to either overnight costs, or to specific capital costs, which is not always strategically expedient from the standpoint of a systematic approach and the life cycle of the NPP. Savings at the moment do not always translate into overall savings. The costs should be calculated for the entire life cycle of the project up to its decommissioning. Also, sometimes, the concentration of "savings" on specific capital costs leads to the "savings" of the profit itself. Simply put, if you invested less, you got less. This may be due to an increase in the payback period due to interruptions in the operation of the plant itself, the so-called operational reliability.

The proposed way of introducing NPP of small and medium power can be briefly described as follows: “now more money will be required, but then the risks will be less”.

The lack of methods for quantitative assessment of the total risk, a systematic approach to them and the "division of labor" (construction and operation) does not currently allow "in conditions of economic pressure" to appreciate and accept this path.

In economics, this method of mitigating key risks in NPP projects is called power hedging, power hedge dispersal. This is a kind of “power insurance” method.

It should be emphasized that the principle of "capacity insurance" applied to NPP construction projects can achieve certain advantages in terms of mitigating many risks. Comparatively, they can be presented in the form of table 1.

In everyday life and business practice, we are accustomed to insurance: car, travel, health, space satellites, freight traffic, etc. We are confident that "by paying more now, there will be fewer problems in the future." But in nuclear power projects, we are so far deliberately taking “capacity risk” for the sake of momentary “economic benefits”, without thinking about further possible and guaranteed problems (for example, decommissioning high-power units, the costs of which are estimated to be comparable to their creation), which will be solved by our descendants (after 50-60-80 years of operation). From an ethical standpoint, this approach does not deserve a positive assessment.

In addition, it should be borne in mind that power gigantism in fire energy has not become widespread - the Kostromskaya GRES (with a unit capacity of a 1200 MW) has remained the only one of its kind; the maximum spectrum of power units lies in the range of 100 - 300 MWe.

In conclusion: the automotive theme is clear to everyone; for illustration, let's imagine, regarding the problem of the power line of power units, that the automotive industry produces only KAMAZes and buses.

The sustainability of natural systems is based on species diversity; nuclear energy as a System is no exception. The declaration at the state level of the transition to "nature-like technologies" obliges the atomic energy community to seriously look at the ethical, economic and socio-humanitarian consequences of its activities.

Conclusion

The risks in nuclear power are very aggravating; the probability of a major catastrophe is very small, but it has a huge economic and social resonance, after which the system sometimes stops developing. Few people realize that in everyday life much more people die (in particular, on the roads) than once in a major disaster, but unfortunately, such subtleties of psychology have to be reckoned with, especially if further development is needed. Changing the psychology of people is much more difficult and labor-intensive many times over than adapting to it.

Table 1 Comparison of the most important risks of NPPs of large and small/medium power

Risks and challenges	NPP unit 1000 MW	Modular NPP of small and medium power
the risk of increased costs from an increase the construction period	big enough	due to its small size and assembly in the factory, it is reduced
find an investor; his risk	only large companies; at least 5-6 billion dollars	expansion of the circle of investors, risks are several times less
relative specific capital costs	1	1,2 – 2,0
risks of electricity supply interruptions	the risk is present, the damage is great	the risk is present, but the damage is reduced several times, depending on the number of modules
use for technological purposes	not applicable soon	wide possibilities of approaching settlements and industries
minimum power reserve in the power system	equal to unit power (1000 MW)	equal to unit power (100 ~ 300 ~ 500 MW)
risks associated with nuclear and radiation safety	estimated by probabilistic methods	deterministically, the probability of risks also decreases, and the magnitude of the damage itself decreases
risks at the stage of decommissionin g	large volume of dismantling, high dose of radiation	large-scale dismantling; the likelihood of risks decreases and the amount of exposure decreases
export risks	the market is relatively small, the competition is high	the emergence of new market niches and competitive advantages
possibility of civil liability insurance	not in full, almost impossible	insurance is possible under many programs
availability of placement sites	limited	within the framework of regional energy, almost everywhere
reuse of the industrial site	almost impossible	possible
social acceptability	psychological barriers (especially after the Chernobyl and Fukushima accidents)	Possibility of visual evidence of increased safety of NPP of small and medium power

And since nuclear energy is one of the few energy sources that will occupy an important place in the future, it is necessary to move on to the next stage of development - one step closer along the path to “risk-free nuclear power”.

It is proposed to use the method of power insurance of risks at the strategic level by switching to splitting high power units into small or medium power units. Shows its qualitative technical and economic effect; In many cases, the construction of large power units from the standpoint of risk management and economic efficiency will be irrational due to the nominally long construction and due to the huge risk of an increase in the construction period of nuclear power plant units of large unit capacity, which leads to large additional cash costs and a decrease in the flexibility of power systems. The transition to blocks of low or medium capacity will also remove many other risks described in the work.

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FEATURES OF CRITICAL FACILITIES DETERMINING FOR THE FUEL AND ENERGY COMPLEX IN RESEARCH OF FUEL AND ENERGY SUPPLY

Beresneva N.M.,[*] , *Pyatkova N.I.*

Melentiev Energy Systems Institute (ESI) SB RAS, Irkutsk, Russia

Abstract. The article reveals the features of selecting critical facilities for the fuel and energy complex (FEC CF) within joint industry and general energy model research. A comparative assessment of the methodology for determining the list of critical industry objects and the methodology for determining the list of FEC CF is given in this paper. A scheme for the preparation and analysis of the fuel and energy complex calculated states is described, the analyzed most important and related model indicators are highlighted, an integral indicator for assessing the criticality of elements is proposed. Also is provided a formalized description of the fuel and energy functioning optimization model and reveals a three-stage scheme for working with it in determining in the CF of FEC based on industry critical elements.

Introduction

The task of critical facilities(CF) identifying for the fuel and energy complex (FEC) his-torically appeared as a evolvement of the identifying industry critical elements task. The relevance of this task was justified by the need to assess these elements criticality degree in the conditions of energy systems joint functioning , taking into account reservation and the interchangeability of resources. The both problems solution was based on the use of a model and instrumental apparatus reflecting the technological and territorial structure of the research objects (sectoral systems and fuel and energy complex). Moreover, the task of the CF finding for the fuel and energy complex gave the evolvement of the FEC functioning model for in terms of detailing sectoral schemes (namely the gas industry, as it is for this system the methodology for determining industry critical elements was previously developed and tested) and in terms of modeling the reserve capabilities in electrical - and heat power sys-tem at the technological level of their presentation in the model. At the methodological level the ideas of assessing the vulnerability of critical infrastructures' elements [1-2], to which relate the fuel and en-ergy complex and its sectoral systems [3], were used and developed, and schemes for identifying critical elements of the gas industry [4-5].

Features of the choice of CF for FEC

The methodology for determining the CFP for the fuel and energy complex is based on scheme of stage-by-stage multilevel model studies (fig. 1). This fact made it possible to assert that:

– the significance of the same critical element for the industry and for the fuel and energy complex may be different, since when determining the CF of the fuel and energy complex, the systemic effect of interaction between energy industries is taken into account;
– the list of sectoral critical elements can be considered as potential CF of the fuel and energy complex, can be used to set calculated conditions in model studies of the fuel and energy complex;
– the list of the CF for the fuel and energy complex may not correspond to the list of sectoral critical elements, it will include sectoral elements that are really critical in the conditions of the interconnected work of the industries.

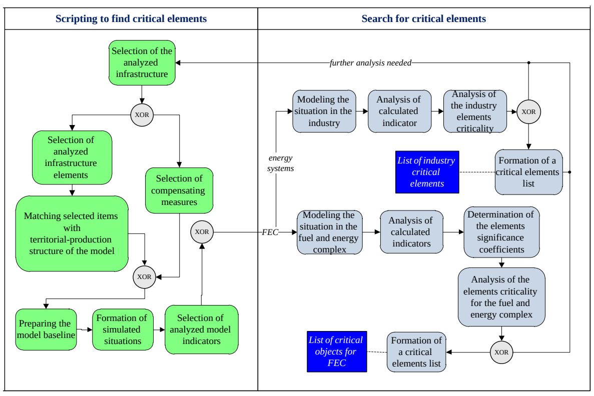

Fig. 1 Scheme for the selection of CF for the fuel and energy complex based on industry critical elements.

This methodology is similar to the methodology for selecting industry critical elements in terms of the formation and assessment of hypothetical calculated states, in terms of using for these purposes the relative deficits of energy resources in various territories,

[*] Corresponding author: beresneva@isem.irk.ru

followed by obtaining quantitative and expert assessments of the criticality these elements. The systemic-functional complexity of the fuel and energy complex is expressed in the presence of energy resources multitude, the processes of their processing and transformation, in the possibility of their interchangeability at electric power system and heat power. This requires taking into account the resulting deficits for all resources using the possibilities of structural redundancy. Comparative analysis of methods for determining critical elements at the sectoral and general energy levels showed the following results.

1. Both methods are focused on the analysis of calculated states formed for the scenarios of analyzed elements outages. Thus, the inoperability consequences of these elements are assessed. When determining sectoral critical elements, it is also possible to assess the consequences of these elements inoperability when compensating measures are introduced. This mechanism [4] is used to adjust the list of sectoral critical elements, allows to exclude elements whose inoperability can be largely compensated for by connecting the reserve capabilities of the industry.
2. Both methods involve model calculations with a different number of simultaneously disconnected elements (in set theory, the size of a set is called its cardinality). When determining the sectoral critical elements, the calculations are analyzed separately for single or multiple disconnections of elements [4]. The methodology for determining the CF for the fuel and energy complex provides for the possibility of joint analysis of calculations with disconnections of groups of elements of different power.
3. Both methods include the idea of assessing the criticality of elements from the standpoint of changing the degree of energy supply to consumers. Therefore, the analysis in both cases involves the relative deficits of energy resources by territories, or by each sectoral system as a whole. In the fuel and energy complex model, which includes more than one industry, this assessment has complex, taking into account the total relative deficits of various energy resources for different categories of users. It also foreseen an assessment of the importance of the analyzed model indicators.
4. A large number of analyzed states required the elimination of states with an acceptable level of energy deficit in the system as a whole. In the case of general energy studies, this provision applies to each sectoral system. The level of permissible relative deficits is established by experts.

Fuel and energy complex research models for analyzing the reliability of fuel and energy supply

Complex scenario calculations in determining the fuel and energy complex CF are carried out on the basis of fuel and energy complex functioning models. These models include the main branch blocks that simulate the interconnected work of branch objects in varying degrees of territorial and technological detail. In the temporal aspect, they are focused on the daily aspect, since at longer time intervals, the consequences of a failure in the operation of industry facilities for the fuel and energy complex as a whole can be leveled. Research models are represented by a triplet *M(Z,S,I)*, where $Z=\{z_t\}$, $t = \overline{1,T}$ - scenarios corresponding to hypothetical states of the fuel and energy complex; *S* - territorial-production structure of the fuel and energy complex and its branch systems; *I* - information base of the model.

The structure of the research model is represented by a set *S(RES,REG,OBJ)*, where $RES=\{RES_i\}$, $i = \overline{1,I}$ - energy resources adopted in the model, $REG=\{reg_w\}$, $w = \overline{1,W}$ - territorial units of the model, $OBJ(OBJ^{tech},OBJ^{ec})$ - objects of the model corresponding to energy or to economic-organizational structures of FEC. In each such object, set of processes $\{p_n\}$ are implemented:

$OBJ_v=\{p_n\}$,

$v = \overline{1,V}$, $n = \overline{1,N}$, where

v - object index,

N - the number of processes implemented in the object.

The processes themselves are represented by a multitude

$P=\{p_q\}$, $q = \overline{1,Q}$, including technologies such as:

– resources extraction (or production);
– resources processing and transformation;
– resources diversification;
– resources storage;
– resources transportation;
– resource consumption.

The objects of the model are tied to its territorial units and are part of the industry systems included in the fuel and energy complex:

$FEC=\{ES_f\}$, $f = \overline{1,F}$

$ES_f=\{Obj_g\}$, $g = \overline{1,G}$, where

FEC - fuel and energy complex of the country,

ES_f - industry system (*F* - number of sectors),

Obj_g - set objects of the industry system *f*.

The information base of the model *I(DI,DR)* is represented by the initial *DI* and calculated *DR* information. Initial information $DI(I^{inp}.I^{rat})$ includes subject I^{inp} (statistical, regulatory-reference) and prepared for calculation (converted subject) I^{rat} model data, where

$I^{inp} = \{i_j^{inp}\}$, $j = \overline{1,J}$ - elements of initial information,

$I^{rat} = \{i_k^{rat}\}$, $k = \overline{1,K}$ - model elements (its variables, coefficients),

$F = \left\{F_k^j : i_j^{inp} \rightarrow i_k^{rat}\right\}$ - algorithms for preparing model data based on subject information.

Calculated information $R = \{i_l^{opt}\}$, $l = \overline{1,L}$ (L is the number of model variables) - the result of transforming model information $\{i_l^{rat}\}$ by an external solver. In the course of analysis, calculated information can be aggregated by groups of territorial units.

Technically, work with the fuel and energy complex models is represented by the processes of preparation and verification of data, procedures for the formation, calculation and analysis of various options for the fuel and energy complex functioning. The starting point of research is the annual balanced variant of the model, on the basis of which daily variant are subsequently formed (the variant of the most loaded day, variants for disconnecting fuel and energy facilities). Such a chain of work is founded by the composition and level of presentation of statistical and analytical industry information, the relative ease of balancing annual indicators Corrective coefficients used to obtain daily variants are formed expertly based on the specifics of the analyzed situations, or are calculated in the presence of monthly industry reports.

Thus, the scheme of work with the fuel and energy complex model is conceptually represented by three stages:

– the stage of debugging a balanced annual variant;

– the stage of debugging the option of functioning of the fuel and energy complex in the most loaded day;

– the stage of calculating and analyzing options for the inoperability of objects in the most loaded day.

At the stage of debugging the annual model variant , massive transformations of subject information are performed in order to obtain the target characteristics of the objects functioning. Produced here:

1. Debugging of the power and heat power unit, including the preparation of data for stations (or their groups) and boiler houses (or their groups), including:

– transformation and verification of data on fuel consumption at the industry facilities (reduction to a single scale of measurement for the same coefficients for each resource);

– determination of the technological characteristics of the functioning of heat and power generating sources (volumes of heat and electricity supplied by them for certain types of fuel, specific fuel consumption);

– control over the correspondence of the supply of converted resources and fuel consumption inside the stations and boiler houses;

– control of the heat and electricity balance of throughout the country.

2. Debugging the fuel supply unit, including:

– determination of the obligatory need for fuel by territories, if necessary, with a breakdown of the obligatory need by separate categories (for example, for the needs of the population and industry);

– data correction in case of imbalance in fuel consumption in the territories;

– analysis of the transport capacity infrastructure in the fuel industries.

3. Balance sheet estimate for all energy resources excluding their reserves.

4. Carrying out optimization calculations that determine:

– "locked" energy resources and determining the causes of their occurrence;

– fuel shortages in the territories associated with the technological of the shortage energy transport infrastructure, or with an imbalance of their own production capabilities and needs in the event of an isolated territory;

– shortages of final types of energy resources, the reasons for their occurrence;

– the level of capacity utilization of production facilities in the fuel and energy complex.

At the stage of debugging the variant of the most loaded day, the coefficients of seasonal unevenness are determined, also the reserve capabilities of industries to cover additional needs for energy resources. At this stage, the following are carried out:

1. In the block of electric and heat power engineering

– correction the production capabilities of stations and boiler houses in the basic mode of their operation;

– determination of reserve equipment capabilities at thermal power plants and boiler houses;

– correction the demand for electricity and heat;

– verification of cost coefficients.

2. In the fuel supply unit:

– determination of the fuel industries reserves;

– correction of obligatory fuel need.

3. Debugging of the option, during which discrepancies are analyzed and eliminated in terms of fuel supply to consumers, its extraction from storage facilities, priority of fuel use in electric and heat power engineering.

At the stage of analyzing the consequences from outages of critical facilities, the relative changes in the analyzed indicators are determined for individual territories or their groups. This information is used to determine the CF for FEC.

Method for determining of FEC critical facilities

The method for determining the sectoral energy facilities criticality for territories in conditions of sectoral systems interconnected operation meets the following basic provisions:

1. The problem is solved within the framework of multivariate and multilevel computational experiments based on the fuel and energy complex models and its industries. A key feature of these experiments is the multiple use of the same data for different levels models. It is allowed to use the same information at different levels in a transformed form.

2. The task assumes specifying a list of industry critical objects, from which the fuel and energy complex critical facilities are selected. Scenarios of inoperability of industry elements are simulated in computational experiments.

3. The solution of the problem assumes a three-stage scheme for transforming the results of computational experiments, including obtaining quantitative, qualitative and expert assessments of the elements criticality. Qualitative and expert assessments are formed on the basis of quantitative ones. Qualitative assessments (categories of elements criticality) make it possible to single out groups of sectoral elements that are problematic to varying degrees for the fuel and energy complex as a whole. The main criterion is the integral criterion of the elements significance, which comprehensively characterizes the changes in the

analyzed indicators in the event of industry elements inoperability.

4. The analyzed model indicators in relation to the task are systematized into two categories. The category of the most important indicators is formed by energy resource deficits, which are a system characteristic of the functioning of industries. The category of related indicators is represented by technologies for meeting the needs of the territories (reserves and reserves, the possibility of interchangeability of energy resources in technological processes). A correct analysis of the elements criticality requires consideration of both types of indicators.

The criterion for the significance of each element is determined for the entire set of calculate states with various combinations of its shutdowns:

$$ZO_i = \sum_{j=1}^{J}\left[\sum_{k=1}^{K} ZO_i^{j,k} \times ZC^j\right] , \qquad (1)$$

$$ZO_i^{j,k} = {ZS_r^{j,k}}/{R} , \qquad (2)$$

where

ZO_i - the significance of the i^{th} fuel and energy complex element,

$ZO_i^{j,k}$ - the significance of the i^{th} element by the j^{th} indicator in calculations with capacity outages groups k,

$ZS_r^{j,k}$ - assessments of states for the j^{th} indicator in calculations with the inclusion of the i^{th} element in the capacity outage groups k,

R - the number of states estimated by the j^{th} indicator with the inclusion of the i^{th} element in the capacity outage groups k,

ZC^j - the significance (specific weight) of the j^{th} indicator,

K - maximum capacity of outage groups in optimization calculations,

J - the number of analyzed indicators,

I - a disconnected elements set of the fuel and energy complex, $i \in I$.

Formalization of the identification of the criticality category of elements (the first category is considered the most critical) can be represented as follows:

$$CAT_i^w = f(ZO_i^w, N) , \qquad (3)$$

$$N = \{n_l\} , l = \overline{1, L} ,$$

$$n_l = \{n_l^{low}, n_l^{up}\} , l = \overline{1, L} ,$$

$$CAT_l^w = \begin{cases} l, \left(ZO_i^{max} \times n_l^{low}\right) \le ZO_i^w \le \left(ZO_i^{max} \times n_l^{up}\right) \\ 1 , \ ZO_i^w \ge \left(ZO_i^{max} \times n_l^{low}\right), l = 1 \end{cases} ,$$

$$ZO_i^{max} = max(ZO_i^w) , w = \overline{1, W} \qquad (5)$$

where

CAT_i^w -the category of criticality for the i^{th} element for the territory w,

ZO_i^w - the coefficient of significance for the i^{th} element for the territory w,

ZO_i^{max} - the maximum value of significance for the i^{th} element for all considered territories,

N - a set of specified criticality categories n_l (L - the number of specified categories of elements criticality),

n_l^{low}, n_l^{up} - the lower and upper boundaries of the criticality category l,

I – a set of disconnected elements of the fuel and energy complex,

W - the number of considered territorial units.

Technically, the problem of determining the CF for the fuel and energy complex (fig. 2) is represented by the processes of data transformation and control during computational experiments, during the analysis of the calculated model indicators, and analysis of the industry elements criticality. The initial information of the task is represented by target settings (maximum power of outage groups, a list of analyzed industry elements and analyzed model indicators, indicators for a qualitative assessment) and a basic daily version of the model, the disturbed variant of which are calculated during of the experiments. The resulting information is quantitative, qualitative and expert assessments, on the basis of which the list of the FEC critical facilities is formed.

Formally, the method for determining the critical facilities for the fuel and energy complex is presented in three stages:

– stage of the strategy formation for choosing the fuel and energy complex critical facilities;

– stage of optimization calculations;

– the stage of forming the list of the fuel and energy complex critical facilities.

At the first stage:

– the objects of the modeled the fuel and energy complex structure are formed;

– groups of industry elements outage are formed for their inclusion in simulated situations;

– a set of criteria for assessing states (the most important and accompanying model indicators) is formed, the significance of these criteria is determined;

– the categories of elements criticality and their threshold values are determined.

At the second stage, optimization calculations of the fuel and energy complex model are carried out, within the framework of which emergency situations with failure of industry elements groups are calculated.

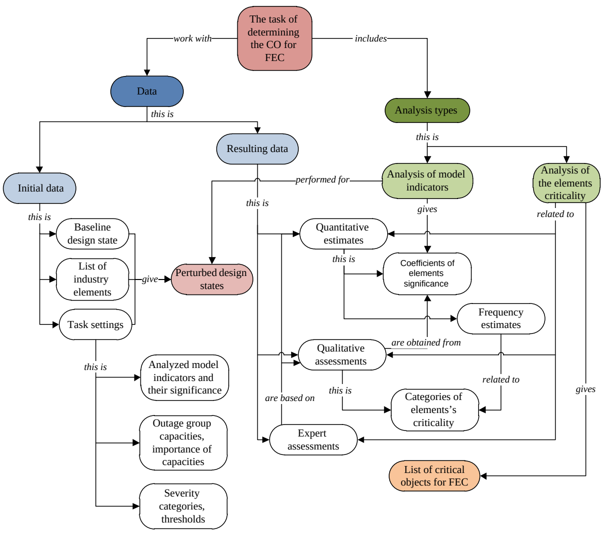

Fig. 2. Conceptual scheme for solving the problem of determining the CF for the fuel and energy complex.

At the third stage, estimates of the disconnected industry elements criticality are formed with the formation of the fuel and energy complex critical facilities list:

– the composition of the analyzed calculated states is adjusted by excluding states with a relative deficit of at least one resource that is acceptable for the country as a whole (at this stage, a 5% threshold for assessing the deficit is adopted);

– criteria for the elements significance for the territories under consideration or their groups are determined;

– the categories of criticality for the analyzed elements are determined;

– a list of the fuel and energy complex critical facilities is formed.

The algorithm of the forming the fuel and energy complex CF list is shown in fig. 3.

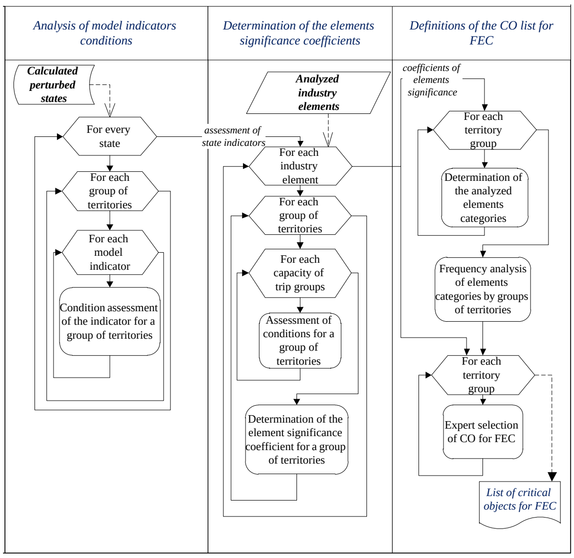

Fig. 3. Algorithm for the formation of the fuel and energy complex critical facilities list.

The presented method has been twice tested on fuel and energy complex models using the example of critical facilities shutdowns in the gas industry. According to the results of the first test approbation, the efficiency and effectiveness of the developed method were proved, some of its key points were adapted [7]. The current approbation of the method was carried out on a more flexible and more adequate version of the model, taking into account the reserve supply of electricity and heat from the electric and heat power stations. The analysis of these results was aimed at:

– identifying disagreements in the priority of the gas industry critical objects and the fuel and energy complex objects;

– assessment of the plausibility of the method, taking into account the influence of the fuel and energy complex systemic effect.

Conclusion

The paper presents the continuity of the method for choosing the fuel and energy complex critical facilities. A general scheme for the selection of the fuel and energy complex critical facilities on the basis of industry critical elements has been developed and formalized. A comparative characteristic of the sectoral (on the example of the gas industry) method for the selection of critical elements and the method for the formation of the critical facilities list in the fuel and energy complex taking into account the systemic effect is given.

The article formalizes the territorial-production model of the fuel and energy complex, which use to determine the fuel and energy complex critical facilities, describes the implemented three-stage scheme of working with it. The developed method for determining the fuel and energy complex critical facilities in the conditions of the interconnected operation of industry systems is presented. For the selection of the fuel and energy complex critical facilities the most important and accompanying model indicators are highlighted, an integral indicator of the industry elements criticality is proposed.

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Impact of the regulatory reserve and capacity demand on the process of justification of the generating sources in respect of the UES Russia management development

Chukreev Yu. Ya, Chukreev M. Yu.*

Institute for Socio-Economic & Energy Problems of the North Federal Research Center of the Komi Science Centre of the Ural Branch of the Russian Academy of Sciences, Syktyvkar, Russia

Abstract. An analysis is made of the regulatory documents used to justify the capacity demand and one of its components - the normative capacity reserve. The methodological principles for considering energy availability at hydroelectric power stations from the standpoint of justification of reserve funds are justified. For the price zones of the UES Russia, retrospective information on the forecast values of maximum loads and power generation at hydroelectric power stations has been compared with their actual values. The article gives the practical results of influence of the identified regulatory documents inconsistencies and deviations of the maximum load forecasts and hydroelectric power generation from the actual power demand values and the justification of the generating sources to cover it under a competitive power selection procedure.

1 Background of the problem

The justification of the generating sources in development management the of the electric power industry and the UES Russia in particular depends, in one way or another, on the values of the planned power consumption and the maximum loads. The latter are known to be formed in the planned for perspective power and electricity balances (fig. 1). This information is in accordance with the decision of the Government of the Russian Federation[471] since 2010 is annually formed in the work «Scheme and program of development of the UES of the country for the 7-years period» (SPD), carried out by JSC «SO UES» and Federal Grid Company.

In a power balance, as in any balance sheet, there are revenue and expenditure sides. The expenditure side of the balance is determined by the demand for capacity and consists of three components: projected maximum load, export/import capacity and the capacity reserve. The incoming part of the balance shall be determined by the installed capacity of the generators of the power plants minus various power constraints on the maximum load, the power inputs after the passing thereof, the power output not released (latched) power. In a balanced variant, the coverage of the demand of the incoming part shall correspond to the demand for the power consumption in the expenditure part of the power capacity balance. The current state of the industry is characterized by the significant excess capacity and corresponds to the picture in Fig. 1. In fact, this explains the strong focus on determination of the capacity demand. Its value determines the justification of the generating sources involved in meeting the demand in managing development of the Russian UES for a period of up to seven years in the market procedure of a competitive power selection (CPS).

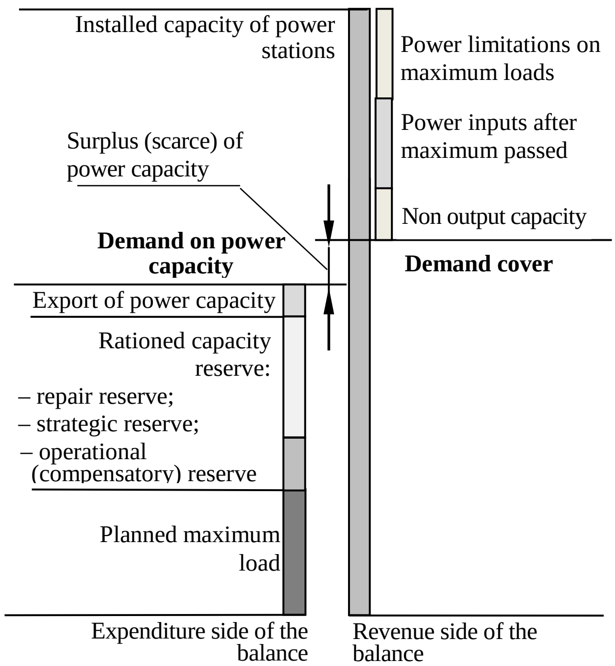

Fig. 1. Structure of the projected power balance.

The planned maximum load for each calendar year of the seven-year period is calculated based on the forecast of capacity consumption in the territories of the constituent

[1] The Rules for Development and Approval of schemes and programs for the Future Development of Electric Power Industry, approved by the Decision of the Government of the RF dated on 17.10.2009 № 823.

* Corresponding author: iespn@.ksc.komisc.; iespn@mail.komisc.ru

entities of the Russian Federation for the conditions of the average multi-year ambient air temperatures of the territories under consideration, for the month of December. Standard (full) capacity reserve includes operational (recently called compensatory), repair and strategic capacity reserves. The operational reserve capacity is a subject to many factors, including the incidental factors. Its justification is based on the task of estimating balance reliability indicators (BRI) for the calculation scheme of the UES of the Russian Federation with its territorial zones of reliability [1-4]. These were in the pre-perestroika period United Electric Power Systems (UPS). Recently, there has been a tendency to apply more detailed calculation schemes of the Russian UES by splitting UES into the territorial zones (from 42 to 56 zones). In our view, due to the complexity of the information content, fragmentation is appropriate in order to solve the task of assessing the BRI development options of the UES Russia. The studies show that such fragmentation is inefficient in terms of both reliability and computational efficiency to justify the operational component of the normative power capacity reserve.

During the pre-perestroika period, the percentage values of the normative power capacity reserve from the maximum load in UPS of UES Russia were given in the methodological recommendations (MR) on the power systems development projecting. The latest edition was made in the mid-1990s [5]. The Ministry of Energy of the Russian Federation approved them only in 2003. The current state of the electric power industry has undergone significant changes that require updating. It was launched in 2011, almost immediately after the start of the annual work of SPD of the UES. JSC «SO UES» ordered by JSC «INSTITUTE OF ENERGOSET'PROEKT» with the involvement of the research institutions, the new edition of the MR was carried out taking into account the changed conditions[2]. On the initiative of the contracting authority of the work in this revision, the values of the normative reserve of capacity were substantially inflated from 17 to 20.5% for the UES Russia and from 12 to 22% for the UPS of Siberia. The increase was primarily in the component of the capacity reserve for providing the routine equipment repairs. For example, in relation to the 2003 edition of the MR, there has been a two-fold increase in the repair component in the European part of the UES (from 4-5% to 9-10%), in the UPS of Siberia even to the three-fold component (from 4% to 12%). The rationale for this increase is known and is dealing with the need to attract investors to meet the obligations of the generating companies to bring in new capacity under condition of the guaranteed payment. The increase in the statutory reserve of capacity and therefore in the demand for capacity certainly contributes to this.

The explanation of this fact is quite simple. With the launch of the market in 2006, the capacity of the normative length and periodicity of repairs, as well as the prospective five-year plans for the repair of the major plant equipment at the power electric stations have lost their regulatory role. The regime-and-balance situation (the sharp decline of electricity consumption), financial possibilities and rules for the wholesale market for electric energy (capacity) allowed energy companies to carry out repairs also in the autumn-winter period. Statistical information on their conduct has changed. While planning of the sectoral development, the December day component of scheduled repairs was included in the value of the standard capacity reserve. Ministry of Energy of the Russian Federation did not approve the MR 2012 in that version.

Early in the year of 2018, Ministry of Energy of the Russian Federation again initiated the work on the procedure for determining the normative reserve of the power capacity. Melentiev Energy Systems Institute SB of the RAS and ISE&EPS FRC Komi SC UB of the RAS participated in the implementation of this work initiated by JSC « NP Market Council ». In the beginning of 2019 the ISE&EPS FRC Komi SC UB of the RAS was suspended for the unknown reasons. Although the completion of the work was foreseen at the end of 2018, the work carried out by Melentiev Energy Systems Institute SB of the RAS has not been completed until the present day.

2 Analysis of the legislation and regulations to justificate the capacity demand

The challenge of justifying the generating sources contributing in covering the power demand (Fig. 1) should now be studied in a completely different way, more in relation to the dismantling than to the introduction of the new generating equipment. In the context of the market relations, justification for introduction of the new generating equipment in the UES Russia is carried out in order to solve the tasks of the power contracts, justification of capacity participating in the demand cover, the status of the forced generation and dismantling of obsolete and obsolete equipment as a result of the competitive bidding in a closed competitive auction.

Implementation of the changed conditions required development in 2010 «Regulations on the procedure for determining the amount of demand for power…» approved by the Ministry of Energy of Russia[3] (thereinafter Order № 431). In accordance with para. 3.1 of this Regulation, the planning coefficient of power reserve of capacity is calculated by JSC «SO UES» for the free power transfer zone(s) (groups of zones), as the sum of the value that equals 1.17, coefficient of the power underutilization factor and the coefficient taking into account electrical energy export. The demand for the power capacity at that is determined by multiplying this coefficient by the predicted combined maximum consumption, taking into account the effect of the temperature factor. This paragraph is in the substantial contradiction with the MR 2003.

[2] Methodological recommendations on the project development of power systems / OJSC «Institute « Energoset'proekt», 2012 (approved by NP «NTS UES», section «Technical regulation in electric power industry» in July 2012.

[3] Regulation on the procedure for determining the demand for capacity for long-term competitive power selection in the wholesale market of electric energy (capacity) and the procedure for determining the planning coefficients for reserving capacity in zones (groups of zones) free flow of electrical energy (power capacity), approved by the Order of the Ministry of Energy of Russia of 07.09.2010.№ 431 (edition on 17.08.2017).

The coefficient 1.17 corresponds to 17% of the full reserve of capacity from the maximum load given in the MR 2003 for the European part of the UES Russia. For UPS of Siberia this percentage in the regulation is only 12%. In the Order №431, the coefficient of 1.17 has been extended to the UES of Russia as a whole for unexplained reasons. The power capacity underutilization coefficient, which is a part of the planned reserve factor, in accordance with the Order №431, para.3.2, takes into account the actual power reduction resulting from the unscheduled repairs of the generating equipment. It is determined by the ratio of the average monthly power capacity reduction from the values specified in the notifications submitted under the Rules of the Wholesale Market for the selection of the equipment composition in the winter months of two years prior to the date of the long-term CPS, to the projected maximum consumption volume. The occasional underutilization of capacity caused by the same causes, and precisely for the month of December, is taken into account and is, moreover, the main reason for the operational reserve component of the standard (full) capacity reserve (coefficient 1.17) received in the MR 2003. There is a double counting of the same random parameter.

The temperature factor is taken into account in the Order №431 by multiplying the projected maximum load by the temperature coefficient over the territorial areas of the UES Russia. This leads to an increase in demand by more than 4%. The same factor, which is generally random, is taken into account in the balance sheet support models by introducing a predictive error parameter [1-3]. Described in the MR 2003 percentage of the full power capacity reserve (17% of the maximum load) are received taking in account that factor. If not considered, this percentage would fall to 12-14% [2]. It can be stated that here again there is a double counting of the same randomly conditioned parameter. Unfortunately, the specialists who prepared the Order №431 did not involve in its preparation and expertise scientists of the academic and university science, as well as the sectoral Institutions, who are in charge of ensuring the balance reliability of the EPS.

Another important point related to the adopted values of the planned calculated reserve ratio is given in the Paragraph 107 of the Rules of the Wholesale Market[4] (hereinafter GD RF №1172). It increased its value for the second price zone of the wholesale market by 8.55%. The rationale for this increase remains a mystery for many energy professionals. It is understood that under the conditions of available excess capacity, the most efficient of existing plant assemblies should be selected when justifying generating sources. In the economic aspect of hydropower stations, if there is excess capacity in the power system are more attractive than the thermal stations due to the lower operating costs (no fuel component). At the same time, their modes of operation depend on weather conditions (low-water years) and these aspects (economy and energy supply) should be taken into account when justifying reserve funds under the present conditions of excess capacity.

3 Methodological principles for taking into account restrictions on the production of electricity at hydroelectric power station when justifying power capacity reserves and their practical applications

It should be noted that the method of justifying the normative reserve of capacity to compensate for the withdrawal of the generating equipment to the unplanned (emergency) repairs (operational reserve as revised by the MR 2003) remains unchanged. In the present circumstances, unfortunately, there are no scientifically based provisions for the application of the criteria for decision-making on the level of reliability. This could be based either on the western European standards (*LOLH* = 3-8 hours/day), or North American (*LOLE* = 0.1 time a year), on the national standards for the territorial zones [1, 4] ($J_д$ = 0,004).

For all of the listed balance reliability indicators, the methodological basis for obtaining them is roughly the same and the information component is quite different, especially with regard to the treatment of the electrical consumption patterns [1]. The European standard for the balance reliability estimates hourly power consumption schedules for all 8,760 hours of the year, while the North American standard only takes into account the maximum hour of the day a year (365 values). The domestic national standard for the balance reliability targets only one average hourly daily schedule in December, assuming that it is valid for all working days of the year. The comparison of these indicators, in terms of their impact on the justification of funds, is a rather complex undertaking. In the research work [1] for the certain conditions, studies have been carried out which have shown an acceptable convergence of results in justifying the value of the operational component of the normative reserve of capacity.

Regardless of the management principles of the power industry (centralized, market), the task of the estimation BRI by using combinatorics or statistical modelling methods is based on two interrelated steps:

– formation of the load levels and random generation capacity conditions caused by the unplanned findings in emergency repair of the power plant equipment;

– assessment of the formed states of provision of the load in the territorial zones.

It should be understood that the task of the BRI estimation is an integral part of solving the problem of justifying the operational component of the normative capacity reserve. So far, in the BRI EPS assessment models the types of the generating equipment involved in meeting the consumer demand have not been specified. Moreover, this was justified because in estimating the BRI out of the multitude of randomly formed states of generating capacity and load is less than a percent. It should be noted that only in these deficit states the generating capacity is fully used. In the states without a deficit, which are more than 99%, the generating power exceeds the load. These states do not affect the PBN,

[4] The Government Decree of the RF № 1172 dated on 27.12.2010 (edit. on 19.01.2018) «On the Approval of the Rules of the Wholesale Market of Electric Energy and Power capacity and on the Amendment of some acts of the Government of the Russian Federation on the Organization of the Wholesale Market of Electrical Energy and Power capacity».

so from the point of view of providing a power balance, the generation can be redistributed as much as possible between different types of stations (HPP, TPP, NPP, RES).

The contribution of a hydroelectric power station in covering the load in the absence of a deficit state can be taken into account only when the power reduction functions caused by the output of the equipment in the unscheduled (emergency) repair can be formed separately for thermal, including nuclear power plants and for hydro units of seasonal (annual) flow control. The methodological approaches for estimating each generation state of a HPP and TPP must also be changed. Considering that the power capacity redistribution between the HPP and the TPP with the NPP can only be carried out in the absence of a deficit state and does not in any way affect the BRI, it is possible to apply the maximum load rule on these states at thermal and nuclear power stations. In this case, the BRI estimation algorithm is designed so that the load at the HPP from one randomly formed absence of the deficit state to another might change [6]. The process of changing is dynamic. The final result of simulating a large number of random states is to achieve, if possible, planned indicators of electricity generation at the HPP (from the perspective of non-renewable energy savings). The simulation is done for all time intervals (day, season, year) for which information is available on the planned indicators of power generation at a hydroelectric power plants.

The application of a separate random state simulations in the estimation of balance reliability indicators for HPP, TPP with NPP makes it possible to determine the generating capacities required to provide the load separately for these types of stations. This opens up the possibility of determining the required additions to the value of the normative reserve of capacity caused by the insufficient energy supply of the hydroelectric power stations in the low-water years. This requires two calculations to determine the operational reserve of capacity, which is an integral part of the statutory reserve of capacity, for the projected hydroelectric power generation and for a low-water year. In both calculations, the operational reserve of capacity remains unchanged, but due to the change in the power supply of the hydroelectric power station, the power generating capacity of the participating payers will be redistributed between the HPP and TPP with NPP. The difference in redeployment will be a premium to the operational and therefore normative capacity reserve due to the reduction in the energy supply of the hydroelectric power station in the low-water years. The most difficult in this approach is the uncertainty of information on the energy supply at a HPP.

Obtaining practical results on energy accounting of a HPP involves modernizing the existing software («Orion-M» [1]), including additional content [6]. The research studies conducted are based on actual information obtained in the course of the research work[5]. Information on the energy supply of HPP Siberia UPS is taken from the work made by SPD. Application of the developed methodology showed the existence of a strict correlation between the percentage of the reduction in electricity production at the UPS Siberia hydroelectric power plants in the low-water years (95673/107377 100=10.9%), the share of the projected value of their electricity production in relation to its total volume (107377/209729=0.512) and per cent additions to operational reserve capacity. The product of the first and second components is almost always the same as the third one. Then the addition to the normative reserve of capacity of a value of 8.55% of the combined maximum load can be obtained when the difference of electricity production at the Siberia UPS hydroelectric power plants for the calculated and low water years is 16.7%.

A natural question arises - what is the significance of the production of electricity at the hydroelectric power station of UES Siberia when justifying the normative reserve of power to be taken as calculated? This is a sufficiently important and unexplored issue in the justification of the normative reserve capacity. The study was not required under the centralized management of the industry. At that time, it was not the task of identifying the most efficient capacities due to their obvious lack of capacity (the frequency in the system was almost always below the regulatory value). In the present situation of excess capacity, the issue of taking into account the energy supply of hydroelectric power is becoming sufficiently topical.

Two options are possible to accept the calculated value of electricity production at the Siberia hydroelectric power plants. The first one is acceptance of the projected with a high-probability to be implemented (formulation from the Electricity Balance in the work of SPD) electricity production volumes. The second option is the acceptance of an average value based on the analysis of retrospective information on the actual electricity production. In order to shed some light on the situation, an analysis of the retrospective information on the actual and projected electricity production at the hydroelectric power plants of Siberia is provided below.

4 Analysis of the forecast of power consumption and electric power production at hydroelectric power stations

The report of SPD 2019-2025, made in 2019, is the 10th since their formation in 2010. This allows based on the retrospective information to make some conclusions and to compare the planned maximum loads and the generation of electricity on a hydroelectric power plants with their actual values. The comparison is made for the period of 2016-2019, for which all the required information is available.

Forecasting of the maximum loads. The value of the planned maximum load is the basis of the capacity demand of the power consumption part of the power balance (Fig. 1). This implies that errors in the forecast have a significant impact on the justification of the generation capacity of the contributing capacity to the power budget. Taking into account these circumstances in JSC «SO UES» the unified system of forecast of production and consumption of electricity and power capacity up to 7 years has been created. The power consumption forecast is prepared for the hour of maximum in December for the average daily temperature of

[5] Report on the scientific research work "Justification of the normative values of the components of the full reserve capacity in the UPS and UES Russia in the planning of their development. / Syktyvkar, 2016 – 66 p. (Contract ISE&EPS FRC Komi SC UB of the RAS with JSC «SO UES», № 926 dated on 22 September 2016).

the maximum power consumption averaged over the 10 years preceding the autumn-winter period. It takes into account the actual capacity balances of previous periods, plans for technological accessions of facilities, and macroeconomic indicators in accordance with socio-economic development scenarios.

It is obvious that the amount of the planned maximum load is influenced by the period of anticipation (from 1 to 7 years). The analysis shows that this period is steadily increasing when conducting the procedure for justifying the generating capacity of participating in meeting the demand for capacity (CPS procedure). So until 2016, the following procedure was based on the two-year forecasts, for 2016 and 2017 with three-year forecasts. For 2024 and 2025 forecasting has reached the limit of 7 years for the SPD.

Let us provide a brief analysis of the comparison of the planned maximum load with their actual parameters for 2016-2019 for a period of one to seven years. Consideration of the time before 2016 is not possible due to lack of information in works of SPD, the first of which gives a forecast for 7 years only for 2016. It is not possible to review later than 2019 due to lack of information on actual parameters of the capacity consumption.

Figure 2. provides information for the period of 2016 - 2019 on the percentage deviations of the projected maximum load parameters (from the work of the SPD) from the actual values for the price zones of the European part of the UES of Russia and Siberia. In Fig. 2 two dotted lines: 2 – average deviations from the actual parameters for the four-year period under review, thinner lines 3 – their max and min bypassing lines. It should be noted, however, that for both price zones from 2013 to 2019 there is a little increase in the actual load maximums by their average value (in Fig. 2 dependence 1 – the line in bold).

significant increase in the forecasted parameters of the maximum load over the actual values for the 4-year period under analysis can be explained by the first works of the SPD 2010-2016 – 2012-2018 trends in the increase of consumption from year to year, which does no credit to the power balance developers. It should be noted that in subsequent works of the SPD this trend is reduced to the reasonable limits. However, a systematic error in forecasting for the first year (from 2 to 3 %, fig. 2) remains. Based on the presented above analysis, when carrying out the justification procedure of the generating capacity, or CPS, the deviations of the 7-year period of anticipation of the maximum load parameters from their actual values should be:

– for the first price zone from 6 to 8 %, and taking into account the systematic deviation for a one-year – 5 %;

– for the second price zone from 11 to 13 %, taking into account the systematic deviation for a one-year – 10 %.

Forecast of the electric power production at the hydroelectric power stations at UPS Siberia. While planning power balances in the SPD operations, the amount of electricity produced at the HPP for the territorial zones in the form of UPS is given for the most water-friendly scenarios. For the Siberia and the Far East, where the share of electricity production at the hydroelectric power plants is significant (from 35% and above), since 2012 the electricity balance is given for a low-water year. Fig. 3 by analogy with fig. 2 shows the percentage variation of the forecasted electricity production parameters from the actual values for the 7-year period for the Siberia hydropower plants and the change in actual electricity production for the period of 2013-2018 from the average values over the years (the solid line in bold –1).

Significant average (10% in Fig. 3, dependency 2) and maximum (15%, dependency 4) deviations of the projected actual values of production at the hydro energy power plants

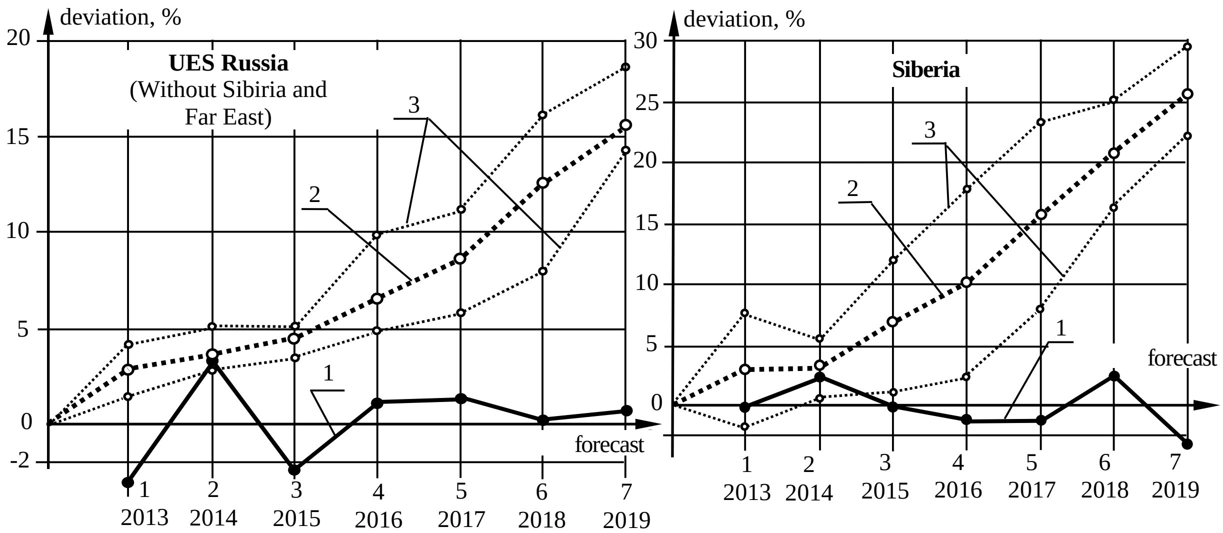

Fig. 2. Deviation of the forecast loads (with a high probability of implementation) from the actual meanings for the UES Russia without UPS Far East and Siberia (from 10 issues of the SPD from 2010 — 2016 until 2019 – 2025).

It can be seen that when the forecast period for both price zones increases the deviations also increase significantly. For the one-year forecast, the average deviations for both price zones are about 3 %, for the seven-year period more than 15,5 % for the first price zone and 25 % for the second price zone. Why such large deviations in forecasting of the maximum consumption for one year cannot be explained. The

from the actual values for all forecast periods. For a low-water year, these forecasts are, as expected, slightly lower than the actual electricity production (4-year averages of about 7 %, maximum possible between 11 and 15 %, dependencies 3 and 4 respectively). At the same time, the planned for the coming year electricity generation for the most likely and the low-water year coincide. Explanations for

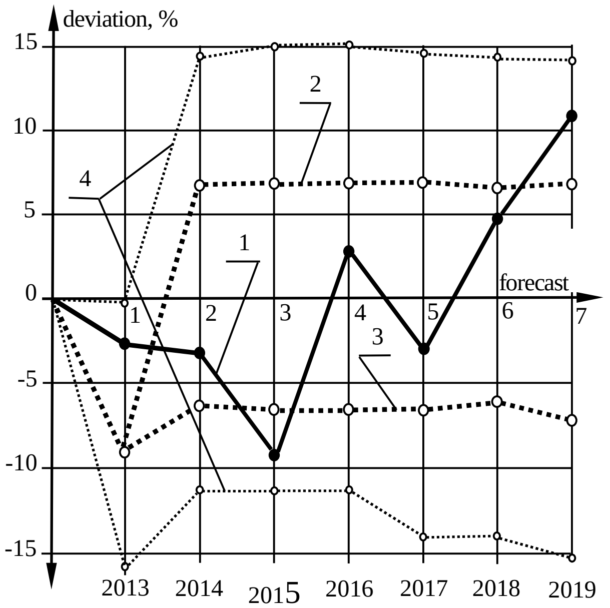

Fig. 3. Deviations of the projected parameters of the electricity production at the hydroelectric power stations Siberia from the actual values for the period of seven years.

this phenomenon, as well as the sharp increase in the period under review from 2016 to 2019 of the average values of the generation of electricity on a hydroelectric power plants for the most likely scenario and the sharp decrease for a low-water year for a forecast period of 2 years or more is not available (dotted lines 2 and 3).

Given in fig. 3 dependence of deviations of the actual values of the electricity production on average for the period of 2013-2019 (line 1) for HPP in Siberia has a sufficiently strong fluctuation. The maximum reduction in electricity production was 9.2 % (2015). If we consider deviations of the average projected electricity production parameters for a low-water year from their actual values for the warning period from 2 to 7 years, they range from 7 % (dependency 3). However, the maximum deviations considered in one out of four studied retrospective period range from 12 % to 15 % (thin dotted line 4 in Figure 3).

Analysis of the retrospective information shows that 16,7 % of the difference in the electricity production at the hydroelectric power plants at the Siberia UPS can only be achieved by considering the maximum deviations of the projected electricity production parameters for the probable scenario and for the low-water year (dotted lines 4 in figure 3). Considering the mean values (dependencies 2 and 3) can only be achieved by 14 %. When considering the projected generation of electricity for the most likely and the low-water years, an interesting picture emerges. The greater the gap in the forecast of the electricity production at the hydroelectric power plants, the greater the additions to the value of the regulatory reserve. At that, the retrospective information on the ratio of the actual electricity production at a hydroelectric power plants with its projected values is not at all taken into account. Thus, the most important parameter of the actual electricity production at the Siberia hydroelectric power plants falls out of consideration. In our view, when justifying a reserve of capacity, it is necessary to consider the risks of underproduction of the electric power at hydroelectric power plants during the low-water years, taking into account the average values of its actual production, taking into account its evolution for the projection period, based on, inter alia, on the analysis of the retrospective information on those parameters. In such case, according to the characteristics given in Fig. 3, the reduction of the electric power production at the Siberia hydroelectric power plants during the low-water years should not exceed 7.0% on average (in Fig. 3, dependence 3), and on the basis of the actual deviations 9.2% (dependence 1, made for 2015). This corresponds to the addition to the normative capacity reserve not 8.55 per cent, adopted in the GD RF №1172, but from 3.58 to 4,72 per cent.

5. Conclusion

The perceived contradictions in defining the projected amount of capacity demand effect on the generating capacity justification that participates in its covering during the competitive power selection procedure. In the beginning of 2020, the CPS procedure was conducted for 2025[6]. Table 1 shows the parameters used for the survey and adjusted to take account of the contradictions in the article on capacity demand in the price zones of the UES Russia. The table shows that the amount of demand for power to justify the generating sources of its covering in the adjusted variant is significantly decreasing – by more than 8,5 % in the first and slightly less than 15 % in the second price zones.

According to the paragraph 107 of the Rules of the Wholesale Market (RF GD № 1172), the price for the power

Table 1. The initial and adjusted information for the competitive power capacity selection procedure for 2025.

Price zone number	Projected maximum capacity consumption, MWt			Planned coefficient of reservation, %		Development of objects of the retail generation	Demand on the power capacity MWt / %
	From the work SPD UES for 2019-2025.	With combination	Taking into account the temperature factor	estimated	applied		
Initial information							
1	132441	127547	133011	18.4	18.4	7143	150342/100
2	34704	33845	35283	18.0	26.55	1311	43339/100
Total	167145	161392	168294	–	–	8454	193681/100
Corrected information							
1	126135	121474	121474	19.05	19.05	7143	137472/91.44
2	31548	30767	30767	13.41	24.41	1311	36966/85.29
Total	154243	148925	148925	–	–	8454	174438/90.06

[6] Website of the JSC "SO UES" "Competitive capacity selection", monitor.so-ups.ru

capacity is determined based on a two-point linear demand function. The important thing is that according to the Government Decree of the Russian Federation № 1172, the prices for the points of demand for the power capacity are strictly determined by the price set by the Government of the Russian Federation in 2017. Taking into account the indexation in the first and second price zones made for 2025, they were 209051.27 and 292415.27 rub. respectively/MWt for the first point of demand. Analysis of the procedures conducted by CPS shows that the final price is no more than 10% different from the initial price of the first demand point. For example, for 2025 the price for the power capacity after the conducted procedure of CPS was 193157,87 for the first price zone, for the second – 303191,67 rubles/MWt. This allows to determine the economic component of the reduction in the cost of the purchasing power by consumers, taking into account the contradictions identified above. For the first price zone it makes the amount of (150342–137472)×193157.87 = 2485930.6 thousand rub/month, for the second one – (43339 – 36966) × 303191.67 = 1932240.50 thousand rub./month. The annual reduction of power charges by large consumers of both price zones will be quite large – more than 53 billion rubles.

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The Forecasting Express-Model of the Energy Companies' Financial State

Oleg Dranko[1*], *Natalia* Maslyakova[2]

[1]V.A. Trapeznikov Institute of Control Sciences of the RAS, 65, Profsoyuznaya str., Moscow, Russia
[2]Formatta LLC, 35 building 3, Bolshaya Tatarskaya str., Moscow, Russia

Abstract. The paper focuses on a forecasting express-model of the financial state of an enterprise. This model includes forecasting the Profit&Loss statement and the Balance Sheet of the organization. The combination of these documents allows forecasting cash flow in an indirect form. We use open data on the financial statements of individual organizations. Estimates of the cash flow deficit have been carried out both for the power generation sub-sector as a whole and for the largest power generating organizations in Russia.

1 Introduction

A large-scale economic crisis has broken out due to the coronavirus COVID 19. Normal activities have been disrupted; many enterprises have stopped working or abruptly reduced business activity; the population is in self-isolation and does not consume goods and services in the same volume. Some researchers compared this crisis to the Great Depression in the late 1920s.

As a result, there was a decrease in energy consumption, and anyone can expect a deterioration in the financial and economic situation of energy companies. "The uncertainty of the future conditions for the development of the energy sector has considerably increased, and there have been significant changes in financial policy and pricing in the energy sector" [4].

The paper presents an express model for forecasting the financial and economic state of enterprises, which allows:
- predicting the financial forms of the enterprise due to a coronary crisis;
- assessing the lack of cash flow;
- evaluating the consequences of anti-crisis measures and enterprise support for normalizing financial condition and preventing bankruptcy.

2 Mathematical Model

An express model for a forecast of the financial and economic condition of the enterprise is used [1, 2]. This model provides links to the projection of the Balance Sheet and the Profit&Loss report.

Let us describe the enterprise balance model as a set of Balance Sheet items *BS*

$$BS = \{FA_j, CA_l, CL_k, D_m, Eq_n\}, \quad (1)$$

where *FA* is fixed assets, *CA* current assets, *CL* current liabilities, *D* debt, *Eq* equity, and *j*, *l*, *k*, *m*, *n* are indices of articles of balance sheet sections.

Similarly, we could describe the model of the Profit&Loss statement as a set of income and expense items *PL*

$$PL = \{S_p, C_r\}, \quad (2)$$

where *S* is revenue, *C* expenses, and *p*, *r* item indices.

Note that there is a key link between the two main financial documents: the balance sheet and the profit& loss statement. It consists of increasing equity by the amount of retained earnings (net profit without dividends) according to the formula

$$\Delta Eq = \pi = (S - VC - FC - Am - k_D D)(1-\tau)(1-u), \quad (3)$$

where *VC* stands for variable costs, *FC* fixed costs (without depreciation), *Am* depreciation, k_D the debt rate, τ the income tax rate, and *u* the share of profit on dividends.

The forecast of the financial state (reflected in the forecast and planning documents - the balance sheet and the Profit&Loss statement) is carried out using the forecasting model

$$(B, P)^F = M(B, P, U, C_U), \quad (4)$$

where *F* is the forecast index, *U* is the control of income/expense items, C_U is the cost of controlling income/expense items.

With independent (directly unrelated) forecasting of various items, the rule that assets are equal to liabilities may be violated. That is, a "financing deficit" (negative

* Corresponding author: olegdranko@gmail.com

cash flow) arises, index 0 denotes a lack of control (initial forecast option).

$$CF_0 = -FA^F - CA^F + CL^F + D^F + Eq^F, \quad (5)$$

where CF is cash flow.

Cash balance at the end of period t must be non-negative

$$Cash_t = Cash_{t-1} + CF_0 \geq 0, \quad (6)$$

3 Initial data

As initial data, we used open data on energy companies:

- open data of the Federal State Statistics Service of Russia on the financial statements of legal entities [5]. In this paper, we consider the sub-sector of electricity generation, according to OKVED-2[a] codes “35.11. Power Generation”. The list of large and medium-sized companies included 116 legal entities more than 800 million rubles revenue. We will call the summary reporting of the aggregate of these organizations the “Consolidated Energy Company”. The technological basis that made it possible to carry out these calculations is the construction of a hypercube or OLAP (On-Line Analytical Processing), implemented in Excel;
- short-term economic indicators for providing electric energy [6];
- financial statements of separate public joint-stock companies for the year 2019.

Unfortunately, the Russian Agency for Statistics provides open data with a long delay (about ten months). The inertial forecast of reports for 2019 was formed using a linear method for three years based on the reporting for the previous year. For the 26 largest companies, actual reports for 2019 were examined, and an adjustment factor of 0.97 is used.

The accumulated retained earnings in the balance sheet were increased by retained earnings of the last year. The proportion of dividend payments of the previous year was used to estimate dividends of the current year.

The difference in forecast assets and liabilities has been adjusted in short-term loans.

4 Analysis of past growth

Russia’s largest energy companies successfully developed until 2019. Revenue of large and medium-sized energy companies grew with a compound annual growth rate (CAGR) of 10.2% per year, which is higher than consumer inflation and GDP growth.

[a] All-Russian classifier of economic activities.

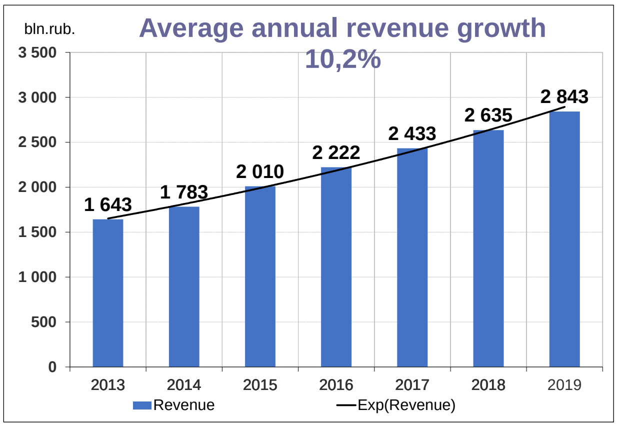

Fig. 1. Revenue of power generating organizations in Russia

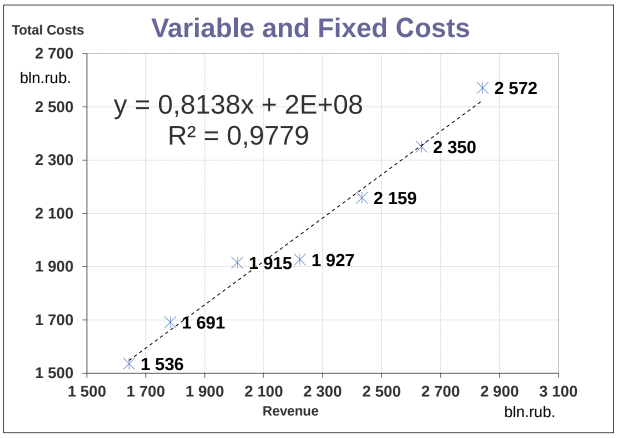

Fig. 2. Variable & Fixed Costs vs. Revenue of power generating organizations in Russia

The dependence of total costs on revenue is characterized by a regression relationship with a variability coefficient of 0.8138, that is, on the increase in revenue per 1000 rubles, full costs increase by 814 rubles. The “Consolidated Energy Company” had the profitability of about 11% in 2018, estimation 12% in 2019, which is noticeably higher than the average Russian figure.

5 Calculation results

The revenue change scenario is an external factor for the express model for forecasting the financial and economic situation. There will be a decrease in energy consumption during the crisis due to COVID-19 and a decrease in economic activity.

According to short-term economic indicators for the supply of electricity [6, sheet 1.2], in May 2020, there was a drop in the supply of electricity, gas, and steam by 4.1% compared to May of the previous year.

According to the UES System Operator [7], for May 2020, electric energy consumption fell by 5.4% compared to the previous year, in June – by 5.9% (see Table 1). Let us estimate the change in the average annual electricity consumption -3%.

Table 1. Power generation and consumption according to UES System Operator data.

Period	Consumption 2020, GWt*h	Consumption 2019, GWt*h	Deviation Generation, %
Total	**564 563**	**580 639**	**-2,77%**
Jan	98 419	101 739	-3,26%
Feb	92 655	91 376	1,40%[b]
Mar	93 095	94 599	-1,59%
Apr	82 474	84 949	-2,91%
May	75 879	80 230	-5,42%
Jun	72 590	77 140	-5,90%
Jul[c]	49 452	50 605	-2,28%

Let us estimate the increase in tariffs by +3% according to inflation. So let us consider the case of the average annual decline in the consolidated energy company's revenue by -0.1%. But we will consider this value as an input parameter for calculations.

The calculation is shown in the table (Fig. 2). While maintaining the same proportions, profit will remain at almost the same level of 271 billion rubles.

In the industry as a whole, the main requirement for financing is to grow fixed assets. For the "Consolidated Energy Company," the estimate is 192 billion rubles. This value is close to the forecast of retained earnings of 187 billion rubles. Considering a slight optimization of expenses and current assets/liabilities by 0.1%, the impact of changes in current assets is insignificant, about 1 billion rubles.

For the authors who have studied many forecasts for the development of companies, this situation looks unusual and rare: retained earnings almost wholly cover the investment program.

The parametric calculation of the estimates of the final cash flow showed a weak dependence on the change in revenue. When the revenue changes from -5% to + 5%, the cash flow changes from +4.3 to -12.6 billion rubles. We hope that operational management can replenish this cash flow.

Express assessments for separate organizations show some differentiation in cash flow (see Table 2). But we note that almost all estimates of the cash flow for the largest organizations are above 0. That is, there should be no difficulties in financing this year.

Note. We carried out the express assessments according to the reports of the head legal entities. For consolidated reporting of groups of companies, estimates may be different.

[b] 29 days in 2020 versus 28 days in 2019.

[c] 20 days of July were available at the moment of this paper preparation.

Income and Expenditure	**Income forecast**	**Income growth**
Revenue	2 839 916	-653
Cost of revenue	-2 185 160	2 187
Selling and administrative expenses	-108 611	0
Income tax	-100 357	-413
Net income	**272 380**	**1 121**
Retained earnings (current year)	**174 711**	
Assets & Liabilities	**Balance sheet forecast**	**Cash flow growth**
Non-current assets	5 500 897	-192 475
Inventory	185 854	186
Receivables	692 293	693
Other current assets	17 258	0
Cash & short-term investments	635 240	0
Accounts payable	378 322	-379
Other current liabilities	54 836	0
Long-term debt	1 258 895	0
Short-term debt	349 901	0
Common stock	2 020 903	0
Retained earnings	1 928 417	174 711
Other equity items	1 023 005	0
TOTAL surplus (+) / deficit (-)	**-17 263**	

Fig. 3. The state forecast of the Consolidated Energy Company

Table 2. Express assessment of cash flow for individual organizations.

Organization	Cash flow, billion rubles
PJSC "T Plus"	5 756
PJSC "Mosenergo"	22 546
JSC INTER RAO-Electrogeneration	30 776
PJSC "Federal Hydrogenerating Company – Rushydro"	-13 315
PJSC "Second Generating Company of the Wholesale Electricity Market"	10 893
PJSC "Territorial Generating Company No. 1"	6 856

6 Measures to improve the financial and economic situation

Negative cash flow is a sign of the unworkability of plans. Management should offer a project for the non-negativity of funds.

Management measures divided into the following categories:

- external: attraction of external financing (taking loans), tariffs increase;
- internal: increasing efficiency by reducing costs, introducing technologies with higher efficiency, optimizing assets and liabilities. The impact of new technologies has significant potential for reducing costs, but projects with long payback periods are virtually unrealizable in a crisis.

The authors' consulting experience with power generation organizations shows that internal management measures have little potential than external actions. In many other industries - interior projects play a much more significant role in improving overall performance and development.

An assessment of financing a cash shortage using external loans shows no substantial change in the structure of liabilities. It is a good scenario in the assumptions and initial data of the current model.

Optimization of investment programs in fixed assets and long-term financial investments will significantly reduce the dependence on external financing in case of a "hard" scenario of the crisis, which is considered as one of the strategic threats to the development of the energy sector [3].

7 Conclusion

An express assessment shows that an abrupt deterioration in the financial and economic condition of energy generating companies in Russia in this economic crisis is unlikely to happen.

On the one hand, this ensures the stability of the industry. On the other hand, a large-scale economic crisis will most likely not be used as an incentive to change and increase domestic efficiency.

The low energy efficiency of Russian energy companies is an obstacle to their capitalization, but this is a topic for separate work.

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Application of high-performance computing for determining critical components of an energy system

Aleksey Edelev[1,*], *Sergey* Senderov[1], *Alexander* Feoktistov [2], *Igor* Bychkov[2], and *Olga* Basharina[2]

[1]Melentiev Energy Systems Institute SB RAS, Lermontov St., 130, Irkutsk, Russia, 664033
[2]Matrosov Institute for System Dynamics and Control Theory SB RAS, Lermontov St., 134, Irkutsk, Russia, 664033

Abstract. This article presents a package for analyzing the energy system vulnerability developed with new technology for continuous integration, delivery, and deployment of applied software. It implements a framework that allows combining and optimally using various methods for modelling energy systems and provides the comprehensive assessment of their vulnerability with regard to various uncertainties. The essential principles to identify and rank critical elements of an energy system are considered in the article. The investigations made with the package shown that the principles seem to be logical for the subsequent construction of the invariant set of measures for improving the energy system resilience.

1 Introduction

Currently, there is an increasing interest in the study of the ability of an energy system to survive when faced with the large disturbances. Their probability is small or unknown, but their impact leads to that the energy system cannot perform its functions without additional supporting measures. In addition, reaction of the energy system to such disturbances, the consequences for consumers, compensation for negative consequences and the system restoration process are studied [1].

One of the major problems in studying energy system resilience is a number of uncertainties arising from incomplete knowledge about the conditions and time of a disturbance, the system's response to a disturbance, a disturbance magnitude and scale, etc.

The resilience is considered as an ability of a system to resist disturbances, preventing their cascading development with the mass violation of consumers supply and recovering after their impact [2]. These steps are schematically shown in Fig. 1.

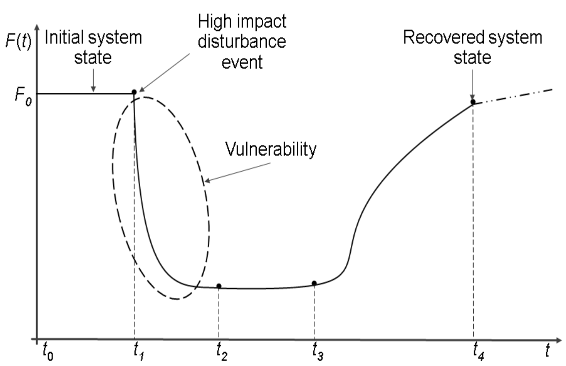

Fig. 1. System performance under a high impact disturbance.

The function *F(t)* reflects the overall system performance at a time *t*.

At the time t_0, its value is F_0.

From time t_0 to t_1, the system is in a stable state and is prepared for the predicted perturbation.

At the moment t_1, a disturbance occurs, the system performance drops to the value $F(t_2)$, and until the moment t_3, the system tries to adapt to the disturbance impact and its consequences.

So, in the time period from t_1 to t_2, a system tries to absorb the disturbance, and from t_2 to t_3 it actively resists the disturbance and mitigates its consequences be means of an efficient resource allocation.

Finally, starting from the moment of t_3 the system tries in various ways to restore its performance to a certain acceptable level $F(t_4)$ [3].

Starting from the moment t_4, the system continues to increase its performance, improves its resilience according to the plans made on the basis of the received experience, and prepares for new disturbances [4].

The stages of planning, preparation, absorption and resistance represents that the system adapts to the requirements of the new situation, and the recovery stage returns the system to normal operation. In other words, the resilience is the system's ability to adapt to various large disturbances and recover to the state in that the system was before their impact [5].

2 Studying energy system resilience

The resilience research is based on the study and analysis of system adaptation and recovery capabilities [6]. The modern scheme of studying energy system resilience is discussed in detail in [7].

* Corresponding author: flower@isem.irk.ru

2.1. Vulnerability concept

The vulnerability (Fig. 1) represents the size and scale of negative consequences for a system which are result of the impact of a particular disturbance [7]. The vulnerability analysis plays central role in the resilience research [8]. The main purpose of the vulnerability analysis is to identify drawbacks in the system design and control mechanisms, which could contribute to the spread of a large disturbance over the system itself and, also, over interconnected systems [8].

The vulnerability analysis involves the following types: global and spatial, as well as the search for critical elements [7].

The global vulnerability analysis is aimed at obtaining general information about the impact of disturbances on the system performance and is carried out by modeling a series of disturbances with gradually increasing degree of impact. Such computational experiments allow determining the threshold values of the impact for certain disturbance classes [7].

The search for critical elements is focused on determining a component or combination of components which failure causes the biggest decrease of the system performance [7]. The key point here is to detect all, even unexpected, combinations of critical elements [9].

The spatial vulnerability analysis focuses on finding critical geographical areas where the system components are located in some proximity to each other and are affected by spatially distributed large disturbances, such as natural disasters [6]. Several different areas may be affected at once [10].

2.2 Modelling energy systems

Modelling energy systems for the resilience research is different for separate and interdependent ones [11]. In the first case, an energy system is usually modelled at more detailed level. In the second case, more aggregated representation of energy systems can be used and the relationships between their components must be taken into account [12]. According to one of the widely used classifications proposed in [13], there are the following categories of interdependencies:

- Physical, representing the flow of a resource from one system element to another,
- Communication for transmitting status and control data,
- Spatial (geographical) connections [10],
- Logical relationships that are not included in any of the above categories.

In addition, there is fifth type of relationships called social. It describes the impact of human behaviour on the system components [14].

Taking into account the structural and dynamic complexity of the systems, the relationships between systems and existing uncertainties, it is emphasized in [8] that the integration of various methods and approaches to modelling systems allows to assess their vulnerability from different points of view (topological and functional, static and dynamic).

2.3 Current challenges in studying energy system resilience

The current state in studying energy system resilience is characterized by the following difficulties:

- Focus on the consideration of separate energy systems and insufficient attention to the study of the relationships between them [15],
- Lack of frameworks that allow combining and optimally using various modelling methods for complex systems such as energy systems for a comprehensive assessment of their vulnerability with regard to existing uncertainties [8],
- Processing and analysis of large data sets that arise due to the combinatorial nature of most problems of energy system resilience studies,
- Need to manage multiple computational experiments and conduct them in an acceptable time.

The last two problems can be solved using high-performance computing.

3 High-performance computing in studying energy system resilience

Using high-performance computing in the study of the functioning and development of energy systems is considered in [16, 17].

The search for critical elements is used to assess an ability of power systems to withstand various combinations of element failures based on the system state assessment. High-performance computing allows evaluating the failures consequences not only of particular elements, but also of their various combinations in acceptable time [18].

Major disturbances in the power systems usually start with a primary disturbance (short circuit in transmission lines due to uncut trees, incorrect operation of protection devices, bad weather), followed by a chain of cascading events. Chains of events that lead to large disturbances are usually long and complicated, so the work on their detection because of their complexity can take months. Here, high-performance computing also makes it possible to speed up the consideration of a significant number of combinations of possible events and perturbation scenarios [19].

If the number of components combinations under consideration is large for the use of combinatorial methods, then simulation modelling is used [8], including Monte Carlo methods focused on high-performance computing [20].

Graph theory is widely used in the vulnerability analysis [8]. There are many software libraries for working on large graphs [21]. Some of them are implemented on the basis of parallel and distributed computations [22].

The study and analysis of the energy system adaptation and recovery capabilities is usually implemented on the basis of mathematical optimization packages [23], which have built-in tools for organizing high-performance computing.

In studying energy system resilience, parallel computations are mainly used for calculating large optimization tasks, such as an energy distribution over real energy system networks [16, 21] or resource allocation when planning an energy system recovery. Distributed computing is used in vulnerability analysis, where problems are mostly combinatorial in nature, and their solution is quite easily scaled.

4 Package for analyzing the energy system vulnerability

We developed applied software for analyzing the energy system vulnerability using special tools for creating subject-oriented heterogeneous distributed computing environments. Applying these tools, we implemented the means for analyzing the energy system vulnerability as a distributed applied software package.

4.1 Environment

Subject-oriented heterogeneous distributed computing environments can integrate cloud and grid platforms, including resources from public access supercomputing centers. The main components of environments are PC-clusters or HPC-clusters. In addition, each environment can include various computational servers, PCs and data storage systems.

Dedicated cluster nodes are used within cloud and grid platforms. At the same time, non-dedicated cluster nodes are used as shared computational resources. When users of environments solving problems, they are given the capabilities to use both the dedicated and non-dedicated nodes.

The aforementioned tools support specialized technology for automating the process of solving large-scale scientific problems. This technology supports the following main operations:

- Extracting subject information from weakly structured sources and converting them into target data structures of packages [24],
- Development, modification, and joint applying of applied software for solving different classes of problems,
- Continuous integration, delivery, and deployment of applied software in both the dedicated and non-dedicated nodes [25],
- Automation of the construction and execution of problem-solving plans,
- Visualization of the obtained computation results on electronic maps,
- Multi-agent dispatching of computations in a heterogeneous environment [26].

We create subject-oriented environments using the Orlando Tools framework [27]. The Orlando Tools framework implements an advanced modular approach to the development and use of a specialized class of scalable scientific applications (distributed applied software packages [28]).

During environment creation and package development, Orlando Tools provides users with ample capabilities for describing the subject domain model, including both the text and graphical languages for its specification and problem formulations on this model.

Problem formulations can be implemented in procedural and non-procedural forms. In the latter case, the synthesis of a problem-solving plan (abstract program) is automatically performed.

A problem-solving plan is a kind of abstract workflow [29]. Resources allocation is carried out at the stage of dispatching computations. A plan generated from a procedural problem formulation can include control constructs for branching, looping, and recursion.

Users form computational jobs to execute problem-solving plans in the environment.

A self-organizing hierarchical multi-agent system with several levels of agents' operation implement dispatching of jobs in the environment [30]. Agents represent resources in the environment, implement of resource monitoring, recognize job properties, and distribute jobs across resources.

Within the multi-agent system, agents can play various roles and perform different functions corresponding to particular roles. Roles can be permanent or temporary. Temporary roles arise at discrete moments in time in the process of local interactions of agents.

Agents are autonomous entities. However, they can unite into virtual communities of agents.

Within the framework of virtual communities, agents cooperate in execution a common job. At the same time, they compete to distribute the computational load for their resources.

A distribution of the computational load is carried out by means of a specialized tender of computational works. This tender is based on the Vickrey combinatorial auction [31]. The computational load is calculated using special models for predicting the runtime of problem-solving plans [32].

A subject-oriented environment for analyzing the energy system vulnerability provides a set of services for preparing subject-oriented data, implementing computations, generating electronic maps, and visualizing the computation results on the generated maps.

4.2 Package

We developed the package for analyzing the energy system vulnerability. Its subject domain model includes 22 parameters (p_1-p_{22}) and 7 modules (m_1-m_7). The modules represent applied software of the package.

The modules was developed based on the new technology of the Orlando Tools framework for continuous integration, delivery, and deployment of applied software. Testing of modules in environment nodes within the framework of this technology ensured high reliability of computations. This provided a significant reduction in the time of the experiments.

On this model, we constructed three problem-solving plans (workflows).

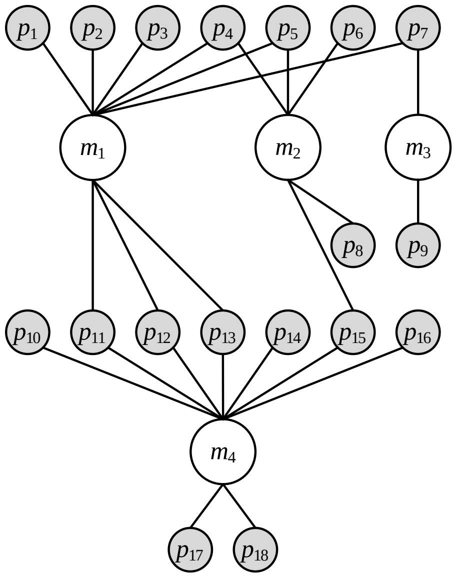

Fig. 2. Plan 1.

Plan 1 creates critical element sets of a specific size, simulates the simultaneous element failures for all sets, and evaluates the consequences of these failures (Fig. 2).

In Plan 1, the modules m_1-m_3 modules can be executed in parallel. The module m_4 is designed to perform parameter sweep computations. Instances of this module are executed with different sets of inputs.

In dispatching jobs, the Orlando Tools framework provides a proportion distribution of the computational load caused by the processing instances of the module m_4 between the agents representing the resources of the environment. Thus, in comparison with well-known workflow management systems, Orlando Tools does not consider each instance separately.

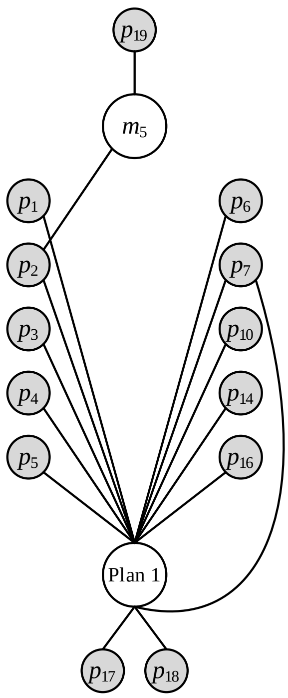

Fig. 3. Plan 2.

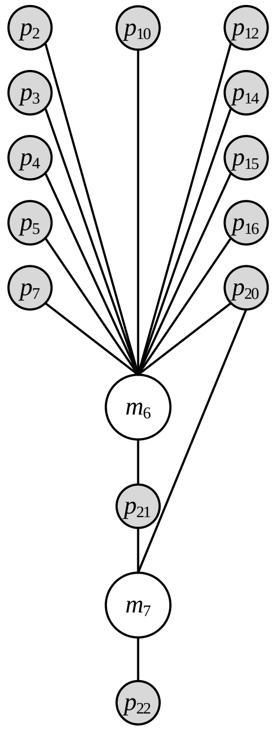

Fig. 4. Plan 3.

This significantly reduces the combinatorial complexity of the tender of computational works.

Plan 2 implements carrying out Plan 1 in a loop with element sets of differing sizes (Fig. 3).

Plan 3 forms electronic maps for the selected sets of failed elements and publishes these maps using geo-information services (Fig. 4).

A detailed description of all parameters and modules of the package is given in [27].

5 Search for critical elements

The search for critical elements procedure is implemented as follows. First, based on the idea of vulnerability analysis from various points of view [8], several indicators are selected to assess the performance of the energy system under study. Next, the disturbances affecting the system components are modelled, and the system performance drop is measured by indicators. The components are sorted on the base of the measurements made, and multi-criteria analysis can be applied here.

In the package for analysing energy system vulnerability, the problem of generating disturbance scenarios is solved by constructing failure sets [9]. Each of them is a combination of the energy system network elements where a failure might occur. For practical reasons, the size of a failure set should not exceed 3 or 4, since the number of possible failure sets increases rapidly.

One of the advantages of the approach [9] is the identification of hidden elements. The single failure of a hidden element produces negligible impact on a system, but a combination with other elements might have synergistic effect and can cause significant damage to a system.

In addition to the deterministic approach [9], the package implements a stochastic approach to determining critical elements [33].

During 2018-2019 the package was used to identify critical elements of the Unified Natural Gas Supply System of Russia. Its network contains 382 nodes, including 22 underground natural gas storages, 28 sources (in the system model they are represented by head compressor stations), 64 consumers, and 268 key compressor stations, as well as 628 arcs representing main natural gas pipelines, their corridors and branches to the distribution networks.

The results of the calculation conducted with the package have shown that potential gas shortage for consumers exists if any of the 441 components of the Unified Natural Gas Supply System of Russia (242 nodes and 199 arcs) is failed. The threshold for critical elements was a potential gas shortage of 5% of the total demand. 61 components have exceeded limit. These components were formed the list of the natural gas industry's critical elements at the federal level. Among these components there are 25 arcs between key compressor stations and 36 nodes, including 30 key compressor stations, 5 head compressor stations, and 1 underground storage.

Then, 207690 failure sets of size 2 were calculated by means of the package. These failure sets did not include critical elements found earlier. Experts have identified 2865 pairs of components, the failure of each can lead to a shortage of 5% of the total demand and higher. After modelling certain resilience improvement measures on the package, the number of the pairs has been reduced to 2516. As a result of ranking the pairs 20 pairs were selected, the failure of which can lead to a shortage of 10% of the total demand and more.

6 Conclusions

The package for analyzing the energy system vulnerability has been developed with the new technology for continuous integration, delivery, and deployment of applied software. It implements a framework that allows combining and optimally using various methods for modelling energy systems for a comprehensive assessment of their vulnerability with regard to various uncertainties.

The package aims to overcome the following challenges in the field of energy system resilience research:

• Processing and analysis of large data sets that arise due to the combinatorial nature of most problems of energy system resilience studies;

• Need to manage multiple computational experiments and conduct them in an acceptable time.

The investigations made with the package shown that the principles to identify and rank critical elements of the Unified Natural Gas Supply System of Russia seem to be logical for the subsequent construction of the invariant set of the resilience improvement measures for the appropriate energy systems.

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A Methodological Approach to the Assessment of the Impact of Digital Technologies Development in Energy Industry on Electricity Price and Demand in a Region

Elena Galperova[1*], and *Vasiliy* Galperov [2]

[1] ESI SB RAS, Department of Energy Security, 664033 130, Lermontov Str., Irkutsk, Russia
[2] ESI SB RAS, Department of Systems of Artificial Intelligence in Energy, 664033 130, Lermontov Str., Irkutsk, Russia

Abstract. The relevance of this study is due to the importance of assessing the prospective dynamics and structure of demand for energy carriers when developing and making strategic decisions in the field of energy and economic security of the country and its regions. The advance of digital technology redefines the properties of electric power supply systems, erases the boundary between electric power producers and consumers, and impacts the formation of electricity price and demand in the region. This study presents a method of electricity costing in the regional power system, which serves as an integral part of the approach to assessing the impact of intelligent systems development on the demand for electricity in the region. The approach is unique in that it simulates the behavior of electricity consumers and producers of various types as they pursue their own interests and assesses the impact of this behavior on the demand and price of electricity in the regional power system. Determining the cost of electricity in the system is based on the consistent alignment of the required amount of electricity consumption with the capabilities of producers seeking to achieve their best economic performance. Each producer is described as an optimization model, which is a standalone agent in a multi-agent power system model.

Keywords. Digital technology, smart grids, active consumer, optimization, agent-based approach, power demand, price.

1 Introduction

Studying and projecting the prospective dynamics of volumes and changes in the structure with respect to demand for fuel and energy resources (FER) is one of the most important tasks when developing and making strategic-level decisions in the area of energy and economic security of the country and its regions and the policy aimed at improving the quality of life. Furthermore, one should have an overall idea of the dynamics and structure of the demand for energy carriers when developing directions for efficient development of the energy sector of the country and its regions, ensuring reliability of energy supply to the individual geographical areas, and developing long-term programs of activities of energy companies, etc.

Difficulties in studying and projecting energy demand are due to the multiplicity and interplay of factors determining the levels and structure of demand for FER, along with their high variability and change over time. Attempts to overcome these difficulties have led to the development of quite a large number of approaches, methods and models for projecting estimates of demand for fuel and energy both in our country and abroad. These are heuristic methods (expert judgment, brainstorming, the Delphi method, etc.) based on the knowledge and experience of professionals active in this field (see, e.g., [1, 2]), extrapolation methods, methods based on long-term trends and patterns in changes in energy consumption and basic macroeconomic indicators of development of different countries (see, e.g., [3-6]), and building of a variety of models (simulation, optimization, and input-output models) (see, for example, [7-10]). Such models are used both for solving standalone problems of projecting demand for fuel and energy resources and for serving as a part of model systems employed to determine directions of energy industry development [11-14].

Despite the availability of a significant number of the methods developed, they fail to account for, or do not take into account to the extent feasible, the changing conditions governing the shaping of prospective demand for energy carriers, in particular, the drastic development and widespread adoption of digital technologies. The emergence of active consumers capable of managing their own energy consumption as well as electricity storage and production increases the importance of projection studies that deal with demand dynamics at the regional level when determining the total demand at the country level and requires further development of methods of studying and projecting the prospective demand for FER.

* Corresponding author: galper@isem.irk.ru

2 Digital technologies in energy production and consumption

Digital technologies contribute to the emergence of new properties of energy supply systems. The key ones are: 1) smart demand management; 2) emergence of small distributed electricity resources, including those based on renewable energy sources; 3) adoption of smart charging for electric vehicles.

2.1. Demand response

This is an arrangement that allows electricity consumers to respond to the system parameters to ensure reliable power supply at minimal cost. Digital metering, control, and communication technologies enable the consumer to continuously monitor the use of energy by their appliances and equipment, transfer this data to the electricity supplier and receive information from them to optimize their own demand in accordance with the supply available in the power system. During the hours when the power supply is limited or the grid is overloaded, connected devices such as smart electric heaters and air conditioners, industrial boilers, and smart home appliances can automatically shut down or operate at a lower load level, and do so without compromising the convenience for the consumer [15-18].

2.2 Distributed generation

The development of small-scale distributed generation helps to reduce power transmission and distribution losses, to respond more flexibly to changes in demand, and in many cases to improve the security of supply. Distributed (small-scale) energy sources include a set of technologies represented by small-scale or even micro-scale installations that allow generating energy near the place of its consumption, such as home solar photovoltaic systems [19-22]. Digital technologies enable consumers to have their own production and/or storage technology and to sell and/or buy electricity from both individual sellers and the power system.

2.3 Smart charging

Smart charging for electric vehicles allows connected electric vehicles to be charged according to price and/or control signals in the power system. For example, they consume power when there is cheap electricity production available, or they stand by when the grid is overloaded. If two-way battery charging is possible, in addition to smart charging, electric vehicles can provide greater system flexibility by selling electricity to a grid operator or making use of it to meet the needs at their own home (Vehicle-to-grid). This two-way energy exchange provides a number of economic, environmental and operational advantages [23-26].

2.4 Blockchain

Given a growing number of heterogeneous devices, owners, and operators in smart power systems, the distributed ledger technology (blockchain) can prove instrumental in solving the problem of their coordination as well as trade automation. A blockchain is a continuous chain of data blocks built in accordance with predefined rules so that each subsequent block is linked to the previous one through the set of records it contains and each block stores all the information in the chain starting from the very first block. All blocks of the network are in strict chronological order and are linked to each other by a cryptographic signature created using complex mathematical algorithms. The block is stored as a "chain" on distributed computers. Any blockchain member can read it or add new data [27-31].

The use of digital technologies in the energy industry contributes to the development of intelligent systems and networks, digitalization of systems of control, metering, and management of energy supply and transforms the network infrastructure into a new cyber-physical platform for flexible and efficient energy supply to various types of consumers. Taking account of the above features in the methods of projecting energy demand will enable us to improve the quality of projections and enhance the validity of prospective options for the energy sector development and strategic decisions in the field of energy and economic security of the country and its regions.

3 Proposed approach to estimate the cost of electricity in the region with the diffusion of digital technologies factored in

This study continues the line of research and further develops the methodological approach to the assessment of the impact of intelligent systems development on the energy demand in the region, the key points of which were covered in [32, 33].

A distinctive feature of the approach is that it simulates the behavior of electricity consumers and producers as they pursue their own interests and assesses the impact of this behavior on the demand and price of electricity in the regional power system.

The key assumptions underpinning the approach are as follows: 1) the regional power system is made up of a centralized power grid with a number of consumers connected to it; 2) the centralized power grid consists of a set of major electricity producers (coal-fired, gas-fired, and nuclear power plants, etc.) with their technical and economic performance indicators (fuel consumption, cost price, etc.); 3) the composition of the power production (the share of individual power plants in the total volume) determines its price level in the grid. Three types of consumers are considered: (1) the stable (passive) consumer who cannot adjust their power consumption due to technological or other constraints, (2) the active consumer who is able to adjust (reduce) their power consumption, (3) the prosumer, who, in addition to being able to manage their demand, possesses their own sources of electricity production and storage as well as the ability to supply it to the centralized grid.

The algorithm of assessing the influence of consumers' behavior on demand in the regional energy system is described in detail in [33] and it allows iteratively estimating the maximum possible reduction of demand for energy in the power system due to changes in the volumes of energy use by active consumers and prosumers in response to changes in its cost.

Below is described the method of electricity cost formation in the regional system as based on simulation of behavior of the individual producer. The method is based on optimizing the key economic performance indicators of an individual power plant. Depending on the actual situation in the system, the following can serve as optimization criteria: maximum profit, minimum cost price, maximum production volume, etc.

Determining the cost of electricity in the system is about the consistent alignment of the required amount of electricity consumption with the capabilities of producers kWh, as (1):

$$\sum_i N_i h_i = \sum_j V_j, kWh, \quad (1)$$

where N_i – installed capacity of power plant i, kW; h_i – the number of hours of utilizing installed capacity of power plant i, hours; V_j - demand for electricity by consumer j, kWh.

Each production facility (power plant) is described as an optimization model, the input data for which are as follows:

- installed capacity of the plant;
- specific capital expenditures;
- the number of hours of the utilization of the installed capacity;
- depreciation rate;
- consumption by auxiliaries of the power plant;
- specific fuel consumption for electricity production;
- fuel cost;
- the ratio of the number of plant personnel per unit of installed capacity;
- the average salary of the personnel.

Each plant can operate in different modes and, accordingly, with different electricity production cost values. Unit cost of electricity production at the condenser-type thermal power plant (CPS), is determined as (2) [34]:

$$C = Z / E\,(1 - \alpha_{aux}), \quad \text{rub./kWh} \quad (2)$$

where E – electricity production, kWh, α_{aux} – the coefficient of electricity consumption by auxiliaries, %, Z – total electricity production cost, is determined as (3):

$$Z = P_f\,(b / Q_l^w)\,N_y h_y + (1+k_m)\,[(n_d+\beta_r)\,K + n_a N_y F], \text{rub} \quad (3)$$

where P_f – the price of 1 ton of the natural fuel, rub/t; b – specific consumption of the fuel for electricity production, g of fuel in coal equivalent/kWh; Q_l^w – combustion value of the natural fuel, kcal/kg; N_y – installed plant capacity, kW; h_y – the number of hours of use of the installed capacity, h; k_m – the coefficient of expenses for miscellaneous needs, usually taken to be 0,2÷0,3 (the greater value is applicable to the CPS of small capacity); K – capital expenditures of the CPS, rub., n_d - weighted average depreciation deductions (in the case of the CPS given the straight line depreciation method adopted for allocating depreciation is taken to be 0.035); β_r – the coefficient that captures the share of costs for repairs as a share of capital expenditures, taken to be 0.04-0.05; F – the average annual gross payroll per employee (with deductions factored in), rub./person; n_a – specific headcount, person/kW.

The profit of the power plant q, is determined as (4):

$$q = ET - Z, \text{rub} \quad (4)$$

where T – the weighted average price of electricity in the power grid.

A two-level optimization scheme is provided, i.e. the operation of each power plant and the system as a whole is optimized. Individual power plants can optimize their operation with respect to the criteria they require, while the system is optimized with respect to minimum weighted average cost per 1 kWh.

The maximum cost of electricity in the grid is determined first. For this purpose, all plants optimize their operation with respect to maximum profit. The weighted average cost of electric power is calculated, which is the initial cost for estimating the influence of consumers' behavior on demand (see [33] for more details). If this cost of electricity does not suit active consumers and prosumers, they reduce their electricity consumption and the next stage of calculations is performed given the new demand value. In order to maintain stable operation, plants may reduce profits or reduce costs to maintain profits, some plants may fail to be profitable under certain conditions. Algorithm for formation of electricity price in regional power system is shown on fig.1, and algorithm to study the impact of consumer behavior on electricity demand on fig.2.

An agent-based approach is employed in the system to model forward and backward links of facilities. The model of each power plant is a separate agent that solves its individual problems under the conditions of the power system. The agent-based approach allows to provide any level of detail and abstraction [35, 36].

4 Conclusion

The drastically decreased adoption costs and the diffusion of digital technologies through energy production (primarily driven by renewable energy sources), the emergence of intelligent systems in the management of energy facilities, the changing role and place of consumers in power systems all fundamentally alter the organizational and technological structure of the energy industry along with the relationships between producers and consumers of electricity and exert an impact on demand and prices on regional energy markets.

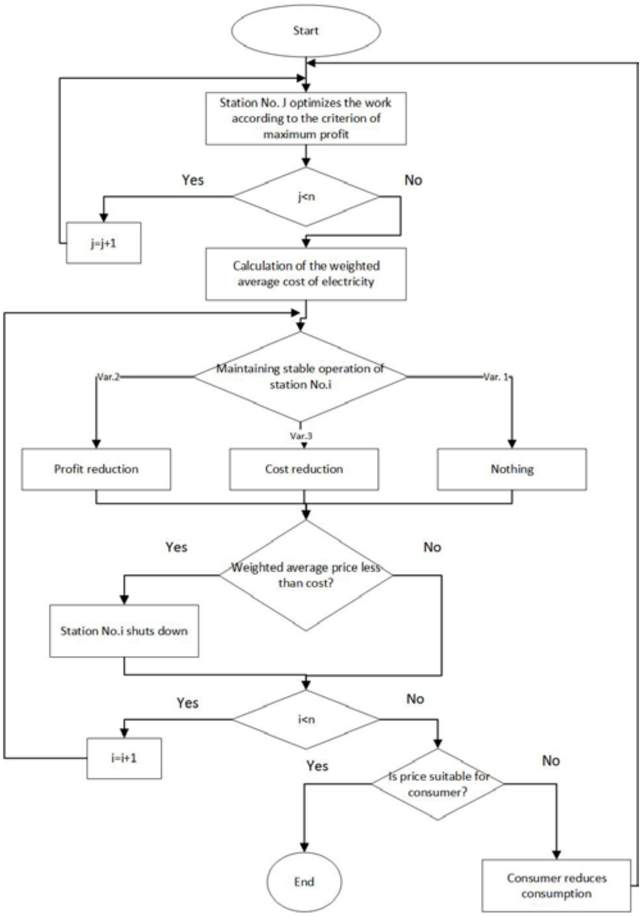

Fig. 1. Algorithm for formation of electricity price in regional power system

Taking account of the above new factors and interrelationships in the methods of projecting energy demand will enable us to improve the quality of projections and enhance the validity of prospective options for the energy sector development and strategic decisions in the field of energy and economic security of the country and its regions.

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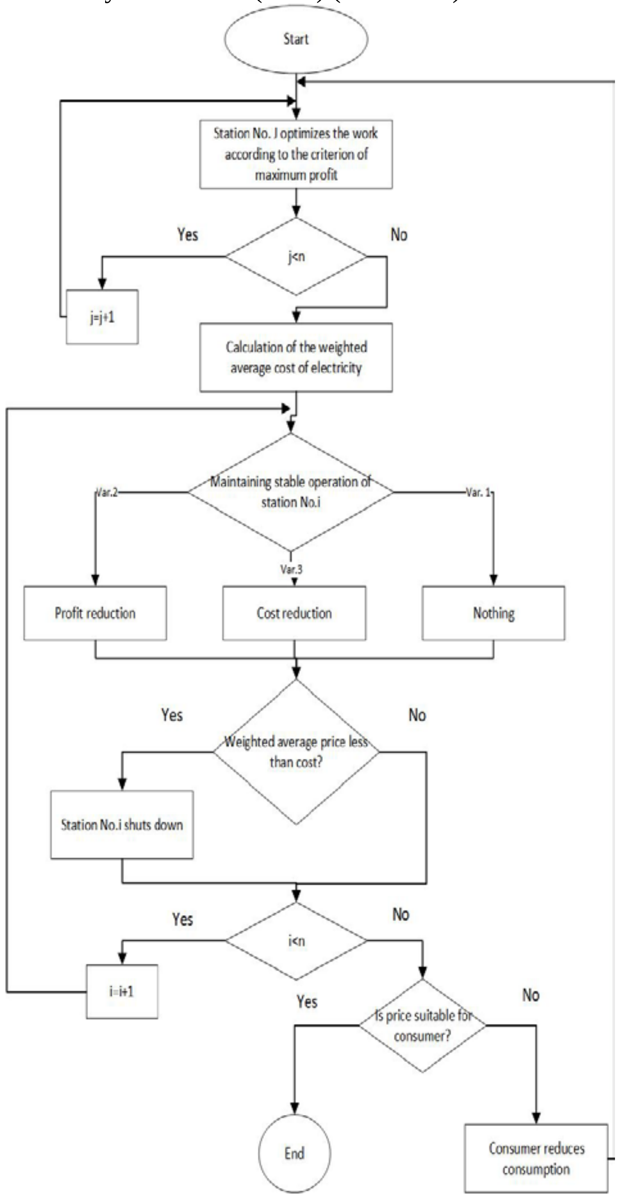

Fig. 2. Algorithm to study the impact of consumer behavior on electricity demand in a regional power system

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Analysis of the prospects of adopting the digital technology across sectors of the economy and its impact on the demand for energy carriers

Elena Galperova[1*], and *Olga* Mazurova[1]

[1,2] ESI SB RAS, Energy security Department, 664033 130, Lermontov Str., Irkutsk, Russia

Abstract. Projections of the demand for fuel and energy resources are an essential and fundamental part of the research that underpins the process of developing and making strategic-level decisions as applied to the national and regional energy and economic security. Identification, analysis, and study of the impact of factors and interrelationships in the energy and economy on the volume and structure of the demand for energy carriers is an integral part of the methodology for long-term projections of energy consumption. The use of the digital technology related to monitoring, acquisition, processing of large amounts of data across all sectors of the economy and everyday life of the population as of now already consumes more than 5% of electricity in the world and its further growth is expected. The study analyzes the possibilities of application of individual digital technologies in various sectors of the economy. Some estimates of their impact on demand for different types of fuel and energy resources are given. We note a great deal of uncertainty in the existing estimates of future energy consumption due to the government policy in this area, changes in the lifestyle patterns of the population, and the speed of development and adoption of technology innovations.

Keywords. Energy consumption, energy efficiency, energy saving, digital technology, data processing center, connected devices.

1 Introduction

The development of the global economy is accompanied by a growing demand for primary energy. It is estimated [1] that global primary energy consumption in the period between 2015 and 2040 may increase by 17-27% while that of electricity - by 60-70%, despite energy saving and slowdown in growth rates.

Assessment of the prospective demand for different types of energy carriers is an important component of the development of programs and strategies of energy and economic development of the country and its regions, as well as policies to improve public welfare. Long-term projections of the demand for energy carriers is a multistage and multilevel process of studying the impact of factors and interrelationships under the changing conditions of energy and economic development on the volumes and structure of fuel and energy resources dynamics. One of the new factors of scientific and engineering progress that radically redefines the interrelation between energy consumers and energy producers is the introduction of the digital technology in the economy and energy industry [2-4]. At the SEI SB RAS, a methodological approach to long-term projections of demand for fuel and energy was developed [5] and is continuously updated [6,7]. Its further improvement is in the direction of factoring in the peculiarities of the development of intelligent electric power systems, in particular, the emergence of active consumers and studies of their impact on the levels of demand for electricity [8, 9]. However, the spread of digital technologies also affects other sectors of the economy, providing them with new opportunities for development and control. For this reason, the analysis of the prospects for the application of the digital technology in certain sectors of the economy and its impact on the level of demand for energy carriers becomes essential and relevant.

In recent decades, the world is experiencing global processes of digitalization of the economy, new infrastructure is being formed, new services are emerging to meet the growing needs of the population. The most important place in this process is occupied by digital technologies such as robotization, Internet of things, Big Data, artificial intelligence, blockchain, etc.

The rapid growth in the application of information and communication technologies in the economy was made possible by technological progress and the rapid cheapening of three components: data, analytics, and communication. The reduction in the cost of sensors (by more than 95% since 2008) [10] led to their widespread adoption, explosive growth in the volume of available data, and the dissemination of digital information. Reducing the cost of computing power, the development of cloud technologies and Big Data, progress in deep analysis, including machine learning and artificial intelligence, opens up new opportunities for monitoring, analysis, and study of processes to obtain useful information, forming new knowledge and ideas. Reduced cost of data transfer through digital communication networks while increasing its speed, the development of technical capabilities to install data transmission and processing modules on transducers, sensors, and small devices, as well as the analysis of the received information create preconditions for mobile

* Corresponding author: galperova_e_v@mail.ru

control of industrial, transportation, and domestic processes.

Nowadays, digital technologies are used in the industrial sector (to control processes and increase labor productivity and safety); in the transportation sector (to control traffic lights, collect passenger fare, identify the position on the road); and in residential and public buildings (to meter the use of energy resources and automatically control the operation of utilities and electrical appliances). The emergence and spread of technologies such as Internet of Things (IoT) and Internet of Services (IoS), smart home and smart city systems are transforming the requirements for running businesses, providing services, and housekeeping and are capable of drastically changing the model of the economy and prevailing lifestyle patterns.

2 Prospects for the use of the digital technology across key sectors of the economy and its impact on energy demand

2.1 Industrial sector

It is projected [11] that the share of the industrial sector in global energy consumption will decline from 40% in 2018 to 35% in 2050. This decrease will be greatly facilitated by the spread of digital technologies at all stages of production, from direct process monitoring and control to business planning and document flow.

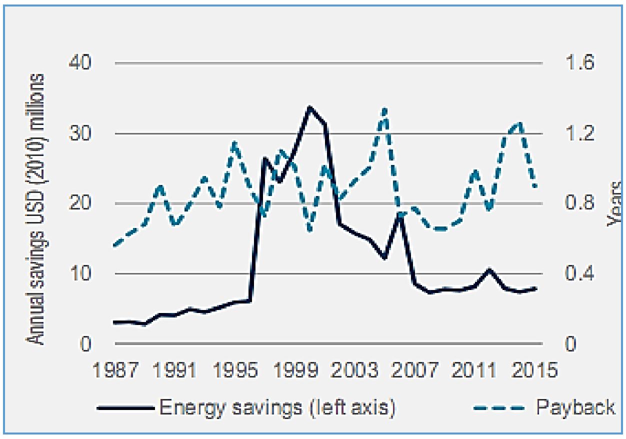
Creating a "digital twin" of real industrial enterprises allows accurately modeling the impact of innovation on changes in the existing production process, speeding up new product introduction to the market, saving time and resources during the design, development and optimization of new production processes.

The use of cloud platforms for the exchange of information of a particular industrial facility with its related enterprises, suppliers, and consumers allows utilizing assets as efficiently as possible and minimizing energy consumption for the transportation of materials and finished products [12].

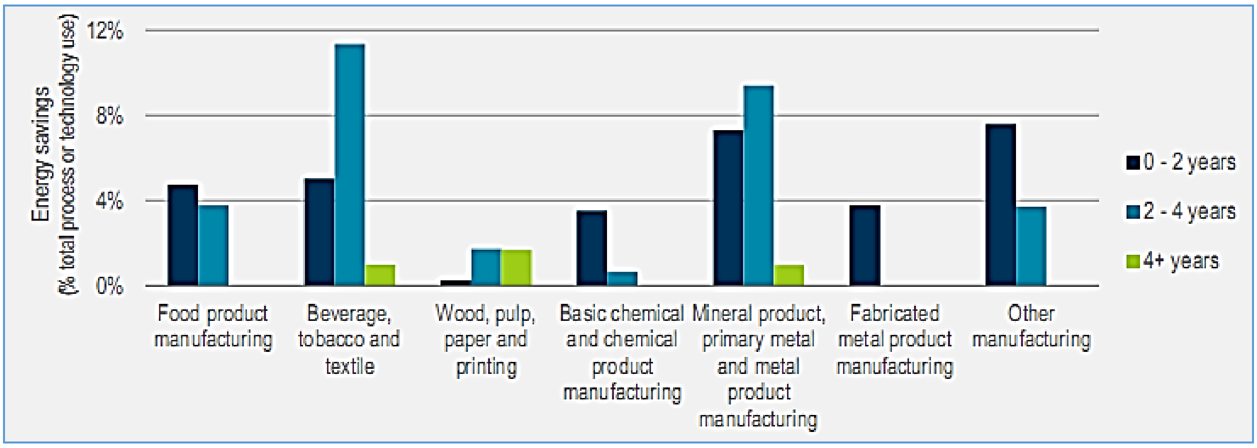
The use of industrial robots and additive technologies (3D printing) can lead to significant energy savings and reduced resource consumption. Industrial robots improve the precision of manufacturing operations, reducing downtime and overheads. 3D printing enables both plastic and metal parts to be produced directly from digital files, which is instrumental in reducing lead times and scrap.

The potential for energy saving through the use of digital technologies in production process control varies significantly across individual industries depending on the type of activity, complexity of the production process, control systems, production culture, and the degree of integration of the enterprise in value chains (Figure 1).

Improved energy efficiency through the use of advanced digital process controls leads to significant energy savings. For example, in the USA, small industrial enterprises saved energy by more than USD 330 million over the period from 1987 to 2015 due to improved process control (Figure 2).



Source: [14]
Fig. 2. Energy savings in digitally enabled optimization of process controls in the United States.



Source: [13]
Fig. 1. Potential energy savings from improvements in process control enabled by digitalization by subsector in Australia, 2010-11.

2.2 Transportation sector

In 2018, energy consumption by all modes of transport was about 40% of the final energy consumption in the world. The adoption of digital technologies helps to increase energy efficiency, reduce maintenance and operation costs of transport. Digitalization of all modes of transport will allow forming a new model of transport activity management, making the movement of passengers and cargo much smarter, more efficient, and more environmentally friendly [15].

The most revolutionary transformations can take place in road transport. Even now the global positioning system (GPS) helps in real-time to choose the right direction, speed and facilitates in rationalizing energy consumption by cars. The widespread dissemination of automation, communication technologies, car sharing services, along with further electrification can completely change the system of its organization. The experts hold [16] that in the long run, these transformations are capable of both reducing energy use in road transport by about half and increasing it by the same amount. The analysis of the scenarios developed by the U.S. Department of Energy for the long term [17], according to which the use of fuel and energy in automated vehicles can both be reduced by more than 90% and tripled, also shows considerable uncertainty in the estimates. Such a wide spread in prospective energy consumption estimates is associated with a high dependence on the scale of technology adoption, their interaction, the behavior patterns of the population, and the priorities of the government policy.

In railway transport, continuous control of the rolling stock operation conditions contributes to the reduction of fuel and electricity consumption. Automated driving technologies are already applied on high-speed and city lines, there are also fully automated trains. Automatic control that makes use of technologies of Big data and artificial intelligence will improve the operation of more trains based on the same infrastructure, optimize speed, increase volume, even out the traffic flow, improve performance, and reduce energy consumption.

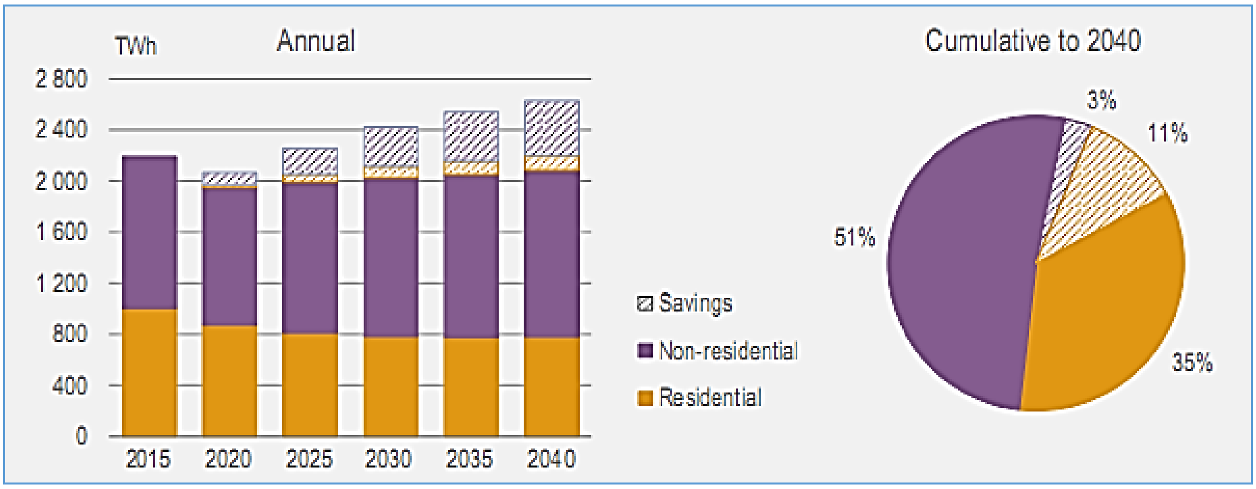
In maritime transport, improved communication between ships and ports provides the opportunity to choose the optimal speed of the vessel in accordance with the requirements of the time of arrival at the port, which provides significant fuel savings.

In air transport, large data analysis helps optimize route planning, aids pilots in make decisions during the flight, and reduces fuel consumption. The use of unmanned aerial vehicles for civil and commercial purposes is still at an early stage of development, but with the widespread dissemination of this technology, cargo logistics and fuel demand may change significantly [18].

2.3 Buildings

It is projected [19] that the share of energy consumption by all types of buildings in global energy consumption will change from 20% in 2018 to 22% in 2050. Among other things, the use of active monitoring and control systems for energy supply to residential and commercial buildings helps contain energy consumption growth. The digital technology provide new opportunities for improving energy supply, increasing comfort and reducing overall energy consumption in buildings. Active control systems collect, process, and analyze data in real-time and allow controlling power consumption from a single interface panel (such as a smartphone or tablet). According to the IEA projection [16], increasing the operational efficiency of buildings using real-time data may reduce the total energy consumption by 10% in the period from 2017 to 2040. This applies primarily to heating and air conditioning processes, where, thanks to the use of sensors and intelligent thermostats [20], potential energy savings can range from 15% to 50% (depending on the type of the building and control system).

Intelligent lighting [21], which consists of high-performance LEDs connected to building control systems, allows analyzing user preferences, illumination, building operation mode and provides a higher quality of lighting with significant energy savings. According to IEA estimates [16], in the period between 2017 and 2040, intelligent lighting can save almost 20% of the total final energy consumption for lighting, in addition to the savings already brought by the widespread use of LEDs themselves. Moreover, commercial buildings account for most of the additional savings due to intelligent lighting (Figure 3).



Source: [16]
Fig. 3. Potential electricity savings from smart lighting in buildings to 2040.

2.4 Transformation of the electric power industry

The use of digital technologies blurs the line between traditional energy suppliers and consumers and creates opportunities for consumers from all sectors of demand to participate directly in the energy system, balancing supply and demand in real-time [3]. This is ensured by the following: (1) the emergence of the consumer's ability to change their energy consumption depending on the situation in the energy system (demand response), (2) an increase in the share of prosumers who have their own sources of energy production or storage and contribute to the development of distributed energy resources, (3) the introduction of "smart charging" of electric vehicles, which switches the demand in off-peak periods (saving investment in new electricity infrastructure), (4) the use of new tools such as blockchain to facilitate the operation of the local system of energy trading [4].

The application of digital technology in the electric power industry is changing the entire business model of the industry, so that the concept of the Internet of Energy (IoE) has already taken off. Its characteristic features are:

- electricity production becomes distributed,
- electricity flows become bidirectional,
- "things" become participants in the new electricity market,
- energy is mobile and available anywhere, like mobile Internet.

3 Energy consumption by information and communication technologies (ICT)

The downside of the process of wide dissemination of digital technologies and the associated reduction of energy consumption across the sectors of the economy is the growth of energy consumption by ICT devices themselves. Even today, information and communication technologies, including data processing centers, data transfer networks and connected devices, have become important consumers of energy. In 2007-2012, the average annual growth rate of ICT energy consumption in the world was approximately 7%, while the total growth rate was only 3% [16]. In 2012, global electricity consumption by the ICT sector was estimated at approximately 900 million MWh, or 4.6% of total electricity consumption [22]. According to estimates presented in [23], currently ICT in the world accounts for 5-9% of total electricity consumption, and by 2030 it may increase to 20%, though without factoring in the potential for efficiency improvements.

3.1 Data processing centers

Data processing centers (DPC) use energy to power both information technology equipment (servers, storage, network devices) and auxiliary infrastructure (e.g. cooling equipment). Energy consumption of data processing centers in the world doubles every 5 years and even now, according to different estimates, makes 3-5% of the total energy consumption in the world (Figure 4). At present, the issue of energy efficiency and energy saving opportunities in data processing centers is very urgent [24, 25].

The main directions of energy saving in data processing centers are [27]:

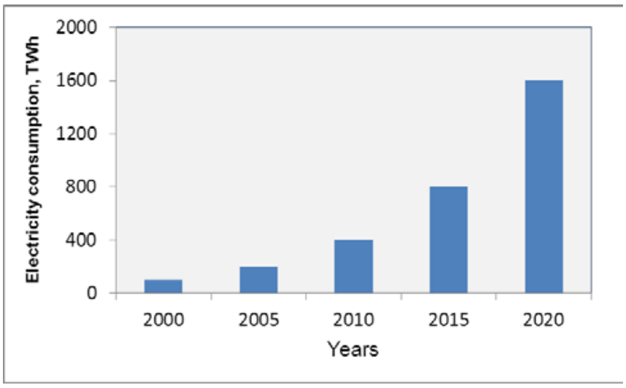
• optimization of the number of units of equipment: this reduces electricity consumption and decreases the amount of heat released;

• application of the free cooling system: this leads to reduction of energy costs;

• increase in acceptable temperature inside the data processing center: increase in temperature by one degree reduces the level of power consumption by 4-5%;

• use of virtualization technology: (when a significant number of services are transferred to a small number of physical machines) this can save 10-40% of energy.

* Corresponding author: galperova_e_v@mail.ru



Source: [26]
Fig. 4. Dynamics of annual electricity consumption by data processing centers in the world.

Moreover, models are developed (see, for example, [28-30]) that describe the power consumption processes in cloud data centers by looking at static and dynamic parts of cloud components and showing how up to 20% of power consumption can be saved by following appropriate optimization directions.

3.2 Data transmission networks

Data transmission networks: they transfer information via fixed and mobile networks between two or more connected devices. In 2015, according to some estimates, they consumed 185 TWh (1% of total demand) of electricity. There is great uncertainty about the power consumption by data transmission networks. It is estimated that by 2021 electricity consumption in data transmission networks may increase by 70% or decrease by 15% depending on future trends in the efficiency improvement policy [16].

3.3 Connected devices

Connected devices and intelligent controls, including simple occupancy sensors and photo sensors, consume power to maintain communication even in standby mode [31] (Figure 5). For intelligent lighting, for example, the consumption varies from 0.15 W to 2.71 W per lighting fixture. Consequently, some connected lamps may consume more energy per year in standby mode than when actually used, reducing their net energy efficiency by more than half. Active control devices in the world in 2010 consumed about 2 kWh/sq.m. on average. It is expected that their continuous improvement and increased use will reduce the power intensity of active control devices by half in the next 25 years [16].

4 Conclusion

The digital technology is already used today across all sectors of the economy and everyday life of the population. Expansion of their use in the future changes the organizational and economic business model of production and provision of services and influences the demand for different types of energy carriers. ICTs are becoming an important energy consumer, whose prospective energy demand levels will be determined by the growth of data processing volumes and an increase in the efficiency of equipment used.

At present, there is a great deal of uncertainty in the estimates of the impact of digital technologies on energy demand in various industries and sectors of the economy, which is due to their great dependence on the priority directions of the government policy, lifestyle patterns, scale and speed of dissemination of technological progress. Further research in this area is a prerequisite for the modernization and development of available approaches to assessing the long-term dynamics of the demand for energy carriers.

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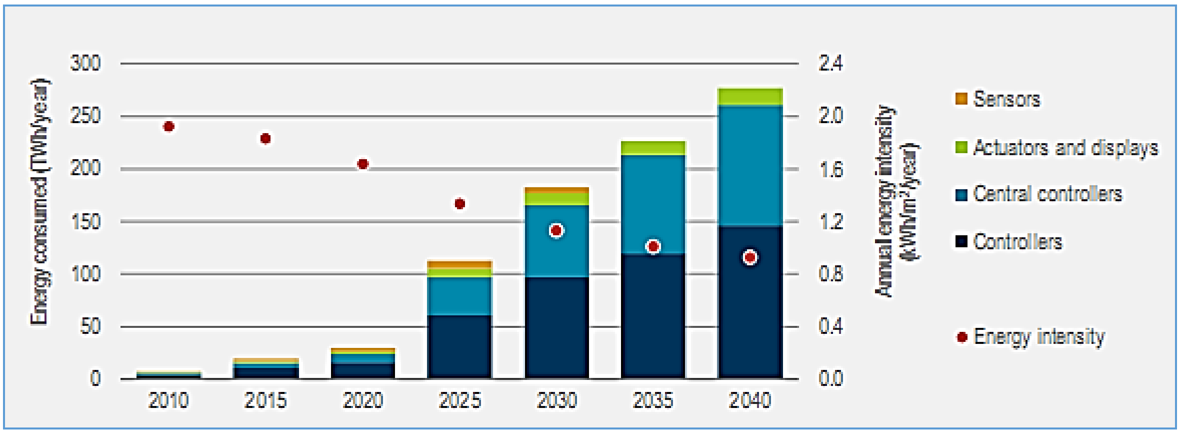

Source: [16]

Fig. 5. Global energy use and average energy intensity of active controls in buildings.

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Analysis power shortage minimization methods in the modern processing software for adequacy assessment of electric power systems

Dmitrii Iakubovskii[1,*], *Denis* Boyarkin[1], *Dmitry* Krupenev[1]

[1] Melentiev Energy Systems Institute of SB RAS, Irkutsk, Russia

Abstract. Analysis of domestic and foreign software systems for assessing the resource adequacy showed a variety of models and methods used in them. Many software systems use both linear and nonlinear models, these models are optimized according to various criteria to simulate the operation of the system. As tools for solving, software usually use commercial high-level modelling systems for mathematical optimization. However, in addition to the existing ready-made commercial solutions, the authors consider the effectiveness of optimization methods, as well as their parallelized versions, which can be independently implemented and applied as a solver for a specific problem. As a result, it was confirmed that these methods can be used to solve the problem, but they are less effective relative to a commercial solver. From the point of view of accuracy and resources spent on calculations, the most effective of the independently implemented methods turned out to be the parallelized method of differential evolution, which was confirmed by numerical experiments on small systems.

1 Introduction

The need to ensure a high level of reliability of electric power systems (EES) has always been relevant, however, modern consumers of electricity impose even higher requirements for ensuring the reliability of power supply. This is also associated with a high level of economic costs in the event of an interruption in the production and supply of electricity to consumers, and directly depends on the equipment and its failures. In view of constant changes towards the enlargement and complication of EPS, early planning, timely correction of changes and redundancy of its elements is one of the main directions of ensuring reliability. Thus, to minimize the number of cases of limiting the supply of electricity to consumers, it is necessary to implement in advance a set of technical and organizational measures aimed at increasing the reliability of the EPS. However, due to the fact that such activities are costly, an objective justification for their implementation requires a qualified assessment. For this, an assessment of the resource adequacy of prospective EPS schemes is carried out. The result of the assessment is reliability indicators that have an economic interpretation.

One of the stages of assessing the resource adequacy when applying the Monte Carlo method [1] is to determine the power deficits of the possible states of the EPS. The basis for calculating power deficits is the simulation of EPS, which includes a mathematical model of the EPS, as well as optimization methods that allow obtaining the value of the power deficit for each of the considered states of the system. The quality of the results, including the speed and accuracy of the calculation, the ability to solve problems with a growing number of optimized parameters, depends on the optimization method used and the correctness of the mathematical model. The statement of the problem of minimizing the power deficit can be presented both in linear and nonlinear form [2]. The most adequate formulation is in a non-linear form, where the losses in power lines have a quadratic dependence on the transmitted power [3].

In the well-known domestic and foreign practice, various optimization methods are used to search for power shortages, for example, in the YANTAR software and computing complex [4-5], the method of internal points is used in conjunction with a linear and nonlinear model, in the ORION-M "[6] a dual simplex method and a linear model are used. In the software " Reliability "a high-level modeling system for mathematical optimization" GAMS "(CONOPT nonlinear optimization solver) is used, as well as various gradient and heuristic methods are investigated, linear and nonlinear models are considered [7 -8]. In turn, foreign software use both ready-made commercial solvers and their own implementations. For example, the GRARE complex uses the implemented methods of linear and quadratic programming to solve a linear problem [9], ROM uses the GAMS system and considers only nonlinear models [10], the ANTARES complex uses independently implemented linear models and optimization methods [11], in several in the PLEXOS complexes - UCo2, CCo1, EU 2030 [12], linear and nonlinear models are implemented, the Gurobi, CPLEX,

* Corresponding author: dmitrii_iakubovskii@isem.irk.ru

XPRESS solvers are used, all of the above complexes are commercially available, closed projects.

Based on the proposed for consideration software computing complexes for assessing the resource adequacy, it can be concluded that the developers of the complexes use both independently implemented optimization methods and off-the-shelf products in the form of linear and nonlinear optimization problem solvers. The presented work analyzes the effectiveness of various independently developed optimization methods and their versions with embedded parallel technologies, as well as available commercial solutions.

2 Brief description of the analysed optimization methods

2.1 Interior point method

Interior point (IP) methods (also called barrier methods) are a specific class of algorithms for solving linear and nonlinear convex optimization problems [13]. The key idea of the interior point algorithms is to eliminate constraints - inequalities from the problem - by introducing a quadratic or logarithmic penalty in the objective function for approaching the boundaries of the admissible region. According to the methods, the starting point for the search can only be selected within the valid area. The choice of the starting point of the search is carried out depending on the formulation of the problem. In the absence of constraints or converting them to penalty functions with an outer point, the starting point is chosen arbitrarily. When constrained or converted to penalty functions with an interior point, the starting point is selected within the valid range. In this case, the set of points is divided into acceptable and unacceptable, depending on the restrictions. In turn, the set of admissible points, depending on the constraints, is also divided into boundary and internal. A function $F : IntK \to \mathbb{R}$ is called a barrier function for a set K if $F(x) \to +\infty$ with $x \to \partial K$, where $IntK$ is the interior space of K and ∂K is the boundary of K. Instead of the original problem, it is proposed to solve the problem:

$$\min_x \varphi(x,t) = tf(x) + F(x). \qquad (2.1)$$

F and φ are given only in $IntK$, the barrier property guarantees that φ by minimum of x is exist, at the same time, the larger t provide the greater influence of f. Under reasonable conditions, it can be achieved that if t would tends to infinity, then the minimum of φ converges to the solution of the original problem.

If the set is given as a set of inequalities $g_i(x) \leq 0, 1 \leq i \leq m$, then the standard choice of the barrier function is the logarithmic barrier:

$$F(x) = -\sum_{i=1}^{m} \ln\left(-g_i(x)\right). \qquad (2.2)$$

The minimum points $x^*(t)$ of the function $\varphi(x,t)$ for different t forms a curve, which is usually called the central path, and the interior point method tries to follow this path.

2.2 Conjugate gradient method

The conjugate gradient method (CG) is an iterative numerical method of unconstrained optimization in a multidimensional space [14-16]. The main idea of the CG method, like other gradient methods, is to descend in the direction of decreasing the gradient, but the search for the desired step and trajectory is carried out using conjugate directions.

The definition of conjugacy is formulated as follows: two vectors *x* and *y* are called *A*-conjugate (or conjugate with respect to the matrix *A*) or *A*-orthogonal if the scalar product of *x* and A_y is equal to zero, that is:

$$x^T A_y = 0. \qquad (2.3)$$

Conjugacy can be considered a generalization of the concept of orthogonality. Indeed, when the matrix *A* is the identity matrix, in accordance with equality (3), the vectors *x* and *y* are orthogonal. One possible way to calculate conjugate directions is to use the iterative method to calculate conjugate directions, Fletcher-Reeves:

$$d_{(i+1)} = d_{(i+1)} + \beta_{(i+1)} d_i \,, \qquad (2.4)$$

$$\beta_{(i+1)} = \frac{r^T{}_{(i+1)}}{r_i^T} \frac{r_{(i+1)}}{r_{(i)}}. \qquad (2.5)$$

Expression (4) means that the new conjugate direction is obtained by adding the antigradient at the turning point and the previous direction of motion, multiplied by the coefficient calculated by (5). The directions calculated by (4) turn out to be conjugate if the function to be minimized is given in the form:

$$f(x) = \left(\frac{1}{2}\right) x^T A_x - b^T x + c. \qquad (2.6)$$

That is, for quadratic functions, the conjugate gradient method finds the minimum in *n* steps (*n* is the dimension of the search space). For general functions, the algorithm ceases to be finite and becomes iterative. At the same time, Fletcher and Reeves propose to restart the algorithmic procedure every *n + 1* steps. A restart is necessary in order to forget the last direction of the search and start the algorithm again in the direction of the fastest descent.

In this paper, in addition to the work of the original algorithm, a version with the use of parallelization technology is also considered. As mentioned above, for the algorithm to work, it is necessary to zero the last search direction every *n + 1* steps, i.e. restart of the procedure. However, this parameter is often selected manually and the rate of convergence of the method, as well as obtaining the result, can vary greatly depending on the chosen restart moment. Thus, not always, a once selected iteration number for zeroing makes it possible to find the optimal solution efficiently in terms of resource and time use. As an experiment, 5 different times of direction zeroing were chosen, and indeed the convergence rate of the method varied greatly, including if the numbers of zeroing iterations changed during the execution of the algorithm. Proceeding from the fact that the rate of convergence of the method depends on the moment of zeroing the direction, it is proposed to investigate the operation of the conjugate gradient method with the condition of parallel launching of two or more calculations with different times of zeroing, as well as synchronized stopping, evaluating the obtained solution and choosing the solution as the starting point, with the smallest value of the gradient norm.

2.3 Differential evolution method

Differential evolution method (DE) - is a metaheuristic method of multidimensional mathematical optimization, belongs to the class of stochastic optimization algorithms and uses some ideas of genetic algorithms, but does not require working with variables in a binary code [17-19]. The method (DE) uses the generation of a certain set of chromosomes or vectors of parameters $X = \{x_1, \ldots ,\ x_n\}$, called a generation, the size of which does not change during the execution of all operations. At each iteration, these vectors are updated by generating a new generation obtained from the previous one using a special procedure that combines the operations of mutation and crossover.

During the existence of the method, many of its modifications were invented, in particular, they concerned the procedure for the formation of new generations. In the implementation under consideration, the essence of this procedure is as follows: in the previous generation, the target vector R_1 is determined, as well as 3 different, random vectors (R_2, R_3, R_4), then the mutation coefficient F is set (a real number in the interval [0,1]), after that the vector "mutant" is formed according to the following expression:

$$MV = R_2 + F(R_3 - R_4). \qquad (2.7)$$

Then the target vector and the mutant vector are crossed, depending on the probability of mutation.

This method only requires the ability to calculate the values of the objective functions, without taking into account the upper and lower constraints on the variables, i.e. these restrictions are already use in the method. DE is designed to find the global minimum (or maximum) of non-differentiable, nonlinear, multimodal (a large number of local extrema) functions of many variables. The method is simple to implement and use (it contains few control parameters that require selection) and in reality is an iterative process of creating new, improved generations with mutations, where the end is finding the best set of chromosomes. Despite this, the differential evolution method can be considered one of the most susceptible to parallelization. The implementation of this mechanism consists in the parallel formation of new descendants, since here they are not directly dependent on each other; the mechanism can have the character of data parallelization. Thus, the process of forming each new vector in a generation can be taken out into a separate problem and solved independently of the others, at each iteration. At the end of the procedure for forming the entire population, a process of stream synchronization is required to start the next iteration or stop calculations.

2.4 A set of optimization methods for the CONOPT package

Many foreign and some domestic computational systems are based on commercial solvers, it is allowed to move away from the direct implementation of optimization methods, but such complexes are no less interesting than their own developments. This paper discusses the use of a high-level modeling system for mathematical optimization "GAMS" [20], this complex is aimed at solving various mathematical problems, including optimization ones. GAMS automatically connects the CONOPT4 solver as a nonlinear optimization problem solver. This solver has a hided code and a complex system for transforming the problem into a simplified form, and also divides the solution of the problem into several stages where several optimization methods interact.

The first step begins with a “starting point setting” procedure, changing individual variables one at a time. The procedure is based on Newton's method with some heuristic modifications. Next, there is a transition to the next stages, where the model is solved by the method of sequential linear programming (SLP), after which, the descent by the method of conjugate gradients occurs, then the solution is started by the method of sequential quadratic programming (SQP).

Successive Linear Programming (SLP), also known as Sequential Linear Programming, is an optimization technique for approximately solving nonlinear optimization problems.

Starting at some estimate of the optimal solution, the method is based on solving a sequence of first-order approximations (i.e. linearizations) of the model. The linearizations are linear programming problems, which can be solved efficiently. As the linearizations need not be bounded, trust regions or similar techniques are needed to ensure convergence in theory.

Sequential quadratic programming (SQP) is one of the most common and effective general-purpose optimization algorithms, the main idea of which is the sequential solution of quadratic programming problems that approximate a given optimization problem. For optimization problems without constraints, the SQP algorithm is transformed into Newton's method of finding a point at which the gradient of the objective function vanishes. To solve the original problem with equality constraints, the SQP method is transformed into a special implementation of Newtonian methods for solving the Lagrange system.

3 Mathematical formulation of the problem of minimizing power deficit

The problem of minimizing the power deficit is formulated as follows: for known values of operable generating capacities, required levels of consumer loads, transmission capacities of EPS links and power loss coefficients in EPS links, it is necessary to determine the optimal flow distribution in the EPS [1], [4-5]. There are several types of models for minimizing power shortages; in this article, the applied models will be considered. The following is a linear formulation of the problem:

Mathematically, the problem is formulated as follows:

$$\sum_{i=1}^{n}(\bar{y}_i - y_i) \rightarrow \min_{y} \quad , \qquad (3.1)$$

when the balance constraints are respected:

$$x_i - y_i + \sum_{j=1}^{n}(1 - a_{ji}z_{ji})z_{ji} - \sum_{j=1}^{n} z_{ij} \geq 0\,, \qquad (3.2)$$
$$i = 1, \dots, n\,.$$

As well as constraints on optimized variables:

$$0 \leq y_i \leq \bar{y}_i, i = 1, \dots, n\,, \qquad (3.3)$$

$$0 \leq x_i \leq \bar{x}_i, i = 1, \dots, n\,, \qquad (3.4)$$

$$0 \leq z_{ij} \leq \bar{z}_{ij}, i = 1, \dots, n, j = 1, \dots, n, i \neq j\,, \qquad (3.5)$$

$$z_{ji} * z_{ij} = 0, i = 1, \dots, n, j = 1, \dots, n, \qquad (3.6)$$

where: x_i - power used in zone i (MW), $\overline{x}_i$ - available power in zone i (MW), y_i - the load served in zone i (MW), $\bar{y}_i$ - the amount of load in zone i (MW), z_{ij} - power flow from zone i to zone j (MW), z_{ij} - bandwidth of the power transmission line between nodes i and j (MW), a_{ji} - specified positive coefficients of specific power losses during its transfer from zone j to zone i, $j \neq i$, $i = 1, \dots, n, j = 1, \dots, n$.

The considered model (3.1-3.6) is a common flow distribution model in the field of assessing balance reliability, the solution of which is carried out by minimizing the power deficit. Model (3.1-3.6) is a transport problem. To solve the presented optimization problem, in view of its relative simplicity, the simplex method and the dual simplex method in their various variations are mainly used.

Based on the linear model (3.1-3.6), which is a flow distribution model, it is possible to apply a modification of the balance constraint, so in [4-5] there is a reasonable conclusion that a model where power losses depend on the square of the transmitted power is a more adequate model, close in physical sense to a real model. For this, the model (3.1-3.6) uses modified balance constraints, where constraints of the form (3.2) are replaced by the constraints presented below:

$$x_i - y_i + \sum_{j=1}^{n}(1 - a_{ji}z_{ji})z_{ji} - \sum_{j=1}^{n} z_{ij} = 0, \qquad (3.7)$$
$$i = 1, \dots, n\,.$$

Thus, the set task can be presented in two forms - linear and nonlinear programming problems. The type of the problem strictly depends on the used balance constraints of formulas (3.1), (3.3-3.7). These models are actively used in the "Reliability" computer complex, and were also previously used in the "YANTAR" software.

4 Analysis of optimization methods used in software systems

Experimental calculations were carried out for systems of various configurations, however, in this work, a comparative analysis of optimization methods and the GAMS complex used in different software, applied to a computational test system with the same initial information, is considered, then a test system (TS).

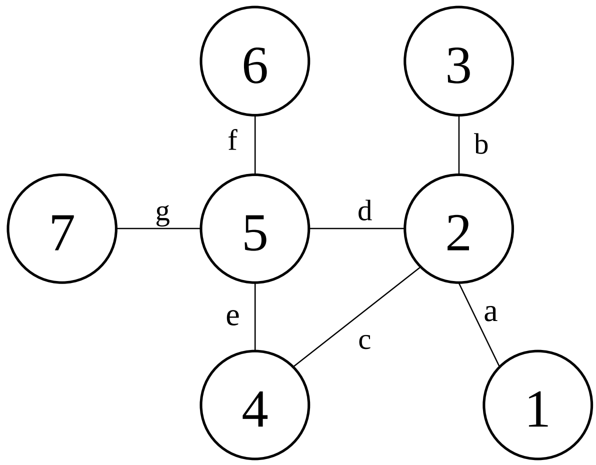

Fig. 1. Schematic diagram of a calculated test system.

Previously, this test system has already been considered for calculating and checking the correctness of models and applied optimization methods in the YANTAR software [4-5], as well as for their research [5], this in turn will add to the comparison methods of internal points implemented by the authors of this complex. Also, for calculations, manually and automatically, a model was implemented, formed from this scheme (Fig. 1) within the framework of the GAMS complex. To test independently implemented optimization methods of the "Reliability" software, this system was created automatically from the descriptive part of this scheme.

Table 1. Characteristics of the reliability zones of the test system.

Reliability zones of the design scheme	Generating power x_i	Load power y_i	Difference in balance
	MW		
1	2458	2734	-276
2	1600	1760	-160
3	383	528	-145
4	1350	170	1180
5	409	1647	-1238
6	921	514	407
7	0	200	-200
System	7121	7553	-432

The main characteristics of the reliability zones of the test system are shown in Table 1. It is worth noting that some reliability zones have excess generating capacity (4, 6), and some are in short supply (1,2,3,5,7).

Table 2. Characteristics of interconnections of the test system.

Interconnection caracter	Begin and end node number by interconnection	Capacity of interconnection in direction		Coefficient of losses on interconnection
		forward	back ward	
a	1 – 2	360	360	0,000078
b	2 – 3	150	150	0,000050
c	2 – 4	200	200	0,000046
d	2 – 5	800	800	0,000017
e	4 – 5	1200	1200	0,000009
f	5 – 6	300	300	0,000008
g	5 – 7	150	150	0,000009

In total, the system has 7 links, the throughput of each link in the directions was the same, in the forward and backward directions. Also, each link had an individual loss rate.

For an indicative comparison of the effectiveness of certain methods, a computational test system was used (Fig. 1), with the characteristics described in Tables 1 and 2. Information about the system and its characteristics, about the work of the method of interior points using quadratic approximations (IPQA) and based on linearization (IPBL) with different calculation accuracy was taken from the source [5]. The calculations obtained using the high-level modeling system for mathematical optimization "GAMS", namely using the CONOPT solver (GAMS_C), as well as the methods of conjugate gradients (CG), differential evolution (DE) and their parallelized versions (PCG, PDE) were carried out independently the authors of the article. Despite the fact that the calculations were carried out on the presented scheme with identical characteristics, the most relevant are the calculations carried out by the authors themselves. A PC with the following set of characteristics was used as the testing equipment: CPU Intel (R) Core i7-8700K @ 3.70GHz, boost 4.50GHz, RAM DDR4 48.0 GB, 15/15/15/36, 2133 MHz.

Table 3. Characteristics of interconnections of the test system.

Method	Accuracy	Count of iterations			Time of calculation
		min	max	avg	Sec
GAMS_C	3e-13	7	8	7.5	0.00256
CG	3e-13	461	2569	1076	0.12268
DE	3e-13	515	2100	593	0,11989
PCG	3e-13	440	1758	874	0,12016
PDE	3e-13	515	2100	593	0,03591
IPQA	ε_1 5e-2 ε_2 5e-2	14	49	19.62	-
IPQA	ε_1 1e-2 ε_2 1e-2	16	74	23.20	-
IPBL	ε_1 5e-2 ε_2 5e-2	14	83	24.22	-
IPBL	ε_1 1e-2 ε_2 1e-2	16	147	40.22	-

In this case, the only objective and available parameter for comparing these methods is the time to solve the problem. The obtained calculation results show the high efficiency of the methods used in the CONOPT solver. The high speed of the solution is achieved by using various approaches and technologies, including simplifying the resulting model, reducing the number of required parameters by expressing them through other variables. The speed of work of independently implemented methods is inferior to a commercial solver. However, due to the fact that the mechanisms used in a commercial solver are not available for open study, it is difficult to estimate the total amount of work done during the period of solving the problem, including taking into account the accuracy of the solution. Unfortunately, the comparison of these methods by the criterion of the number of iterations is incorrect, due to the fact that iterations of different methods can have a different amount of computation. For example, the SG method in one iteration calculates the value of the function, additionally calculates the value of the gradient and several times the value of the function during one-dimensional optimization, while the DE method calculates in one iteration only the value of the function for each element of the population.

Despite the fact that the calculations by the DE method last about the same as the calculations by the SG method, the parallelized version of the PDE using 6 streams received an almost 6-fold reduction in the calculation time. This speaks of the efficiency of using parallelization technologies, and in turn allows using more efficient systems, with a large number of threads, and performing calculations faster.

5 Conclusions

The speed and accuracy of solving the problem of minimizing the power deficit affect the obtaining of adequate values of the EPS reliability indicators and are a necessary condition for solving the problem of substantiating the value of the power reserve. This paper considers various methods and systems used in modern complexes for assessing the resource adequacy of EPS, as well as the application of parallelization technologies to the methods of conjugate gradients and differential evolution. As an experiment, the calculation of a test 7-node system was carried out using the method of internal points, methods of conjugate gradients and differential evolution, as well as using the CONOPT solver from the GAMS package, which is popular in foreign complexes for assessing reliability. Experimental studies have shown that the CONOPT solver from the GAMS package turned out to be the most efficient in terms of the speed of solving the problem, however, when using powerful multiprocessor systems, the differential evolution method in its classical design can be no less effective. Thus, it should be noted that the parallelization mechanisms have shown their efficiency in this situation can significantly reduce computation time and equipment downtime.

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How the excitation system parameters and the generator protection settings affect the reliability of electricity delivery from distributed generation facilities

Pavel Ilyushin[1*], and *Aleksandr* Kulikov[2]

[1]Energy Research Institute of Russian Academy of Sciences, Nagornaya St., 31, bld. 2, Moscow, Russia
[2]Nizhny Novgorod state technical university n.a. R.E. Alekseev, Minin St., 24, Nizhny Novgorod, Russia

Abstract. The paper analyzes the causes of disruptions in electricity delivery to critical users in power areas that operate distributed generation facilities (DG), hereinafter referred to as DG areas. Statistics is shown to be affected by the types of the excitation systems (ES) chosen for the DG generators, as well as by the relay protection (RP) settings as configured when designing the facilities. The paper dwells upon the specifications of the ES's used in low-power generators, their effective applications, as well as the consequences of disturbances in the power area or in an external grid. It is proven herein that RP settings as configured by generator manufacturers are often suboptimal, which jeopardizes their further operation, prevents the operator from aligning these settings to those of the grid RPs, and results in unnecessary disconnections. The paper also details upon calculating the parameters of DG-enabled grids in the common software suits, as well as on how to make a list of effective contingencies. It further gives recommendations on grouping the calculation problems by initial disturbance to optimize the number of projected scenarios. The authors prove that ES selection and generator RP configurations must be appropriate if DG facilities are to deliver electricity reliably.

1 Introduction

Statistics of enterprise-level disruptions in electricity delivery in DG areas is analyzed herein, and the finding is that appropriate design for ES parameters and RP settings is important for reliable electricity delivery.

Cases of industrial DG areas being disconnected from the grid due to a short SC-induced voltage sag are reported on a regular basis. The gravest situations occur when a power area is only powered by a single power transmission line, and the external grid is switched to maintenance mode. In that case, DG facilities either end up being unable to reliably cover the load in the area, which results in disconnecting it; or are disconnected by the RP devices triggered by undervoltage [1-3].

Reason #1 is that ES's were selected inappropriately when designing the area's electricity system. Reason #2 is that a voltage sag might be longer or deeper than what the generator RPs are designed for. The consequences can be grave if that results in disconnecting life support systems or continuous production processes [4, 5].

There are several ES types that have some fundamental differences that must be borne in mind when integrating DG facilities in local grids, as well as some small differences that have little to no effect on generator operations. Depending on the operating situation and which electric devices are connected to the areal grid, some ES properties will be decisive while others will be insignificant.

Generators by foreign manufacturers use ES's designed in compliance with their respective national or common European standards. At the same time, it is the ES algorithms and settings that determine voltage quality in the area, the stability of generators exposed to external disturbances, the parameters of transients, abnormal, and emergency operations.

The paper describes generator ES's widely used at DG facilities and details their operating principles as well as how to approach RP configuration from the standpoint of consumers' quality and reliability requirements.

2 Specifics of generator excitation systems

Let us discuss the commonly used DG generator ES types listed here by reliability for consumers in ascending order, and analyze their features:

– SHUNT is used at generators up to 150 kVA or even up to 500 kVA in certain cases; it is designed to control generators only in steady state, and it does not support continuous voltage control.

Since SHUNT is powered by the generator busbars, it can maintain present excitation current or generator voltage (reactive power; power factor) in steady states when the voltage, the power, and the current are within the acceptable limits. This is effective when one needs to

* Corresponding author: ilyushin.pv@mail.ru

optimize the local parameters, e.g. to minimize the losses, and the area has other parameter control tools.

SHUNT shows its vulnerability when the generator busbars have a voltage sag, i.e. when the external or internal grid short-circuits, the automated reclosing is unsynchronized, etc. In case of lack of voltage control, the generator excitation current decreases proportionally to the busbar undervoltage, which prevents the operating parameters from stabilizing. Whether SHUNT-equipped generators are suitable must be checked by calculating the parameters for specific operating situations.

– PMG, or permanent magnet generator, differs from SHUNT in the sense that the ES has a power source of its own; it is a rotary exciter that is independently subexcited by permanent magnets, so the excitation current does not depend on the generator busbar voltage; this reduces the risks of busbar voltage sags having negative impact.

Figure 1 shows the calculated transients for a 3-phase SC (t_{sc} = 0.18 s) in an area that has a DG facility weakly connected to the external grid; the calculations are done for SHUNT- and PMG-equipped generators. The SC reduces the voltage below the generator RP setting ($U \leq 0.8U_{nom}$) for > 1.2 s in case of SHUNT and > 0.8 s in case of PMG, see Figures 1a and 1b, respectively; the reason is the motors self-starting.

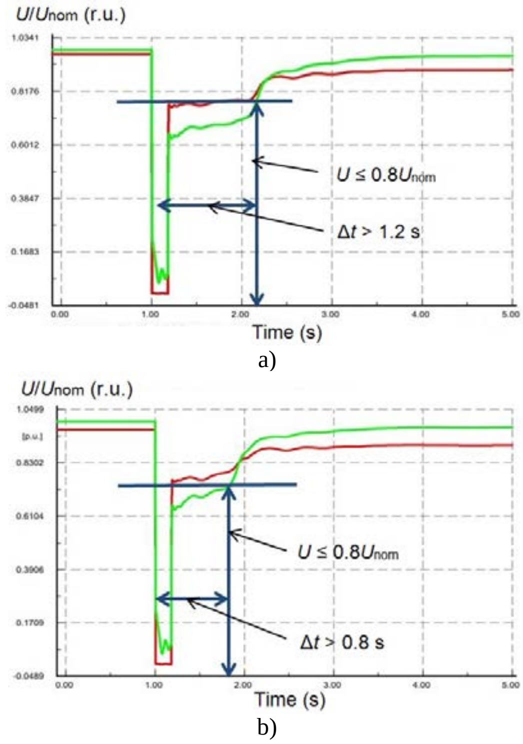

Fig. 1. 3-phase SC transient: (a) SHUNT-equipped generators; (b) PMG-equipped generators.

If the generator RPs are configured to be voltage-triggered after ~1 s, SHUNT will disconnect them while PMG will not.

– AREP (patented by Leroy-Somer) performs similarly to PMG as shown by transient calculations; it somewhat stabilizes the load by increasing the excitation current as the stator current rises (it implements compounding by stator current),

– Analog or digital automatic voltage regulator provided upon the Customer's request.

These regulators are used with low-power generators and differ in terms of response latency as well as in what parameters can be used in the control law. Important factors include the maximum excitation current and the rate at which it builds up, which determines how fast the operating parameters are stabilized after the disturbance has been addressed.

– A specialized automatic voltage regulator with additional functionality to improve the parameters of transients in load surging and shedding.

Possible regulation options include:

– *U/f* ratio to enable nearly instant generator voltage rise after a busbar voltage sag;

– Load Agreement Module to provide a more complex control law that could be adaptively configured for load surges exceeding 60 % of P_{nom}.

These types of regulation are most important for generators operating in insular energy systems (herein referred to as 'power areas', 'areas', and such) or when a power area is islanded by the grid. Analysis of such controls shows that:

– Reducing the voltage of a generator driven by an internal combustion engine (ICE) by means of a Load Agreement Module is an effective method for reducing dynamic frequency drops when the generator is facing a load surge provided that the active load magnitude is essentially dependent on the voltage,

– Voltage reduction might not have a positive effect if the load does not (significantly) depend on the voltage, which is typical of load sites where most active power is used by motors,

– If the load power is switching without a dead time as is the case for triggering automatic load transfers (ALT), this jeopardizes further self-starting and starting of asynchronous motors as the voltage sags,

– When the Load Agreement Module undervolts the generator, this undervoltage can be unacceptable if it disconnects the electricity users and triggers a voltage collapse in the area [6, 7].

Thus, before commissioning generators that have a Load Agreement Module in their ES's, one must analyze the transient parameters to confirm that the function is suitable for their specific operating conditions.

Leroy-Somer lists the following key applications for ES types: SHUNT is for basic power backup and telecommunications; PMG and AREP is for maritime industries, construction, hospitals, banks, and electricity generation. Note that delivery electricity to industrial facilities that carry multiple motors is not listed as a suitable application for these ES's.

Besides, PMG and AREP also allow the stator current to reach the triple value of I_{nom} for 10 seconds, which is due to free currents in the SC current rather than due to forcing an excitation.

Thus, SHUNT, PMG, and AREP all have the same effective application: steady state, no overload, stable busbar voltage. Short-term undervoltage due to external disturbances will have the highest chance of disabling a

SHUNT generator and the lowest chance to disable an AREP generator.

Transient calculations show that reliable electricity delivery to industrial users from SHUNT, PMG, or AREP-equipped generators is impossible in most operating situations where a disturbance occurs, whether it is within a standard tolerance range or (and especially) exceeds it.

Regulation algorithms for steady states and transients alike can be implemented in excitation systems equipped with an analog or digital automatic voltage regulator or a specialized automatic voltage regulator with additional functionality.

3 Configuring the generator RPs

To protect generators from drastic fluctuations in operating parameters, manufacturers tend to configure RPs in such ways as to significantly narrow the acceptable operating range, which prevents these protections from running normally.

Generator disconnection reasons are associated with their tendency to be ever more efficient and cost-effective given that emergencies are being handled ever quicker, and the post-emergency parameters stabilize at ever greater rates. However, operators fail to bring the generator RP settings in line with those of the grid elements, resulting in unnecessary disconnections [8, 9].

Non-selective generator disconnections at DG facilities disrupt electricity delivery to consumers and cause load surges in the adjacent grid, overloading it. One important consideration here is that generator RPs cannot be reconfigured without the manufacturer's permit until the warranty expires, and unauthorized reconfiguration renders the warranty null and void.

Consider a gas-piston power plant (GPPP) that comprises 4*2.4 MW generators configured to disconnect if in all the three phases, the voltage stays above 110 % or below 90 % U_{nom} for 0.2 seconds. How specifically a transient goes depends to a great extent on what comprises the load and on the resulting stability of AC motors. As a GPPP that carries an industrial-grade load becomes islanded with a 15% active power deficit, it causes all the generators to disconnect, and the electricity delivery is disrupted, see Figure 2.

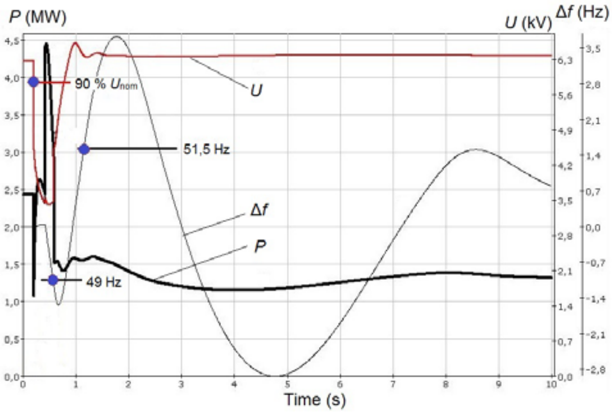

Fig. 2. Transient: GPPP loaded, islanded.

Figure 2 shows RP settings, namely *U* sag and *f* deviation thresholds; the RPs are off. As can be seen there, the transient would be satisfactory if the RPs did not disconnect the generators.

Configuring the generator RPs to be triggered by undervoltage without monitoring the currents is not advisable, as GS windings can only be damaged by overheating if the stator/rotor current overloads are longer or stronger than permissible [10, 11].

The permissible magnitudes of currents are tailored by the manufacturers specifically to the design of the generators, primarily to the thermal endurance class (temperature index) of its windings in correlation with the temperatures, cooling system type, and coolant used with the stator and rotor windings.

In case the stator current exceeds the permissible duration or magnitude, RP disconnects the generator from the external grid; if the rotor current does the same, RP lowers the excitation current (de-excites) to a threshold, below which the rotor windings cannot dangerously overheat.

Besides, when configuring generator RPs, it should be borne in mind that the actual sag duration *U* ~ is twice as long, especially in case of a three-phase SC, as SC-shut motors demand greater current to return back to their normal rotation speeds. Figure 3 shows a transient where the post-SC voltage sag is longer due to the motors self-starting at the load nodes.

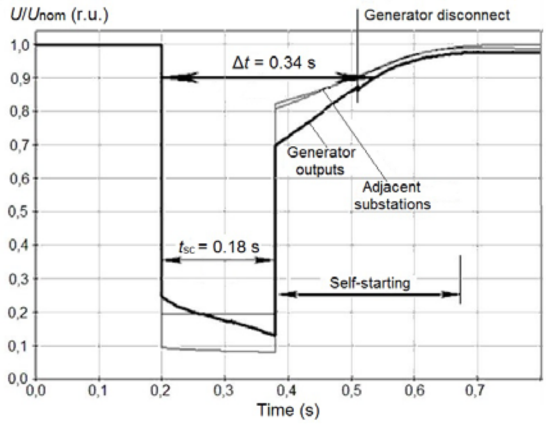

Fig. 3. Three-phase SC transient with motor self-starts.

Importantly, generators can be disconnected by RPs triggered by frequency deviations ($f < f_{min}$ and $f > f_{max}$), which are designed with the following in mind:

– Mechanical speed constraints (mechanical strength),

– Avoiding getting too close to resonant frequencies, as those greatly amplify the vibrations,

– Avoiding rotation speed drops to prevent failures or inappropriate functioning of the auxiliary equipment designed to enable the generator drive to function properly, e.g. when the air-and-fuel mixture fails to ignite properly in the ICS cylinders.

Significant load surge or shedding not associated with an SC may also result in disconnecting the generators in islanded operation, which can happen when connecting or disconnecting high-power users or their groups. Generator manufacturers specify maximum acceptable voltage surges that depend on the initial generator load and will not cause the RPs to initiate disconnection routines.

In this case, it is advisable to use process automations that will sequentially start small motor groups while controlling their voltage; the whole procedure must be adjusted to the processes of the facility or to the soft-starter (variable frequency drive) of the most powerful motors.

If the generator voltage busbars are connected directly or through the power transformer to an extensive 6-35 kV grid, where time-selective overcurrent protections are used primarily or as backups, the generators have a far higher probability of disconnecting unnecessarily.

Thus, when designing DG areas, it is important to rigorously analyze the transient calculations to find out whether specific generator types (ES parameters and RP settings) are suitable for reliable electricity delivery from DG facilities to the users.

4 DG-equipped grids: specifics of parameter calculation

This analysis must be carried out for normal and abnormal operation. If a generator disruption will damage the consumers, the effective contingency list must be made by calculating the parameters of all possible and hazardous operating situations [12-14].

For such calculations, one should bear in mind two specific features of software suites in use:

– Some of the suites have simplified descriptions of the systems that regulate the current power reachable by the steam turbine engines, which is not suitable for simulating gas-turbine engines and ICEs unless adjusted,

– Suites are mainly intended for designing backbone grid infrastructure where transients depend little on whether the load models are correct; however, this is crucial for power areas with DG facilities.

When making the calculation model and running the calculations, focus should be made on:

– Accuracy of the parameters of the grid and power plant (DG facility) equivalent circuits for the power area under consideration as well as for the adjacent sections of the grid,

– RP configurations in the adjacent grid: one needs accurate data on how long an SC the power area and the adjacent grid may have,

– Parameters of the AC motors, the list of which will depend on which software is used, which processes are in place, the motor voltage and installed capacity, as primary motors should be added to the model one by one while others can be generalized by equivalence,

– Statistics on single-phase and multiphase SCs of varying duration, which serves as auxiliary data to help get an idea of disturbance probabilities and their consequences,

– Settings of the process automations that control the core processes. These details are needed to check the settings for consistency with the generator RP settings to prevent unnecessary generator disconnections and minimize the damage associated with disruptions in electricity delivery.

The key factor that makes it difficult to calculate the transients in DG areas consists in the variety of calculation scenarios to be covered, namely:

– The original circuitry of the area and its repair varieties, as the key factor is whether there are any repair varieties and how many of them are there, or the lack of connections to the grid,

– The disposable generation capacity for the current circuitry of the area,

– Features of the DG facility generators: ES parameters, RP settings and time offsets; generator drive power control laws, the regulation principles and the delays of power gain,

– Load magnitudes and variations of what comprises them if such variations are significant (maximum to minimum in case the placement within the area differs),

– Standard and above-standard disturbance application spots, taking into account statistics,

– Peculiarities of RP triggers in the local grid, most importantly the maximum durations of multiphase SCs,

– Other specific features of the power area, which, among other things, may appear in future circuits.

If the calculated transients end in a failure, i.e. some of the electrical equipment is and remains disconnected, some of the motors trip and are disconnected by the RPs, cost-effective contingencies must be in place, such as:

– Automated emergency response systems, the algorithms and configurations of which must be in line with those of the process protections,

– Increasing the installed capacity of the DG facilities,

– Installing an energy storage unit, etc.

When selecting contingencies, it should be borne in mind that normally, the calculation covers not the entire transient (from the initial disturbance to getting back to normal operation) but only its onset that detects the equipment that could be affected by the transient, which is what determines the characteristics of abnormal operation.

In case of a large power area, the circuit used for calculations includes only that equipment, the parameters of which may significantly affect the calculation results. This means that any calculation attempt must strive to:

– Simplify the calculations by excluding the basic cases, handling which only requires understanding the nature of the transients, e.g. when generator RPs are triggered by undervoltage in case of a close SC,

– Reduce the number of logical and calculated scenarios by pregrouping the calculation by class (e.g. types of standard and above-standard disturbances) so as to be able to analyze the results and conclude on the effectiveness of the contingencies.

Consider an example of grouping the calculation problems by initial disturbance for a DG area.

1. Normal start of a major motor (it is most important to analyze direct starts to make a list of contingencies, since such starts have a significant impact

on the grid parameters).

2. Motor groups switching with a dead time for process or electricity-related reasons other than SCs in the local grid, if such switching may occur.

3. SCs in a grid where ALT, automatic reclosers (ARC), etc. have a deadtime. In that case, the calculation needs to find whether motor self-start or automatic voltage-controlled restart is possible and permissible.

The calculations require adjustments for SCs in the local grid as well as in any connected grids, especially low-voltage ones that use time-selective (for long SCs) overcurrent protections as primary protections or backups.

In most cases, two initial disturbance parameters must be set: the voltage sag depth as measured at the generator busbars at the SC onset (U_0), and the SC duration. U_0 is an easy-to-calculate parameter convenient for comparing the severity of SCs in different operating situations. However, it alone is not enough for any substantiated conclusion on whether generator RPs will be triggered by voltage or not, as until an SC is over, voltage will continue going down because the braking motors will draw increasing current. It is therefore necessary to monitor the entire transient $U(t)$.

Figure 4 shows the calculated parameters of an islanded DG area. This calculation was made to find the conditions, under which all the motors would be able to self-start while the RPs would not disconnect the generators by frequency drop (the frequency threshold = 47.5 Hz, the time offset = 2 seconds).

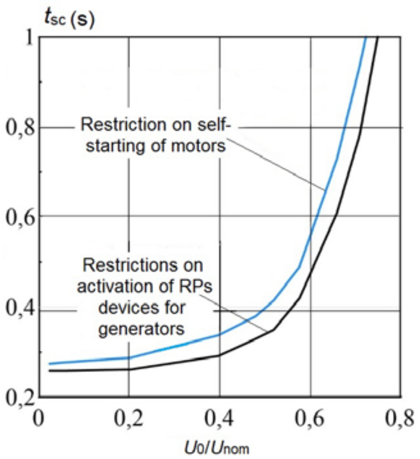

Fig. 4. Permissible SC-induced voltage sag and duration.

Additional calculations should find whether disconnecting non-critical motors that help the more important ones to self-start is permissible, e.g. when reducing the voltage.

5 Conclusions

Industrial DG areas regularly report short-term SC-induced voltage sags disrupting electricity delivery to critical users, resulting in an emergency shutdown of the processes, which entails associated damage.

DG facilities commonly use generators that employ excitation systems designed to control only steady states at stable busbar voltage and no overload; they are not designed for continuous voltage control.

It is proven herein that RP settings as configured by generator manufacturers are often suboptimal, which jeopardizes their further operation, prevents the operator from aligning these settings to those of the grid RPs, and results in unnecessary disconnections.

Calculating the transients for DG areas has its own specifics that distinguishes it from similar calculations for backbone grids; this must be borne in mind when designing the system.

If the calculations show that disrupting the generators would jeopardize critical electricity users, then effective contingencies must be placed when designing the area.

For more reliably electricity delivery from DG facilities to users, especially when the area is islanded, the design must provide appropriately selected excitation systems and generator RP settings.

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Circuit-mode Features of the Distribution Network in the SAIDI and SAIFI Forecast

Yuri Kakosha[1], *Lyudmila* Myshkina[1,*], and *Inna* Sabadash[1]

[1]Novosibirsk state technical university, Karla Marksa, 20, Novosibirsk, Russia

Abstract. The adoption of any technical solutions at the design stage of the distribution network significantly affects the change in the indicators of uninterrupted power supply to consumers: SAIDI and SAIFI. However, methodological support for their determination for the future is not enough. The development of an appropriate methodology and its implementation into design practice is necessary, this is especially important in connection with the appearance of distributed generation, which has a significant impact on the circuit-mode conditions of power supply systems. The developed methodology makes it possible to determine the most effective from the many possible ways of integrating distributed generation and local power supply systems, considering the of the technical condition indices, the structural and functional reliability of the distribution network and the existing mode restrictions, which is a necessary element of development management during design.

1 Introduction

Electric networks diagrams shall ensure the necessary reliability of power supply, transfer of the required amount of electricity of the required quality to the consumers, possibility of the further network development and connection of new consumers, convenience and safety of operation [1]. Therefore, requirements to indicators demonstrating reliable power supply to the consumers are of primary importance for the distribution electric networks.

Indicative reliability indexes have been used at the operational stage since 2012. These include SAIDI (System Average Interruption Duration Index) and SAIFI (System Average Interruption Frequency Index) indexes demonstrating the average duration and frequency of interruptions in power supply to consumers in the area of electric networks, values of which affect the electricity transmission service tariffs [2].

Currently, when designing distribution networks, a technical and economic comparison of power supply options is used, which is based on the of the consumer reliability category concept. However, to a great extent this situation does not correspond to the current state of the distributed generation, electric network digitalization and changes in the control system. It is required to introduce additional criteria to increase technical solutions validity at the stage of managing the distribution networks development. It is proposed to introduce SAIDI and SAIFI forecasted reliability indexes, which values, as noted above, affect economic efficiency of the company.

The need to combine centralized and decentralized control presupposes creation of automation that influences the circuit and regime operating conditions of the distribution network in addition to conventional regime and emergency control devices. This requires to improve the distribution network design process in order to form certain properties - reliability, recoverability, controllability, durability and others. Consequently, tasks of developing the appropriate methodological support, regulatory framework, new means and ways to achieve the set goal are relevant tasks, which determines relevance of the research carried out by the authors, as well as scientific and practical significance of the obtained results.

The purpose of the work is to develop a methodology for calculating the forecasted values of uninterrupted power supply indexes (SAIDI and SAIFI) taking into account the circuit and regime changes in 10 kV distribution network section (DSS) when designing:

- new network equipment;
- connection to the distributed generation network.

DSS is an element of the power supply system for consumers powered from one power supply center. Obviously, selection of the circuit and power lines composition, number of distribution point stations, number and capacity of 10/0.4 kV transformer points and switching equipment depends on two factors:

- capacity of power transformers of the district 110/10 kV substation and 35/10 kV substation;
- number and capacities of consumers, their distribution over the territory;
- distribution of consumers by the power supply reliability category.

Scientific novelty consists in taking into account technical condition of network equipment when

* Corresponding author: Lsmyshkina@gmail.com

calculating uninterrupted power supply indexes, as well as in developing a method for determining "critical" hubs and requirements to justify network redundancy or connection to the distributed generation network.

Practical significance consists in supplementing the methodological base for the development of consumers technological connection diagrams and power distribution schemes by power plants. It is noteworthy that obtained results make it possible to solve a set of tasks for the creation of local energy systems and their integration with the UES for synchronous parallel operation with the possibility of separating them to maintain uninterrupted power supply in case of 35 kV and higher network technological failure.

2 Status of the challenge addressing

To assess power equipment reliability and service continuity 35 kV and higher network, which form the federal and regional power supply systems, the following methods and guidelines are currently used:

- Methodology for assessing technical condition of the main technological equipment and power transmission lines of power plants and electric networks approved by Order No. 676 of the Ministry of Energy of Russian Federation dated 26.07. 2017 (as amended on 17.03. 2020) [3];
- Methodological guidelines for calculating the probability of failure of a functional unit and a piece of the main technological equipment and assessing consequences of such a failure approved by Order No. 123 of the Ministry of Energy of Russian Federation dated 19.02.2019 [4].

Both methodologies cover the following technological equipment of electricity generation facilities, which technical condition is being assessed: Steam turbines with the installed capacity of 5 MW and higher; Steam (power-plant) boilers providing steam to steam turbines with the installed capacity of 5 MW and higher; Hydraulic turbines with the installed capacity of 5 MW and higher; Gas turbines with the installed capacity of 5 MW and higher; Hydrogenerators with the rated power of 5 MW and higher; Turbine generators with the rated power of 5 MW and higher; Power transformers with voltage of 110 kV and higher; Power transmission lines (hereinafter, transmission lines) with the voltage of 35 kV and higher (hereinafter, main technological equipment).

The available methodology [3] determines the procedure for assessing technical condition of the main technological equipment and determining optimal type, composition and cost of technical impact on the equipment. One of the main purposes of the technical condition index (TCI) determining methodology is to address challenges of decision-making on the technical impact on technological equipment, i.e. the methodology is applied at an operating facility taking into account statistical data collected during the operation. The available Methodological guidelines [4] determine the procedure for calculating the probability of failure of a functional unit and a piece of the main technological equipment of power plants and electric networks, as well as the procedure for assessing consequences of such a failure. The methodology ensured accelerated determining of uninterrupted power supply indicative indexes.

The calculation of the probability of failure of a piece of the main technological equipment and (or) its functional unit shall be based on:

- Forecasting changes of technical condition index of the piece of the main technological equipment
- Forecasting probability of failure of functional units of the piece of main technological equipment
- Forecasting probability of failure of the piece of main technological equipment.

The mentioned methodologies [3] and [4] are applied to 35 kV and higher electrical networks (power supply centers) characterized with high observability and sufficient scope of statistical documents for the main technological equipment. Circuit and regime peculiarities and structure of these networks allows determining technical condition indexes for each piece of equipment, as well as taking into account the forecasted reliability indexes when designing. However, there is a number of differences between 10 kV distribution networks and 35-220 kV supply networks, which makes it impossible to apply methods [3] and [4] in these networks. Let's analyse these differences. One of the main features of power distribution networks for domestic and agricultural consumers is their ramification and length. This is due to the variety of connected consumers (both in size and composition of loads), proximity of the connection points, mainly radial method of loads connection and the lack of these networks future development schemes. Structure of the distribution networks is ramified and complex due to many switching devices and overhead lines, which leads to frequent technological failures of these networks. As a result, failures in 6-10 kV networks cause about 70% of all power supply disturbances to consumers, which reduces technical efficiency of these networks [5].

As an example, we can take a part of the real power supply scheme of Sverdlovsk Region of Irkutsk (REN) of the Southern Electric Networks of JSC "IESK" (see Fig.1). Based on the circuit analysis results, one 35/6 kV power center supplies 44 transformer substations of 6/0.4 kV, two Central Distribution Point Stations of 6 kV and more than 60 km of 6 kV lines. At the same time, maximum power of the load connected to the power supply points of 6/0.4 kV transformer substation is 9 MW, although 2x10 MW transformers are installed in the power supply centers. According to the current rules, size of the connected load is limited in terms of reliability requirements, i.e. based on n-1 criterion. A large number of main electrical equipment with different technical characteristics makes it impossible to apply the available methods for calculating the TCI and the probability of the equipment failure. Calculation of distribution networks reliability indexes is also complicated by the lack of periodical examination of the main equipment necessary parameters, and as a result, impossibility of annually calculation of changing TCI for each piece of the equipment.

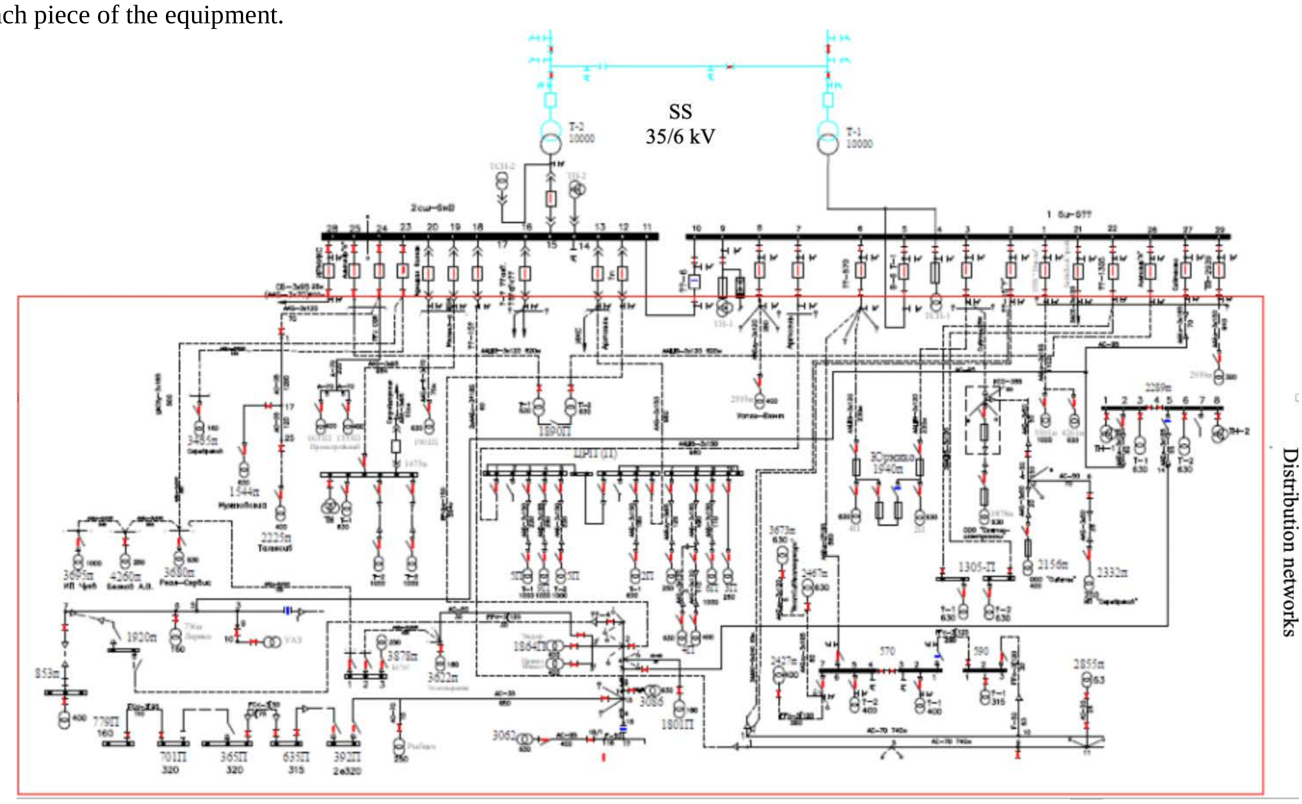

Fig. 1. Part of REN power supply diagram

Uninterrupted power supply depends mainly on distribution networks, and taking into account the forecasted reliability indexes of these networks can increase validity of decision-making at the design stage. However, methods applied today prevent from the task fulfilling in distribution networks, i.e. to determine the forecasted SAIDI and SAIFI indicative reliability indexes at the stage of distribution network development management. Consequently, it is required to develop additions that will allow using the methodologies for calculating technical condition indexes and probability of failure-free operation of electrical equipment in the distribution network, as well as determining promising indicative indexes of uninterrupted power supply.

3 Main provisions of the proposed methodology

First of all, when designing electric distribution networks, conditions of reliable and high-quality power supply to consumers must be observed, in contrast to the main system-forming networks, where compliance with technical conditions ensuring safety and reliability of electrical power systems and maintaining stable synchronous operation in normal and post-emergency regimes is of primary importance.

In addition to the existing methods for determining forecasted indicative power supply reliability indexes in distribution networks, it is proposed to calculate generalized TCI for groups of equipment (elements) of the distribution network rather than for each piece of equipment individually.

3.1. Generalized index of the distribution network technical condition

Main elements of 10 kV distribution network are a power transformer, cable line, an oil circuit breaker. Table 1 shows main functional units of the elements identified in the frame of this work.

Table 1. Functional units of distribution network elements.

Facility	Functional units
Power transformer	Insulation system; transformer windings; magnetic circuit; high-voltage bushing; voltage regulation system
Cable line	Auxiliary equipment; terminal and connecting couplings, power cable
Circuit breaker	Drive, arc-suppression chamber, contact system

The adopted methodology for assessing technical condition of the main technological equipment [3] does not indicate how certain weighing factors were assigned for the functional units taken into account for the functional units technical condition index calculation.

The proposed method envisaged weighting coefficients of the network element functional units to be determined based on the expert assessments and statistical data of technological disturbances caused by the failure of functional units corresponding to this element.

The final score was determined by the method of expert assessments and the Saati method [6] with the introduction of coefficients demonstrating the experts competence. Expert assessments shall be drawn up for each distribution network section taking into account its peculiarities. Authors of the study assumed that the boundary values of the scoring scale characterizing functional units technical condition and level of performance of the required functions. functional units scoring multiplied by the functional units weight allows obtaining the generalized TCI. Value of the generalized TCI will be applied in determining the prospective values of the indicative power supply reliability indexes.

3.2. Generalized index of the distribution network technical condition

When calculating forecasted probability of failure of the main technological equipment functional unit or a PTL segment for a forecasted period of 5 years, methodology [4] uses a correction factor that takes into account the ratio of the value of the main technological equipment functional unit technical condition index or the PTL segment before and after the last technical impact or during the previous and current calendar year.

However, system of collecting information on the parameters characterizing technical condition of the equipment currently used in distribution networks does not allow obtaining reliable data. It has been established that data collection process is not conducted systematically, in a timely manner, and does not provide formal data analysis. Causes of numerous network elements failures (up to 50%) have not been identified. This indicates an unsatisfactory condition of the system for collecting repair and operational information at the power grid complex facilities, as well as insufficient number of technical diagnostics and automated monitoring systems [7]. All of the above indicates impossibility of obtaining a reliable correction factor value that demonstrates impossibility to determine network functional unit failure probability.

In this regard, the proposed methodology provides for the correction of λ_i distribution network element failure rate determination, which is proposed to be used taking into account the required and actual values of the technical condition generalized index:

$$\lambda = \lambda_s \left(\frac{TCI_g{}^r}{TCI_g{}^c}\right) \tag{1}$$

where λ_s is the statistical value of the power supply system element failure rate; $TCI_g{}^r$ - the required value of the technical condition generalized index, $TCI_g{}^r$ is taken equal to 85 points for the distribution network elements since it corresponds to the running-in period; $TCI_g{}^c$ - distribution network element technical condition generalized index under actual operating conditions.

Therefore, to calculate idle time of the power supply system element (T), the well-known expression shall be taken:

$$T = \lambda t_r \tag{2}$$

where t_r - is the recovery time of the i-th element of the power supply system.

Forecasted System Average Interruption Duration Index ($SAIDI_F$) for the local grid company supplying energy to the point of delivery, taking into account the distribution network, shall be determined by the formula:

$$SAIDI_F = SAIDI_C - \left[\left(\frac{\sum T_i \cdot N_i}{N_{max}}\right)^C - \left(\frac{\sum T_i \cdot N_i}{N_{max}}\right)^F\right] \tag{3}$$

Forecasted System Average Interruption Frequency Index ($SAIFI_F$) for the local grid company supplying energy to the point of delivery, taking into account the distribution network, shall be determined by the formula:

$$SAIFI_F = SAIFI_C - \left[\left(\frac{\sum \lambda_i \cdot N_i}{N_{max}}\right)^C - \left(\frac{\sum \lambda_i \cdot N_i}{N_{max}}\right)^F\right] \tag{4}$$

where C - is the indexation of the current power supply system condition; F - indexation of the forecasted predicted supply system condition; λ_i- failure rate of the i-th critical element of the power supply system, h; N_i - the number of delivery points that disconnected as a result of a technological upset due to the failure of the i-th critical element of the power supply system, pcs; N_{max} - number of delivery points in the power supply system, pcs; T_i - idle time of the i-th critical element of the power supply system;

Power supply system critical elements according to the methodology is the element, which failure causes the largest number of disconnected points of connection. To determine power supply system critical elements, it is necessary to determine the number of units switched off in case of the network i-th element (N_i in (3), (4)) failure. It is proposed to simulate the element failure with control of the steady-state electrical regime and registration of the disconnected units with RastrWin3, ANARES, Eurostag, ETAP or others.

$$N_i = \max(N_{i_g}) \tag{5}$$

where N_{i_g} is the number of disconnected consumer connection points in case of the g-th element of the j-th type failure; j = 1… J is the sequential number of the network element type (transformers, cable power lines, switches and other key type elements of the power supply system); g = 1… G is the sequential number of the same type element, G is the number of the same type elements. In this case, it shall be assumed that there are no interrelated failures, only single equipment failures shall be taken into account.

It can be noted that there are quite ambitious plans to reduce uninterrupted power supply indexes in Russia. The average SAIDI in Siberia as a whole by the end of 2019 amounted to 2.53 hours, as a result of Digital Transformation 2030 program implementation, this figure will decrease in 2024 to 2.39 hours, and in 2030 it will reach 2.22 hours, which is 1.1% per year. The average SAIFI in Siberia amounts to 1.63 units, owing to the program implementation, in 2024 this figure should decrease to 1.55 and in 2030 it should reach 1.44 [8], which is 0.9% per year.

Obviously, the main influence on these indicators changing will be provided by technical solutions at the level of 0.4-10 kV distribution networks, which emphasizes relevance of the proposed methodology and expediency of its practical application.

3.3. Application of distribution network development management methodology

The proposed methodology provides for calculation of the forecasted uninterrupted consumer power supply indexes, as well as makes it possible to take specific technical decisions aimed at increasing of distribution network reliability while managing its development.

Comparison of the forecasted continuity indexes allows identifying critical network elements, which failure causes disconnection of the greatest number of consumers (both in terms of power and in terms of power supply restoration), which allows taking appropriate measures to ensure redundancy of these network elements.

One of redundancy provision methods and the current trend in the development of networks [9] is the construction of distributed generation (DG). DG can be used to ensure reliability of the power system since its introduction decreases main and supply networks load, increases reserves the network transmission capability and exudes problem of local energy shortage in the areas of closed power centers [10]. DG introduction will help to significantly reduce investments in the distribution network development and increase power supply continuity.

The proposed methodology makes it possible to determine the most optimal generation connection points to improve reliability of power supply to consumers "under the threat" of power loss. Thus, it will increase reliability of the entire electric network. Also, it will introduce additional criteria for the DG capacity selection taking into account the need to ensure redundancy not only of the part, but of the entire network. The methodology can also be used to determine optimal points of combining several local power supply systems into a single low-power system [11] and to create universal Microgrid, energy cells with an AC infrastructure [12].

Below is an example of the proposed methodology approbation by the authors, which makes it possible to judge the obtained results reliability.

4 Example of the methodology approbation

Approbation of the proposed methodology was carried out on the example of the residential microdistrict DSS, power supply of which is carried out from SS-1 (Fig. 2). The load structure is mainly domestic consumption with a small share of non-production enterprises related to the service sector. The total number of supply points in the analysed area is 108, power of the connected load is 9.42 MW.

Based on the results of the structural and functional network reliability analysis using ETAP programming and computing suite, values of the continuity indexes of the analysed power supply system current condition were determined:

- $SAIDI_C = 2.6420$, h;
- $SAIFI_C = 0.2411$, 1/year

Further, having analysed steady-state regimes, critical elements, which failure causes maximum number of the disconnected delivery points, were determined:

- K-10, which causes disconnection of 12 delivery points,
- transformers TP-3438 causing disconnection of 9 delivery points;
- failures of circuit breaker do not cause customer interruption.

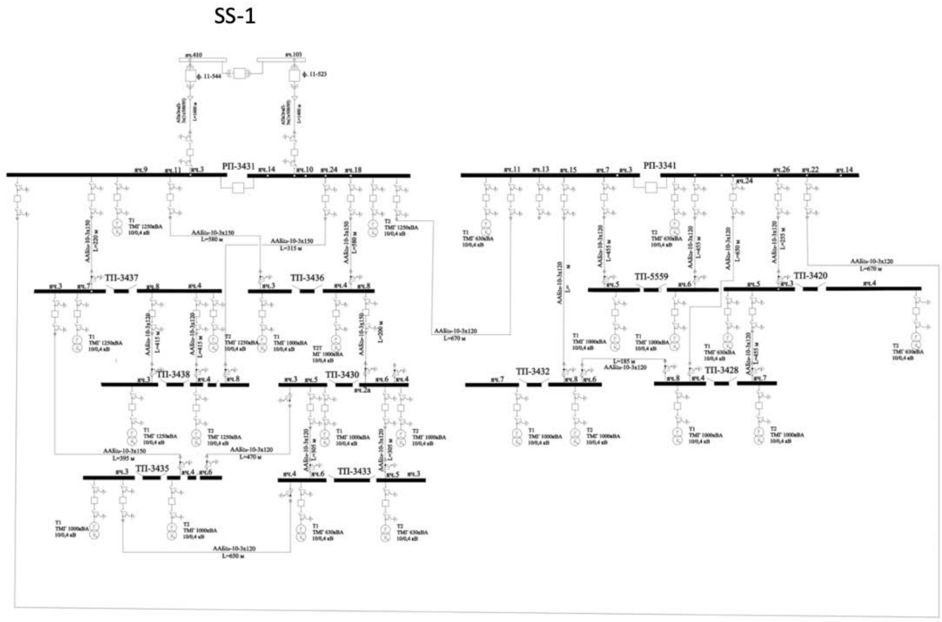

Fig. 2. Design single-line diagram of 10 kV distribution network section

Since the largest number of disconnected delivery points is caused by K-10 failure (the highlighted area in Fig. 3), a decision on the need to ensure the line redundancy was made.

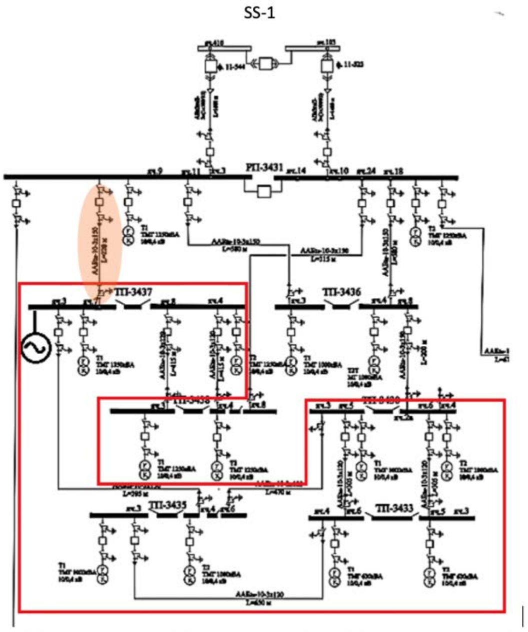

Fig. 3. Dedicated local power supply system.

DG connection and creation of the balanced local power supply system based thereon is considered as a measure to ensuring the improved uninterrupted power supply. Fig. 3 schematically demonstrated DG connection point (bus of TP-3437) with the highlighted local power supply system.

It is modelled that the DG performs network redundancy function, therefore, disconnecting K-10 does not lead to the load disconnection within the selected area, and then its power is determined based on the power of the load connected to the units considering 20% of the emergency reserve: $P_{DG} = 4$ MW.

Therefore, let's build a model providing for the connection of 4 Gas Engine Generators (GEG) of 1 MW each. Performance indicators of the selected GEG: $\mathrm{t_r} =$ 14.43 h; $\lambda = 6.17$ times/year.

According to the proposed methodology, the forecasted uninterrupted power supply indexes were calculated when connecting the DG and creating a local power supply system (Table 2).

Thus, DG construction in the area of the analysed DSS allows improving SAIDI and SAIFI: the indicators decreased by 11.5% and 9%, respectively. This proves effectiveness of the DG construction with the purpose to improve the uninterrupted power supply to consumers.

Table 2 demonstrates comparison of the results obtained using methodology proposed by the authors and results of calculations using ETAP programming and computing suite.

Deviations of the forecast indicators determined by the methodology did not exceed 5% of the indicators obtained using when calculating using ETAP programming and computing suite. This makes it possible to judge the methodology reliability and possibility of its application to increase validity of technical solutions decision taken at the stage of distribution networks development managing without use of additional expensive software.

Table 2. Comparison of the forecasted SAIFI and SAIDI values obtained by various methods.

Method	Methodology	ETAP	Deviation, %
SAIDI	2,3651	2,3632	0,1
SAIFI	0,2211	0,2076	5,0
Δ SAIDI, %	11,5	11,8	-
Δ SAIFI, %	9,1	16,0	-

5 Conclusions

Dependence of the economic efficiency of network companies and uninterrupted power supply is determined by the current procedure for determination of the electricity transmission services tariffs in Russia. However, when making decisions at the stage of regional power supply systems and 0.4-10 kV distribution networks development management, these indicators are not taken into account.

To increase validity of design solutions for 10 kV and lower distribution network, efforts were made to develop a methodology allowing to calculate the forecasted SAIDI and SAIFI indexes values when designing the distribution network development, which can complement the current methodology developed by the Ministry of Energy of Russia.

It is proposed to apply generalized indexes of the distribution network elements technical condition and relationship with the perspective uninterrupted power supply indicative indexes. The methodology was tested on the example of the distribution network section. By comparing the results with the calculations performed using ETAP programming and computing suite, reliability of the obtained results was proved: deviations did not exceed 5%.

Availability of the forecasted SAIDI and SAIFI indexes values in project activities will contribute to increasing validity of the made decisions, including decisions on justification circuits of distributed generation during technological connection to networks, measures for the creation of local power systems and their interconnection taking into account equipment technical condition indexes, structural and functional reliability of the distribution network and the existing operating restrictions, which is a necessary element of development management at the stage of design.

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Multy-year oscillations investigation of winter temperatures Prediction of integrated temperature difference during the heating period

Ivan Khazheev*

[1]Melentiev Energy Systems Institute SB RAS, Department of Applied Mathematics, 664033 Irkutsk, Lermontov st., 130, Russia

Abstract. To estimate possible deviations in fuel consumption for heating based on meteorological observations of previous years, the integrated temperature difference inside and outside the building during the heating season is used. When the heating period is divided into two subperiods relative to the considered date (for example, before and after December 1), the accumulated and residual integral temperature differences are obtained. The assumption about the presence of a statistical relationship between the accumulated and residual integral temperature difference is confirmed. A model for predicting the probability of the expected values of the integral temperature difference for the upcoming heating period is developed. The model is focused on obtaining matrices of conditional probabilities of observations from intervals of dividing the accumulated integral temperature differences into intervals of residual integral temperature differences.

1 Introduction

Due to the long heating period and low winter temperatures, the study of climatic parameters of the heating period is of greater importance for Russia. These are the outdoor temperature, wind speed, air humidity, the intensity of solar radiation. The values of these indicators are used to assess the winter season of the region in question.

Usually the heating period of the region in question is determined by its duration and ambient air temperatures. In coastal areas, an additional cold load can be caused by relative humidity.

The article explores the possibilities of short-term forecasting of the integral temperature difference based on weather data of the first months of the heating period. The assumption of the presence of a statistical relationship between the accumulated and residual integral temperature differences is tested. A model is being developed for predicting the probability of expected values of the integral temperature difference for the upcoming heating period.

Let $\tau = 1,2,\ldots,T$ are the numbers of the studied heating periods, T – the number of heating periods. L_τ denote the duration of the heating period τ. The values $i = 1,2,\ldots, L_\tau$ as the sequence numbers correspond to day heating period τ.

Each heating season starts in the autumn of one calendar year and ends in the spring of the following calendar year. Therefore, each ordinal number of the heating period corresponds to two calendar years. So, the last heating period began in 2019 and ended in 2020.

The article uses the estimated duration of the heating period. To determine it, the following rule is used: the heating period begins if, for five consecutive days, the average daily temperature of atmospheric air is below 8 degrees Celsius. The heating period is considered over if the air temperature is above 8 degrees Celsius for five consecutive days. This formal rule is usually followed by heating systems in settlements.

In solving many problems associated with the heat supply of buildings, an indicator of the integral temperature difference inside and outside the building for the heating period is used. For the considered settlement or district, the indicator of the integral temperature difference is calculated by the formula:

$$B_\tau = \sum_{i=1}(t_n - t_{\tau i}), \quad i=1,2,\ldots, L_\tau, \ \tau = 1,2,\ldots,T \qquad (1)$$

Here, the value $t_{\tau i}$ is the average daily temperature of the air on the day i of the heating period τ. The indicator B_τ is determined on the basis of meteorological observations.

The value t_n is the specified normative value of the air temperature inside the building. Depending on the purpose of the building, there may be different values of normative temperatures. For residential premises, a temperature of 20 degrees Celsius can be used for the standard, for children's institutions - 24 degrees Celsius, for office premises - 18 degrees Celsius. Whereas in production rooms and warehouses, the normative temperature can be 14 degrees Celsius. In the calculations presented in this article, a standard value of 18 degrees Celsius was used.

The use of the indicator of the integral temperature difference inside and outside the building for the heating

* Corresponding author: ivan-khazheev@yandex.ru

period (1) is based on the law of thermal conductivity: the loss of thermal energy through the fencing, in the construction of buildings is proportional to the difference in temperature inside and outside the building. Therefore, the ratio of the integral temperature difference in different settlements or in different years for the same settlements reflect the ratio of heat energy consumption for heating and, as a result, fuel consumption for heat for heating.

The integral temperature difference is in practice applicable for calculating the optimal building structures at which heat losses are minimized.

The temperature of the air is not the only factor determining the requirements for the heat supply of buildings. In some cases, other natural factors, such as wind speed and direction, air humidity, the intensity of solar radiation, as well as technical characteristics and features of the operation of buildings, are essential.

At the same time, the indicator of the integral temperature difference is one of the most important characteristics of the degree of climate severity during the heating period for the region under consideration.

2 Cumulative and residual integral temperature differences inside and outside the building

Divide the heating period into two sub-periods: before and after the date of consideration (for example, before and after December 1). Then the integral temperature difference B_τ can be decomposed into two indicators. There are cumulative integral temperature difference inside and outside the building:

$$B_{\tau\, before} = \sum_{j=1}(\underline{t}-t_{\tau j}), \quad j=1,2,\ldots, L_\tau', \qquad (2)$$

and residual integral temperature difference inside and outside the building:

$$B_{\tau\, after} = B_\tau - B_{\tau\, before}. \qquad (3)$$

Is it possible to predict the indicator of the integral temperature difference for the heating period on the basis of meteorological observations of the beginning and the first half of the heating period? Is there a relationship between the accumulated and residual integral temperature differences inside and outside the building?

Let's check the assumption that if the first half of the heating year was cold (warm), then the probability of a colder (warm) remaining part of the heating period increases.

To test the assumption, a method is used that is based on counting and estimating the frequency of distribution of observations over the quadrants of the coordinate plane.

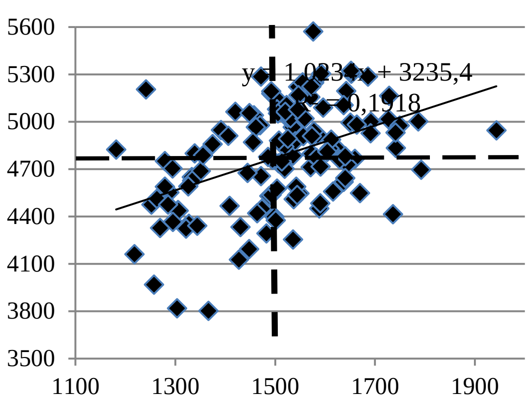
The sets of observations (accumulated and residual integral temperature differences) for all considered heating periods are divided into two subsets according to two criteria. Firstly, the accumulated integral temperature difference of a given heating period relative to the arithmetic mean value for the entire long-term period is more or less. Secondly, more or less the residual integral temperature difference of the mean long-term value of this indicator. In the unlikely cases of coincidence in terms of the indicator under consideration with its average annual value, this heating period is half taken into account in one subset, and half in the other.

The result is a partition of the set into four subsets. The distributions of heating periods by the accumulated and residual integral temperature differences in Irkutsk are shown in Figure 1. The index of the cumulative temperature difference accumulated by a given date is considered along the abscissa axis, and the residual integral temperature difference along the ordinate.

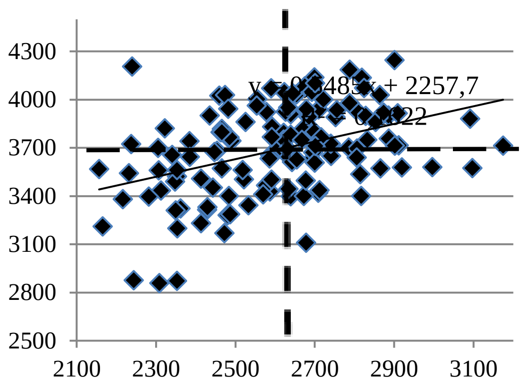
The resulting quadrants of the division of the coordinate plane can be interpreted as follows:

- I quadrant describes the distribution of heating periods corresponding to the "cold winter" (large values of accumulated and residual integral temperature differences);
- III quadrant describes the distribution of heating periods corresponding to "warm winter" (small values of accumulated and residual integral differences);
- II and IV quadrants describe situations of "asynchronous fuel consumption", until a certain moment winter is cold (warm), then it becomes warm (cold).

on December 1



on January 1



on February 1

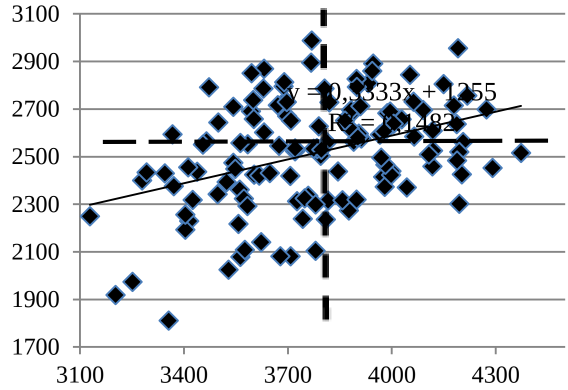


Fig. 1. Distribution of heating periods by accumulated and residual integral temperature differences, Irkutsk

To assess the tightness of the relationship between the accumulated and residual integral temperature differences, an indicator of the synchronicity of the deviations of the integral temperature differences for the past and forthcoming heating periods is introduced:

$$k = (n_1 + n_3) / (n_2 + n_4), \quad (4)$$

where n_i , i = 1,2,3,4 is the frequency of distribution of heating periods along the quadrants of the coordinate plane.

Table 1. Indicator of synchronicity of deviations of accumulated and residual integral temperature differences in cities of Russia for the period 1900-2019.

City	December 1	January 1	February 1
Irkutsk	1,95	2,10	1,60
Novosibirsk	1,08	1,20	1,08
Moscow	1,17	1,41	1,95

The data in Table 1, as in the following, are ranked in descending order of the integral temperature difference inside and outside the building during the heating period.

Table 1 shows the results of calculating the synchronicity index (4) for the selected observation points and three dates of the heating period. For all observation points, the synchronicity index is greater than one.

To identify the relationship between the accumulated and residual integral temperature differences, we will use the second method - the construction of a regression relationship between the values under consideration.

Table 2. The values of the indicators of the tightness of the relationship between the accumulated and residual integral temperature differences for the period 1900-2019.

City	December 1	January 1	February 1
Paired correlation coefficients			
Irkutsk	0,4	0,4	0,4
Novosibirsk	0,3	0,3	0,3
Moscow	0,1	0,2	0,4
Linear regression slope coefficients			
Irkutsk	1,0	0,5	0,3
Novosibirsk	0,7	0,4	0,2
Moscow	0,3	0,4	0,3
Determination coefficients			
Irkutsk	0,2	0,2	0,1
Novosibirsk	0,1	0,1	0,1
Moscow	0,0	0,1	0,1

Table 2 shows the values of indicators of paired correlation, linear regression slope, determination coefficients. The positive values of the slope and correlation coefficients indicate a stable positive statistical relationship between the deviations of the accumulated and residual integral temperature difference inside and outside the building. At the same time, the coefficient of determination shows that this linear relationship cannot be considered significant.

3 Model for predicting the probability of the expected integral temperature difference for the upcoming heating period

The set of values of the accumulated integral temperature difference for the heating period $B_{\tau\, before}$ is divided into n intervals with the same discrete step:

$$\delta = (max\ B_{\tau\, before} - min\ B_{\tau\, before})/n. \quad (5)$$

Similarly, the residual integral temperature difference is divided into m intervals with the same discrete step.

The vectors of numbers of the partition intervals are introduced for the accumulated integral temperature difference:

$$N_{before} = \{1, 2, ..., i, ..., n\}, \quad (6)$$

for the residual integral temperature difference:

$$N_{after} = \{1, 2, ..., j, ..., m\}, \quad (7)$$

Next, a matrix of distribution of the accumulated and residual integral temperature differences over the intervals is formed (to simplify the calculations, $n = m = 3$ is taken).

Table 3. Distribution matrix of accumulated and residual integral temperature differences over intervals i , j= 1,2,3.

	Intervals of accumulated integral temperature difference N_{before}			
	№	1	2	3
Intervals of residual integral temperature difference N_{after}	1	γ_{11}	γ_{12}	γ_{13}
	2	γ_{21}	γ_{22}	γ_{23}
	3	γ_{31}	γ_{32}	γ_{33}
$\sum_{j=1} \gamma_{ij}$		γ_1	γ_2	γ_3

Here γ_{ij} , i, j = 1,2,3 is the number of observations from the i interval of accumulated integral differences in the j interval of the residual integral temperature differences; γ_i , i = 1,2,3 is the total number of observations in the i interval of accumulated integral differences:

$$\gamma_i = \sum_{j=1} \gamma_{ij} , \; i,j = 1,2,3. \qquad (8)$$

To obtain the matrix of conditional probabilities of the "transition" of observation from the i interval of accumulated integral differences to the j interval of residual integral temperature differences, use the formula

$$p_{ij} = \gamma_{ij} / \gamma_i , \; i,j = 1,2,3. \qquad (9)$$

Table 4. Matrix of conditional probabilities of "transition" of observation from the *i* interval of accumulated integral differences to the *j* interval of residual integral temperature differences

p_{11}	p_{12}	p_{13}
p_{21}	p_{22}	p_{23}
p_{31}	p_{32}	p_{33}

Where p_{ij} , i, j = 1,2,3 is the conditional probability of the observation "transition" from the i interval of accumulated integral differences to the j interval of residual integral temperature differences.

The sum of the conditional probabilities of the matrix over the columns is equal to one. This effect is achieved due to the previously adopted method of obtaining conditional probabilities:

$$\sum_{i=1} p_{ij} = 1, \; i,j = 1,2,3. \qquad (10)$$

For the matrix of conditional probabilities, the following relation is fulfilled (shown in Table 4).

Table 5. Matrix of conditional probabilities and distribution frequencies of cumulative and residual integral temperature differences

p_{11}	p_{12}	p_{13}	×	$p_{before\ 1}$	=	$p_{after\ 1}$
p_{21}	p_{22}	p_{23}		$p_{before\ 2}$		$p_{after\ 2}$
p_{31}	p_{32}	p_{33}		$p_{before\ 3}$		$p_{after\ 3}$

Here $p_{before\ i}$, i= 1,2,3 is the distribution frequency of the accumulated integral difference over the partition intervals N_{before}; $p_{after\ j}$, j= 1,2,3 is the distribution frequency of the residual integral difference over the partition intervals N_{after}.

The splitting intervals of the accumulated integral temperature difference can be interpreted as follows. Interval 1 characterizes the past part of the heating period as a relatively “warm winter”. Interval 2 is like "average winter", the realized part of the heating year is within the range of average annual indicators. Interval 3 is "cold winter".

The partitioning intervals of the residual integral temperature difference can be interpreted as follows. Interval 1 characterizes the coming part of the heating season as a relatively “warm winter”. Interval 2 is like "average winter". And interval 3 is "cold winter".

Consider the matrices of conditional probabilities for the three cities of Irkutsk, Novosibirsk, Moscow by states for December 1, January 1, February 1.

Table 6. Conditional probability matrices for selected cities on December 1, January 1, and February 1

on December 1			on January 1			on February 1		
Irkutsk								
0,3	0,0	0,0	0,3	0,0	0,0	0,2	0,1	0,0
0,6	**0,6**	**0,6**	**0,5**	**0,6**	**0,5**	**0,7**	**0,5**	**0,5**
0,1	0,4	**0,4**	0,2	**0,4**	**0,5**	0,1	**0,4**	**0,5**
Novosibirsk								
0,4	0,3	0,2	**0,4**	0,2	0,0	0,3	0,2	0,0
0,6	**0,7**	**0,5**	**0,6**	**0,8**	**0,9**	**0,6**	**0,7**	0,3
0,0	0,0	0,3	0,0	0,1	0,1	0,1	0,1	**0,7**
Moscow								
0,5	0,3	0,3	**0,4**	0,2	0,0	**0,4**	0,2	0,0
0,3	**0,5**	**0,6**	**0,5**	0,3	**1,0**	**0,6**	**0,5**	**0,6**
0,2	0,2	0,1	0,2	**0,4**	0,0	0,0	0,3	**0,4**

The conditional probabilities shown in Table 6 can be commented on as follows. Suppose for Irkutsk, based on the temperature data for December 1, we observe a "warm winter", then with a probability of 0.3 the upcoming part of the heating period will be warm, with a probability of 0.6 the rest of the winter is expected within the mean annual values, the winter will be cold with a probability of 0.1.

From Table 6, we see that as the heating period ends, the distribution of observations in the conditional probability matrices tends to the main diagonal. The distributions of observations over Novosibirsk and Moscow are indicative, while “medium winters” and “cold winters” are typical for Irkutsk.

4 Conditional entropy as an estimate of the model forecasting efficiency

Entropy is used to assess the efficiency of predicting the integral temperature difference inside and outside the building for the heating period using conditional probability matrices.

Entropy can be viewed as a “measure of uncertainty” when an event occurs.

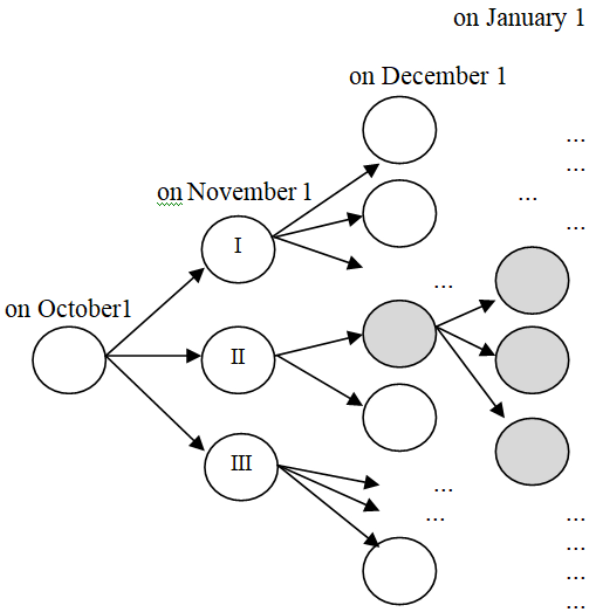


Fig. 2. Hierarchical graph future scenarios

Indeed, choosing a certain scenario for the implementation of the remaining part of the heating period using the matrices of conditional probabilities of the development scenario, we reduce the uncertainty of the future, thereby reducing the value of entropy (Figure 2).

Let's introduce the indicators:

1) the general entropy $H(J)$ is the entropy of the frequencies of the distribution of the residual integral temperature difference over the partition intervals N_{after}:

$$H(J)=-\sum_{j=1} p_{after\ j} \cdot log\ p_{after\ j}\ , \qquad (10)$$

where $p_{after\ j}$ is the distribution frequency of the residual integral difference over the partition intervals N_{after}.

The general entropy $H(J)$ shows the uncertainty of the future in case of refusal to choose the scenario for the implementation of the current winter.

2) The partial entropy $H(J_i)$ is the entropy of the column vector of the matrix of conditional probabilities:

$$H(J_i)=-\sum_{i=1} p_{ij} \cdot log\ p_{ij}\ , \qquad (11)$$

where p_{ij} is the conditional probability of the observation "transition" from the i interval of accumulated integral differences N_{before} to the j interval of residual integral temperature differences N_{after}.

The partial entropy $H(J_i)$ shows the uncertainty associated with the choice of the i-th scenario of future development.

In most cases, the partial entropy is less than the general one, since when choosing a scenario, we have less uncertainty of the future than when refusing to choose (Figure 2).

However, exceptions are possible, when the private entropy is greater than the general one: the future uncertainty arising when choosing a certain development option is greater than uncertainty - without choosing a scenario.

3) The weighted average entropy:

$$weighed\ H(J)=\sum_{i=1} p_{before\ i}\ H(J_i), \qquad (12)$$

where $p_{before\ i}$ is the distribution frequency of the accumulated integral difference over the partition intervals N_{before}; $H(J_i)$ is the private entropy of the i-th scenario of future development.

The weighted average entropy reflects the weighted average future uncertainty with the probabilities of the current winter.

The percentage of uncertainty of the future eliminated by choosing the i-scenario is calculated.

$$\delta H_i=[H(J_i)-H(J)]\ /\ H(J)\cdot 100\%,\ i=1,2,3, \qquad (13)$$

where $H(J)$ is the general entropy, $H(J_i)$ is the partial entropy.

Uncertainties of the future, eliminated by predicting the integral temperature difference using conditional probability matrices, are calculated:

$$weighed\ \delta H_i=\sum_{i=1} p_{before\ i}\ \delta H_i\ , \qquad (14)$$

Numerical calculations of the partial entropy, the general entropy and the weighted average entropy for the city of Irkutsk on December 1 are presented in Table 7.

Table 7. Partial entropy, general entropy and weighted average entropy of Irkutsk on December 1

Conditional probability matrix			The distribution frequency	
			of the accumulated integral difference	of the residual integral difference
0,3	0,0	0,0	0,3	0,1
0,6	0,6	0,6	0,7	0,6
0,1	0,4	0,4	0,1	0,3

Partial entropy for each scenario i			Weighted average entropy	General entropy
0,8	0,8	0,7	0,8	0,9

δH_i for each scenario i		
-9%	-10%	-29%

From Table 7 we see that the partial entropy does not exceed the general entropy, i.e. the choice of any scenario for the implementation of the current winter for Irkutsk on December 1 reduces the uncertainty than in the case of refusal to choose the scenario. As expected, the weighted average is also less than the total entropy.

From Table 7 it follows that the choice of the future scenario allows reducing the uncertainty to an average of 16%, in some cases, this effect can be achieved by 30%. Knowledge of possible scenarios for the implementation of the current winter can significantly reduce future uncertainty.

Conclusions

The possibility of predicting the integral temperature difference inside and outside the building for the heating period on the basis of meteorological data for the first months of the heating year has been investigated.

An assumption is proved about the statistical relationship between the accumulated and residual integral temperature differences.

A model has been developed for predicting the probability of expected consumption of heat energy and fuel for heating for the entire heating period according to meteorological data of the beginning of the heating period. The model is focused on the construction of matrices of conditional probabilities of "transition" of observation from the interval of partitioning the accumulated integral temperature differences into the interval of residual integral temperature differences.

The conditional probability matrices allow to estimate the probabilities of the scenarios for the rest of the heating period. Matrices can be used when adjusting fuel supply programs.

Entropy is used to assess the efficiency of predicting the integral temperature difference inside and outside the building for the heating period using conditional probability matrices. On average, the choice of future scenarios can reduce entropy by up to 16%.

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MATRIX OF VULNERABILITY OF DECENTRALIZED AREAS TO LOCAL ENERGY SECURITY RISKS IN THE NORTHERN AND ARCTIC ZONES IN THE STRUCTURAL SET OF SOLUTIONS

Violetta Kiushkina[1], *Boris* Lukutin[2]

[1]*Chukotsk branch of the North-Eastern Federal University Scientific, Anadyr, Russia*
[1]*Technical Institute (branch) of North-Eastern Federal University Scientific named after M.K. Ammosov, Neryungri, Russia*
[2]*National Research Tomsk Polytechnic University Energy Engineering School, Tomsk, Russia*

Abstract. The tension of the state of decentralized power supply systems in the northern regions, including the Arctic zones, has always been determined by the specific features of their geographical location and the functioning of the economy, which in themselves generate a number of local energy security risks. Nevertheless, both modern and retrospective analysis of energy zones in isolated hard-to-reach territories retains an assessment of the crisis of the situation without the dynamic type of its improvement in ensuring energy security. The aggregate analysis of the formed risk matrix with the heterogeneous nature of their sources, the categorization of the depth of consequences and the probability of implementation, made it possible to obtain a map of local risks of energy security in decentralized regions. On the basis of this, an approach and structure of a set of recommendations for improving energy security is presented in the model of combining the rank of the indicator's importance, the priority of risks and the expected social, environmental and economic effects in a reasonable option for choosing solutions and recommended measures to ensure a stable state and development of decentralized zones of power supply and energy facilities of territories Northern regions and Arctic zones.

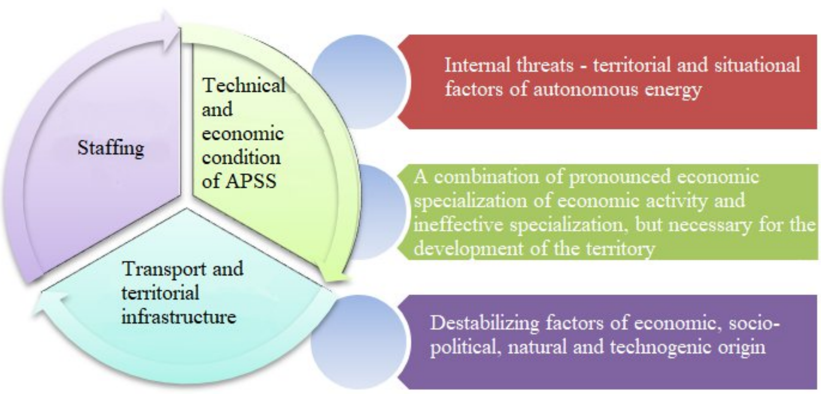
1 Introduction

The combination of territorial factors (specific features of the geographical location of the decentralized zones of the northern regions) and situational factors of autonomous energy forms the structural basis for the model of the local hazard measure - the risks of reducing the acceptable level of energy security (EnS) of the studied territories.

Accept that the "oppressed" state of the decentralized energy zone in relation to energy security - a decrease in indicators and abilities that characterize the provision of comfortable living conditions for the population and the functioning of energy facilities, with a certain degree of vulnerability of the EnS level protection associated with negative events (risk intensity, duration of exposure to risks, severity consequences, dynamics of changes in risks and threats).

Based on the analysis of factors, conditions and statistical data for hard-to-reach territories of the regions of the North and the Arctic zones with the features of decentralized power supply and the composition of their inherent threats, a list of examples of local risks was formed (table 1) [1]. The analysis of groups of factors showed that the state of energy security of decentralized power supply complexes is influenced by many factors, among which the most significant are shown in Figure 1. These factors are interconnected with other factors of a different nature that enhance or mitigate the impact of a certain threat, and at the same time, they themselves affect stabilizing others.

Fig 1. Influencing factors on the state of EnS of decentralized energy complexes



2. Local risks of energy security of decentralized areas

Table 1. Possible local risks of EnS of the decentralized power supply zone

№	Risk name	Threat status, probability of transformation
R_1	The risk of undersupply of electrical energy due to a disruption in the supply (natural conditions, financial instability) or the supply of incomplete fuel resources (aggravated by the dominance of one fuel resource)	Strategic character, weakening with diversification of resources, formation of logistics of guaranteed and reliable fuel supplies, taking into account the climatic characteristics of the northern regions, transportation routes, pricing policy
R_2	The risk of periods of forced downtime and emergency situations due to low / lack of qualifications of personnel	Current character, zeroed when the educational cluster is strengthened
R_3	The risk of a decrease in the rate of optimization of the structure of autonomous power supply systems (APSS) in case of insufficient / lack of investment	Strategic character, weakening with the strengthening of trends in the introduction of new available technologies, the fulfillment of established requirements, an orientation towards social investment
R_4	Risk of disruption of uninterrupted power supply to consumers	
R_5	The risk of high losses (energy, consumption of fuel resources) due to an ineffective process of electricity production and reduced technical and economic indicators of the APSS	
R_6	The risk of long-term elimination of a failure due to an unacceptable reaction to an accident (climatic conditions, personnel situation, transport-territorial factors)	
R_7	The risk of undersupply of electrical energy due to the lack of strategic supply of fuel in the required volume of decentralized energy complexes (DECPS)	Strategic character, weakened by resource diversification and targeted regional policy action
R_8	Risk of high equipment failure rate due to degradation state	Strategic character , weakening with the strengthening of trends in the introduction of new available technologies, the fulfillment of established requirements, an orientation towards social investment
R_9	The risk of long-term restoration of equipment due to the complexity of the service (lack of spare parts for a wide range of types of units, limited competence of working personnel)	Current character, zeroing in case of complex implementation of organizational and managerial development measures
R_{10}	The risk of increasing the cost of electricity production	Strategic character, weakening with resource diversification
R_{11}	The risk of an increase in the number of insolvent population - an increase in restrictions on expenditure items	
R_{12}	The risk of inappropriate priority of the use of funds	Current character, weakening when adjusting regional policy, the formation of internal sources of development of the territory
R_{13}	The risk of an unacceptable decrease in the energy efficiency of DECPS	Current nature, weakening with strengthening trends in the introduction of new available technologies
R_{14}	The risk of unacceptable losses of electricity due to inefficient transmission	

The list should vary based on the individually analyzed territories where the decentralized energy complex of power supply operates, and the clearly established composition of the EnS threats for the current period of time. It is advisable to single out a group of risks for EnS associated with an internal threat specific to decentralized energy zones.

The risk of undersupply of electrical energy associated with fuel supply for such energy zones characterizes the failure to meet the requirements for fuel and energy saving to consumers, based on the definition of EnS, which can bring a natural threat (sharp and long-term adverse natural phenomena, climatic changes in the overlap of the navigation terms sea-river-winter road), financial and economic threat (insolvency of the population, spending of funds in case of unplanned deposit and additional equipment to release delivery routes, ineffective use of energy resources with inefficient DECPS, one-sidedness of energy saving measures, insufficient reliability of the tank farm of fuel resources, absence and limitation of permanent transport links in during the year between the zones, lack of diversification of power supply, insufficient fuel reserves), which led to interruptions and untimely supplies of fuel resources and a shortage of electric energy in winter time.

The risk of downtime of DECPS and unacceptable decrease in the efficiency of DECPS associated with staffing characterizes the violation of the reliability component of EnS, which can bring a pronounced social, personnel, and labor resource threat (low qualification of personnel, lack of qualified personnel, low qualifications of engineering and technical workers, weak social responsibility), which led to an increase in equipment failures, erroneous decisions, power outages.

For decentralized energy zones, in contrast to other territorial entities and centralized systems, due to the specifics of the existence and autonomy of power supply, there are no risks that are insignificant for the state of EnS. This is due to the high degree of susceptibility to the impact of real and potential threats, primarily generated by the properties of territories, as the internal potential of a source of risk. Acceptable (permissible) risk (ALARA principle - "as low as possible within reasonable") combines technical, social and economic aspects that require joint consideration. For decentralized zones, the ALARA principle is implemented to the level of conditional probability for the current period of time.

3.Matrix of vulnerability of decentralized energy zones

The elements of risk are the probability and sources of origin of the risk, which is described as a combination with the element of the potential consequences of its exposure. In the absence of relevant statistical information, the task of constructing a risk matrix simplifies the use of a point assessment of the probability of risk occurrence and the severity of consequences. In accordance with this, for the studied territories, a classification of the point assessment of the probability of occurrence (table 2) and the severity of the consequences of risks (table 3) for EnS was formed, using the main provisions of the theory of risks [2], deeply studied and adapted in works and developments to assess individual regions [3].

The risk probability classes are determined using a gradation of points with a large step and descriptions, taking into account the specifics for autonomous power supply systems, which recognizes only the rigid boundaries of their state in the current conditions.

Risk analysis uses the levels of consequences characteristic of decentralization conditions and the descriptions associated with them. The class of the category of consequences according to the degree of "destruction" and the attainability of the level of susceptibility and vulnerability of EnS for a specific territory in conditions of autonomy, isolation, and severity of the climate.

Table 2. Classification of the probability of risks

P_j	Weight coefficient	Description	Justification of risk manifestation
$P_1(R_i$	5 points	Absolutely accurate with high probability	Expressed territorial-geographical, natural, technological, socio-economic factors
$P_2(R_i$	3 points	Really with the expectation of a random negative event	Expressed territorial-geographical, natural and situational factors of autonomy
$P_3(R_i$	1 points	Unlikely, but acceptable under existing conditions	Expressed territorial-geographical, natural factors

Table 3. Classification of the severity of the consequences of risks

Class weight coefficient		Consequences to the level of "oppression"	Compliance with the level of risk
$П_1$	5 points	High / emergency state	Unacceptable with the transition to an emergency state, leading to a serious threat to EnS / its components or a complete disruption of activities (requires a decrease in the degree of impact for the further existence and functioning of the decentralized zone
$П_2$	3 points	Borderline / depressive state	Unacceptable in conditions of autonomy, with the loss of some functions, caused by significant changes (requires an assessment of measures to reduce the degree of impact)
$П_3$	1 points	Weak / conditionally safe current	Acceptable / tolerable without consequences, as a

		state	prerequisite for the possibility of manifestation (requires continuous monitoring of the situation and in the absence and with weak symptoms of the appearance of danger)

$$DT_p = \begin{array}{ccccl} \Pi_3 & \Pi_2 & \Pi_1 & & \\ 1 & 3 & 5 & R_1, & \text{Group A} \\ 1 & 3 & 3 & R_2, & \text{Group A, B, C} \\ 1 & 3 & 3 & R_3, & \text{Group B, C} \\ 1 & 3 & 3 & R_4, & \text{Group A, B} \\ 1 & 5 & 5 & R_5, & \text{Group C} \\ 1 & 5 & 5 & R_6, & \text{Group A} \\ 1 & 3 & 3 & R_7, & \text{Group A} \\ 1 & 5 & 5 & R_8, & \text{Group B, C} \\ 3 & 3 & 1 & R_9, & \text{Group C} \\ 1 & 5 & 1 & R_{13}, & \text{Group B, C} \\ 5 & 1 & 1 & R_{14}, & \text{Group B, C} \end{array} \quad (1)$$

$$TH_{EnS} = (5,3,3,3,3,5,3,5,3,5,3) \quad (2)$$

$$RISK\ RATIO = \begin{array}{cccc} \Pi_3 & \Pi_2 & \Pi_1 & \\ 5 & \mathbf{15} & \mathbf{25} & R_1 \\ 3 & 9 & 9 & R_2 \\ 3 & 9 & 9 & R_3 \\ 3 & 9 & 9 & R_4 \\ 3 & \mathbf{15} & \mathbf{15} & R_5 \\ 5 & \mathbf{25} & \mathbf{25} & R_6 \\ 3 & 9 & 9 & R_7 \\ 5 & \mathbf{25} & \mathbf{25} & R_8 \\ 9 & 9 & 1 & R_9 \\ 5 & \mathbf{25} & 5 & R_{13} \\ 15 & 3 & 3 & R_{14} \end{array} \quad (3)$$

Pre-decentralized territories, on the example of the Republic of Sakha (Yakutia), as a leader in terms of the scale of operation of small-scale energy facilities in conditions of discomfort, were subjected to clustering according to the manifestation of the intensity of factors prerequisites for risks (territorial-geographical, situational for autonomy). For the example under consideration, an analysis of the local risks of the EnS was carried out and a matrix of vulnerability of the decentralized territories of the North and the Arctic zones to them was compiled. As a result of the aggregate analysis of the general matrix of local risks (1), and the categorization of the depth of damage and the probability of risk realization (2), a map of EnS local risks (3) was obtained for the whole decentralized energy supply zone of the study area, excluding risks with index 10-12 this research view.

Thirty five experts took part in the procedure for judging the formation of a vulnerability matrix and a vector of threats for decentralized energy zones, twenty five of whom belong to a group of scientists (professors, associate professors), ten - to specialists, managers of production facilities (chief engineers, chief power engineers, chiefs of power supply regions, chief engineers electrical networks of the East, etc.). The involvement of a wide range of specialists as experts, most of whom are related to the autonomous power industry of the Far East, which is the leader in the scale of operation of small-scale energy facilities and territorial affiliation to the decentralized sector, allows us to assume a priori a sufficiently high reliability and representativeness of the initial expert assessments. The conclusions of the expert practitioners are based on their own professional experience in decentralized power supply systems. The risk analysis also includes the results of many years of research into the features of decentralized power supply in the North: retrospective collection of data on situations; statistical data of periodic observation of the relevant industry services at the facilities of decentralized power supply systems in the North and the Arctic.

Group A indicates the dominant dependence on the factors of autonomy and potential of territories to generate risks in the conditions of existence. Group B - the predominance of dependence on sources associated with economic factors in conjunction with the specialization of economic activities. Group C represents the key impact of a group of threats with the essence of an ineffective level, incomplete focus, imperfection and low dynamism in the formation and implementation of the economic policy of the region, regional energy security policy.

The local risk map is a visual diagram of the interpretation of the most vulnerable point in the EnS through the characteristic of a certain risk that may appear for a cluster of decentralized territories with the most unfavorable consequences. The highest risk priority (criticality coefficient) in the map reflects the most potentially dangerous risk, taking into account the damaging factors for the territory in comparison with others, represents the rank of risks, which will allow taking measures in advance to prevent and neutralize them. The cells of the map, in which the "Risk ratio" has the maximum index, show the realization of the threat with the most severe consequences for the decentralized zone in the conditions of its existence. Namely, for a separate example of decentralized territories [4], in case of manifestations of factors of failure in the supply of fuel resources caused by climatic and other situations, and manifestations of technical and technological factors of energy complexes, aggravated by isolation, limited availability, low competence and the level of operating personnel. What entails a probable shortage of electricity and heat energy to the consumer with the possible manifestation of severe consequences during long periods of a sharp cold snap. A more individual consideration of the degree of vulnerability of each decentralized zone shows the likelihood of the manifestation of a set of sources and situations that give rise to the realization of risks of a certain group, which will reveal either the duration of the aggravation of the consequences, or its short duration with rapidly eliminating violations and failures.

Also, when carrying out the analysis, the sphere of vital activity of each municipal formation of the investigated decentralized energy zones was taken into account. As a result, three spheres of varying degrees of severity of economic specialization of economic activity were formed: agricultural, industrial spheres, and a mixed group of regions in which agriculture and industry are developed approximately equally. The conducted clustering within each group made it possible to identify the most vulnerable spots. This analysis for the period under review is a good basis for developing top-priority recommendations for neutralizing threats to energy security in groups of the same type.

4. Structured diagram of the focus of measures to improve the energy security of decentralized energy zones

The performed analysis is incorporated into a generalized model (figure 2) of the combination of the rank of the importance of the indicator, the manifested group of aggravating factors of specificity, the priority of the risks of the map of local risks of the developed list, the expected effects of the direction of the proposed measures for decentralized power supply zones and the choice of solutions for the energy sector of the territories of the Northern regions and the Arctic zones.

The structured scheme allows you to form an individual trajectory of each territory in successful positions for increasing the EnB, using a matrix and a map of local risks to plan a reasonable focus of activities as a composite tool for analyzing and managing the energy security of decentralized energy zones of such complex territories.

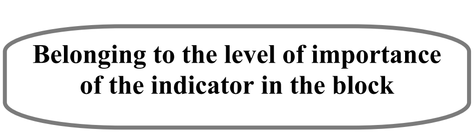
The structural model is subject to systematic revision due to a possible change in reality and a change in the form of actions (strengthening / weakening) of various factors for threats. This makes it possible to form measures of a permanent nature, to define a tough area of monitoring, to reduce the risks of forming incorrect decisions in energy policy and the choice of the sequence of investment and other measures.

As a whole, the tool for analyzing and managing energy security through assessing the impact of local risks of the EnS and understanding changes in its index should create conditions for building a competent, appropriate and effective regional energy security policy. Drawing up individual maps of the situation of decentralized power supply as part of regional energy security should include the context of adequacy and usefulness for conceptualizing threats and challenges, forming an advanced policy for the stable implementation of preventive measures to neutralize risks in a complex relationship with the dynamics of changing factors, conditions, situations, objectives and goals of sustainable, strategic and socio-economic development. Energy security risk management of territories and electrification facilities in a decentralized environment limited by various factors and conditions should be a fixed level in the regional segment of the state assessment.

As a consequence of the impact of local risks of EnS for a decentralized area, there is a potential combination of a decrease in energy supply levels and a comprehensive provision of comfortable living conditions for the population, the disappearance of the culture of the indigenous peoples of the North (IPN), a violation of the eco-heritage of the North and fishing zones, a disturbance of the environment for the traditional form of nature management (reindeer husbandry and etc.). in general, the "damage" to the social component of the EnS is characterized as the essence of the EnS of a decentralized zone, which can bring a socio-political threat (unaddressed actions of regional authorities, which led to an energy imbalance of the territory, stagnation of economic efficiency, deterioration of the availability of electricity to the consumer), management and legal threat (ineffectiveness of regional and social policy, which led to the same consequences).

The observed stagnation of the socio-economic development of the decentralized zone, the growth of differentiation of the level and quality of life of the population of the decentralized zone, persist due to the conditions in which the DECPS functions and are of a strategic nature of an immediate decision. Adjustment of regional policy - development by identifying the merits and advantages of each decentralized zone, strengthening the effective focus of measures for the development of the territory in the changes in the energy structure of modern energy.

Thus, the analysis has identified the most critical set of identified vulnerabilities in the decentralized regions of the North and the Arctic zones. The proposed vulnerability matrix makes it possible to assess and predict the impact of local risks associated with individual threats, reflecting to a greater extent the specificity of the territories in combination with the autonomy of power supply and creating the greatest possibility of causing damage to decentralized energy. The resulting map of local risks of decentralized areas, taking into account these factors, gives an idea of the risks with a high criticality coefficient, and the need for constant monitoring of changes in their dynamics, measuring significant indicators and the general level of energy security of the area. The proposed structure for the choice of measures allows plan targeted criteria for choosing the direction of measures, to correctly assess their rationality and appropriate sequence for the energy zone or their groups with the same type of impact of threats.



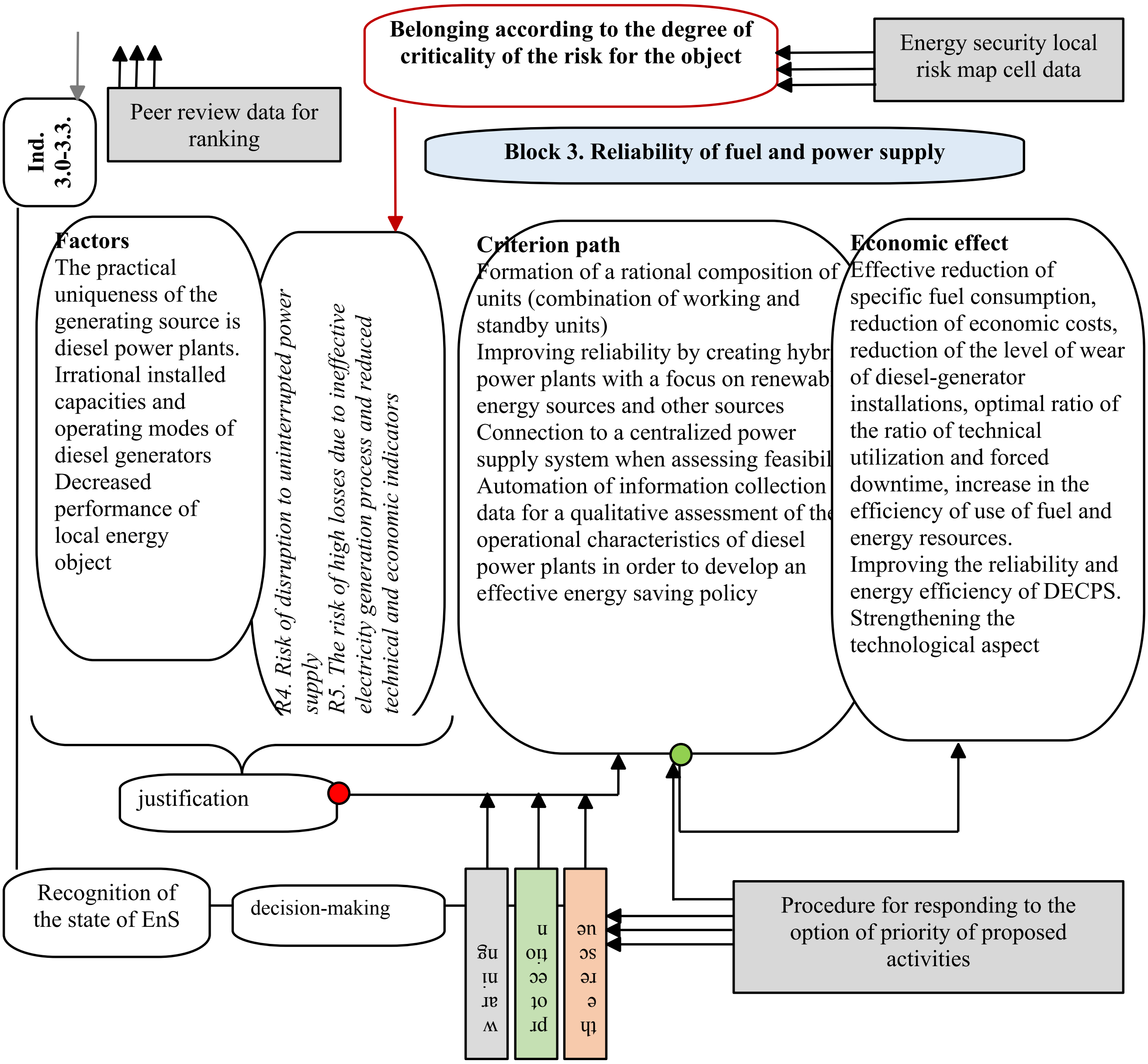


Fig. 2. A fragment of the structural diagram of the substantiation of the choice of the direction of measures to maintain the conditions for the implementation of the ENB of the infrastructural isolated DECPS territories of the North and the Arctic zone of the Russian Federation

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An attempt at assessing the economic component of strategic threats to energy security

Dmitrii Kononov*

* Melentiev Energy Systems Institute, SB RAS, Irkutsk, Russia

Abstract. The paper studies the main economic threats to energy security and the indicators descriptive of them. Available models to estimate the numerical values of these threats are presented. The results of modeled calculations are provided.

Keywords: energy security, strategic threats, indicators, risks.

The International Energy Agency defines energy security as "the uninterrupted availability of energy sources at an affordable price" [1]. This interpretation attests to the important role of the economic component of energy security and the consideration of such strategic threats as the shortage of production capacity in the energy sector and the dynamics of energy prices that are unacceptable for the country's economy. The quantitative assessment of the significance of these threats, the probability of their occurrence, and possible damages is an essential and challenging problem, and there are no satisfactory and generally accepted methods for solving it [2-6].

The threat of possible long-term capacity shortage may be caused by lack of investment and other resources for timely implementation of large-scale projects, issues with the required development in linked industries and infrastructure, and time constraints (inertia).

Investment risks of projects and options for the development of the electric power industry and the share of power plants with unacceptable risk in the mix of new capacity additions can be used as indicators of energy security. For their numerical evaluation, in studies conducted at the SEI SB RAS the MISS-EL stochastic model (computer program) that integrates optimization with the well-established Monte Carlo method is employed [7]. It allows identifying rational options for the development of regional electric power supply systems based on the criterion of minimum discounted cost required to meet the predefined demand for the electric power.

An important feature of the MISS-EL model is that all key input data and constraints are specified not as point estimates but as ranges of possible values, with the ability to factor in the different probability laws that govern the distribution of values within such intervals. The model makes it possible to obtain hundreds of balanced and optimal options under different input data, to select the most stable of them, and to estimate the probability of newly built and reconstructed power plants of various capacity that are getting included into this main option. The lower the probability, the higher the risk to the investor. Accordingly, the investment risk is defined as an inverse value of the probability.

The presented results of calculations performed with the MISS-EL model refer to the option of electric power supply of 6 federal districts of the European part of Russia, including the Ural federal district. The conditions defining this option are similar to those of the minimum capacity option in the General Scheme (Master plan) of new power plant capacity additions until 2035, adopted by the Government of the Russian Federation in June 2017 [8].

The investment risks, as well as the cost of electricity generation, are significantly affected by the projected demand for electricity (Figure 1). This effect manifests itself differently for different plants and depends on the magnitude and nature of uncertainty of the input data (Table 1).

Table 1. Investment risks of new power plants and their dependence on changes in projected electricity demand, %

Power plants	Deviation from the reference case		
	-5%	**0%**	**5%**
Steam-electric power plant, gas-fired	14-21	13-20	11-18
Central heating and power plants, gas-fired	2-4	1,5-4	1-2
Central heating and power plants, coal-fired	17-31	4-23	2-18
Nuclear power plants	25-35	19-26	9-17
Hydropower plants	16-20	14-17	11-14
Renewables	20-40	12-32	11-22
Average risk value	12-20	8-17	6-13

Note. The lower bound was arrived at when assuming the normal probability distribution of the input data, the upper one corresponds to the interval uncertainty.

The modeled calculations demonstrated noticeable regional differences in probability (risks) of the power plant capacity shortage (Table 2).

The table shows that under minimum uncertainty of input data (normal distribution of their probability) the

* e-mail: stranger72@bk.ru

weighted average risk of total new capacity additions for power plants in some regions ranges from 4 to 15%, while in the case of interval uncertainty it is 10 to 20%. In this case, the risk of investing in the construction of individual plants may exceed 50%.

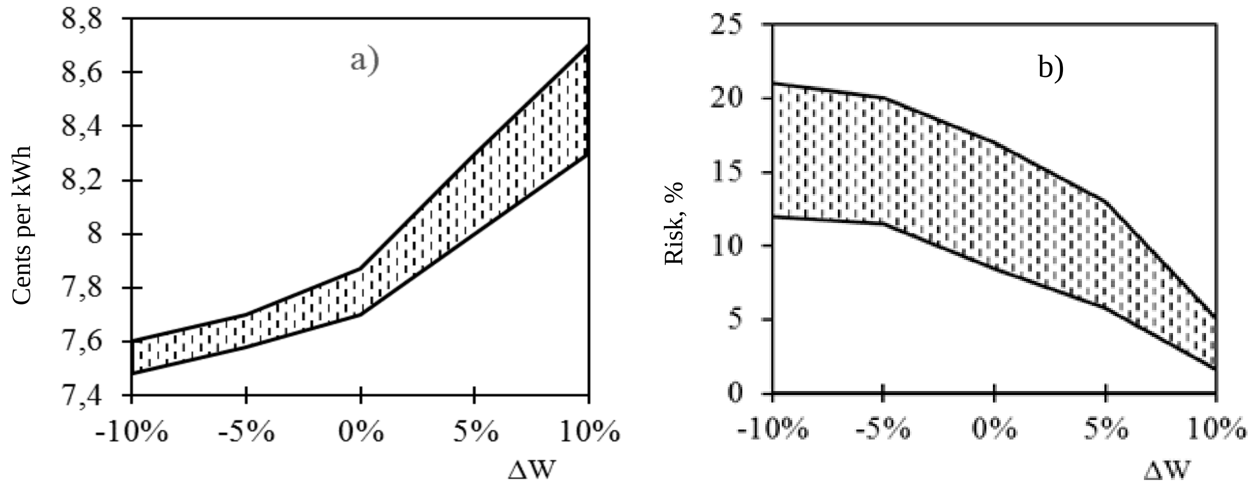

Figure 1. Effect of changes in electricity demand on the average generation cost (a) and risk for investors (b)
Note. The lower bound was arrived at when assuming the normal probability distribution of the input data, the upper one corresponds to the interval uncertainty.

Table 2. Effect of the nature of uncertainty of the input data on investment risks and electricity cost in some of the regions (Federal districts)

Indicator	Unit of measurement	Nature of uncertainty	Regions					
			1	2	3	4	5	6
Investment risks of power supply options	%	Normal distribution	9	15	15	2.5	4	7
		Interval uncertainty	19.5	20	19.5	10	12	17
Percentage of capacity of plants with the risk of more than 50%	%	Normal distribution	2.5	2.2	3	1.2	0	7.3
		Interval uncertainty	6.5	9.3	5.5	0	0	6
Electricity cost	Cents per kWh	Normal distribution	7.3	7.7	7.8	8.1	7.7	7
		Interval uncertainty	7.3	8	8	8.6	8.3	7.3

The mix of new power plant capacity additions also depends on the uncertainty of specified conditions. This is evidenced, for example, by the share of HPPs and renewables in the mix of new power plants (Table 3). It changes markedly not only if compared to the deterministic option, but also when comparing options with different types of uncertainty. At the same time, due to the specified constraints on new capacity additions in some regions, the change in the uncertainty of the input data leads to an increase in the role of these power plants, while in others - to its decrease.

Modeled calculations provide evidence for a noticeable effect of the discount rate assumed during optimization on the mix of new capacity additions and, accordingly, on investment risks (Figure 2).

For a comprehensive assessment of the capacity shortage threat in the implementation of an electric power sector development option, it is required to know not only the probability (risk) and magnitude of the shortage, but also the possible macroeconomic damage it does. The cross-sector optimization model MIDL is used to determine it [9]. It follows from the modeled calculations that with an annual one-percent capacity shortage of power plants, the GDP decrease may exceed 0.15 percent.

Table 3. The share of hydroelectric and renewable-energy power plants in the overall makeup of newly built power plants as a function of the way the conditions of the development of regional energy supply systems are handled, %

Input data specification	Regions						Aggregated region as a whole
	1	2	3	4	5	6	
Deterministic	1.7	11.3	0.7	11	16.9	7.3	6.9
Normal probability distribution	1.2	11.1	2.1	12.9	16.5	7.4	7.1
Interval uncertainty	1.2	10.7	3	10.5	15.8	11.5	7.5

* e-mail: stranger72@bk.ru

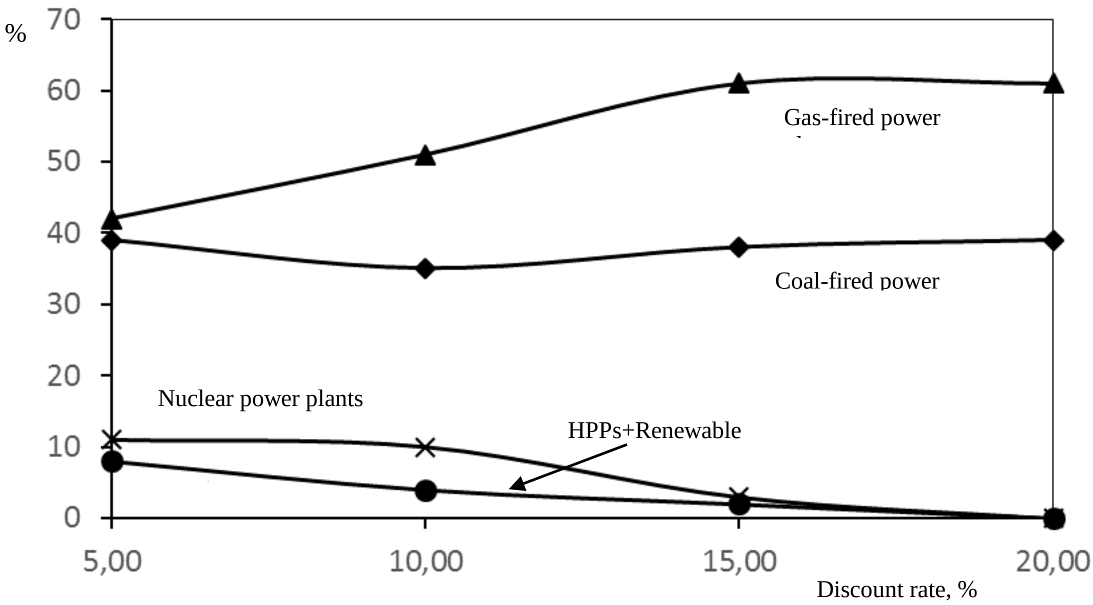

Fig. 2. The effect of the discount rate on the mix of new power plant additions

The reasons for the threat of unacceptable dynamics of an electricity price increase may be any of the following: contradictions between the interests of producers and consumers, uncertainty of the market state, slower improvement in living standards, low adaptability of consumers to price changes, or high energy intensity of the economy. Among the most important energy security indicators characterizing this threat one can highlight the following ones:

1. Price elasticity of demand for electricity.

The higher the price elasticity of demand for electricity, the higher the level of consumers' adaptation to the threat of its rise in price.

2. Share of electricity costs in the GDP

This share in Russia is now about 11%, which is 2-3 percentage points higher than the world average. However, it could increase significantly with the implementation of the Paris Agreement to reduce CO2 emissions.

3. Decrease in the GDP growth rates given increased electricity price

The latter indicator, which characterizes the negative response of macroeconomic indicators to increased electricity price can serve as an overall characteristic of the price threat to energy security. For the purposes of its approximate numerical estimation, it is possible to use the system of models developed at the SEI SB RAS (Figure 3), the main role in which is played by the cross-sector optimization MIDL model, as well as models that assess the impact of increased prices of energy carriers on prices in the production sector and on reducing final consumption of goods and services in the tertiary sector. An example of such assessment is given in Table 4.

The results of modeled calculations show that depending on the structure and pace of economic development and other factors, the price elasticity of the GDP with respect to the price of electricity may vary in the medium term from -0.12 to -0.16%. In the long run, the impact of electricity cost changes on economic growth should diminish.

Among the unsolved problems of numerical evaluation of strategic threats to energy security, one can highlight the problem of constructing a composite (overall) index of these threats that would take into account their interrelationships and relative significance of these threats as it changes over time.

Table 4. Changes in macroeconomic performance indicators given an increase in the electricity price, %

Performance indicators	**Growth in electricity tariffs**					
	by 20%		**by 50%**		**by 100%**	
	Year 2010	Year 2030	Year 2010	Year 2030	Year 2010	Year 2030
Inflation rate	0.7	0.3	2.2	0.95	4.8	2.3
Cost of living	0.8	0.7	2.4	1.9	5.2	4.2
GDP	-2.0	-1.6	-3.6	-3.1	-6.3	-5.5
Final consumption of goods and services	-2.4	-1.6	-4.5	-3.2	-8.1	-5.9

* e-mail: stranger72@bk.ru

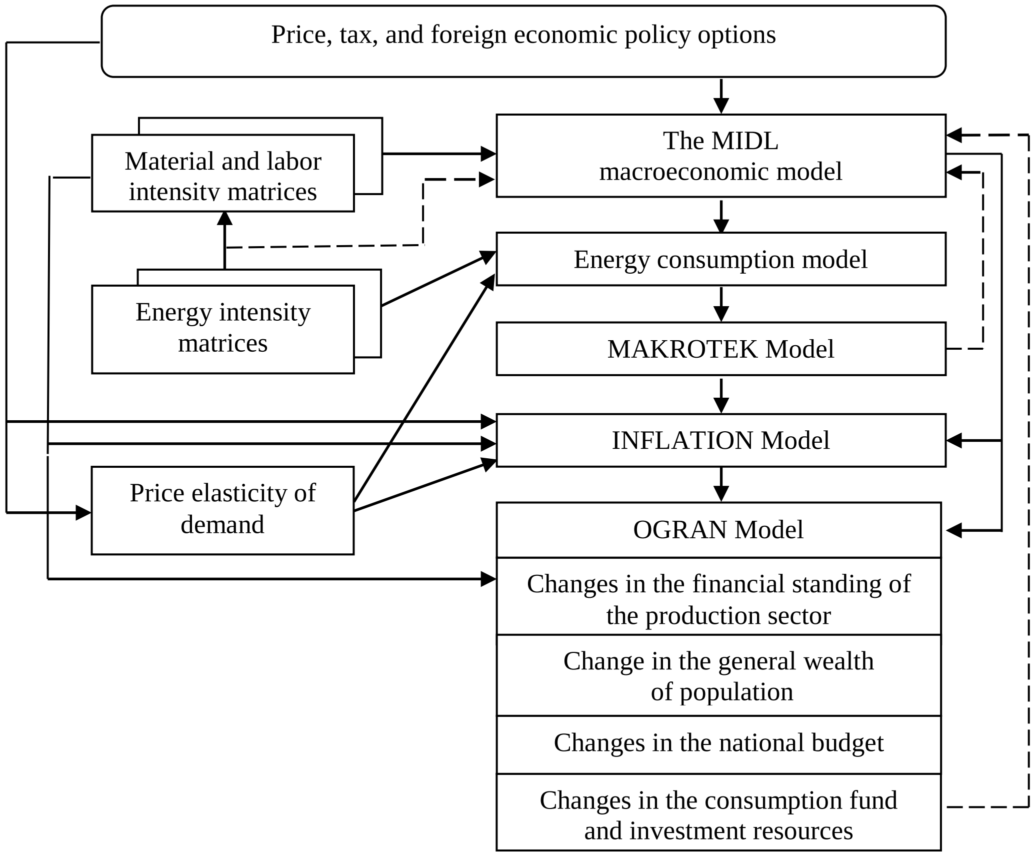

Figure 3. The MESTEK model system

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* e-mail: stranger72@bk.ru

Effect of the projection time frame on the techniques for assessment of energy security performance

Yuri Kononov*

* Melentiev Energy Systems Institute, SB RAS, Irkutsk, Russia

Abstract. The paper studies the problem of overall assessment of energy sector development options from the standpoint of meeting energy security requirements. It is shown that as the projection time frame extends further into the future, its economic component gains in importance on a par with integral indicators descriptive of strategic threats to and sustainability of energy systems development. Methodological approaches to assessment of these indicators are proposed.
Keywords: energy security, energy sector, projections, sustainability

The methodology behind long-term projections of energy systems development should take into account two essential factors: the exponential growth of uncertainty of future conditions and the diminishing importance of projection results for making priority strategic decisions as the time frame extends into the future. This means that depending on a given time period, the importance of indicators telling of the energy security performance of the country changes and, accordingly, different methods of their numerical evaluation are required.

International practices are those of adopting the methods of energy security assessment that are based on the choice of composition and evaluation of different indicators, assigning different weights to them, and designing composite indexes [1]. An example of such a procedure based on the indicator analysis technique is an overall indicator (index) used by the Global Energy Institute U.S. Chamber of Commerce to characterize the dynamics of U.S. energy security [2]. It incorporates the values of 37 measures in nine categories, with these metrics used to create four sub-indexes (Figure 1).

The World Energy Forum (WEF) adopts another composite index that incorporates 15 indicators to assess the energy security performance of 127 countries annually. On this index, Russia ranks 48th out of 127 countries [3], and it scores 45th out of 125 countries on the Energy Trilemma Index of the International Energy Council [4].

The composition of the indicators used largely depends on the interpretation of the concept of energy security. Over 80 interpretations are proposed in the research published abroad [5]. A conceptual definition of energy security is given by the International Energy Agency: "uninterrupted availability of energy sources at an affordable price" [6].

The economic component in the structure of composite energy security indexes used by different international organizations accounts for about 30 percent (Table 1). In fact, its share is larger as it is present in the resource and environmental components as well.

Table 1. Structure of overall indexes of energy security in approaches to assessment of its current performance: the case of the studies published abroad

Components of energy security	Some of the key indicators	Share, %
Economic	Electricity and fuel prices Energy intensity of the GDP	20-30
Geopolitical	Volatility of global energy markets Import dependence	15-25
Reliability, flexibility, and quality of energy supply	Energy reserves Political stability	15-25
Environmental sustainability	CO2 emissions from power plants The share of RES and NPPs	20-30

An analysis of the practices adopted in Russia and abroad for assessment of the current and prospective energy security performance of the country [7] shows that the composition of the indicators used and their weights (significance) remain constant, independent of the considered time period. These and other shortcomings, that are getting all the more pronounced when making long-term projections, can be eliminated with the use of optimization models. The significance of individual indicators can be approximated by the impact on changes in the functional (objective function) of the model of the given level or a higher level.

Systems of optimization and simulation models become indispensable in identifying strategic threats. This comprehensive characteristic of the energy security performance should be defined and generalized at different hierarchical levels. At the same time, the composition and degree of aggregation of employed models should depend on the given time frame (Figure 2).

The main strategic threats to energy security include the threat of long-term shortages of energy carriers and electricity and fuel prices that prove unacceptably high

* Corresponding author: kononov@isem.irk.ru

for the economy. Quantitative assessment of these and other strategic threats to energy security calls for solving a number of interrelated problems (Figure 3).

An overall indicator of strategic threats could be used to assess the sustainability of the considered option of the energy sector development.

Of different interpretations of the concept of resilience of energy systems development available, the most suitable, for the purposes of solving the problems of long-term projections, is the following: the ability to preserve the given development path under external and internal impacts or to return to it within an acceptable period of time at an acceptable cost [8].

Obviously, all other things being equal, with the system's sustainability improving, the security of its development also increases. However, its numerical evaluation proves challenging.

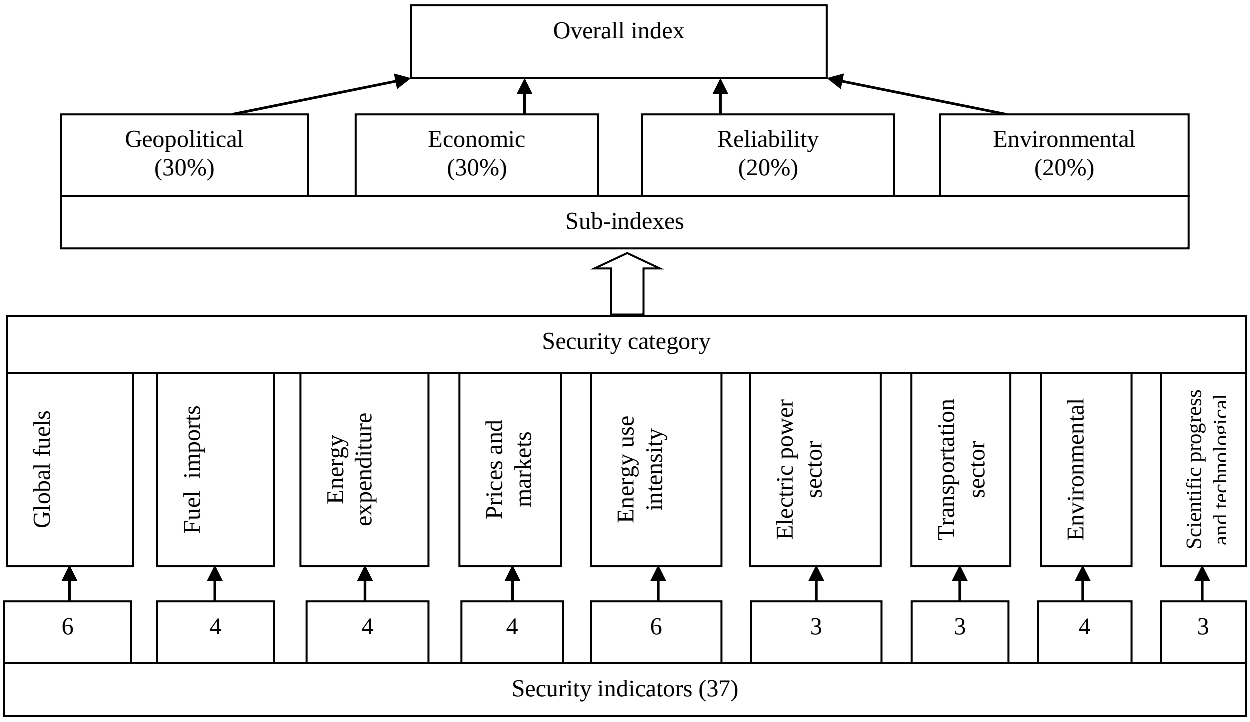

Fig. 1. Construction of the overall index of U.S. energy security risk

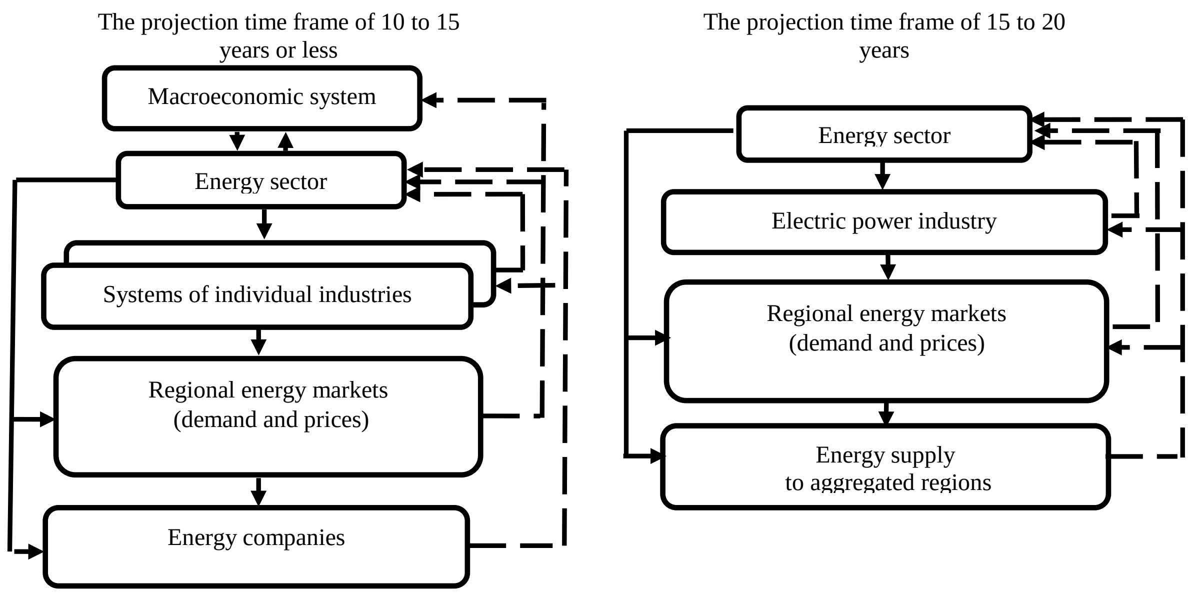

Fig. 2. Reasonable composition of optimization models for overall assessment of the energy security performance at different stages of projection studies of energy sector development

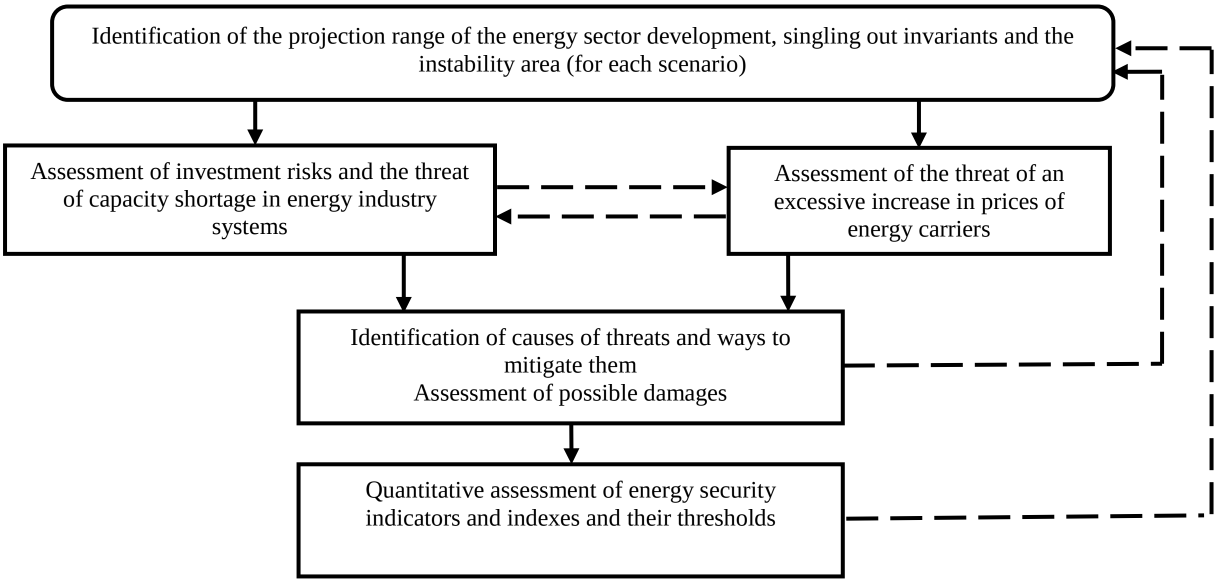

Fig. 3. Problems to be solved in the course of the study and quantitative assessment of the main strategic threats to energy security

In the studies published by the Energy Research Institute of the Russian Academy of Sciences [9], it is proposed to use the deviation of the country's GDP from its value in the reference case as a quantitative measure of Russia's energy sector development sustainability. Such deviation results from a possible realization of scenarios other than the reference one. This approach is suitable for comparative assessment of the options, but it is not clear how to determine the sustainability of the reference option itself.

It appears that it is necessary to distinguish between the relative and actual sustainability of the energy sector development options. The former can be defined by comparing it against the results of the reference case. The assessment of the latter, however, would require summarizing the results of a sustainability analysis of individual industries that make up the energy sector and regional energy supply systems. Overall indicators of strategic threats would also facilitate such an assessment.

In the end, the sustainability of a given option of the system development is determined by the sustainability of dynamics of indicators characterizing the key takeaways of the projection.

An important role in factoring in the uncertainty when making long-term projections of the energy sector development is played by the scenario approach, i.e. modeled calculations under various possible states of the external environment. Based on the analysis of a set of options deemed optimal under certain conditions, the projection range of projected indicators is formed. The sustainability of dynamics of these indicators can be measured by the width of the "uncertainty cone" or by the deviation from one of its boundaries.

The weighted average sustainability value of individual projected indicators allows to assess the sustainability of the reference case or the projected case selected otherwise.

Conclusion

Numerical evaluation of options for the development of the energy sector and energy supply systems as based on the energy security criterion should become an essential component of projection studies.

The methods for energy security performance assessment depend on the given time frame and the objectives of projection studies.

As the projection time frame extends into the future, the indicators characterizing the economic component of energy security gain in importance.

The indicator analysis technique as applied to energy security performance plays a key role in short-term projections. In projections that go up to 10-15 years into the future, of more importance is the assessment of strategic threats, while in case of long-term projections it is the assessment of the sustainability of development pathways and trends of the country's energy sector.

When constructing overall energy security indexes and evaluating their projected values, a special role is played by contingency calculations that utilize economic and mathematical optimization models.

An important and still unsolved problem of the studies in this field is a numerical evaluation of threshold values of indexes and overall indicators of energy security. These estimates should depend on both the conditions (scenarios) of development of the economy and the energy sector and the projected time frame.

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* Corresponding author: kononov@isem.irk.ru

Reserves of Generating Capacity for Perspective Planning of Development of the Unified Energy System of Russia

Dmitry Krupenev[1*], *Denis* Boyarkin [1], *Dmitrii* Iakubovskii [1], *Gennady* Kovalev [1], and *Ludmila* Lebedeva [1]

[1]Melentiev Energy Systems Institute of SB RAS, Energy Security Department, 664033 Lermontov str. 130, Russia

Abstract. Determination of reserves of generating capacity is one of the main tasks in planning the future development of electric power systems. There are many problems that affect the rational level of redundancy of generating capacities in Russian power industry. Modern changes in the Russian electric power industry concerning the level of redundancy of generating capacity in the long-term planning of the development of the Unified Power System (UPS) of Russia are analyzed in the article. The optimization problem of determining the necessary reserves of generating capacity in the power system, based on the assessment of adequacy, taking into account the modern features of the development of the UPS of Russia is presented. The results of assessing the adequacy of the UPS of Russia at the level of 2022 and the value of the optimized reserves of generating capacity in the UPS of Russia are showed in the final part.

Introduction

The problem of determining the rational level of redundancy of generating capacities is one of the main ones in the long-term planning of power systems development [1]. The reserve of generating capacities in the power system should have an optimal value corresponding to the technical and economic criterion. Many factors influence on determination of the level of optimal redundancy of generating capacity. Among the main ones are the level of accidents in power equipment, the rules for scheduled repairs of power equipment, the development of the electric network, the amount of damage to consumers from insufficient reliability of the power system. The main criterion for solving the problem of optimal reserves of generating capacity of the electric power system (EPS) is to minimize the amount of costs to increase the reliability of the EPS and the damages resulting from insufficient reliability of the EPS [2-4].

A wide range of indicators is determined in adequacy assessment. They are associated with damage and characterize the level of reliability of the power system. The probability of deficit-free operation can be used instead of using damage from low reliability in the problem of optimal reservation of generating capacity. In the main, the probability of deficit-free operation is used as an additional constraint [4]. This formulation of the problem is equivalent to a formulation with a damage; moreover, with this formulation, it is possible to take into account possible requirements from electricity consumers in ensuring the standard level of reliability of power supply.

It is advisable to substantiate the level of reserves of generating capacity in accordance with the development of the network part of the power system. In terms of ensuring the reliability of electricity consumers, these technological links are connected in series and the overestimated reliability of one of the links will not lead to the effect of ensuring the required level of reliability of electricity consumers [5].

The amount of generating capacity reserves influence to many strategic mechanisms for the development of the power system. For example, within the framework of the capacity market, the main mechanism is competitive power take-off (CPT) [6]. The amount of the generating capacity reserve is included in the demand for capacity during the CPT and, accordingly, directly affects the final price of capacity. As a first approximation, for the first price zone of the Unified Power System (UPS) of Russia, a decrease in demand and, accordingly, in the amount of the generating capacity reserve by 5% will lead to a decrease in the price during CPT by 15%, and in the second price zone of the UPS of Russia, a decrease in demand by 5% may lead to a 12% decrease in the price CPT.

At the present stage of the development of the electric power industry in Russia, a number of various problems have accumulated in the EPS of Russia. One of the essential is significant volumes of morally and physically obsolete generating capacities [7]. Combined with low demand for power from consumers and problems with old capacity, the efficiency of the power system is extremely low. In addition, in modern conditions of the functioning and development of power systems, the uncertainty in power generation increases due to the integration of renewable energy sources into the power system, which makes the task of determining the optimal level of reserves even more urgent [8].

* Corresponding author: krupenev@isem.irk.ru

In addition, in the legislative framework of the Russian Federation, the requirements for the levels of reserves of generating capacity in the UPS of Russia are not clearly formulated, and in some documents, they contradict each other. Work is currently underway to eliminate this deficiency at present time.

Problem statement

When determining the level of redundancy of generating capacity, an important factor is the selection and justification of the criterion of redundancy. Adequacy indices are used as such a criterion. Obtaining adequacy indices is carried out using a technique based on the Monte Carlo method [9,10]. In this case, the power system, as a rule, is represented as a set of reliability zones connected by inter-zone connections. The reliability zone is a part of the power system within which there are no power limitations in all possible steady-states. Inter-zone communication is a set of transmission lines that connect two identical zones of reliability. In the power system, there is a concept as a controlled section. The controlled section is a set of power transmission lines for which the maximum permissible active power flow has been determined. In the design scheme for adequacy assessment, the inter-zone connection and the controlled cross-section may not coincide; in this case, when minimizing the power deficit, it is necessary to use special algorithms to take into account the network component [11].

As already noted, the probability of a deficit-free operation can be taken as a criterion for ensuring adequacy [9,12]. To substantiate the normative value of this indicator, a methodology has been developed, which is presented in [13].

As mentioned above, the current state of the UPS of Russia is characterized by surpluses of old and inefficient generating capacities, with local problems in some power regions. Therefore, the task for the study was formulated as the task of minimizing the available power of the EPS, corresponding to the standard level of probability of deficit-free operation, taking into account the decommissioning of the existing generating units.

The considered problem is:

$$\sum_{j=1}^{J} x_j \xi_j \rightarrow min, \quad (1)$$

where constant x_j - available capacity of the existing generating unit j; J is the number of generating units in the EPS; the variable$\xi_j \in \{0, 1\}$ is a sign of the presence of the generating unit j as part of the EPS generation.

Variables constraints:

$$\begin{cases} P_i \geq P_{norm}, \text{ если } P_{init,i} \geq P_{norm} \\ P_i \geq P_{init,i}, \text{ если } P_{init,i} < P_{norm} \end{cases}, \; i = 1, \dots, I, \quad (2)$$

where P_i is the probability of deficit-free operation in the i reliability zone, I is the number of reliability zones in the EPS; P_{norm} - standard level of probability of deficit-free operation in EPS; $P_{init,i}$ - the probability of deficit-free work in the reliability zone i for the initial version.

The P_i values for $i = 1, \dots, I$ are calculated by evaluating the balance reliability of EPS (F_i) for the current composition of generating units.

$$P_i = F_i(\xi), i = 1, \dots, I. \quad (3)$$

Experimental investigation

When preparing the initial data for the research, a significant amount of statistical data on the operation of the equipment of the UPS of Russia was processed. The study was carried out for the development plans of the UPS of Russia for 2022 [14]. When clustering the UPS of Russia, 106 safety zones were identified. The variant of development of the UPS of Russia, presented in [14], was characterized by the data of the energy balance per hour of the coincident maximum power demand, presented in Table 1. Table 2 presents the data on the energy balance for parts of the UPS of Russia within the boundaries of interconnected power systems (IPS). When clustering the UPS of Russia into reliability zones, the Smolensk energy system was assigned to the 13NW reliability zone. This zone is part of the Nord-West IPS, although the Smolensk energy system is in fact part of the Central IES. In the results, all the parameters characterizing the Smolensk energy system are presented in the initial data of the IPS of the North-West, namely its own maximum power consumption, which in 2022 is equal to 1086 MW, other characteristics of power consumption, generating units with their characteristics, the capacity of which is 3995 MW.

Table 1. Power balance in the UPS of Russia at the level of 2022 (initial version)

Installed capacity, MW	236442
Installed capacity limitations, MW	18341
Available capacity x_{UES}, MW	218101
Coincident maximum power demand y_{UES}, MW	165202
Capacity reserve, % ($k_{rez} = (x_{UES} - y_{UES})/y_{UES}$)	32

Table 2. Power balance in the UPS of Russia at the level of 2022 (initial version)

EPS Name	Available capacity, MW	Coincident maximum power demand, MW (with UPS of Russia)	Capacity reserve, %
Nord-West IPS	25634	16470	55
Central IPS	43797	37120	18

South IPS	21794	17840	22
Middle Volga IPS	25181	16953	43
Ural IPS	51309	38820	32
Siberia IPS	38544	31483	22
East IPS	11843	7137*	66

* IPS of the East operates in isolation from the UPS of Russia, using its own maximum power consumption.

As can be seen from Tables 1 and 2, the level of generating capacity redundancy in the UPS of Russia and, particularly, in IPSs is high. If we compare the presented values of capacity reserves with the values presented in [15], we can see that, for example, recommended value for the IPS of Siberia is 12% [15], instead of the real 22%. Moreover, when determining the actual reserve ratio, all limitations were taken into account, including hydroelectric power stations output limitations.

The UPS of Russia was divided into reliability zones as part of an adequacy assessment. Each reliability zone was assigned an index and a conditional name. After adequacy assessment of the initial variant of the UPS of Russia development, it was determined that the probability of deficit-free operation in almost all 106 reliability zones turned out to be higher than the standard level, with the exception of:

1. Reliability zone 8NW (NW – Nord-West), covering the energy region in the North-West IPS. In fig. 1 shows the energy balance in the area of the 8 NW reliability zone. The probability of deficit-free work in this area was 0.9955.

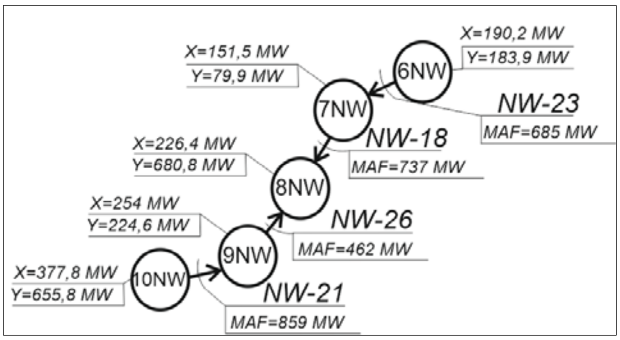

Fig. 1. Power balance of 8NW and adjacent reliability zones. (X is the available power, Y is the power consumption).

When analyzing the balance situation around the 8NW reliability zone, it was determined that the network capabilities of the controlled sections connecting the 8NW with other reliability zones are sufficient to cover the power deficit in the 8NW even in the event of a failure of one of the network elements affecting the maximum allowable flow (MAF) of the controlled sections. However, the generating capacity capabilities of the reliability zones adjacent to the 8NW are not sufficient to cover the capacity deficit in the 8NW. Thus, we can conclude that power shortages during the billing period with a high probability may arise due to the lack of generating capacities in the considered power region and the "weak" transit of power from the power system of the Leningrad oblast.

2. Reliability zone 4S (S - South) is part of the power system of the Rostov oblast. The probability of a deficit-free operation of this reliability zone was 0.9968, which is lower than the accepted standard. In fig. 2 shows the energy balance in the 4th and in the adjacent reliability zones. The own maximum power consumption of the considered reliability zone is 2782.8 MW, and the value of the available capacity within the reliability zone is 640.1 MW, thus the own deficit of 4S is 2142.7 MW. The 4S reliability zone is connected to the 7S reliability zone by two 220 kV power lines and 500 kV power lines, which are included in several controlled sections; to the 5S is connected by 220 kV transmission line and two 500 kV transmission lines, also included in several controlled sections; to the 1S by 220 kV transmission lines and 500 kV transmission lines included in several controlled sections; with a reliability zone of 14S 500 kV transmission lines included in several controlled sections. Figure 2 shows the power balance of the 4S and adjacent reliability zones.

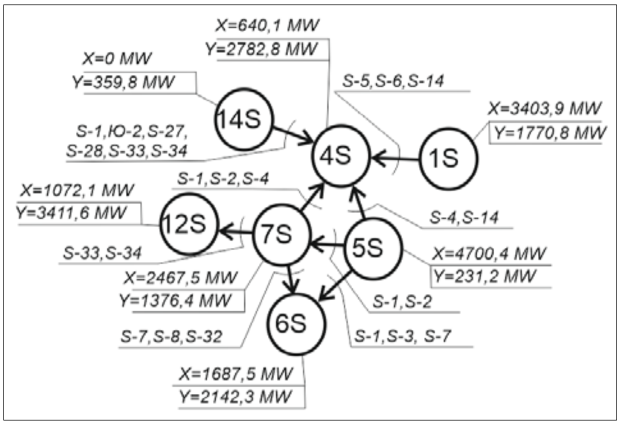

Fig. 2. Power balance of 4S and adjacent reliability zones.

When considering the balance situation of the 4S reliability zone, we can conclude that the generating capacity of the neighboring reliability zones and the transmission capacity of the transmission lines connecting the 4S with neighboring reliability zones should be sufficient to cover the power deficit in 4S. However, a number of reliability zones, including 6S and 12S connected to 7S, are also in short supply. The main donor zones for 4S are 1S and 5S. The main controlled section limiting the transfer of power from 1S and 5S to 4S is S-14. In the event of failure of one of the power lines of the section S-14, the MAF of the repair scheme S-14 becomes 1450 MW, instead of 2271 MW in the normal scheme, which with a high probability will lead to a power deficit of 4S during the hours of maximum power consumption. During the initial analytical analysis of the situation with the failure of the power transmission line, it can be determined that the influence of this power transmission line on the probability of deficit-free operation in 4S will be 1 - 0.00324 = 0.9968, which coincides with the probability of deficiency-free operation, determined when adequacy assessment. Thus, in the course of adequacy assessment of the UES of Russia in a number of considered design states in the 4S reliability zone, power shortages were determined.

3. Reliability zone 1U (U - Ural) includes a part of the power system of the Yamalo-Nenets Autonomous Okrug with the capture of a part of the Vankor power region of the Krasnoyarsk Krai. The probability of deficit-free work in the 1U reliability zone turned out to be 0.9989, which is slightly lower than the accepted standard. The own maximum power consumption of the 1U reliability zone is 945.9 MW, the available capacity is 1019.8 MW. 1U has a surplus of its own generating capacity, which is equal to 73.9 MW. The 1U reliability zone is connected only with the 2U reliability zone with a controlled section U-33, which includes three 220 kV power lines, the MAF of the normal U-33 circuit in the 1U direction is 48 MW. In fig. 3 shows the balance of power 1U and the adjacent reliability zone.

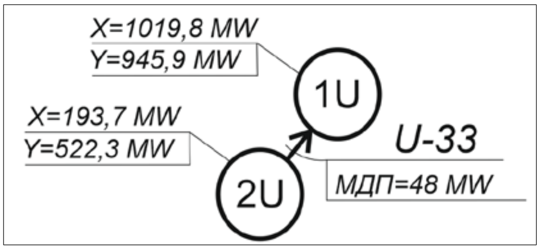

Fig. 3. Power balance of 1U and adjacent reliability zone.

Since the reliability zone 2U and the subsequent 3U are in short supply, the transfer of power to compensate for a possible power deficit in 1U is unlikely. MAF of the controlled section U-33 is low, and in repair schemes it is equal to zero, which can also prevent compensation of the power deficit in 1U. In 1U at Urengoyskaya power station there are three large generating units, the capacity of each is more than 150 MW, and the accident rates are 0.00925, 0.00007 and 0.00030. The failure of each of the generating units leads to the failure of the entire station, thus the integral probability of failure of a system of three generating units is 0.00962, and, accordingly, the probability of deficiency-free operation in the 1U reliability zone during the period of maximum power consumption can be defined as 1- 0.00962 = 0.99040, which led to the values of reliability indicators below the standard level.

4. Reliability zone 9E (E - East) includes a part of the power system of the Amur Oblast and a part of the power system of the Zabaykalsky krai. The probability of deficiency-free operation in the 9E reliability zone turned out to be 0.9987, which is slightly lower than the accepted standard. The 9E reliability zone does not have its own generation, its own maximum power consumption is 92.3 MW. When carrying out the calculations, it was assumed that the power lines on the western side are constantly open. On the east side, 9E is connected to 8E by two 220 kV transmission lines, which are included in the controlled section E-9 with MAF 215 MW in normal and repair schemes. The adjacent 8E reliability zone also does not has its own generation. In fig. 4 shows the balance of power 9E and adjacent safety zones.

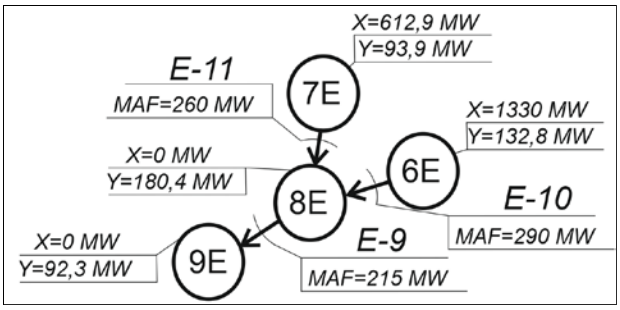

Fig. 4. Power balance of 9E and adjacent reliability zones.

There is no own generation in the 9E reliability zone and the only adjacent 8E reliability zone. For this reason, ensuring adequacy in these zones is entirely dependent on the operability of the transmission lines that connect these zones with the rest of the East IPS. Reliability zone 8E is connected to reliability zones 6E and 7E, which have a surplus of generating capacity at the level of 1700 MW. Thus, having studied the balance situation of the energy region under consideration, we can conclude that power shortage in 9E arise due to failures of the power lines of the E-10 and E-11 controlled sections.

Further, calculations were made to optimize the generating capacity reserve in accordance with the statement of problem (1) - (3). At the same time, the standard value of the probability of deficit-free work was adopted at the level of 0.999. Table 3 shows the calculated data on the power balance of the UPS of Russia per hour of the coincident maximum power consumption in 2022 for the options for ensuring the standard level of probability of deficit-free operation at the level of 0.999, taking into account the conclusions of generating capacities. Table 4 presents the results for IPS of Russia.

Table 3. Power balance in the UPS of Russia at the level of 2022 ()

Installed capacity, MW	183902
Generation capacity disconnection, MW	34198
Coincident maximum power demand, MW	165202
Capacity reserve, %	11,3

Table 4. Power balance in the UPS of Russia at the level of 2022 ()

EPS Name	Available capacity, MW	Generation capacity disconnection, MW	Coincident maximum power demand,	Capacity reserve, %

			MW (with UPS of Russia)	
Nord-West IPS	19960	5674	16470	21
Central IPS	38094	5703	37120	5,6
South IPS	18810	2984	17840	5,4
Middle Volga IPS	19562	5619	16953	15,4
Ural IPS	43690	7619	38820	12,5
Siberia IPS	35090	3454	31483	11,5
East IPS	8696	3147	7137	21,8

After the calculations, in which the generating capacities were disconnected, it was determined that to ensure the probability of deficit-free operation in the reliability zones of the UES of Russia at the level of 0.999, 183,902 MW of available capacity is sufficient, of which 18,700 MW are reserves of various types.

It can be seen from table 4 that the distribution of generating capacity reserves calculated of IPSs is rather uneven. This is due to the strong ties between the zones of reliability of neighboring IESs, which make it possible to redistribute redundancies of generating capacity between zones of reliability, including between different IPS, and to carry out power flows to maintain the required level of adequacy. So, you can see that, for example, in the Central IPS, the value of the reserve of generating capacity is low, in this case, ensuring the standard level of probability of deficit-free operation in the Central IPS depends on power flows from other IPSs. The high level of redundancy in the East IPS is explained by the specifics of the structure of generating capacities. In the power balance of East IPS there are about 40% of hydroelectric power stations, the output of generating units of which was not carried out when determining the reserves of generating capacity corresponding to the standard values of the probability of deficit-free operation. This condition influenced the level of redundancy of the East IPS.

Conclusion

Determination of the rational level of generating capacity reserve in modern conditions of long-term planning of the development of power systems is a mandatory procedure and should be carried out when drawing up development plans for the UPS of Russia. The rational level of generating capacity reserve is determined when solving the optimization problem. For different conditions of the functioning and development of the power system, the optimization problem can have different target functions and a set of restrictions. In modern conditions of development, the UPS of Russia has accumulated a significant redundancy of generating capacities that have exhausted their resource. Under these conditions, the objective function of the optimization problem of determining the reserve of generating capacity can be defined as maximizing the total capacity of the disconnected generating units or minimizing the total capacity of the generating units remaining in operation, subject to the mandatory criterion of adequacy level.

In the article, using the example of the development plans of the UPS of Russia for 2022, the situation with the power balance is analyzed and calculations are carried out to determine the generating capacities, without which it is possible to ensure the probability of deficit-free operation in the reliability zones of the UPS of Russia at the level of 0.999. In the existing development plans, the probability of a deficit-free operation in almost all reliability zones of the UPS of Russia is higher than the accepted standard, and the generating capacity reserve is at the level of 32%, which is economically inexpedient. During the study, it was found that to ensure the probability of deficit-free operation at the level of 0.999, it is possible without 34198 MW of generating capacities. As a result, ensuring the adopted standard for the probability of deficit-free operation is possible while maintaining the generating capacity reserve at 11.3%.

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Methodical aspects of the energy industries interconnected operation modeling at the energy security research under modern conditions

Krupenyov Dmitry, *Pyatkova* Natalya, *Senderov* Sergey, *Boyarkin* Denis

Melentiev Energy Systems Institute, 130 Lermontov str., Irkutsk, Russia

Abstract. The relevance and significance of energy security problems studies in modern conditions of energy systems operation, during the period of negative trends growth in the energy sector, is undeniable and concerns two main aspects:
- the need for long-term, deficit-free provision of consumers with the required types of energy resources during the functioning of the energy sector under normal conditions;
- the need to create conditions for providing consumers with energy resources when implementing threats to energy security.
Due to the impossibility of conducting full-scale experiments on operating fuel and energy systems, work related to the modeling of these systems, the development of specialized software and tools, the rational organization of a computational experiment to find ways to provide consumers with energy-free supplies when operating in normal contingency conditions.
The main result presented in the article is a complex of energy systems models that take into account the intellectual nature of modern systems as much as possible and allow conducting energy security studies of the country and regions at a new qualitative level.

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1. Introduction

In modern conditions of the energy systems functioning and development, the relevance and significance of research on energy security problems increases. This is primarily due to high damage and sometimes catastrophic consequences in cases of interruption in the supply of energy resources to consumers. Energy security concerns two aspects:
-the need for long-term deficit-free provision of consumers with the required types of energy resources during the operation of the energy sector under normal conditions;- the need to create conditions for the provision of energy resources to consumers in the conditions of the threats implementation to energy security.
As knowт, the of threats realization to energy security leads to significant damage to the economy of the country and regions. This, for example, a decrease in investment opportunities, which can lead to a decrease in the levels of oil and gas production in the country, to an increase in the share of physically and morally obsolete fixed production assets in the energy sectors, to a slowdown in the rate of decline in the value of the specific energy intensity of GDP, which is currently.
A decrease in investment opportunities in the sectors of the fuel and energy complex is traced for the electric power, gas and coal industries [1-3], namely:
• in the electric power industry, the reduction in investments in 2018 compared to 2011 was 35%;
• investments in the gas industry decreased by more than 40%;
• investments in the coal industry were declining - in 2016 they amounted to 44% of the 2012 level.
In the event of natural threats, deviations of the maximum seasonal heating loads of the regions, depending on their climatic conditions, from the composition of consumers in them, up to 20-30% are possible. Also, deviations can be accompanied by a significant increase in the demand for energy resources both for a single climatic zone and for several neighboring regions.
Technogenic threats are most critical for the gas industry and the electric power industry. In the gas supply system, one of the most dangerous factor is the possibility of damage to transcontinental gas pipelines running from a large gas-producing region through the Urals to the European part of Russia []. In the electric power industry, significant undersupply can be caused by breaking ties between individual power systems or emergency situations at specific power plants (for example, an accident at the Sayano-Shushenskaya HPP in 2009, a systemic accident at power facilities in the Northwestern Federal District due to a failure at the Bratsk HPP in June 2017).
As for the oil industry, there is a lag in the reproduction of the oil production raw material base, which is accompanied by a decrease in the oil recovery factor (from 49% to 30% and below).
The dominant, in some cases almost monopoly role of natural gas in the boiler and furnace fuel balance in European regions of Russia, which has developed over the past twenty years and is slowly overcome in the future, is

* Corresponding author: nata@isem.irk.ru

a serious strategic threat to Russia's energy security. The danger here lies is that such a virtually monostructure makes the economy and population of this region too dependent on the reliability of gas supplies, produced and transported mainly from one gas-producing region and through one pipeline system owned by one company-a monopolist, and besides subject to increased danger of technogenic and natural influences.

In all branches of the fuel and energy complex, the share of equipment that has exhausted its resource (standard service life) is increasing. This is characterized by a high accident rate, significant costs and duration of repairs, low technical level.

To date, about 70% of the main oil pipelines were over 20 years old, of which about half were in operation for more than 30 years, while, despite the commissioning of new oil pipelines, there has been no qualitative change: the share of worn out equipment remains large. In the gas transportation system at the beginning of 2009, about 30% of the pipelines linear part and 10% of of compressor stations gas pumping units have been in operation for more than 30 years []. The problem of production assets depreciation in the power industry is becoming extremely acute. The total capacity of obsolete equipment at the country's power plants is about 38% of the installed capacity.

Due to the impossibility of carrying out full-scale experiments on operating energy systems of the fuel and energy complex, research, related to the modeling of these systems, the development of specialized software and tools, the rational organization of a computational experiment to find ways to provide consumers with energy resources without deficiency when operating under normal conditions and in emergency situations are particular importance.

Modern conditions for the development of information technologies, the emergence of high-performance computing facilities, as well as the intellectualization of energy systems and the need for their functioning in a digital economy impose special requirements on the used model computing facilities on the one side. On the other side, they present opportunities to increase the adequacy and correct-ness of modeling real systems, to take into account in the models the processes inertia, the dynamics of the emergency situations development in the models of the fuel and energy complex optimization; take into account nonlinearity for increasing adequacy of the processes representation in energy systems to improve the accuracy of decisions.

This work is an integral part of energy security studies. Similar research and development, and models for these studies are focused mainly on solving the problems of long-term planning of the energy systems in normal operating conditions with a horizon of up to 15-20 years. Similar works carried out in other teams is of a local or regional nature with the study of individual aspects of the problem [4-13]. Comprehensive studies that allow assessing the possibilities of all interconnected energy systems functioning and determining the consequences for energy consumers in the event of emergencies in the work of one industry or several industries have not been carried out at the earlier time.

Studies similar to those carried out by the authors are distinguished by their focus on solving the problems of assessing the behavior of energy systems in the context of the threats implementation to energy security, optimizing the modes of energy systems interrelated operation in emergency situations for reliable energy supply to consumers. Based on the results of the research, it is proposed to form a certain list of measures to ensure the level of energy security at the appropriate level.

2. Methodology of interconnected modeling of energy systems for solving problems of ensuring energy security.

To study the energy security problems in modern conditions, it is proposed to develop new and improve (adapt) existing mathematical models and methods of interconnected operation of large energy systems within the framework of a single fuel and energy complex (FEC) in various operating conditions. The use of a new model-instrumental complex will allow conducting research to assess the possibilities of providing consumers with energy resources under the energy security threats implementation of various nature.

The general scheme of the tasks to be solved when assessing the effect of ES threats on the energy security state is shown in Fig. 1.

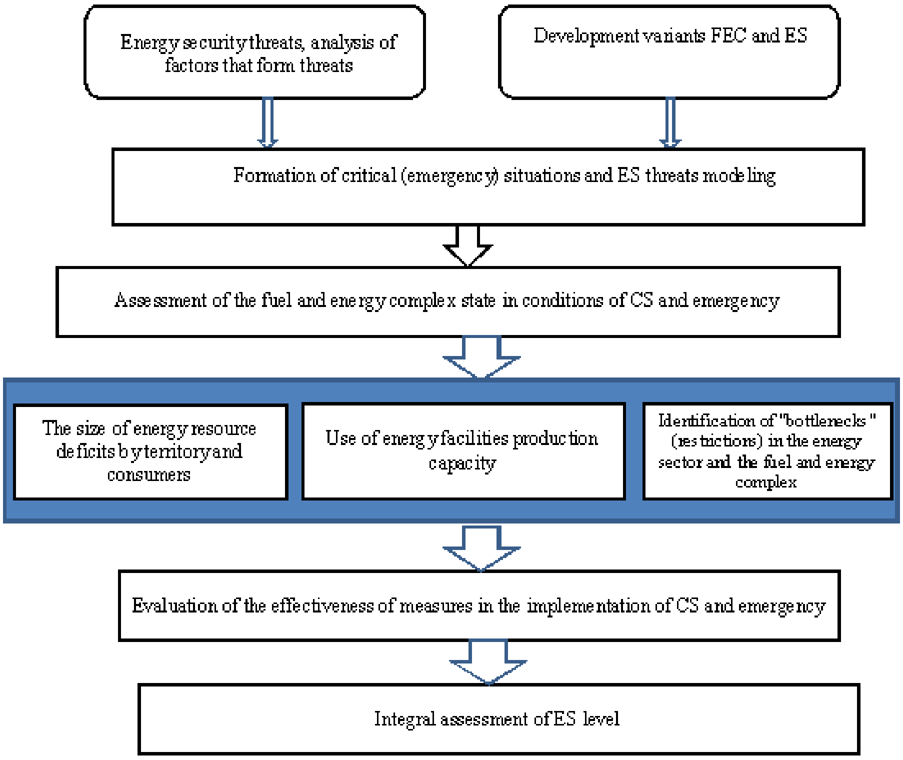

Fig. 1. General scheme of research on ES problems

The initial basis for research is the technical and economic characteristics of energy facilities and reporting data on the state of energy systems, the results of research on the development of the fuel and energy complex, justifying the choice of a long-term strategy and the formation of an energy policy. Based on the socio-economic development program of the country's economy adopted for the future, which determines the demand for fuel and energy resources, an analysis and assessment of energy consumption levels is carried out, taking into account energy conservation.

On the basis of the above characteristics and analysis of ES threats, design conditions are formed for a computational experiment, which is carried out using models of energy systems.

3. Models of energy systems

Models of energy systems represent a system of economic and mathematical models for assessing the territorial and production structure of the fuel and energy complex, taking into account the requirements of energy security [15]. These models can be used in two modes:

- in the mode of determining the energy technologies optimal development (taking into account the structural redundancy in the form of capacity reserves, fuel reserves, interchangeability of energy resources) and the optimal distribution of consumed energy resources,
- in the mode of determining the energy resources underdelivery (FER deficits) in the country as a whole and in individual regions.

The structure of the fuel and energy complex models is shown in Fig. 2. Technologically, it consists of the energy complex sectoral subsystems (gas, coal, oil refining (in terms of fuel oil supply) industries, electricity and heat power engineering) and a block of consumers (energy consumption at various types of power plants and boiler houses for generating electricity and heat, other consumers and export consumers are highlighted separately)

* Corresponding author: nata@isem.irk.ru

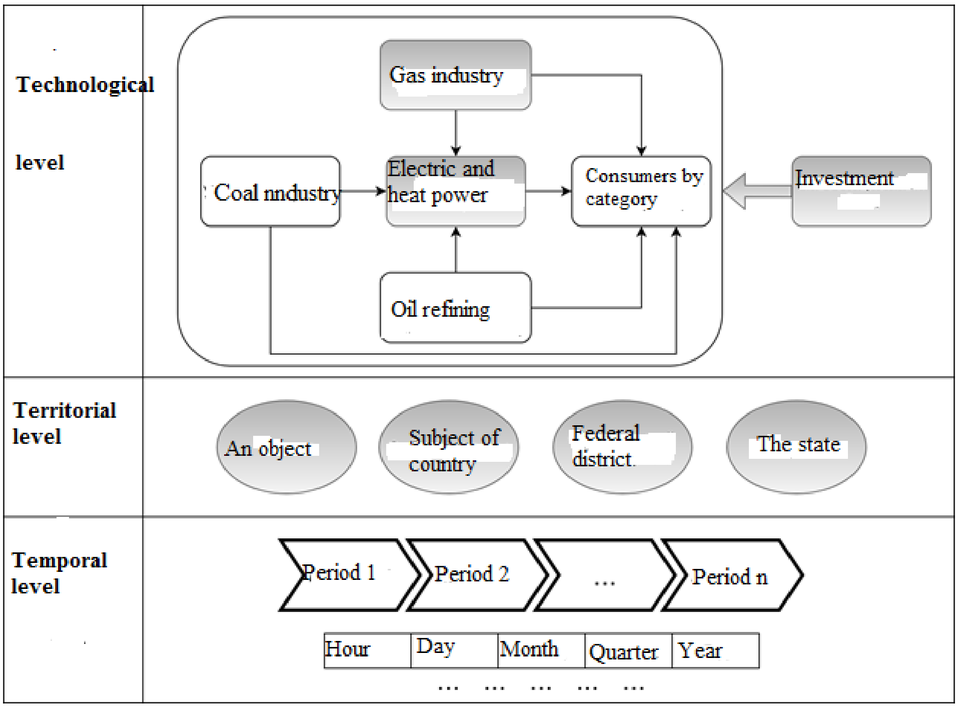

Fig. 2. Territorial, temporal and technological structure of models

The final implementation includes a financial block that describes the investment costs of reconstruction, modernization of existing facilities, obsolete equipment removal, commissioning of new facilities at energy facilities. The development dynamics were also taken into account, which made it possible to track such features of the multi-step process of the fuel and energy complex development as:

• commissioning of new production facilities;
• dismantling and conservation of old objects,
• reconstruction of facilities with a change in the technological scheme.

The dynamics are taken into account in the form of *T* independent static blocks, each of which describes all the territorial and technological connections of the fuel and energy complex in relation to stage *t* of the billing period. Dynamic connections between the blocks are built using equations that formulate for all x_i objects of the fuel and energy complex the condition for the continuity of their performance at different stages of the billing period. For the first stage, this condition is written as:

$$x_{i1}^{o} + x_{i1}^{c} + x_{i1}^{d} = P_{i0}, \qquad (1)$$

and for subsequent stages in the form of equations

$$x_{it-1}^{o} + x_{it-1}^{c} + x_{it-1}^{n} = x_{it}^{o} + x_{it}^{c} + x_{it}^{d}, \quad (2)$$

where P_{i0} - the technology productivity (object *i*) by the beginning of the billing period,

x_{it-1}^{n} - the performance of the technology new part (object *i*) at stage *t-1*,

x_{it}^{o} - the performance of the technology acting part (object *i*) at stage *t*,

x_{it}^{c} - conservation of a object part *i* at stage *t*,

x_{it}^{d} - liquidation of a object part *i* на этапе *t*.

For the convenience of forming bonds, equation (2) is divided into two parts

$$-x_{it-1}^{o} - x_{it-1}^{c} - x_{it-1}^{n} + Z_{it-1} = 0,$$

$$-Z_{it-1} + x_{it}^{o} + x_{it}^{c} + x_{it}^{d} = 0,$$

where Z_{it-1} - an intermediate variable characterizing the total productivity of object *i* at the beginning of stage *t*. It takes into account the removal of capacities at stage *t* and the introduction of new capacities at time stage *t + 1*.

In general, these models are used to determine the following characteristics (indicators):

-the size of undersupply (deficit) in energy resources certain types for the considered categories of consumers, allocated territorial associations and the country as a whole, as the magnitude of the discrepancy between a given demand and the possibility of producing this type of energy resource (taking into account reserves, the possibilities of replacing this type of energy resource with others consumers, etc.);

- changes in the throughput of transport links, determined by comparing the corresponding indicators of the considered option with the original;

- rational use of energy facilities production capacities, as well as the distribution of energy resources certain types for the selected categories of consumers.

The main the models in the proposed implementation of the model-instrumental complex are the models of the gas industry and the power industry, the mathematical description of which is presented in the next section.

* Corresponding author: nata@isem.irk.ru

4.Mathematical description of models of the gas and electric power industries

The flow distribution model in the unified gas supply system (UGSS) is intended to assess the production capabilities of the UGSS during different disturbances. The aims of such studies is to minimize gas deficits at consumption nodes. The gas industry in the model is presented as a combination of three subsystems: gas sources, trunk transport network and consumers [16].

When solving the problem of network state estimation after a disturbance, the optimality criterion for the flow distribution is the minimum gas deficit for consumer with the minimum cost of gas delivery to consumers. This problem can be solved by finding the maximum network flow. The maximum flow problem is formulated as follows [16]:

$f \to \max$, (3)

under the conditions that

$$\sum_{i \in N_j^+} x_{ij} - \sum_{i \in N_j^-} x_{ji} = \begin{cases} -f, & j=O \\ 0, & j \neq O, S \\ f, & j=S \end{cases}, \quad (4)$$

$0 \le x_{ij} \le d_{ij}$, для всех (i, j). (5)

In this case, f is the maximized variable corresponding to the maximum flow.

When working with complex schemes, there may be several solutions, that is, several possible maximum flows. Then it is advisable to talk about minimizing the cost of delivering gas to consumers and using the Basaker-Gowen algorithm:

$\sum_{(i,j)} C_{ij} x_{ij} \to min$, (6)

$x \in X^*$,

Its application makes it possible to determine the maximum gas flow at its minimum cost or the optimal volumes of daily gas withdrawal from underground gas storage facilities (UGS), which maximally ensure the specified volumes of gas supply to consumers at minimum costs for production, transportation of gas and its extraction from UGS.

Here O is the total source; S is the total sink; N^+_j is a subset of arcs "incoming" in node j; N^-_j is a subset of "outgoing" arcs from node j; f is the value of the cumulative flow in the network; x_{ij} is the flow in an arc(i, j); d_{ij} - limitations on the flow in the arc (i, j); X^* - the set of solutions to problem (4) - (6); C_{ij} – price or specific costs of gas transportation.

Node O is connected by fictitious arcs with all real sources of energy resources, and node S - with all consumers.

In the UGSS flow distribution model, the Basaker-Gowan algorithm is used to calculate the maximum flow of the minimum cost, which, as a result, makes it possible to determine the possible level of consumer satisfaction with gas. As a result of the implementation of various abnormal situations, it is possible for consumers to have a gas shortage caused by a lack of carrying capacity in certain sections of gas pipelines. Bypassing such narrow or limiting the production capabilities of the system places, in acceptable volumes, will allow reduce the gas shortage among consumers that has arisen in the situation under consideration.

In the case of a gas deficit for consumers, caused by a transmission capacity decreasing of the corresponding gas pipelines, other branches of the main gas pipelines that are not affected by the violation in question can increase gas throughput volumes. In such a situation, the network congestion changes and a transmission capacity decreasing in other sections of the main gas pipelines is possible.

Subsequent clearing of bottlenecks in the GTS will allow minimizing gas deficits for consumers and makes the assessment and identification of possible critical combinations of gas facilities as adequate as possible.

5. Electric power system model

As already shown, the EES model is the central link at the fuel and energy complex modeling. The purpose of EPS modeling is to determine the power capacity shortage and undersupply of electricity to consumers as a result of accidents at the fuel and energy complex. For correct modeling of emergency situations, an adequate mathematical model of the EPS is required. The problem to be solved can be formulated as follows: for a known structure, parameters of elements and a capacity consumption graph of a the EPS, it is necessary to determine the power deficit and shortage of electricity for the period from the beginning of an emergency to it's completely eliminated. The computational model of the EPS is a graph of which nodes are energy zones, and arcs are inter-zone connections. The energy zone includes a part of the energy system, as a rule, it is a regional energy system that contains a set of generating units and is characterized by power consumption in every hour of the settlement period. Inter-zone communication includes power lines that connect two energy zones. Thus, for each hour of the calculation period, it is necessary to solve the following problem [17]:

need to find:

$\sum_{i=1}^{I} (\overline{N}_{\text{потр},i} - N_{\text{потр},i}) \to min$, (7)

given balance sheet constraints

$N_{\text{ген},i} - N_{\text{потр},i} + \sum_{j=1}^{J} (1 - z_{ji}\, a_{ji}) z_{ji} - \sum_{j=1}^{J} z_{ij} = 0, i = 1, \dots, I,\ i \neq j$, (8)

and linear constraints-inequalities on variables

$0 \le N_{\text{потр},i} \le \overline{N}_{\text{потр},i}, i = 1, \dots, I$, (9)

$0 \le N_{\text{ген},i} \le \overline{N}_{\text{ген},i}, i = 1, \dots, I$, (10)

$0 \le z_{ji} \le \overline{z}_{ji}, 0 \le z_{ij} \le \overline{z}_{ij}, j = 1, \dots, J, i = 1, \dots, I, i \neq j$, (11)

where $\overline{N}_{\text{потр},i}$ is the amount of capacity consumption in the energy zone i, MW; $N_{\text{потр},i}$ - ensured capacity consumption in energy zone i, MW; $\overline{N}_{\text{ген},i}$ is the available generating capacity in energy zone i, MW; $N_{\text{ген},i}$ - used generating capacity in the zone of reliability i, MW; $\overline{z}_{ji}$, $\overline{z}_{ij}$ - inter-zone communication throughput, MW; z_{ji}, z_{ij}

- actual load of inter-zone communication, MW; $I = J$ - number of energy zones.

6. New opportunities in energy security research

The proposed model-instrumental complex, consisting of industry models connected by information flows and an integrating the fuel and energy complex model as a whole, developed for the energy security research will improve the existing practice of assessing the implementation of energy security threats in the following directions:
-to determine the mutual influence of energy systems on each other and to give a comprehensive assessment of the threats impact to energy security;
- will allow taking into account the dynamics of the emergency situations development in the optimization models of energy systems and the fuel and energy complex;
- will allow to keep track of the power consumption schedule, which imposes requirements on industry systems from consumers;
- will allow to take into account nonlinearity for the adequacy of the representation of processes in energy systems to improve the accuracy of decisions made (in models of industry systems)
- take into account natural factors in terms of the impact on the operation of renewable energy sources (periods of low water for hydroelectric power plants, cloudy days for solar power plants, low wind periods for wind farms);
- take into account the influence of inertia in the gas, coal, oil refining industries on the development of emergency situations and link with their development in the power industry, which is key for the fuel and energy complex.
- take into account the peculiarities of the mutual influence of the gas and electric power industries when fulfilling the conditions for the reliability of gas and electricity supply to the production facilities of these industries;
- take into account the peculiarities of the mutual influence of the oil and oil refining and electric power industries when meeting the conditions for the reliability of the supply of electricity and oil products to the production facilities of these industries.

Conclusion.

The paper presents the methodological features of modeling the interconnected work of industries in modern conditions and an approach to creating a specialized software and instrumental complex that combines models of industry energy systems and the fuel and energy complex model integrating them. The complex being developed is intended for experimental research to find ways of supplying consumers with energy resources without deficits while operating under normal conditions and in emergency conditions. A more detailed representation of energy objects in models will improve the correctness and adequacy of the simulated systems.
The proposed complex of models of energy systems will allow taking into account the intellectual nature of modern systems as much as possible and will allow conducting research on the energy security of the country and regions at a new qualitative level.

• Acknowledgment

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Enhancing the safety of energy systems functioning at their digitalization

Natalia Kuznetsova [1], and *Yuri* Konovalov[2,*]

[1]PhD in Economics, Novosibirsk State Technical University, Novosibirsk, Russia
[2]Candidate of technical sciences, Angarsk State Technical University, Angarsk, Russia

Abstract. Informational safety threats have been analyzed for energy systems digitalization. It was established, it is impossible to completely eliminate the human factor in insuring cybersecurity of energy facilities being digitized. At the same time, a better understanding of how human actions affect reliability and safety will make it possible to predict the human factor influence and help to enhance safety of the power systems operation. The analysis of the digital transformation evelopment lines indicates that power generation companies have to move to more complex forms of digital management organization for all processes with due consideration of the human factor. Using the anthropocentric approach, the main factors that determine the reliability of IT employee ensuring functioning of energy systems during their digitalization, have been considered. A profile of the reliable employee, who is an empirically constructed set of qualitative characteristics inherent in personnel involved in the digital transformation of the power generation sector at all its levels.

1 Introduction

Energy sector of the XXI century is the basic part of the contemporary industrial complex. In the course of their development, power generation companies are faced with the problem of modernizing their own information structures to enhance the performance of big data processing [1, 2]. Currently, the cloud technologies facilitate the implementation of this task. The principle of cloud technologies operation is the use of third-party resources by clients, subject to the resources required:
for data storage, for creating one's own operating systems and applications and, up to the presentation of completely ready-to-use workstations.

In relation to the power engineering facilities the advantages of 'clouds' are the availability of information in the joint document flow for the facility state for different services monitoring the operating mode, defining the service life of the facility, scheduling repairs and replacement of devices when accessing databases that are structured in the 'cloud'. Taking into account the distributed nature of electrical devices in the distribution networks of different configurations, information exchange through the cloud structure is also an undisputable advantage. An important element is the ability to provide the required reliability for power facilities by specialized structures with the presence of additional power sources, security, professional employees, with continuous data backup, high resistance to DDOS-attacks.

As a result, cloud technologies are becoming increasingly important for power engineering companies with the ambition to grow and develop. The 'cloud' helps them get on-demand access to more data than ever before, and to increase computing capacity to obtain significant results and recommendations. There is a need to study the impact of cloud technologies and related processes on the safety of power engineering facilities functioning, with due consideration of their activities specifics [3].

Due to migration to the 'cloud', digitalization of energy sector occurs. The digitalization of energy can be called the basic part of the architecture of the 'Digital Economy of the Russian Federation' program, which is reflected in the passport of the 'Russia's energy sector digital transformation' program [4].

The aim of digitalization is to create a unified information environment and a common programming language. It includes the following benefits:
increasing automation and diagnostics levels; development of information infrastructure dedicated to data transmission; digitalization of innovation activities; development of human capital.

The demand for digital technologies among Russian energy companies is associated with the need for a considerable replacement of fixed assets in the domestic energy sector.

According to the decree of the President of the Russian Federation 'On national goals and strategic objectives of the Russian Federation development for the period up to 2024' [5], the power generation industry, being one of the fundamental life support systems covering the state needs, has to make a scientific, technical and socio-economic breakthrough. The development strategy of Russia's power grid companies, currently, consists in the comprehensive modernization

* Corresponding author: yrvaskon@mail.ru

of the power grid infrastructure using up-to-date electrical equipment and digital technologies.

A number of technological innovations, such as the Industrial Internet of Things, real-time information technology systems and solutions to optimize energy production and distribution, have given impact to global changes in the energy sector around the world, which have opened up new growth opportunities. In this regard, the problem of digital technologies' uniform standards development for the use in energy companies and ensuring cybersecurity, comes to the fore.

Studies show that energy companies could increase their capitalization by using a combination of several lines of digitalization [6, 7]. About 50% of energy companies executives say they are trying to effectively combine fast-growing technologies. However, only 9% of companies chief executives declare that their profit growth is due to digitalization and indicate the difficulty in measuring the effectiveness of investments in digital technologies.

The digitalization of energy systems, along with the solution of technical issues, the development of information infrastructure, implies the development of human capital in the formatting of new professional competencies in energy companies employees [8].

2 Safety issues of energy systems functioning

If we talk about cybersecurity in the course of digitalization, then it should be noted that the 'cloud' is exposed to the same threats as traditional infrastructures. It doesn't matter what kind of data you transferred to the 'cloud': whether it's a list of personal data or data of a utility company's consumers, they are all attractive targets for attackers. At the same time, the severity of potential threats directly depends on the importance and significance of the data stored. For energy facilities, this can be commercial information on tariffs and mutual settlements, tender purchases of expensive equipment, on the operation of relay protection and automation devices setpoints and algorithms, the change and violation of which can result in significant damage and even death. Thus, increased requirements are imposed on energy facilities with respect to information protection and cybersecurity.

An overview of information security threats during the power systems digitalization allows us to highlight the most important of them.

1. Inconsistency of the digitalization objectives with the real situation at the facility. The existing high energy intensity of the Russian economy, low rates of equipment renewal, high moral and physical wear and tear of fixed assets pose a threat to the energy facilities safety, on the background of violating the existing conditions for their functioning. In this case, the digitalization of individual parts of the power system complex equipment leads to an increase in the load on personnel, who, while performing their main functions, must simultaneously fend off all the shortcomings and unreliability of power systems equipment in order to preserve its operability. All this leads to an increase in the power facilities personnel role in ensuring their trouble-free operation, as well as the scientific justification of the operability and the limits of permissible actions of personnel in the real conditions of power systems operation [9].

2. The threat of data loss, when the necessary information from the cloud can permanently disappear. Note, that now, with the development of cloud services, cases of data loss without the possibility of recovery due to the service provider are extremely rare, but hackers may well set such a goal for themselves and achieve success.

3. Data leakage, which is often the result of negligence in authentication mechanisms issues, where weak passwords are used and encryption keys and certificates are not properly managed. In addition, energy companies encounter issues of rights and permissions management, whereby employees are assigned much more authority than it is actually required. The problem also occurs when an employee is transferred to another position or dismissed, in which case his account should be immediately deleted, but this rarely happens. As a result, the account contains much more capabilities than it is required. And this is a cybersecurity bottleneck. In addition, cyberthreat experts point out that one should always remember that hackers can be helped by an insider or he himself can be a hacker. This risk can come from current or former employees, system administrators, contractors, or business partners. Insiders-attackers pursue a different goals, ranging from data theft to just a revenge. In the case of the 'cloud', their aim may be to completely or partially destroy the infrastructure and gain data access.

4. Cyberattacks are possible that pose a threat of violation of the automation and relay protection functioning algorithms. Security threat analysis shows that cyberattacks are not uncommon these days. Possessing sufficient knowledge and a set of relevant tools, one can achieve a desired result. It is not so easy to detect an attacker who wants to establish and nail down his own presence in the target infrastructure. Cloud providers use advanced security tools to minimize risks and prevent such threats.

5. Other threats to domestic energy companies that have decided to use cloud technologies, include a lack of understanding of such decisions essence. If an entity switches to cloud solutions just because it is a current trend, without understanding cloud capabilities, then it encounters risks. For example, when the development team is not sufficiently familiar with the specifics of cloud technologies and the principles of cloud applications deployment, operational and architectural problems arise. In this case, security is at risk again.

6. Downgraded qualifications of employees. Digital transformation leads to a decrease in the personnel role, who are reduced to passive observers, which leads to downgrading of their qualifications.

7. Misuse of the advanced technologies advantages. The proliferation of IoT (Internet of Things), equipped with embedded technologies to interact with each other or with the external environment [10] and 5G networks,

contributes to the development of new technologies and applications, such as intelligent transport systems, intelligent electrical grids, 'smart city', 'smart home', virtual reality, geolocation, etc. However, IoT technology is becoming ineffective due to the increase in the number of devices equipped with various sensors, such as smartphones, tablets, smart home appliances, etc., which can read a large amount of data from the environment. In manufacturing, including energy sector, the Industrial Internet of Things (IIoT) is being developed – one of the most promising concepts in the global industry. This problem pushes developers to move into the era of IoE (Internet of Everything – the concept of intelligent connecting everything: people, processes, data and objects ('things')) [10, 11]. Compared to IoT, IoE is more oriented toward the intelligent communication of people, processes, data and devices, rather than communication between IoT devices. With the introduction of IoE technology at industrial facilities IIoE (Industrial Internet of Everything), edge network devices are getting transformed from consumers to data producers with huge information processing capabilities, such as data collection, pattern recognition and data mining. At the same time, edge devices are equipped with Internet applications providing the integration of user computing services with cloud data processing centers. But now it is high time to think about safety, especially at production facilities. IIoE offers unprecedented possibilities, but if used incorrectly, the likelihood of human-related threats increases.

Thus, the introduction of digitalization in the energy sector entails the above disadvantages, largely related to the human factor. Research results indicate that the human factor accounts for up to 90% of accidents and failures, which are caused by operator errors in the power facilities management [12]. Roughly 30% of equipment failures are also directly or indirectly related to the human error. The most common causes of errors are [12, 13, 14]: the lack of practical skills in active management in emergency situations, monotony in the operator's work, which reduce the acuteness of his reaction, reduce the situation-based thinking while leading to a loss of vigilance, insufficient level of professional training, discrepancy between personal (primarily psychophysiological) qualities and required ones, ergonomic shortcomings of technical systems. Largely unintentional actions are due to the fact that a person's capabilities are limited by the physiological properties of the its body and the psychological characteristics of each individual [15]. At the same time, the power systems digitalization increases the psychophysiological load on the employee due to the continuous increase in the complexity of the actions performed, their abundance of intellectual functions, an increase in the volume and intensity of data processed, and the indirect participation of a person in the systems operation.

To reduce the negative impact of the human factor, a proactive approach should be employed, which includes personnel recruiting in accordance with the profile of the reliable employee having appropriate qualifications. For the successful implementation of digital and technological transformation, a common security structure is required, which considers the human factor as well. Expert assessments show that work on probabilistic safety assessments cannot be considered apart from an integral assessment of human reliability [12]. Therefore, taking into account the human factor in the energy facilities digitalization, the management of which can be represented as human-machine systems, is a factor to increase the safety of energy systems functioning.

3 Approaches to improve safety when considering the human factor

[13, 14, 16] are referred to the main methods in eliminating the human factor in the energy facilities management in the course of their digitalization:

- Transfer of decision-making functions from the man to intelligent technical control systems.
- Taking into account the features of human interaction with technical systems, which implies taking into account the equipment ergonomic properties, as well as the conditions of human interaction with them: improving the structure of the human operator's activity, rational distribution of functions between man and machine, using the concept of an active operator, the machine adaptation to the man.
- Assessment of the main factors that determine the reliability of the human-operator, including the degree of engineering and psychological consistency of technology with the psychophysiological capabilities of the human-operator, the level of the operator training and fitness, his psychophysiological properties: features of the nervous system, sensitivity thresholds, health status, psychological constitution of the individual, etc.
- Human-operator state management based on social and psychological events.
- Professional and psychological selection, including a set of measures aimed at ensuring that persons who, in terms of the level of development of professionally important qualities, cannot master the profession in a timely manner and effectively perform their functional duties, should not be appointed to this position. At the same time, this procedure shall be used not only for hiring, but also personnel transfer, and must also be applied, if the employee has committed violations when operating and maintaining the technical system.
- Raising the level of personnel professional training. At the same time, a modern personnel training system should be carried out based on a two-stage cycle: the first – the study of equipment and technological processes, the rules of operation, the electrical installations and safety codes using specially developed computer programs and examiners, the second – training in the skills of operating in regular and emergency modes on specially designed simulators and digital twins, which adequately simulate both the operator workstation, and technological processes of power facilities.
- Periodic control of whether the employee has the necessary professionally important qualities as a

guarantee to prevent his dysfunctional behavior: incompetence, inconsistency with the position held, errors caused by this in the course of performing his functions that entail damage.

- Conducting specialized training for employees on recognizing hacker techniques, using advanced security tools, the ability to properly manage processes, on gaining knowledge about scheduled incident response, and applying preventive methods that enhance the cybersecurity level.

The importance of the human factor forms the tasks for the personnel selection, ensuring the safety of power systems functioning in the course of their digitalization.

4 Solving the problem of taking into account the human factor for purposes of safety improvement

To take into account the influence of the human factor on ensuring the energy facilities safety, it is important to understand how security threats are associated with an employee's certain personal qualities and characteristics. These circumstances made it possible to formulate an assumption about the possibility of constructing some generalized profile of an employee, who is 'reliable' for the control and maintenance of energy facilities.

Based on the study of theoretical approaches to assessing the employees reliability, its moral and ethical component, special methods used to assess the personnel reliability, stable characteristics were identified that correlate with the concept of a 'reliable employee'. All in all, six groups of characteristics were identified, forming its generalized profile: he knows and understands the rules and procedures for ensuring cybersecurity, has a commitment to a safety culture, is professionally reliable, does not suffer from various kinds of addictions, does not have an increased vulnerability to external environment, is morally and psychologically reliable (fig. 1).

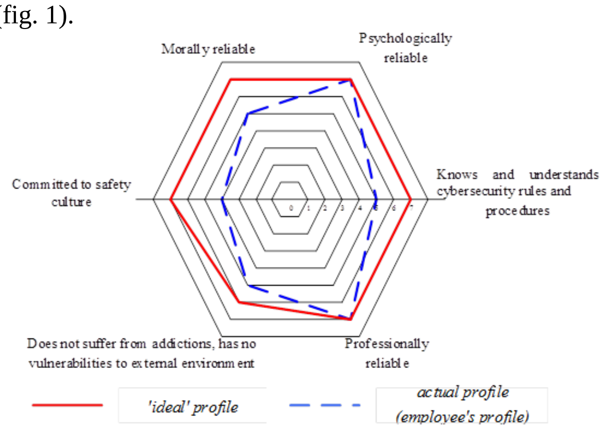

Fig. 1. Reliable employee profile model

Further, each group of profile characteristics was subjected to a detailed study, which resulted in a detailed description of the qualities, character traits, and behavioral features of the reliable employee. As a result, a detailed profile of the reliable employee was generated, which presents the most significant qualities, character traits and behavioral indicators that reveal his characteristics.

To analyze the obtained expert assessments of the values of characteristics maturity of the reliable employee profile, it is possible to use a scale with seven assessment values: complete characteristics immaturity; initial level of immaturity; under average level; middle level; the above average level of maturity; high level; complete characteristics maturity (fig. 2).

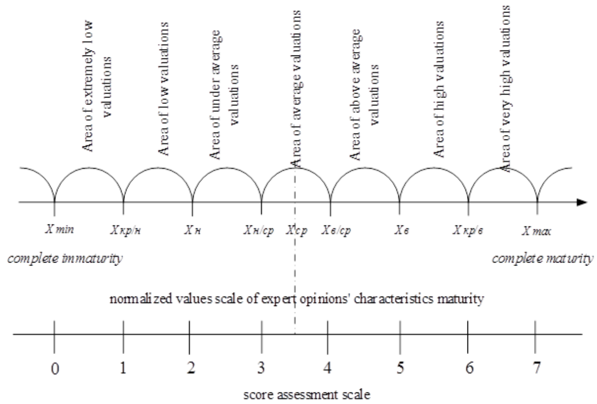

Fig. 2. Evaluation scale of values of the reliable employee's characteristics maturity

To determine the regions of the characteristics maturity, the following values are calculated: Xav – the arithmetic mean; Xmin – the minimum value; Xmax – the maximum value. Based on this data, the boundaries of the regions are determined.

The final assessment of the degree of profile characteristics maturity (S) can be determined using the formula:

$$S = \sum_{i=1}^{6} (Q_i \cdot k_i) / m,$$

where Q_i – the sum of points for the i-th profile characteristic, which are given by experts; k_i – the weight (significance) of this profile characteristic, which is assigned by experts; m – the number of experts who have assessed the degree of the profile characteristics maturity.

Thus, a profile of the reliable employee has been obtained – an empirically constructed set of qualitative characteristics inherent in an employee whose activities are safe for an energy facility in the course of its digitalization. Using this profile, the requirements for personal and professionally important qualities, the behavior of IT employees from the point of view of ensuring the cybersecurity of energy facilities can be meaningfully described and the degree of their manifestation can be assessed. The profile can be used at the stage of employee selection, in the process of personnel promotion and training, and is an effective tool for assessing an employee's reliability.

5 Conclusions

It is impossible to completely eliminate the human factor in managing and ensuring the cybersecurity of energy facilities during their digitalization, at the same time, a better understanding of how human actions affect reliability and safety will make it possible to predict the influence of the human factor and help to improve the safety of the power systems functioning.

The analysis of the digital transformation development lines indicates that power generation companies have to move to more complex forms of digital management organization for all processes with due consideration of the human factor.

Using the anthropocentric approach, the main factors that determine the reliability of IT employee ensuring functioning of energy systems during their digitalization, have been considered. A profile of the reliable employee has been developed, which is an empirically constructed set of qualitative characteristics inherent in personnel involved in the digital transformation of the power engineering at all its levels

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Remote Study of Aufeis along the ‘Power of Siberia’ Gas Pipeline in the Aldan River Basin

Dmitry D. Nogovitsyn, *Dmitry D.* Pinigin* and *Nadezhda A.* Nikolaeva

Larionov Institute of Physical and Technical Problems of the North SB RAS, 1 Oktyabrskaya, Yakutsk, Russia

Abstract. The ‘Power of Siberia’ gas pipeline route passes through the territories of South-West and South Yakutia, where the natural conditions are characterized by severe climatic, complex engineering geological and geocryological conditions. A variety of environmental conditions are mandatory for construction and operation in different areas with long-term soil and hazardous geocryological processes: debris flow formation, aufeis formation, soil heaving, thermokarst, thermosuffosion. Aufeis formation processes will be of particular importance during the construction of the pipeline. As a degree of their occurrence in the Republic of Sakha (Yakutia), it should be mentioned the Aldan upland. Aufeis occur almost in the majority of local stream valleys as a small areas of ice formations, basically confined to floodplain and riverbed.

Aufeis areas had been identified in trace areas by the method of deciphering satellite images within the territory of the hydrogeological zones of the Lena-Amur interfluve. As a result of remote studies, territorial and quantitative distributions in hydrogeological zones have been identified. As a result of the monitoring results the areas of each aufeis are determined and their contours are decoded due to satellite images of recent years (2018-2020).

1 Introduction

One of the priority, economically feasible projects of the present time in the Republic of Sakha (Yakutia) is the implementation in Eastern Siberia of ‘Power of Siberia’ pipeline, supplying natural gas from the Chayandinskoye oil and gas condensate field to Primorsky Krai and the Asia-Pacific countries.

In the Republic of Sakha (Yakutia), the gas pipeline route has been laid through the territories of South Yakutia within the Olekminsky, Lensky, Neryungri and Aldansky regions.

The natural conditions of the territory along which the main gas pipeline route passes are characterized by severe climatic, complex engineering-geological and geocryological conditions [1]. Various natural conditions of the route cause a number of specific problems, including environmental ones, at the stages of construction and operation within areas with permafrost and hazardous geocryological processes [3].

The main exogenous geological processes that complicate the operating conditions of the gas pipeline are cryogenic processes (kurum formation, aufeis formation, heaving, thermokarst, thermosuffosion), erosion processes; karst-suffusion processes. Aufeis formation processes will be of particular importance during the construction of the gas pipeline.

According to the degree of their manifestation, the Chulman plateau landscape province is distinguished, which belongs to the category of aufeis with a coefficient of relative development from 0.1 to 1%. Aufeis formations are formed practically in most of the valleys of local watercourses in the form of small ice crust formations, confined mainly to their floodplain and riverbed [4]. This site belongs entirely to the Aldan River basin.

The object of the work is a route section of the ‘Power of Siberia’ pipeline located in the catchment area of the Aldan River. It has a length of 509 km, and is located on the territory of the Aldan and Neryungri regions of the Republic of Sakha (Yakutia), forming a corridor with the ESPO-1 transport system with a width of up to 7.0 km.

Physically and geographically, the main pipeline route in the Aldan River basin runs along the southern edge of the Prilensky plateau, which passes along the gas pipeline to the Aldan Upland at elevations of 700-1000 m above sea level , and further to the northern slope of the Stanovoy Range, with heights of 850-1100 m above sea level.

Thus, the aim of the work is to identify the primary characteristics of aufeis recorded remotely at the

* Corresponding author: pinigind@mail.ru

crossings of the ‘Power of Siberia’ pipeline through the watercourses of the Aldan River basin.

2 Method of work

The methodological basis of the work is the aerospace method, which consists in fixing aufeis ice massifs on aerospace materials in different seasons.

The use of satellite imagery makes it possible to determine the location and shape of aufeis, their dimensions - width, length, area. The analysis of high-resolution satellite images also makes it possible to obtain data on the location, conditions of emergence of aufeis-forming sources, to determine the paths and boundaries of water spreading over the aufeis [5].

High resolution color space images of ‘Google Maps’ service were used in the shell program QGIS 3. Also combinations of different spectra satellite images from spacecraft Sentinel-2 to identify aufeis formation processes and true color images (TCI) for aufeis contours deciphering.

In view of the difficulties in fixing the contours of aufeis in the winter period, the relatively late melting of snow cover and high spring cloud cover rate within the study area, the most qualitative option for interpreting aufeis in 2018-2020 was the interval from the last decade of May to the first decade of June. Thus, the data on the areas of aufeis cover reflect their area during the period of destruction, i.e. dissection into isolated ice massifs, drying, etc. [5]

In this regard, the calculation took into account the remnants of aufeis, representing separately lying ice blocks within a radius of up to 1.0 km from the pipeline crossing. Moreover, the sum of their areas was designated by the area of aufeis formed during the winter and spring periods of a given year. An example of deciphering aufeis on the river Tit is shown in Fig. 1-2.

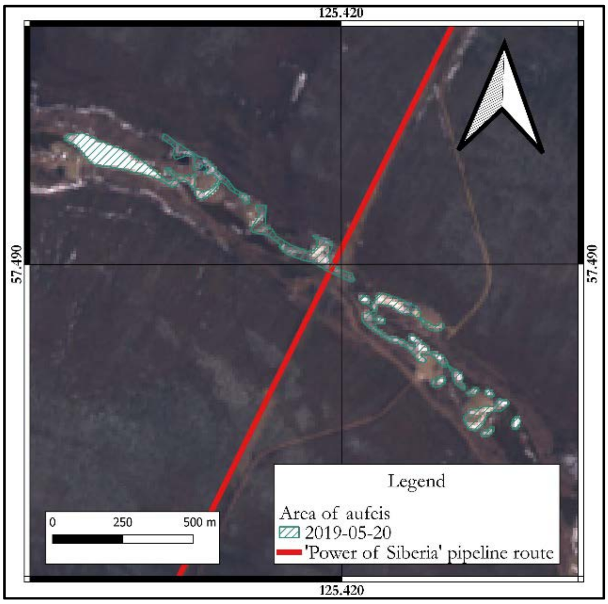

Fig. 1. Ice massifs on the Tit River near the route of the ‘Power of Siberia’ pipeline (May 20, 2019).

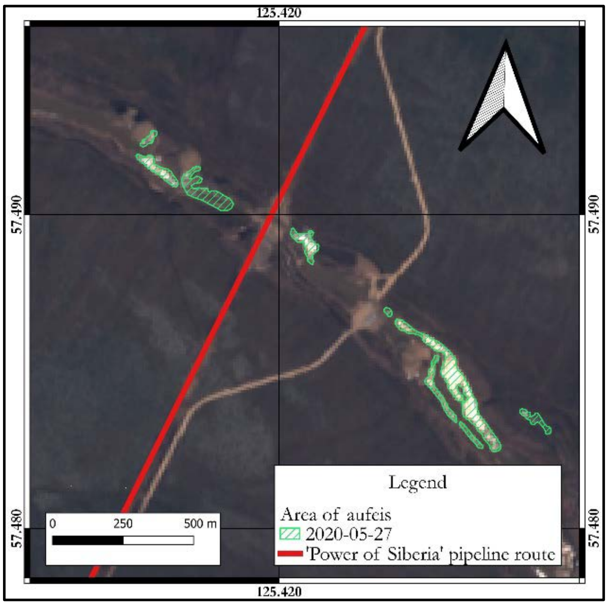

Fig. 2. Ice massifs on the Tit River near the route of the ‘Power of Siberia’ pipeline (May 27, 2020)

3 Results and discussion

As a result of space images analyses of high (‘Google Earth’ web service) and medium (images by Sentinel-2 spacecraft) resolution for 2018-2020, the contours of 22 aufeis sections, intersected by the ‘Power of Siberia’ pipeline during the construction and operation period, were deciphered.

The maximum aufeis areas were calculated, thereat it was revealed that some of them were deciphered not each year. A possible reason is either the complete absence of the manifestation of aufeis or its rapid drying due to the significantly lower formed capacities.

The list of the aufeis areas distributed along the gas pipeline with an aufeis area (S) and an area of aufeis within the right-of-way of pipeline route (S_{row}) is shown in Table ...

Table 1. Maximum decrypted aufeis area along ‘Power of Siberia’ pipeline in the Aldan Basin

№	Stream	Flows into	S. ha	S_{row}. ha
1.	Billyakh	Ollongoro	2.2	1.0
2.	Lekechekhtakh	Kumakhilakh	0.2	0.07
3.	Tabornyi	Kumakhilakh	2.4	0.3
4.	Zvezda	Seligdar	11.1	0
5.	Krasnyi	Seligdar	12.3	0.6

* Corresponding author: pinigind@mail.ru

6.	Komandirskii	Kerak	6.6	0.4
7.	Khangas-Nipipelineerkan	Bol'shoi Nimnyr	11.8	0.2
8.	Achchygyi-Legleger	Legleger	44.6	1.1
9.	Ulakhan-Legleger	Legleger	8.6	0.5
10.	Tit	Legleger	1.6	0.04
11.	Erge	Legleger	40.7	0.45
12.	Malaya Murkugu	Khatymi	1.4	0.55
13.	Yngyr	Chul'makan	1.4	0.06
14.	Chul'makan	Timpton	21.9	0
15.	Zimovie	Gorbyllakh	9.4	0.05
16.	Olongro	Gorbyllakh	2.1	0.04
17.	Untitled stream	Buoyuma	17.7	0.8
18.	Untitled stream	Ulakhan-Nierichchi	13.8	0.5
19.	Severikan	Iengra	50.7	0.2
20.	Amyna	Manakhta 2nd	24.0	0.8
21.	Untitled stream	Timpton	2.6	0.7
22.	Untitled stream	Yakut	9.4	0

Identification of aufeis annual manifestation in 2018-2020 remote methods are typical both for significant (more than 40 hectares) in areas and for insignificant (for example, a section of the Tit River with an area of less than 2 hectares) aufeis. Aufeis of a pronounced anthropogenic character were identified on three watercourses (Billyakh, Zimovie and the right tributary of the Timpton River) as well. One of those anthropogenic aufeis on the Billyakh River, first deciphered in images of 2019 is shown in Fig. 3.

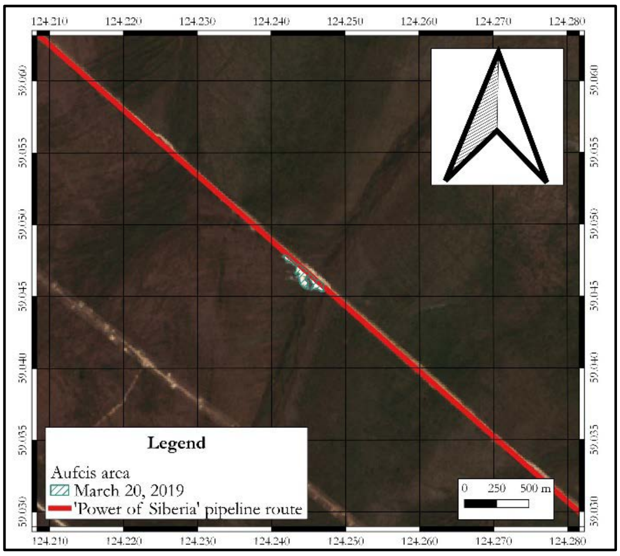

Fig. 3. Billyakh aufeis area on the Sentinel-2 satellite image (date: March 20, 2019)

To fix anthropogenic character of aufeis formation analyses of satellite images by Landsat-8 spacecraft, taken before the gas pipeline route construction start were conducted, which show no considerable ice massifs deciphered in the aufeis stream reaches (Fig. 4).

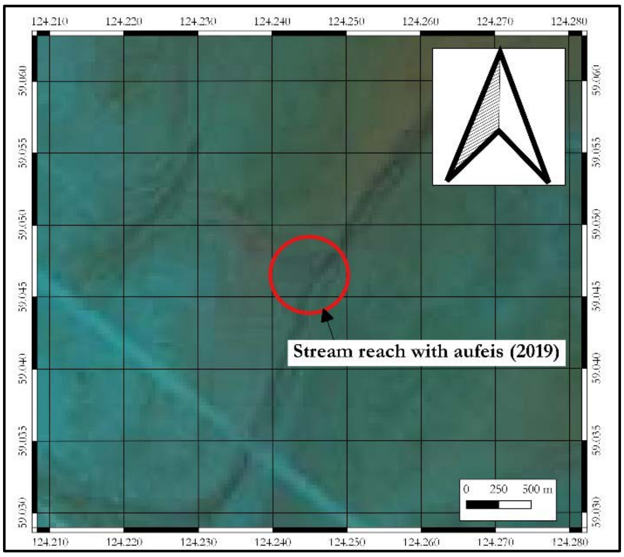

Fig. 4. Billyakh aufeis area before gas pipeline construction on the Landsat-8 satellite image (date of survey: May 9, 2015)

The development of new aufeis formation is a dangerous phenomenon, as it leads to a change in energy and mass transfer in river valleys, which in turn can affect the exogenous geological processes and water balance of the territory [5].

To determine the confinement of aufeis manifestations to hydrogeological structures, a study of the location of aufeis areas relative to hydrogeological regions was carried out. Zoning of the Lena- Amur interfluve was used [6] in view of the proportionality of the scale of the map schemes and the full coverage of the study area.

Thus, according to the zoning, the aufeis areas are located within the Yakut complex artesian basin, the Baikal- Dzhugdzhur complex hydrogeological fold area, and artesian basins of the Aldan type [6] (Fig. 5).

* Corresponding author: pinigind@mail.ru

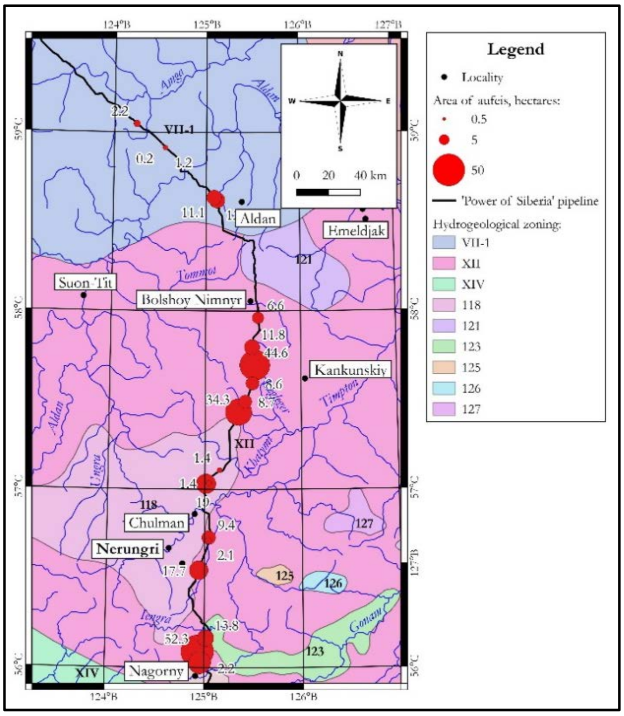

Fig. 5. Schematic map of the hydrogeological zoning of the interpreted aufeis crossed by the 'Power of Siberia' pipeline. Legend: Artesian basins of the second and third orders: VII - Aldan wing of the Yakut artesian basin, VII-1 – Tolbinsky ; hydrogeological folded areas of the second order: XII – Aldan, XIV – North Dauria; artesian basins of the Aldan type: 118 – Chulmansky , 121 – Yukhtino-Ylllymakhsky, 123 – Tokarikano-Iyengrsky, 125 – Mölemkensky, 126 – Guvilgrinsky, 127 – Anamzhaksky.

The largest number of deciphered aufeis belongs to the Baikal- Dzhugdzhur complex hydrogeological region of the 1st order, on the territory of which 344.3 km of the pipeline was laid (65.7% of the studied area), while 77.3% of the found aufeis are represented here, and in the areal expression - 91.2%. According to [6] this area is replete with large-scale debit sources; the nature of water manifestations here is directly dependent on tectonic fragmentation and the degree of freezing of rocks.

Among the hydrogeological regions of the 2nd and 3rd orders, the Aldan hydrogeological fold area of the 2nd order stands out, occupying approx. 36% of the route with 11 aufeis with a total decoded area of aufeis 71.0%. The hydrogeological region of the third order - Yukhtino-Yllymakhsky, where not a single aufeis along the pipeline is represented with the length of the gas pipeline here - 34.5 km (or 6.7% of the studied part of the main gas pipeline) turned out to be relatively less aufeis hazardous.

Conclusion

Deciphering the contours of aufeis crossed by the 'Power of Siberia' route within the study area revealed the presence of 22 icy areas with a total area of icy massifs of more than 295 hectares, while the approximate nature of this indicator is noted in view of the difficulties in deciphering aerial photographs of the spring period in the Aldan Highlands.

Aufeis areas of anthropogenic origin were recorded, expressed in new manifestations of aufeis processes in the sections of river crossings of the gas pipeline, where aufeis was not recorded before the start of construction work.

The confinement of aufeis areas to hydrogeological areas has been determined. As a result, a relatively lesser aufeis hazard of the Yukhtino-Ylllymakhsky artesian basin of the Aldan fold area is shown.

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* Corresponding author: pinigind@mail.ru

The character of transformation of the threats to Russia's energy security as the basis for evaluating the possibilities to meet the prospective demand for primary energy resources

Sergey Senderov[1, 2,*], *Viktor Rabchuk* [1]

[1]Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, 130 Lermontov str., Irkutsk, Russia
[2]Federal State Budget Educational Institution of Higher Education «Irkutsk National Research Technical University», 83 Lermontov str., Irkutsk, Russia

Abstract. The paper analyses the situation with ensuring energy security in Russia over the past five years and provides an assessment of the nature of the transformation of the most significant threats to Russia's energy security until 2030. It is shown that by 2030 the annual potential of fuel and fuel in the country Energy complex for the production of primary fuel and energy resources together with the import of fuel and energy to Russia will significantly exceed its domestic needs. At the same time, the ability to export Russian natural gas could be significantly reduced. The paper shows that the situation with the decline in opportunities for the production and export of natural gas in Russia is not very encouraging. There are no prerequisites for a significant increase in world prices for hydrocarbons until 2030. And at the same time, there is a constant increase in the cost of oil and gas production and transportation on average across Russia. The paper concludes that the possibilities for the development of the Russian economy through the sale of only natural resources are practically exhausted by now.

1 Introduction

The paper assesses the potential situation with the fulfillment of the most important requirement of energy security (ES) of Russia - reliable provision of domestic demand for primary fuel and energy resources (FER) [1], taking into account the need to export Russian gas until 2035. The need to assess the potential volumes of such exports is due, on the one hand, to a noticeable increase in the cost of Russian gas due to a drop in production levels in old regions and the need to enter new regions with significantly higher unit costs for their development, and on the other hand, a significant decrease in world gas prices (USD 100 / thousand m^3 in January 2020 (even before the COVID-19 pandemic) with a further decrease [2]) in the absence of prerequisites for a significant increase in these prices in the period up to 2035. In addition, one has to take into account some uncertainty regarding recoverable gas reserves in new fields from which export was planned to the east (Chayandinskoye oil and gas condensate and Kovykta gas condensate fields [3, 4, etc.]).

It is proposed to forecast the situation with the fulfillment of the specified ES requirements on the basis of an assessment of the potential production capabilities of the Russia’s energy industries in the period up to 2035. For this, it is initially required to assess the expected nature of the transformation of the most significant threats to the Russia’s ES. The general research procedure is as follows:

– analyzed the analyzed period until 2035 is divided into three time periods: 2020–2025; 2026–2030 and 2031–2035;
– at each time interval, the most significant emergency threats are selected and the nature of their transformation is assessed;
– the expected capabilities for the production of primary FER are formed by reference years. This is done on the basis of the results of assessing the character of the threats transformation and taking into account the retrospective indicators of the functioning of the Russian fuel energy complex (FEC);
– possible volumes of Russian natural gas export are determined. These volumes are determined by comparing the values of the expected demand for primary FER and the possibilities of their production, taking into account imports.

2 The main threats to Russia’s ES for analyzing the character of their transformation

When choosing the threats to consider in the period until 2025, we will take into account the results of the functioning of the energy industries in Russia in previous years (Table 1), as well as the expected features of the functioning of these industries in the period until 2025.

* Corresponding author: ssm@isem.irk.ru

Table 1. Russia's FEC in 2014-2019 [5-8].

Index	2014	2016	2018	2019
Production of primary FER, mln tce, incl.	1863	1931	2032	2083
natural and assoc. gas, bcm	*642*	*653*	*725*	*737*
oil and gas condensate, mln t	*527*	*547*	*556*	*560*
coal, mln t	*359*	*383*	*401*	*397*
hydro and nuclear power, other FER, total, mln tce*	*149*	*158*	*160*	*162*
Import of FER, mln tce, incl.	33	29	27	23
natural gas, bcm	*12*	*12*	*9*	*8*
Total (income), mln tce, incl.	1896	1960	2059	2106
natural gas, bcm	*654*	*665*	*734*	*745*
Domestic consumption of primary FER, mln tce, incl.	1034	1062	1092	1057
natural and assoc. gas, bcm	*455*	*471*	*494*	*469*
Share of gas in domestic consumpt. of primary FER, %	*51*	*51*	*52*	*51*
oil used directly and oil products total, mln tce	*229*	*234*	*231*	*228*
coal, mln t	*228*	*223*	*205*	*191*
hydro and nuclear power, other FER, total, mln tce*	*149*	*158*	*160*	*162*
Export of FER, mln tce, incl.	862	898	967	1049
natural gas, bcm	*187*	*194*	*247*	*276*

* fuel burned at condensing stations to produce the same volumes of electricity

According to the data in Table 1, since 2014, the production of FER has grown noticeably - mainly due to the growth in hydrocarbon production. At the same time, the maximum possible levels of their production and export corresponded to the period of decline in world prices. In 2019, the price of gas reached $ 120-140/mmcm, and oil - $ 50-55/barrel (for comparison, the average world price of oil in 2012 was $ 110/barrel, and gas price $ 400/mmcm) [1, 9]. Revenues from the export of hydrocarbons with a decrease in world prices for them had to be obtained by increasing the volume of their sales. The low gas price prompted the importing countries to buy this gas for future use, filling all underground gas storage facilities and creating the preconditions for reducing the price for it in 2020. Winter 2018 in the European part of Russia was somewhat colder than the last winters, this fact led to a decrease in natural gas consumption in 2019 compared to 2018 to the average values of recent years. As for coal, electricity generated at hydroelectric power plants and nuclear power plants, and other FER, then from 2016 to 2019 their annual production volumes remained practically unchanged.

Based on the scale of underperformance of investment programs in the previous period [10-13] and taking into account the low investment opportunities of the fuel and energy complex (due to low income from hydrocarbon exports), the most significant threat to Russia's ES until 2025 will be a lack of investment in the energy sector. This threat should be included in the list of threats under consideration.

The lack of investment affects the values of physical and obsolescence of production assets (PA). For example, in the gas industry the physical deterioration of the PA has exceeded 65%, in the oil industry it has approached 55%. With a lack of investment, the lag in the rate of replacement of morally and physically obsolete PF in the energy sector will continue. Therefore, this threat should also be included in the list of considered threats.

One of the reasons for the large share of obsolete PA in the Russian fuel and energy complex is the low rate of implementation of the best available technologies (BAT). The BAT requirements in various sectors of the fuel and energy complex of the country meet from 10 to 20% of PA (world practice - from 40 to 60%) [14]. Accordingly, the threat of low rates of BAT implementation should also be included in the list of threats until 2025. Low rates of BAT implementation and the need to enter new, much more expensive oil production areas, along with the depletion of deposits in old regions, significantly increase the cost of this energy resource. According to [15, 16], the average break-even cost of Russian oil is $ 42-44 per barrel. The factors of growth in the cost of Russian oil from year to year, with the expected relatively low world price for it (60-70 USD/bbl), oblige to include among the considered threats until 2025 the threat of reduced opportunities to increase oil production and export.

The threats under consideration should also include the threat of reducing the ability to maintain natural gas production. The main reason for this (in addition to the rapid decline in gas production at the old fields of the Nadym-Pur-Tazovsky region, where up to 85-90% of all Russian gas was produced 10-15 years ago) is the obvious inexpediency of developing new (very expensive) gas production areas (shelf The Barents and Kara Seas, the Gydan Peninsula) due to the lack of prerequisites for a noticeable increase in gas prices in the future until 2035. The scale of this threat is reinforced by the facts of incorrect assessment of recoverable gas reserves at the Chayandinskoye and Kovykta fields in Eastern Siberia [2, 3, etc.].

The active implementation of this threat also requires consideration of the threat of natural gas domination in the FER balances of the regions of the European part of Russia and the Urals. At present, the share of gas in the domestic consumption of primary FER in the country remains at the level of 51-52% (Table 1). However, in a significant part of the mentioned regions, this share reaches 90-99%. This situation is unacceptable due to a decrease in gas production opportunities in the country and due to difficulties with fuel and energy supply to consumers in the context of large-scale emergencies in the gas industry (the bulk of gas is produced in 2.5-3 thousand km from the places of its main consumption). At the same time, there are no peak UGS facilities designed to supply gas to the gas transmission network in emergency conditions in the UGSS system.

The character of the transformation of ES threats until 2025 and the factors determining this character are presented in Table. 2.

Judging by the data in the table 2 and taking into account the expected features of the functioning of the energy industries in 2026–2030 the threat of underinvestment in the energy sectors should be left for analysis.

Table 2. The character of the transformation of the most significant threats to Russia's ES until 2025

	ES threats	Amplifying factors	Weakening factors	The transformation character
1	Lack of investment in energy industries	- accumulated problems with the financing; - deterioration of reserves in old areas of oil and gas production; - the need to develop much more expensive areas of oil and gas production; - expected low income from hydrocarbon exports; - a large role of the state in business management; - unattractiveness of business (corruption, raiding); - foreign economic sanctions	- the expected increase in hydrocarbon prices by 2025; - lack of serious motivation to increase the production of FER (low prices on world markets, low growth in domestic demand); - awareness of the need to prioritize when planning energy development	Significant increase
2	Low rates of PA renewal in energy industries	- lack of serious motivation to accelerate the replacement of outdated PA (low growth rates of domestic demand for FER); - lack of investment; - monopoly of FER suppliers; - unattractiveness of business in Russia; - foreign economic sanctions; - unavailability of cheap loans; - difficulties with the implementation of BAT	- the need to ensure industrial safety requirements; - development of information technologies with a corresponding update in PA; - increasing consumer requirements for the FER quality.	Slight increase
3	Low rates of BAT implementation in energy industries	- lack of investment; - great inertia in the development of energy industries; - monopoly of FER manufacturers and suppliers; - foreign economic sanctions; - unattractiveness of business in Russia	- stagnation of the economy; - possible improvement of the investment climate	Slight increase
4	Reduced opportunities to increase oil production	- depletion of currently developed oil fields; - transition to new, more expensive areas of oil production; - expected relatively low prices for liquid hydrocarbons. - foreign economic sanctions, including the introduction of BAT	Expected - increasing the depth of oil refining at Russian refineries; - increase in the share of oil products in the structure of export of liquid hydrocarbons	Significant increase
5	Reduced ability to maintain natural gas production	- rapid decline in production levels in the NPTR; - inexpediency of the development of the gas shelf of the Barents and Kara Seas (lack of investment, increased competition and low prices in the world gas markets, an increase in the share of renewable energy sources in countries importing gas); - growth in the prime cost of gas supplies.	- stagnation of the Russian economy with no growth in FER demand; - decrease in the possibilities of exporting russian gas for foreign economic and foreign policy reasons.	Significant increase
6	Dominance of natural gas in the FER balances of the regions of the European part of Russia and the Urals	- great inertia in the development of the FEC; - gas preference in terms of price-quality ratio; - decrease in production volumes in old areas and the need to develop new expensive areas; - reduced opportunities to increase gas production volumes; - growth in the prime cost of gas supplies.	- low growth of FER domestic demand; - the expected awareness of the great negative significance of this threat	Slight increase

Instead of two threats (low rate of replacement of PA and low rate of implementation of BAT) from 2026 to 2030 let us consider only one - the low rates of BAT implementation in the energy industries. Replacement of obsolete PA should mean, mainly, the introduction of BAT, and replacement of physically outdated PA should be mandatory even due to industrial safety requirements. Threats to reduce opportunities to increase oil production and maintain gas production from 2026 to 2030 should be considered already as threats to reduce oil and gas production levels. The decline in gas production levels makes it mandatory to consider the threat of gas domination in the European part of the country and in the Urals.

The results of assessing of the transformation character of the listed threats from 2026 to 2030 and the factors determining this character are presented in Table 3.

For the period 2031–2035, it is proposed to consider only those threats, the character of the transformation of which in the previous period (Table 3) was assessed as "a significant increase". The results of assessing the transformation of these threats in the specified period are presented in table 4.

* Corresponding author: ssm@isem.irk.ru

Table 3. The character of the transformation of the most significant threats to Russia's ES from 2026 to 2030

	ES threats	Amplifying factors	Weakening factors	The transformation character
1	Lack of investment in energy industries	- expected growth of domestic demand for FER; - striving to retain Russia's share in external markets for hydrocarbon sales in the conditions of low prices; - the need to increase investments to increase the share of renewable energy	Expected: - improving the investment climate; - diversification of the structure of GDP; - easing of foreign sanctions	Slight mitigation
2	Low rates of BAT implementation in energy industries	- growing importance of factors: lack of investment, inertia in the development of the energy sector; - technological development of energy in the world, scientific and technological progress, competition in energy markets	- expected easing of foreign sanctions	Significant increase
3	Decrease in oil production	- strengthening of factors: deterioration of oil reserves; decrease in the competitiveness of Russian oil on world markets decrease in the growth of global demand for liquid hydrocarbons	- low annual growth in domestic consumption of oil products; - a significant difference between the volume of oil production in the country and the volume of its refinary	Significant increase
4	Decrease in gas production	- strengthening of factors: reduction of production levels in old regions, high cost of development of new regions, lack of prerequisites for a noticeable rise in gas prices on world markets; - dominance of gas in the FER balances of the country and some regions	- the expected decrease in the politicization of decisions on the development of the gas industry	Significant increase
	Dominance of natural gas in the FER balances of the regions of the European part of Russia and the Urals	- inertia of changes in the structure of FER balances within the country and regions; - expected growth in demand for FER (corresponding to the pace of economic development); - decrease in gas production	Ожидаемые: - weakening of the state role in the development of the gas industry; - transition to equal profitability of gas in the external and internal markets; - easing of foreign sanctions	Significant increase

Table 4. The character of the transformation of the most significant threats to Russia's ES from 2031 to 2035

	ES threats	Amplifying factors	Weakening factors	The transformation character
1	Low rates of BAT implementation in energy industries	- lack of investment; - the inertia of the FEC development; - preservation of the great role of the state in the field of energy management	- change in the structure of the income part of Russia's GDP with a decrease in the dependence on the oil and gas sector	Slight mitigation
2	Decrease in oil production	- the need to develop new expensive oil production areas; - lack of investment; - insufficient rates of BAT implementation; - lack of prerequisites for a noticeable increase in world prices for oil and oil products	- reducing the dependence of Russia's GDP on the oil and gas sector; - decrease in the volume of oil exports; - no growth in domestic consumption of oil products with an increase in the role of electricity in transport	Slight mitigation
3	Decrease in gas production	- rapid decline in gas production in old areas, - inexpediency of the development of the gas shelf of the Barents, Kara and Okhotsk seas for export purposes due to the high cost of production, processing and transportation of gas in the absence of prerequisites for a significant increase in world gas prices; - dominance of gas in the FER balance of the country and some regions	- a noticeable decrease in the growth rate of gas demand in importing countries associated with an increase in the share of renewable energy sources in the structures of FER balance	Significant increase
4	Dominance of natural gas in the FER balances of the	- inertia of changes in the structure of FER balances within the country and regions; - a noticeable decrease in gas production volumes in old gas production areas;	- the absence of prerequisites for an increase in world prices for gas and the high cost of its production and transport cause the inexpediency of its export;	Slight increase

* Corresponding author: ssm@isem.irk.ru

	regions of the European part of Russia and the Urals	- lack of investment for the development of new expensive gas production areas (gas shelf of the Barents, Kara and Okhotsk seas)	- change in the structure of GDP in the direction of growth of non-energy-intensive, knowledge-intensive industries with limited growth of the country's internal energy needs	

3 Expected opportunities to meet Russia's internal needs for primary FER in the considered perspective

3.1 Possible internal needs for primary FER

The total annual domestic needs of the country for primary FER can be logically determined as $Q_t = Q_{t-1}(1 + K^t_{GDP} - K^t_{in})$, where Q_{t-1} is the volume of consumption of these FER in *(t – 1)* year; K^t_{GDP} and K^t_{in} are the coefficients of change in Russia's GDP and the specific energy intensity of GDP in *t* year relative to *(t – 1)* year. When determining internal needs for primary FER, the following average annual values were taken for K^t_{GDP} and K^t_{in}, Table 5.

Table 5. Assumed coefficients of change in Russia's GDP and specific energy intensity of GDP for the perspective up to 2035

Time period	K^t_{GDP}	K^t_{in}
2020–2025	0,015–0,017	0,005–0,010
2026–2030	0,020–0,025	0,010–0,015
2031–2035	0,025–0,035	0,020–0,025

Taking into account the impact of the COVID-19 pandemic on the Russian economy in 2020, it is possible to assume a decrease in GDP compared to 2019. At the same time, when the economy exits the conditions of the pandemic in 2021, it can be assumed that the recovery rate will be slightly increased with the achievement of the targets outlined earlier. Accordingly, in 2020 we propose the value of the country's internal needs for primary FER to be considered approximately equal to 2019 (1057 mln tce), and then follow the values of the indicators presented in Table 5. Then it can be assumed that in 2025 this value will be at the level of 1090-1110, in 2030 - 1150-1170 and in 2035 - 1180-1230 mln tce.

3.2 Production capabilities of Russia's energy industries

3.2.1 Russia's oil industry prospects

In 2018 and 2019, the consumption of oil products in the country together with oil used directly was 231 and 228 million tons of fuel equivalent, respectively (taking into account [15]). From 2020 to 2035, domestic demand for light petroleum products will grow by no more than 0.5-1% per year due to the expected active increase in the share of electric transport. The volume of oil directly flared will decrease. Accordingly, the total volume of petroleum products and crude oil used within the country should not increase until 2035, but it will not decrease significantly either. We will assume that in 2020 it will remain approximately at the level of 2019 - about 230 mln tce, in 2025 it will be 220-230, in 2030 - 215-225 and in 2035 - 210-220 mln tce. These volumes are much less than the volumes of liquid hydrocarbon production today (in 2019 - 560 mln t or 790 mln tce). Apparently, such an excess of production volumes over domestic consumption may persist until 2035. The possibilities for increasing oil production in the country will most likely be exhausted by 2025 (Table 2). In 2020, oil production in Russia could amount to approximately 560-565 mln t. At the same time, according to the "OPEC +" deal, during the period of reduction in oil prices in the world in 2020, oil production will probably be at the level of 500-510 mln t. This recession should lead to some revival of the world economy, perhaps the previous level of oil production (550-560 million tons) will be restored by 2025. Outside 2025, we should expect a decrease in oil production to 500-520 mln t in 2030 and up to 400-450 mln t by 2035.

3.2.2 Russia's coal industry prospects

Annual levels of coal consumption in the country have been declining over the past 5 years. From 2020 to 2025, due to a reduction in opportunities to increase gas production in the country, the possibilities for replacing coal-fired electricity and heat generating capacities with gas ones will also be exhausted. Accordingly, if from 2020 to 2025 one can expect a slow but decrease in the volume of coal consumption, then after 2025 its consumption should grow slightly (by 0.3-0.5% per year). This will slightly neutralize the threat of gas dominance. Accordingly, domestic consumption of coal will be: in 2020 - 185-190, in 2025 - 180-190, in 2030 - 185-195, and in 2035 - 200-210 mln t against 191 mln t in 2019 The volumes of Russian coal exports (taking into account the growing competition on world markets) are likely to decrease slightly and will be approximately as follows: 2020 - 190-200, 2025 - 180-190, 2030 - 170-190, 2035. - 160-180 mln t.

3.2.3 Nuclear-, hydropower plants and other renewable sources

The total production volumes of primary FER in Russia at hydroelectric power plants, nuclear power plants and other sources have changed insignificantly in recent years. In terms of the volume of hydrocarbon fuel for generating the same amount of electricity at TPPs in 2019, these volumes amounted to 166 mln tce. Taking into account a slight increase in the share of non-traditional FER and electricity production at hydroelectric and nuclear power plants, the indicated volumes can be 165-170 in 2020, 180-190 - in 2025, 190-210 - in 2030 and 220-250 mln tce in 2035.

3.2.4 Assessment of the possibilities of meeting the internal needs of Russia in primary FER with the formation of requirements for the gas industry

The aforementioned about the coverage of the expected domestic demand in Russia for primary FER for all reference years from all energy industries except the gas industry is reflected in Table 6. The same table shows the requirements for the country's gas industry to cover the specified total needs for primary FER.

Table 6. Expected opportunities to meet Russia's internal needs for primary FER with the formation of requirements for the gas industry*

Index	2019	2020	2025	2030	2035
Internal needs for primary FER, mln tce	1057	1060	1100	1160	1210
Covering by					
Oil industry, mln tce	228	230	225	220	215
Coal industry, mln tce	124	120	120	125	130
Nuclear-, hydropower plants and other renew., mln tce	166	170	185	200	230
Requirements for the Gas industry, mln tce bcm	539 469	540 470	570 495	615 535	635 550

* Average values of respective ranges are used.

In Table 6, we have identified the requirements for gas volumes to cover the Russia's domestic needs for primary FER. Now let's consider the possibilities of the gas industry to ensure these volumes. We will also consider the possibilities (taking into account the planned imports) to ensure the export of Russian gas for the same perspective.

3.2.5 Russia's gas industry prospects, taking into account the requirements of possible gas exports

Gas imports to Russia in 2019 amounted to 9 bcm [17]. Until 2035, it is unlikely to exceed 10 bcm/year. When assessing the levels of gas production (both natural and associated), we should take into account the following points:
1. Decrease in opportunities to increase gas production until 2025 and decrease in gas production after 2025 (judging by the character of the transformation of threats to Russia's ES).
2. Low world gas prices in 2020 and the absence of prerequisites for a noticeable increase until 2035 with an increase in the average cost of gas production and transportation and a high cost of Russian LNG production.
3. By the beginning of 2021, the decline in gas prices will probably stop and this price will most likely stabilize until 2035 (in the absence of prerequisites for a noticeable increase). The price range for European countries can be 200-230 USD/mmcm. How far these prices will differ from the cost of Russian gas from new regions of its production on the border with Germany can be estimated from the data in Table 7. At the same time, under the cost of gas, in contrast to only operating costs [18, etc.], we mean the ratio of the sum of all capital and operating costs associated with the development of a gas field during the entire development and operation of the field to the total volume of gas production during this time. The same approach is applicable to the calculation of the cost of gas transportation to delivery points.

Table 7. Expected cost of Russian gas from new regions of its production on the border with Germany*

Production area, method of development	Cost, USD/mmcm			
	2020	2025	2030	2035
Yamal (operat. fields): pipeline gas LNG	 150–170 180–190	 160–180 190–210	 170–190 200–220	 170–190 200–220
Yamal (new fields) pipeline gas LNG	 170–190 200–210	 210–230 240–260	 240–270 260–290	 240-270 260-290
Shelf of the Kara Sea (under development) pipeline gas		290–320	340–380	340-380
Gydan peninsula (under development), pipeline gas		240–280	280–300	280-300

* Estimation of the authors [19, etc.].

4. Comparison of the expected world gas prices with the data in Table 7 indicates that there is no economic feasibility of developing gas fields on the Gydan Peninsula and on the shelf of the Kara Sea for export purposes (at least until 2035). Due to the unresolved nature of a number of fundamental technical issues and the same expected low gas prices until 2035, the development of the Shtokman field (shelf of the Barents Sea) cannot be expected.
5. Gas production growth rates in Yamal will not be as high as in 2018-2019 (26 bcm) - LNG production capacities were being increased. Production growth rates will be constrained by low world gas prices. According to the authors' estimates, this increase will not exceed 2-3 bcm/year by 2025. Outside 2025 (up to 2035) - after the development of the Kharasaveyskoye field, the increase in production in Yamal will increase again, but only within the range of 5-6 bcm/year.
6. The Chayandinskoye (Yakutia) and Kovyktinskoye (Irkutsk Region) fields will be developed with gas production here in 2020 - 1-2 bcm, and by 2025 - 20-40 bcm/year (currently there is uncertainty with the confirmed gas reserves for these fields [2, 3, etc.]).
7. Due to the lack of investment, it is difficult to expect a noticeable increase in gas production on Sakhalin and the shelf of the Sea of Okhotsk until 2035.
8. The decrease in gas production in NPTR will continue (on average, in recent years, production has fallen by 16 bcm/year).

9. By 2030, a slight decrease in oil production will lead to a decrease in the production of associated gas (from 100 bcm in 2019 to 80-90 bcm by 2035).

Taking into account the data in Table 6 and the reasoning given above, Table 8 was formed, which presents the situation with the balance of Russian gas expected until 2035. The incoming part of this table takes into account the possibilities of the main gas-bearing regions and imports. The actual figures for recent years are also given here.

Table 8. Actual and expected up to 2035 values of the Russia's gas balance (total natural and associated gas), bcm

Index	Actually		Forecast			
	2017	2019	2020	2025	2030	2035
Gas production (natural and associated), incl.	691	736	730	720	690	630
Nadym-Pur-Tazovsky region	*468*	*436*	*420-425*	*350-370*	*280-310*	*200-240*
Yamal Peninsula	*75*	*101*	*105-110*	*120-140*	*160-190*	*180-220*
European part of Russia	*51*	*59*	*60-65*	*60-70*	*60-70*	*50-60*
Tomsk region, Eastern Siberia	*22*	*28*	*28-30*	*45-50*	*50-60*	*50-60*
Ob-Taz Bay and Bolshekhetskaya Depression	*40*	*68*	*60-65*	*60-65*	*40-60*	*30-50*
Far East	*35*	*44*	*45-50*	*50-60*	*50-60*	*50-60*
Imports	9	9	10	10	10	10
Available volumes*	**700**	**745**	**740**	**730**	**700**	**640**
The required volume of gas to cover internal needs for primary FER	**469**	**469**	**470**	**495**	**535**	**550**
Technical capabilities of gas export	***231***	***276***	***270***	***235***	***165***	***90***

* Sum of average values of ranges of possibilities.

As can be seen from the data in Table 8, the capabilities of the Russian gas industry, taking into account the small volumes of imports, fully cover the gas requirements to meet the country's internal needs for primary FER. At the same time, the technical (excluding the situation on the world gas markets) opportunities for the export of Russian gas are significantly reduced.

4 Conclusion

Real quantitative indicators of the functioning of the Russian fuel and energy complex in 2014-2019, as well as the results of assessing the character of the transformation of the most significant threats to the Russia's ES until 2035, made it possible to assess the available capabilities of its energy industries to meet the country's internal needs for primary FER. The technical capabilities for the export of Russian gas for the period up to 2035 were also assessed. The paper showed that by 2035 the total annual capabilities of the country's fuel and energy complex for the production of primary FER together with the import of FER to Russia will exceed its internal needs. A decrease in oil production will also not affect the provision of domestic needs of the country with petroleum products. At the same time, by 2035, we should expect a reduction in the possibilities for the export of FER from 1,049 mln tce up to 700-800 mln tce. Opportunities for the export of Russian gas, provided that the country's internal needs are met without deficits, will noticeably decrease (from 276 bcm in 2019 to 90 bcm/year by 2035).

The decline in the possibilities for the production and export of hydrocarbons is accompanied by the absence of prerequisites for a significant increase in world prices for them until 2035. In the same period, an increase in the share of non-traditional types of FER in the energy balances of countries importing hydrocarbons is expected. Accordingly, competition among hydrocarbon exporting countries will intensify. All these processes will coincide with the steady increase in the average cost of oil and gas production and transportation in Russia due to the depletion of reserves in most of the currently operating production areas and the need to develop new very expensive oil and gas production areas.

There can be only one direction of measures to improve the situation: a rapid change in the structure of the Russian economy towards an increase in the share of science-intensive and low-energy-intensive spheres of activity with the release of competitive products with high added value. The possibilities for the development of the Russian economy through the sale of natural hydrocarbons for the near future have been exhausted.

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Analysis of perspective technical solutions for the implementation of integrated heat and cooling systems in a harsh continental climate

Semen Vasilev[1]

[1] V.P. Larionov Institute of the Physical-Technical Problems of the North of the Siberian Branch of the RAS, Yakutsk, Russia

Abstract. The possibility of introducing the technology of integrated heat and cold supply in a sharply continental climate is considered on the example of a specific district of the city of Yakutsk, the Republic of Sakha (Yakutia), Russia. In this paper is analysed the possibility of district cooling system based on absorption for one district. The characteristics of specific cold consumers are analysed. Various options for district cooling technologies for the conditions of the North are compared. Calculations of cold consumption for buildings of series 1-464A are made. The analysis of the composition of the equipment, technical solutions, reconstruction of buildings, etc. A comparison of the financial and economic efficiency of the chiller-fan coil system and local split systems for a specific consumer is made.

1 Introduction

Energy development trends are currently leading to the integration of various types of energy into a single complex. A fundamentally new technological paradigm creates a change in the structure of the energy system and a transition from the vertical structure of CHP-network-consumer to a horizontal structure based on intellectualization and integration [1]. This paper examines the issues of the validity of the development of the Russian energy sector in a new vector of development. One specific element is considered, the introduction of integrated heat and cooling supply systems.

The refrigeration and air conditioning market already has a significant place in the global economy. It exceeds the diamond jewelry market and the wind turbine market. The Economist Intelligence Unit (EIU) estimates annual global sales will grow from 336 million in 2018 to 460 million by 2030. The amount of sales in monetary terms will be approximately equal to USD 170 billion [2].

The district cooling market has many types and upgrades of equipment. The main technical characteristics of the technology is the type of energy used to create cold. For example, the main criterion in European countries is the use of renewable energy sources that use river energy, geothermal energy, solar, etc. The main drivers for the increase in the share of alternative technologies for district cooling in the European Union are the high price of traditional fuels and the limitation of CO2 emissions into the atmosphere [3].

Absorption chillers have a significant share in the cooling market. According to research, the presence of waste, cheap heat from CHP operation or waste incineration contributes to the energy efficiency of the system with absorption chillers. Studies show the high efficiency of the integrated heat and cooling system with a confluence of certain factors [4].

The climatic conditions of the city of Yakutsk are of a harsh continental character. Low temperatures in winter contributed to the strong development of the heat supply system. Significant volumes of waste heat and heating networks with high operating temperatures are available. High temperatures in summer create a demand for cold. For example, the number of hot hours (with temperatures above 25 ℃) in Yakutsk in 2015-2019 is on average 3 times more hot hours in Stockholm, Sweden, where district cooling system has been successfully operating since 1995 [5,6]. For these reasons, this technology has the prerequisites for high energy efficiency, compared to the existing traditional system of combined generation of electricity and heat.

* Corresponding author: vasilievss_ykt@mail.ru

2 Waste heat availability

There are 2 thermal power plants in Yakutsk with combined generation of electricity and heat. The consumption of thermal energy in the city of Yakutsk for the winter period is 2.3 million Gcal per year. The length of high-level heat network and heat inputs is 123 kilometers. The length of distribution heat networks 298 kilometers. Equipment composition for 2019:

- Co-generation power plant number 1 – YaGRES. It installed capacity is 368 MW, the turbine park includes 12 gas turbine units of Russian production with 8 waste heat boilers PSV-2. Gas turbine units (GTU) include 3 types of turbines: GTE-45, GT-35 and GTG-12V.

- Co-generation power plant number 2 - YaGRES New. It installed capacity of 193.48 MW, the turbine park includes 4 gas turbines with LM 6000 PF DF turbines with 3 waste heat boilers KV-GM-116.

The average heat load by plants for the summer period of 2019 is given in Table 1 [7]. The amount of waste heat is calculated using formula (1) as the difference between the total heat supply from the extractions and the total heat load of 2 stations.

$$\sum Q_{heat}^{waste} = \sum Q_{extraction}^{turbine} - \sum Q_{load}^{heat} \qquad (1)$$

The heat load of the station is calculated by the formula (2) by multiplying the average monthly load by the time of the station operation.

$$\sum Q_{load}^{heat} = q_{heat\ load}^{average} \cdot n \qquad (2)$$

Table 1. Average hourly heat load in summer by stations

Power station	2019 year		
	June	July	August
YaGRES, Gcal/h	32	37	40
YaGRES New, Gcal/h	17	0	11

2.1 Waste heat from YaGRES

The total heat extraction from gas turbine units is calculated according to the energy characteristics of the turbines Fig. 1 and Fig. 2. Gas turbine units with GTG-12V turbines do not produce thermal power.

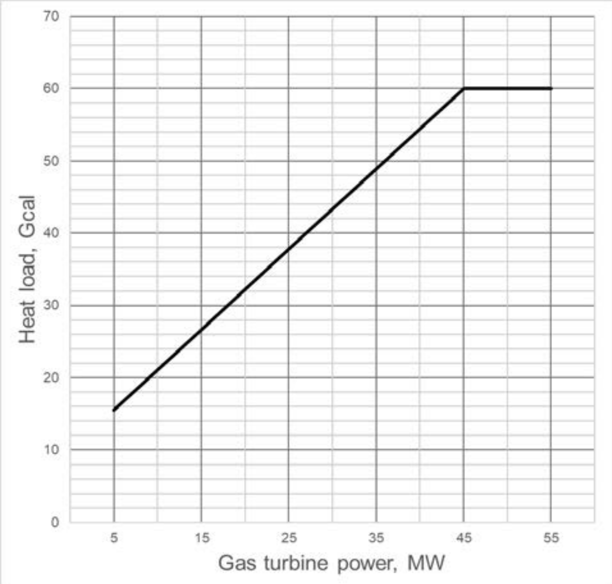

Figure 1. Dependence of heat load on electrical power of GTE-45

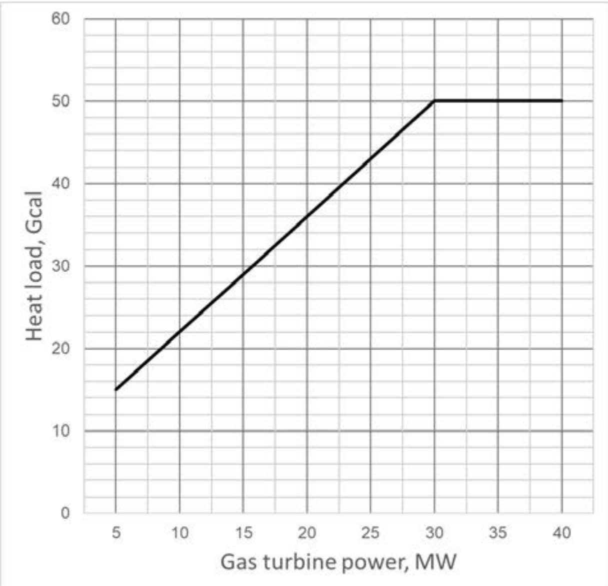

Figure 2. Dependence of heat load on electrical power of GT-35

The calculation of the heat load of each of the gas turbine units was carried out according to the data of the hourly electrical load of the gas turbine units of the station for 3 months: June, July, August.

Next, the total waste heat of the power plant for the month is calculated. The values of the total waste heat from the station were calculated according to formula 1 for June, July, August 2019, the results are given in Table 2.

2.2 Waste heat from YaGRES New

There are no data on the energy characteristics of LM 6000 PF DF turbines at YaGRES New. Waste heat is calculated as the difference between the possible total heat release from the extractions and the heat load of the plant. The possible total supply of heat from the extraction is calculated using the ratio of energy production Z_{T} in winter time (Table 2). The maximum value of the ratio is 2.62 in December. The total possible supply of heat is calculated according to formula (3), assuming such values of the coefficients in the summer for June, July, August.

$$\sum Q_{extraction}^{turbine} = \sum (Z_{\text{T}} \cdot N_{electrical\ load}^{summer}) \qquad (3)$$

Table 2. Waste heat in 2019

Waste heat, thousand Gcal				
№	June	July	August	Sum
YaGRES	235,1	207,4	230,5	673
YaGRES New	97,4	50,3	126,7	274,4
Sum total	332,5	257,7	357,2	947,4

3 Object of study

The object of the study is a unified heating system districts 129 and 54 in the centre of the city of Yakutsk. The criteria that were used when choosing the object of research: the presence of significant demand for cold, the ability to connect to a source of thermal energy, the connection of various types of consumers (residential, administrative, commercial, etc.).

Districts 129 and 54 include 40 large potential cold consumers. It includes 22 residential buildings with administrative premises, 4 residential buildings, 14 administrative buildings. Small buildings, garages do not need cold, therefore they are not taken into account in the calculations.

During a visual inspection of districts, it was found that local autonomous split systems cover the cold needs of office buildings by about 70%. And in residential buildings, split systems cover the need for cold by about 10%.

3.1 Design features of buildings series 1-464A

As the object of a more detailed study, buildings series 1-464A was selected (Figure 3) [8]. During the construction period of the city, this type of project was the most common. The calculation for this building will be useful for further scaling the model.

The building at Poyarkova 17/1, series 1-464A has 4 floors, 4 entrances, 16 apartments are located on one floor. Apartments are divided into 4 types with areas of 31, 47.5, 67.6, 71.7 m^2.

Further, possible technical solutions for organizing cold supply in a building of series 1-464A are considered.

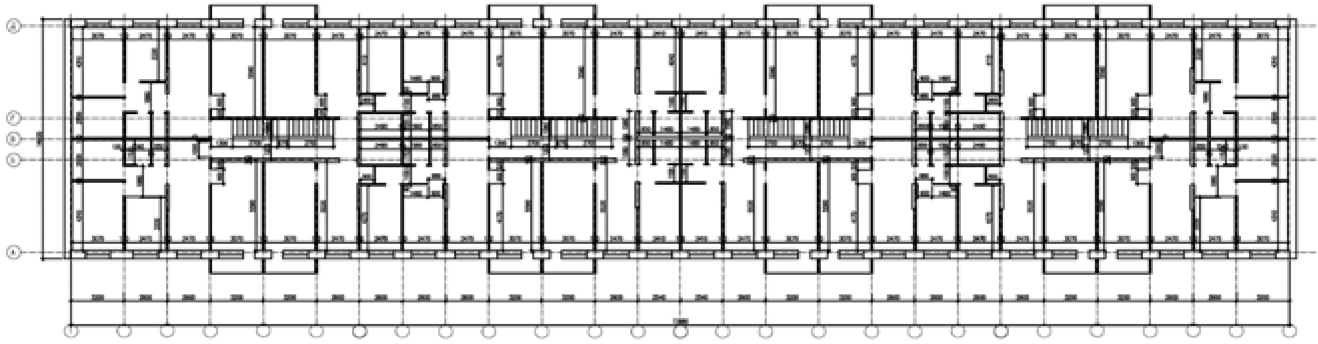

Figure 3. Floor plan of the building series 1-464A

3.2 Various cooling options in 1-464A buildings

3.2.1 Option 1. Using the heating system for cooling

In the cities of Russia, most of the old buildings of the 50-60s. have a heating system with steel and cast iron radiators, which are not designed for high water consumption. Cooling a house with heating radiators, with a coolant temperature of approximately 8℃, requires a much higher coolant flow and the outer surface of the radiators. Also, the heating system scheme is mostly made in a single circuit, covering all residential and non-residential premises, which excludes the possibility of sectioning and correct regulation of the cooling capacity. Another difficulty in implementing such a system is the formation of condensation. Due to the loopback of the entire system and the difference in comfort temperature, intelligent control is required to maintain the desired temperature and avoid condensation. All these and many other factors make this type of cooling impossible.

3.2.2 Option 2. Local air conditioning systems

To ensure a comfortable air temperature in residential and public (office) premises t = 20-23 ℃, ϕ= 40-60%, split-system air conditioners are most widely used [7]. The split system consists of an outdoor unit (compressor, condenser, fan) and an indoor unit (evaporator, fan, filter). The outdoor unit can be installed on the wall of the building, on the roof or on the balcony. Most often in Yakutsk, the external unit is installed on the wall of the building, which worsens the appearance of the building. The indoor unit is designed for cooling, filtering and creating air mobility located directly in the room.

Also, to provide air conditioning (AC), various technical options are possible for local air conditioning systems (ACS): on the basis of on-line air conditioning units, on the basis of on-line fans, on the basis of evaporative air conditioners, etc.

For further calculation, the option with local ACS based on autonomous air conditioners (split system) was selected. The advantages of such a system are easy accessibility to the air conditioning market and no need for additional changes in the building structure. For different types of apartments, local autonomous air conditioners of different capacities were selected, depending on the estimated cold consumption.

3.2.3 Option 3. Centralized ACS

Exhaust systems with natural ventilation are installed in buildings of the 1-464A series. They are made in the form of holes in the walls with a radius of 150 mm and are located in the kitchen and in the toilet. The air in the room is connected to the collection ducts, from there the used air is discharged into the atmosphere through the deflectors [8]. Centralized ACS requires a significant reorganization of the ventilation system: an increase in the diameters of the air ducts, a change in design, etc.

Significant expenses for the reconstruction of the building, complex construction and engineering work make such a system uneconomical.

3.2.4 *Option 4. Chiller and fan coil system*

An absorption chiller can be located in a central chiller station (CCS) near to an existing central heating station (CHS). CCS can be connected to main heating networks with parameters 150-70 ℃. The water cooled in the chiller with a temperature of 5-10 ℃ enters the user stations of buildings (heat exchangers, automation, control systems, etc.) through external cooling supply networks located parallel to the heating networks. Further, through the building's cooling system, cold water enters the fan coil units.

Such a system requires high capital investments, but has a cheap energy source and a high COP of the chiller.

4 Calculation of the cooling demand of a typical building

The cooling demand of a building of series 1-464A is calculated by the graphic-analytical method [9]. The initial data are the orientation of the building, the parameters of the outside and inside air, the number of people, the number of windows, amount of solar radiation. air exchange required to cover heat gain is calculated by the formula (4):

$$G_Q = 3.6\frac{Q_t}{(I_i - I_o)} \quad (4)$$

where I_i, I_o are the specific enthalpies of the indoor and outside air, kJ / kg, taken according to the I-d diagram; Q_t - total heat surpluses, W.

The cold consumption is also determined by I-d diagrams and calculated by the formula (5):

$$Q_{cooling} = G_Q(I_o - I_i) \quad (5)$$

The approximate specific consumption of cold per square meter of a residential building in Yakutsk is calculated using the formula (6) and is equal to 28.8 W/m^2:

$$Q_{\text{specific consumption}} = \frac{Q_{cooling}}{S} \qquad (6)$$

The specific consumption of cold for administrative premises is taken according to specific heat surpluses [10] and is equal to 50 W/m^2.

The calculation of the total demand for cold in districts is calculated using the specific cold consumption per square meter. The operating time of the ACS is equal to the arithmetic mean of the hot hours in Yakutsk with temperatures above 25 ℃ from 2015 to 2019. Air temperature measurement data with an interval of 3 hours were obtained from "Yakutsk meteorological station No. 24959" [5].

Table 3. Cold demand 2019

Area of premises, m^2	Cooling capacity, kW	Number of hours of work, hr	Total cooling demand, Gcal
167677	6237,8	269	1443,1

5 Initial technical and economic calculation of the district cooling system

Two options for cooling the buildings of districts are compared: local ACS with individual split systems and a district cooling system with absorption chillers. Cooling options are compared for economic efficiency.

Various cold demand scenarios are used to predict future cooling demand. The scenarios modeled in this article are presented in Table 4.

Table 4. Scenarios of cold consumption

№	Cooling system load, %	
	Administrative premises	Living premises
Scenario №1	100	100
Scenario №2	100	0
Scenario №3	50	50
Scenario №4	100	50
Scenario №5	100	20

The calculation was carried out according to the standard method for evaluating the effectiveness of investment projects [11]. The electricity tariff for the city of Yakutsk was 6.49 rubles / kWh in 2019. The calculation results are shown in Table 5.

In all scenarios, the payback period of the project exceeds the service life of technical facilities. The reasons for the economic inefficiency lie in the low cold load density, in the limited hours of air conditioning operation and in the relatively cheap cost of electricity.

6 Conclusions

The assessment of the introduction of technologies for district cooling system based on absorption chillers shows the technical feasibility of the project.

The project can become cost-effective by increasing cold consumers and considering the systemic effect. The systemic effect appears by increasing the energy efficiency of the entire system. When a large number of air conditioning systems use waste heat as a source of energy instead of electricity, the overall efficiency of the system increases.

Also, this technology may become relevant if other criteria prevail over economic ones. For example, district cooling system helps to reduce CO^2 emissions into the atmosphere by reducing the consumption of electrical energy for air conditioning.

In further work, it is planned to develop a methodology for the introduction of integrated heat and cold supply systems adapted to the conditions of Russia. Work is planned in the following areas:

• Development of methodological tools for creating a stochastic model of a cold consumer;
• Hydraulic calculation of the pipeline system;
• Development of plausible scenarios for an integrated heat and cooling system;
• Development of a mathematical model of the heat and cold supply system;
• Analysis of the impact of the introduction of heat and cold supply technology in the power system of Yakutsk.

Such a methodological apparatus can be used when planning the development of large, urbanized cities in the south of Russia, which there is a shortage of cheap fossil fuels.

Table 5. Technical and economic indicators of the district cooling system

№	Indicators	Scenario №1	Scenario №2	Scenario №3	Scenario №4	Scenario №5
1	Payback period, year	67	-	-	79	100
2	Operating costs, thousand RUB	1797,6	1690,8	1684,3	1744,2	1712,2
3	Investments, million RUB	400,2	254,6	262,1	327,4	283,7
4	Proceeds, thousand RUB	3020,4	1597,1	1510,2	2308,7	1881,7
5	Cooling load, thousand kWh/year	1677,9	887,2	838,9	1282,6	1045,4
6	Cost value, RUB/kWh	1,071	1,906	2,008	1,360	1,638
7	Tariff, RUB/kWh	1,800	1,800	1,800	1,800	1,800
8	Profit contribution, thousand RUB/year	1222,8	-93,8	-174,1	564,5	169,5
9	Rental fee for 2.5 kW of cold, RUB/year	1210,5	1210,5	1210,5	1210,5	1210,5
10	Split system electricity bill, RUB\year	1396,6	1396,6	1396,6	1396,6	1396,6

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Methodology for determining critically important objects of energy systems from positions of ensuring energy security

Sergey Vorobev[1*], *Sergey* Senderov[1]

[1]Melentiev Energy Systems Institute, 130 Lermontov str., Irkutsk, Russia

Abstract. An increase in the number of major accidents in energy systems in recent years has been due to the significant depreciation of fixed assets, and the lack of significant financial investments in their reconstruction. Large-scale accidents in energy systems resulting from the failure of the most important system objects entail significant, sometimes irreparable, damage to consumers in the form of large short deliveries of final types of energy. Thus, the identification of the most important facilities and their combinations in energy systems with the subsequent development of measures aimed at reducing the importance of such facilities is relevant today. The article reflects the main points of the comprehensive work on the search and identification of critical objects of the gas industry. The lists of these objects and their combinations, ranked by the degree of influence on consumers, are formed. Possible invariant measures aimed at reducing the importance of such objects are presented.

1 Introduction

The energy security of Russia and its regions concerns two main aspects:
- the need for long-term deficit-free provision of consumers with the required types of energy resources during the operation of the energy sector under normal conditions;
- creation of conditions for providing consumers with energy resources in emergency situations.

Consideration of the second aspect, first of all, requires the allocation of critical objects in the fuel and energy complex, i.e. those facilities, partial or complete failure of which can cause significant social and economic damage to the country.

The selection of the critical objects of fuel and energy complex is directly related to two major tasks:
- identification and neutralization of various kinds of threats to sustainable fuel and energy supply to consumers (including the threat of terrorist acts at the fuel and energy complex);
- early preparation of objects and systems of the fuel and energy complex for work during emergencies caused by the implementation of threats of various types.

Such work should obviously be carried out in terms of determining the critical objects for the main energy sectors separately, and then for the fuel and energy complex as a whole. To solve the set tasks at the level of sectoral energy systems, sufficiently detailed simulation mathematical models should be used. The use of such models should give results in terms of assessing the dependence of the performance of the relevant energy sectors on the operation of specific energy facilities. Those objects on which such a dependence of the entire system is tangible and, moreover, critical, should be recognized as critical from the standpoint of ensuring the operability of the system as a whole. Precisely such objects should be primarily targeted by measures to ensure the survivability of the corresponding energy system. When analyzing the critical objects of the fuel and energy complex level, a specialized model apparatus can be used that adequately describes all aspects of the interrelated functioning of energy industries within a single fuel and energy complex from the standpoint of energy security. Such a model apparatus will make it possible to determine the total capabilities of the country's fuel and energy complex and the fuel and energy supply systems of specific regions to meet the needs of individual territories in various types of energy, which actually develop in various conditions (including emergency situations). At the same time, the own capabilities of the fuel and energy complex will be taken into account to compensate for the negative consequences of the loss of efficiency of the critical objects of various industries. First of all, these are the possibilities of interchangeability of various fuel and energy resources in the production of final types of energy and the possibility of diversifying energy sources. Only with the help of a model apparatus for relevant studies at the fuel and energy complex level can one get an idea of the potential list of the fuel and energy complex, i.e. those critical objects of the energy sectors, the negative consequences of the loss of working capacity of which cannot be compensated even with the indicated possibilities of the interconnected work of the

* Corresponding author: seregavorobev@isem.irk.ru

energy systems within the framework of a single fuel and energy complex.

The solution to any complex research problem must start from the bottom of the components of a large system. As for the Russian fuel and energy complex as a whole, for the European part of Russia the main type of fuel is natural gas. In the country as a whole, the share of gas in the balance of boiler and furnace fuel (mainly fuel for thermal power plants) is about 77%. In a significant part of the regions, its share in the fuel balance exceeds 90-95%, and sometimes it reaches 99%.

Thus, an urgent task today is to develop a methodology for determining critical objects of energy systems from the standpoint of ensuring energy security and the corresponding definition of such objects and their combinations in energy systems with the subsequent development of measures aimed at reducing the importance of such objects.

2 Analysis of published works in the field of search and identification of critical objects of energy systems

The analysis of the published works has shown that today research is being actively conducted concerning the identification of critical objects of energy systems.

In works [1, 2], the authors analyzed the gas transmission network in order to determine its most important elements. The methodological approaches applied in this case are based on topological network analysis with an emphasis on the study of issues of reliability and controllability. This analysis makes it possible to quantitatively assess the reliability of the gas transmission network and determine the role of each component of the network in different time slices. A real gas transmission network in several EU countries is considered as an example. The article presents the results of the analysis of such a critical infrastructure, shows the need to take into account physical characteristics, such as restrictions on the throughput of gas pipelines. To assess the consequences of the implementation of negative external influences on the possibilities of gas supply to consumers, a special flow model has been developed. Vulnerability analysis is performed from three perspectives: global vulnerability analysis, demand reliability, and critical analysis of gas pipelines. The global vulnerability analysis is carried out taking into account possible disturbances in the operation of gas sources and transport. Demand reliability analysis assesses the ability of consumers to withstand external influences on them. The critical analysis of gas pipelines considers the impacts on specific gas pipelines.

Work [3] presents a method for defining and ranking critical components and component sets in technical infrastructures. The criticality of a component or set of components is defined as the vulnerability of a system to failure when a particular component or set of components fails. The question is also devoted to the problem of multiple simultaneous failures, and even with synergistic consequences. The proposed method solves this problem. An analysis of the power distribution system in a Swedish municipality is presented as an example of this method.

In [4], a comprehensive model is proposed for assessing the impact of the interdependence of electrical and gas systems on the reliability of energy supply to consumers. The operating mode of the gas network is modeled using restrictions on the operation of the main elements. Gas supply restrictions can affect the change in the operating modes of the electric power industry. This is shown by illustrative examples given by the authors.

In [5], through the analysis of the possible impacts of the integrated gas and electric network, it is shown that failures of the gas supply system can be considered more decisive for the integrated power supply system than failures in the power supply subsystem itself. Accordingly, the authors paid attention to possible control actions aimed at minimizing the negative impact of failures in the gas supply system. At the same time, such an approach is possible provided that the basis of electricity generation is made up of power plants using natural gas.

In works [6-8], the authors come closest to the definition of critical objects of the energy system, in this case, the gas transmission network. At the same time, they assign different indices to different objects of the system in a complex that determine the vulnerability of the system in case of disruption of the operation of this object.

Taking into account the previously gained experience and based on the analysis of research carried out in the world at the present time in [9, 10] formulated a methodology for the formation of lists of critical objects from the standpoint of ensuring the operability of these systems on the example of the gas industry in Russia.

3 The main provisions of the methodology for determining the critical objects of gas industry

Significant gas reserves are concentrated in Russia (the Yamal and Gydan peninsulas, the shelf of the Barents and Kara Seas). The country has an extensive system of main gas and oil pipelines and a complex geographically distributed system of fuel and energy supply, covering the entire territory of Russia. The existing territorial structure of the Russian gas supply system determines its significant shortcomings. For example, the European part of the country is not provided with its own reserves of fuel and energy resources. It mainly uses natural gas, more than 90% of which is produced in one gas-producing region (Nadym-Pur-Tazovsky district of the Tyumen region). This area is located 2–2.5 thousand km from the places of the main gas consumption. Thus, practically all Russian gas is transported over long distances through the systems of main gas pipelines, which have a large number of mutual intersections and bridges; moreover, the lines of powerful main gas pipelines are often laid at a short distance from each other. Currently, in the gas transmission system of Russia, more than 20 potentially dangerous for the functioning of the system of intersections of main gas pipelines can be noted. The most significant of them is located almost at the very outlet of gas from its main fields: Urengoyskoye and Yamburgskoye. Disruption of the operation of such an intersection of gas flows can lead to an almost complete (90%) limitation of gas needs at the national level as a whole.

The consequences of the implementation of various emergency situations in power systems with large-scale negative manifestations of natural and climatic processes, for example, abnormally cold periods in winter with a peak increase in the need for additional volumes of fuel, can be much more severe. In this case, the extremely increased demand for fuel may manifest itself not only in one single region. Most likely, this situation will be typical for a single climatic zone or several neighboring regions. In particular, this issue is relevant for the territories of the European part of the country characterized by a high share of natural gas consumption, because in such regions, the share of their own fuel and energy resources in their fuel balance is usually low.

With this in mind, as a first step, research was carried out using the example of the gas industry:

- developed an algorithm for identifying the critical objects of a specific system;
- an assessment of the role of specific critical objects in ensuring the operability of a specific energy system in the context of the implementation of various kinds of emergency situations;
- a list of measures was formed to minimize the negative consequences of a decrease in the level of performance of each selected critical objects of the energy system under consideration;
- a substantiation of the list of invariant measures to minimize the negative consequences from the action of various kinds of emergency situations on the selected critical objects of the considered power system was carried out, taking into account possible simultaneous combinations of emergency situations at different objects.

4 Mathematical formulation of the problem of identifying critical objects

When developing this methodology, to determine the critical objects themselves, and to search for critically important combinations of objects, were used the flow model, which is the core of the "Russian Oil and Gas" software, to determine the critical objects itself and to search for critical combinations of objects [11-15]. The use of this "Russian Oil and Gas" software allows user to determine the degree of satisfaction of gas needs within the country and ensure export supplies. In addition, the "Russian Oil and Gas" software allows user to identify bottlenecks — sections of network that in some cases limit the production capabilities of the system.

The flow distribution model in the Unified Gas Supply System of Russia in the "Russian Oil and Gas" software is designed to assess the production capabilities of the Unified Gas Supply System of Russia in conditions of various kinds of disturbances. The purpose of such studies is to minimize gas deficits at the consumption sites. The Unified Gas Supply System of Russia in the model is represented as a set of three subsystems: gas sources, main gas transport network and consumers.

When solving the problem of estimating the state of a system after a perturbation, the criterion of the optimality of the distribution of flows is the minimum gas deficit in the consumer with minimum costs for delivering gas to consumers. This problem can be solved by finding the maximum flow through the network, followed by minimizing the cost of gas delivery to consumers [16]. The mathematical formulation of this problem is described in [17].

In the flow distribution model in the Unified Gas Supply System of Russia, as already mentioned, the Basaker-Gowen algorithm is used to calculate the maximum flow of minimum cost, which as a result allows you to determine the possible level of gas consumer satisfaction. As a result of the implementation of various emergency situations, a gas shortage among consumers may occur due to a lack of flow capacity in certain sections of gas pipelines. Bypassing such narrow or limiting production possibilities of the system's places, in acceptable volumes, will allow reducing the gas shortage arising in the situation under consideration by consumers.

An integrated approach to solving the assigned tasks along the entire Unified Gas Supply System technological chain allows obtaining an overall assessment of the production capabilities of the entire system under extreme conditions. The result of solving the problem is to determine the possibilities of satisfying consumers with network gas with the identification of volumes of possible undersupply of gas to consumption nodes in a particular emergency situation. Based on these results, it is possible to obtain a list of facilities, as well as a list of combinations of facilities in the gas industry, the termination of which will lead to a potential shortage of gas in the network. We rank this list by the relative magnitude of the gas deficit in the network. By cutting off objects, the withdrawal of which will lead to a potential shortage of gas in the network less than the assigned value, for example, 5%, it is possible to obtain a list of the critical objects of the gas industry. Such a list should also be ranked according to the degree of impact on network performance. The same mechanism applies to the procedure for determining critical combinations of gas facilities.

5 Identification of critical objects In gas industry

The design scheme of the Unified Gas Supply System used in this work takes into account all the main features of the functioning of the Unified Gas Supply System of Russia and contains:

- 378 nodes, including: 28 gas sources; 64 gas consumers (constituent entities of the Russian Federation); 24

underground gas storage facilities; 266 nodal compressor stations;

- 486 arcs representing the main gas pipelines and branches to the gas distribution networks.

Relevant studies were carried out on the model of the Russian gas industry presented above. The initial conditions for the calculations are as follows: the average day of maximum gas consumption in the network, based on statistics on gas consumption by region in January [18-20]. On such days, the operation of the network can be considered extremely intense relative to the average annual load. The total gas flow through the network on such a day, taking into account export supplies, amounted to approximately 2,250 million m3. The results of these studies have shown that potential gas shortages among consumers will be observed when 441 facilities of the Russian gas industry are shut down (242 nodes and 199 arcs of the network computational graph). The threshold of being included in the list of critical objects with a potential gas shortage (total in 5% of the total gas demand) in conditions of shutdown of one of these facilities was crossed by 61 facilities. These objects were included in the list of the critical objects of the federal level for the gas industry. Among these objects there are 25 arcs between nodal compressor stations and 36 nodes, including 30 nodal compressor stations, 5 head compressor stations at the outlets from large gas fields and one underground storage facility. Information on the calculated values of the relative gas shortages in the network when specific nodes and arcs are turned off in a form ranked by the degree of gas deficit reduction is presented in Table. 1 (the real names of the Unified Gas Supply System of Russia facilities in this article are replaced with conventional numbers).

Table 1. Estimated relative gas shortages in the network on the most intense day in January 2017

# of object	Object type	Gas shortages, %
1, 2, 3, 4	Node	21
5, 6, 7	Arc	21
8	Node	19
9, 13, 14	Arc	16
10*, 11, 12, 15	Node	16
16	Arc	12
17, 18, 19, 22, 23	Node	10
20, 21	Arc	10
24	Node	9
25, 26, 28*	Node	8
27, 29	Arc	8
31, 33, 35, 37, 39, 41	Arc	7
30*, 32, 34, 36, 38, 40	Node	7
42, 48, 50	Arc	6
43*, 44*, 45, 46**, 47, 49, 51	Node	6
52, 55, 56, 59, 60	Arc	5
53, 54, 57, 58, 61	Node	5

* - the node refers to production targets, i.e. to the gas compressor station at the exits from the fields.

** - the node refers to underground gas storage facilities (UGS).

From the data table. 1 that when each of the first eight objects of the ranked list of the critical objects of the gas industry at the federal level is disconnected, the relative gas deficit in the system can be about 20% of the required total supply. Disabling each of the following 15 objects can result in a 10-16% system flow restriction. Disconnection of all other objects from the list of critical objects can provoke a relative shortage of gas in the system within 5-9% [10].

6 Identification of critical combinations of gas facilities

After the above list of the gas industry critical objects was formed from the standpoint of ensuring its operability, calculations were carried out on this calculation scheme to determine the critical combinations of UGSS facilities with each individual critical object. In addition, the next step was to simulate the process of "breaking" bottlenecks aimed at minimizing gas shortages among consumers by increasing its flow through individual sections of the network.

The criterion for the inclusion of each combination of gas industry facilities with a specific critical object in the list of critical combinations will be the difference in the relative total gas deficit among consumers when the i-th critical object stops working and the combination of the i-th critical object with the j-th object of the settlement network stops working:

$$\Delta Q_{ij} = Q_{ij} - Q_{i,} \quad i = 1,..., K;\ j = 1,..., N; i \neq j \qquad (1)$$

$$\Delta Q_{ij} \geq \delta \qquad (2)$$

Q_{ij} - is the total relative gas deficit among consumers caused by the termination of the operation of the combination of the i-th critical object and the j-th facility of the settlement network. Q_i - is the total relative gas deficit among consumers caused by the termination of the i-th critical object, δ is the limitation of the relative increment of the total gas deficit at consumers to be included in the list of critical combinations of gas facilities.

Calculations show that more than 15 thousand combinations of other facilities with dedicated air cooling systems lead to an increase in gas deficit among consumers. Based on considerations of the acceptability of the expert analysis, we will limit the value of δ within 5%. Because of calculating in pairs all 61 critical objects of UGSS with the rest of the system objects (in total, more than 61 thousand pairs were analysed for their simultaneous shutdown). 630 pairs were obtained, consisting of one critical object and another object of the gas industry, the failure of which can lead to the emergence more than 5%.

It can be noted that the termination of the operation of critical combinations of UGSS facilities can lead to an increase in gas shortages to consumers by an average of 8-10% of the required gas volumes compared to the shortage caused by the termination of the operation of the corresponding UGSS facilities. In some cases, this increase can reach 20%.

As for measures to bypass bottlenecks, in situations with the termination of operation of the considered critical combinations of facilities, such measures lead to a relatively insignificant decrease in the total gas deficit among consumers (on average by 2-3%). This fact additionally confirms the high importance of identifying these combinations. [10].

7 Application of the method for determining critical elements in the networks of technical infrastructures in the search for critical objects of the gas industry

Determining critical elements is usually a straightforward task when considering only single failures. When considering multiple concurrent failures, this task can become much more complex.

It is especially difficult to identify critical groups of elements with a so-called synergistic effect. In this context, the synergistic effect means that the negative consequences of the failure of the group as a whole are higher than the total impact of individual failures of the elements included in the group. In other words, the failure of a group of two elements with serious negative consequences can have a synergistic effect if the failure of each of the elements does not in itself cause any significant consequences.

The method for determining critical elements in networks of technical infrastructures [21] facilitates the identification and ranking of such groups of elements (as well as groups of elements, the failure of which does not give a synergistic effect). Found critical elements or sets of elements can then be studied in more detail using probabilistic methods of risk analysis [22].

The essence of the above method is to study the sets of failures, each of which represents a set of faulty elements, has only one negative effect on the system, and is characterized by a size that specifies the number of elements whose failure occurs simultaneously.

The number of elements whose failure occurs simultaneously is a set of failures n, its size is chosen by the researcher depending on the total number of system elements t. However, for practical reasons, n should not exceed 3 or 4, since the number of possible sets of failures equal to $t!/((t-n)!*n!)$. Grows rapidly as n increases, which inevitably leads to an increase in the computation time. In addition, if we talk about a real power system, such as the UGSS, the probability of a simultaneous failure of a large number of independent elements of this system is very small.

The ranking of the sets of failures is carried out in accordance with the magnitude of their synergistic effects.

Using the design scheme presented above, the search for the critical objects in the UGSS was carried out using the method for determining the critical elements in the networks of technical infrastructures. As a result of calculations, 5 sections of main gas pipelines were obtained, which are critical both from the point of view of the maximum gas shortage among consumers and in terms of their contribution to the synergistic effect. Disruption of the functioning of these sections will lead to a significant gas shortage among consumers, from 15 to 21% in total throughout the entire system. All these factors make it possible to classify these sections of main gas pipelines as the critical objects of the gas industry.

The application of the method for determining critical elements in the networks of technical infrastructures in the search for critical objects clearly shows that the disruption of the functioning of several unconnected sections of the main gas pipelines, as well as the disruption of the functioning of the intersection of the main gas pipelines, will most likely cause more harm to the system than the disruption of the functioning of one section of the main gas pipelines. Taking this fact into account, we can talk about the greater importance of the sections of main gas pipelines as critical objects with a high value of the criticality index [23].

8 Determination of the most important combinations of gas facilities

All possible major combinations of gas facilities were identified and analysed. The most important combination of objects within the framework of this study means a pair of unconnected, independent objects, the failure of which can lead to a significant gas shortage among consumers. At the same time, the objects under consideration should not be included in the list of critical objects, or in the list of critical combinations of objects.

Taking into account the previously obtained 61 critical objects and 630 pairs of critical combinations, calculations were carried out for the pairwise disconnection of all other objects of the design scheme, followed by "uncovering" bottlenecks - by taking measures aimed at minimizing gas shortages among consumers. These calculations were carried out using a software package [24] that reflects in detail the functioning of the Russian gas transmission network and allows simulating various conditions for the functioning of its facilities, including a complete shutdown. The calculations were carried out using the parallel computation methodology in [25].

As a result, out of the 207690 pair combinations obtained, 2865 object pairs were selected, the failure of which leads to a total gas deficit in the system of 5% or more. After solving the problem of bypassing the bottlenecks, 2555 pairs of objects remained.

Table 2 shows 20 combinations of facilities, the failure of which can lead to a gas shortage in the system as a whole 10% or more.

Table 2. Combinations of Unified Gas Supply System of Russia objects, failure of which will lead to a maximum gas shortage in the system as part of the study

№ of pair	Object type №1	Object type №2	Gas shortage, %
1	CS	CS*	11
2	CS*	CS	11
3	Arc	CS*	11
4	Arc	CS*	11
5	CS	CS	11
6	CS	CS*	11
7	CS	CS*	10
8	Arc	CS	10
9	Arc	Arc	10
10	Arc	CS	10
11	CS	CS	10
12	CS	CS	10
13	Arc	CS	10
14	Arc	CS	10
15	CS	CS*	10
16	CS	CS*	10
17	Arc	CS*	10
18	Arc	CS*	10
19	Arc	Arc	10
20	Arc	CS	10

When analyzing the table 2, it is necessary to highlight an object - one nodal compressor station (CS*), which is not included in the list of critical objects. CS* is present in 10 combinations from the table 2. In addition, this CS* is present in 25% of all combinations leading to a total gas deficit of the system as a whole of 5% or more.

In general, the following should be noted from the results of the study. Violation of the functioning of the most important combination of objects can lead to a significant gas shortage among consumers (5-15%).

In this situation, measures to bypass bottlenecks lead to a slight decrease in the gas deficit in the system as a whole (by an average of 2-3%). This fact confirms the high importance of the identified combinations. It is worth noting that in the framework of this study, as a result of bypassing bottlenecks, the number of possible most important combinations of objects was reduced by 10%.

The results of this study showed that in the modern configuration of the UGSS, situations are possible when, in the event of a failure of a pair of network objects that are not critical object, the total gas deficit among consumers can reach 15% of the total gas demand [26].

9 Identification of especially significant objects of the gas industry

In addition to the critical objects, there is a significant number of facilities in the rather complex and ramified gas transportation system of Russia, the termination of which can lead to significant restrictions on gas supplies to a particular region. It was proposed to name these objects as especially significant objects of the UGSS. They were identified in the course of a special study [26], and a ranked list of them was formed. The list of especially significant objects UGSS by the number of objects exceeds the list of critical objects UGSS and fully includes all of them.

As a result of model studies that simulate the operation of the Russian gas industry in the conditions of alternate shutdowns of each of the facilities of the Russian gas industry, 193 UGSS especially significant objects were identified, the failure of which would lead to a gas deficit in any region in the amount of 10% or more. Among these objects there are 94 nodes of the gas transmission network and 99 arcs. At the same time, the total number of UGSS facilities participating in the calculation is 1004. Thus, 19% of them are included in the list of UGSS facilities.

The results of the study showed that for some regions, the termination of each facility from the list of especially significant objects affecting gas supplies to a given region leads to a 100% gas deficit. That is, for example, the termination of the operation of any of the 33 especially significant objects affecting the process of gas supply to the Kirov region will inevitably lead to a complete cessation of gas supply to this region.

Further, scenarios were calculated for the simultaneous shutdown of combinations of such objects by 2. Research showed that when searching for the most significant, from the point of view of consumer satisfaction, combinations of UGSS objects, 1,789 thousand combinations were analyzed, respectively, the same number of calculations were carried out. As a result, 18,528 combinations of UGSS facilities were found, the failure of which could cause a 10% or more relative gas shortage in at least one of the regions under consideration.

The identification of especially significant UGSS facilities and especially significant combinations of UGSS facilities and the formation of their lists is the next step after identifying the critical objects of the gas industry on the way to form a list of especially vulnerable regions from the point of view of fuel supply in the context of various emergencies in the gas industry. Taking into account in these studies the concept of vulnerability of the fuel supply system of a particular region makes it possible to draw conclusions about the need to plan measures to reduce this indicator in a number of regions.

10 Conclusion

The article reflects the main points of comprehensive work on the search and identification of critical objects of the gas industry, which form the basis of the methodology for determining critical objects of energy systems from the standpoint of ensuring energy security. The results of research are presented to determine:

- critical objects of the gas industry, 61 facilities, the failure of which can lead to a gas deficit of 5% or more throughout the system;

- critical combinations of gas industry facilities, 630 pairs of facilities, total gas deficit in case of a pair failure - by 5% or more from more than one critical object;
- the most important combinations of gas objects, 2555 pairs of facilities, failure of which leads to a total gas deficit in the system of 5% or more;
- especially significant objects of the gas industry, 193 facilities, the failure of which will lead to a gas deficit in any region in the amount of 10% or more;
- especially significant combinations of gas industry objects, 18,528 combinations of facilities, the failure of which can cause a 10% or more relative gas shortage in at least one of the regions under consideration.

Conclusions are drawn about the necessity and feasibility of searching for and determining these objects, with the subsequent development of invariant measures aimed at reducing their significance.

One of the possible directions for the development of this study is shown, associated with deepening into the problems of vulnerability of fuel supply systems in regions and their dependence on natural gas supplies.

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Analysis of Economic-Technical Potential of Renewable Power Sources for the Establishment of National Renewable Energy Center in Ninh Thuan Province, Vietnam

Vu Minh Phap[2], Doan Van Binh[2], Nguyen Hoai Nam[2,*], A. V. Edelev[1], M. A. Marchenko[3]

[1] Melentiev Energy Systems Institute SB RAS, Irkutsk, Russia
[2] Institute of Energy Science, Vietnam Academy of Science and Technology, Hanoi, Vietnam
[3] Institute of Computational Mathematics and Mathematical Geophysics SB RAS, Novosibirsk, Russia

Abstract. Currently, Vietnam‘s energy source structure is being changed by which renewable energy sources play more important role to meet the electricity demand and reduce greenhouse gas emissions from fossil energy sources. Vietnam's energy development strategy determines to build some renewable energy centers, of which Ninh Thuan is the first province designated to become a national renewable energy center. This is based on Ninh Thuan’s endowment as a province having the largest renewable energy potential in Vietnam. Development of a large renewable energy center allows power system planners to overcome the mismatch in timescales associated with developing transmission power grid and renewable energy generation. Besides, renewable energy center can facilitate a significant pipeline of large-scale renewable energy and storage projects. However, Ninh Thuan province is far away from the major load centers of Vietnam so the calculation and analysis of economic indicators need to be studied. This paper will present the results of the analysis of economic indicators of major renewable electricity sources in Ninh Thuan (onshore wind power, offshore wind power, solar power) to provide scientific arguments for developing a renewable energy center in Vietnam. Also the paper addresses the problem of the large-scale penetration of renewable energy into the power system of Vietnam. The proposed approach presents the optimization of operational decisions in different power generation technologies as a Markov decision process. It uses a stochastic base model that optimizes a deterministic lookahead model. The first model applies the stochastic search to optimize the operation of power sources. The second model captures hourly variations of renewable energy over a year. The approach helps to find the optimal generation configuration under different market conditions.

1 Introduction

The overall global renewable power capacity increased to around 2,378 GW by the end of 2018 and achieved more than 33% of the world’s total installed power generating capacity [1]. An estimated new renewable power capacity of 181 GW was installed worldwide in 2018, in which, the total capacity of solar power accounted for 55% of renewable capacity additions, followed by wind power (28%) [1]. The power system can receive a large proportion of renewable energy without using fossil fuels and nuclear power with the role of running "baseload", based on the flexibility of the electricity system, power grid connection, advanced technology solutions such as ICT (Information and communications technology), power storage systems and virtual power plants. It is not only helping to balance the change in the electricity generation stage but also optimizes the power system and reduces generation costs. As a result, some countries successfully control peak loads or surpassing the target of 100% of electricity produced from renewable energy.

There is a huge difference between renewable energy centers (wind and solar power) and traditional power centers such as a thermal power center in a national power system.This is because the peculiarities of its primary energy source. When developing a thermal power center, the preferred conditions for choosing a location are near large load centers or strong power grid or infrastructure (coal ports, for example). In the case of the renewable energy (RE) center, the preferred condition is the geographical areas with high solar radiation or good wind speed and efficiency in land use. This leads to the challenges of synchronizing and optimizing the transmission and distribution grids so that RE resources can be fully utilized in the considered geographical areas to reduce transmission losses as the load centers are usually far from the RE source. Some countries have been building large RE centers such as Asia RE Hub - AREH [2] in Western Australia and RE

* Corresponding author: nhnam@ies.vast.vn

Zone [3] of Texas, USA. A large RE center (RE Hub or RE Zone) is a geographic area supporting cost-effective renewable energy (RE) development, including high-quality RE resources, suitable topography, and strong developer interest. Development of a large RE center allows power system planners to overcome the difference in timescales associated with developing transmission power grid and RE generation. Besides, RE Hub or RE Zone can release a significant pipeline of large-scale renewable energy and storage projects.

Vietnam's electricity consumption increased steadily in recent years, from 90 TWh in 2010 [4] to 227 TWh in 2019 [5], with an annual growth rate of about 11 %/year. At the same time, the power system's maximum installed capacity also raised from about 20000 MW in 2010 [5] to about 55000 MW in 2019 [6]. It is forecasted that Vietnam's electricity demand will achieve about 570 billion kWh by 2030 [7]. Currently, Vietnam is changing energy source structure, in which potential renewable energy sources play an important role to meet the electricity demand and reduce greenhouse gas emissions from fossil energy sources. It is expected that the solar power would reach 4,000 MW in 2025, and 12,000 MW by 2030 while the wind power ‘s capacity may increase to 2,000 MW by 2025, and 6,000 MW by 2030 [8]. The actual installed solar power capacity at the end of 2019 reached about 5,6 GW [9] while a total wind power capacity installed about 425 MW [10]. The feed-in-tariffs (FIT) for solar and wind power project were introduced at 7.09 cent$/kWh for ground-mounted PV project and 7.69 cent$/kWh for floating solar projects [11], 8.5 cent$/kWh for onshore wind and 9.8 cent$/kWh for offshore wind [12].

Vietnam's energy development strategy determines to build some renewable energy centers, of which Ninh Thuan is the first province designated to become a national renewable energy center as the province has the largest renewable energy potential in Vietnam. The national renewable energy center established in Ninh Thuan will play an important role in supporting the development of the renewable power industry in Vietnam.

However, Ninh Thuan province is distanced from the major load centers of Vietnam so the calculation and analysis of economic indicators need to be studied. This paper will present the results of the analysis of economic indicators of major renewable electricity sources in Ninh Thuan (onshore wind power, offshore wind power, solar power) to provide scientific arguments for developing a renewable energy center in Vietnam.

2. Potential of solar and wind energy source in Ninh Thuan province

2.1. Geographical site

Ninh Thuan, located in the southern part of Vietnam Central Coastal region, borders Khanh Hoa in the north, Binh Thuan in the south, Lam Dong in the west, East sea in the East.

The province has total natural surface of 3,360 sq. kilometers, 7 administrative units including 1 city and 6 districts. The city of Phan Rang - Thap Cham, as provincial city, constitutes a political, economic and cultural center of the province, distant from Hochiminh City by 350 km, from international Cam Ranh airport by 60 km, from the city of Nha Trang by 105 km and from Da Lat by 110 km with favorable conditions for circulations in service of socio-economic development.

2.2. Solar energy potential

Ninh Thuan is located in an area with the annual average solar radiation of about 5.5 kWh/m^2.day, the average number of sunshine hours is about 2,600-2,800 hours per year (equivalent to 200 sunny days/year), and a total solar power installation scale of about 1,500 MW. In Ninh Thuan, the area of Ninh Phuoc district and Thuan Nam district where having large solar energy potential can be effectively exploited [13].

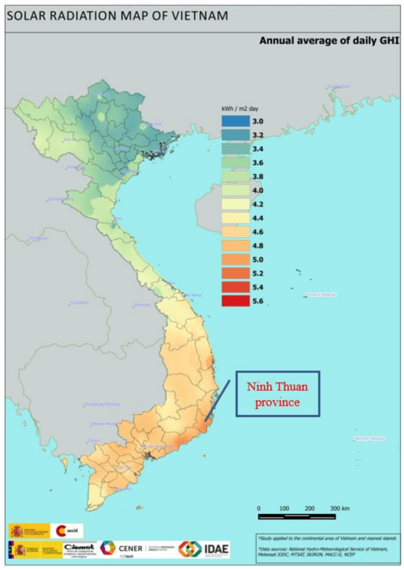

Fig. 1. Solar energy potential of Ninh Thuan province [6]

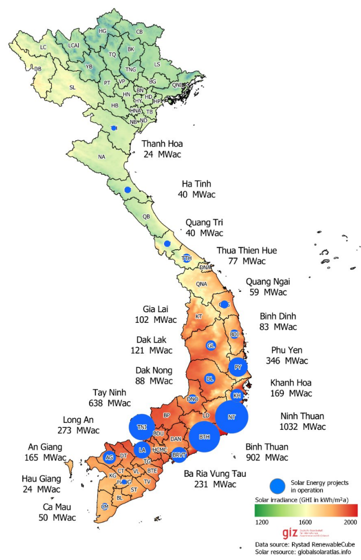

Fig 2. Installed solar power capacity in Vietnam [6]

Until August 2019, the number of completed solar power projects in Ninh Thuan was highest in Vietnam with the total installed capacity of about 1032 MW [6].

2.3. Wind energy potential

Ninh Thuận province also has the largest wind power potential in Vietnam with the annual average wind speed of about 7m/s at the height above 65m. The whole province has 14 potential wind regions with about 8,000 ha, concentrated mainly in three districts of Ninh Phuoc, Thuan Nam and Thuan Bac. Especially, storms in Ninh Thuan is not much and the wind blows steadily for 10 months at a speed of 6.4 - 9.6 m/s, ensuring stability for wind power development. The technical wind power potential and the highly feasible area of Ninh Thuan are 1,442 MW with 21,642 ha [14].

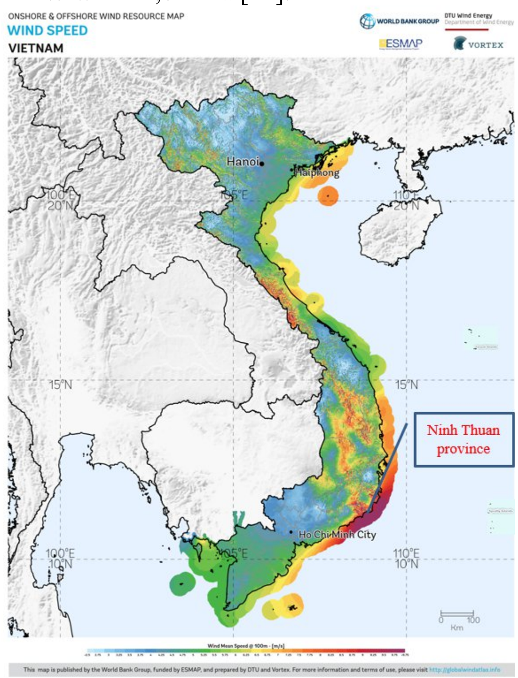

Fig 3. Wind energy potential in Vietnam [15]

Up to August 2019, Ninh Thuan achieved the largest number of commissioned wind power projects in Vietnam with the total installed capacity of about 109 MW as shown in Figure 4 [6].

2.4. Methodology

In this study, the electricity of solar farm is calculated by using PVSYST program [16, 17] while the output from wind turbine is determined by using design data of wind farm projects in planning of wind power development in Ninh Thuan [14].
The economic potential was determined by considering the annualized investment costs and the annual O&M costs. The goal is the calculation of the minimum Feed in tariff (FIT) level. Currently, the level of FIT can be calculated on the basis of a calculation of the levelized cost of electricity (LCOE) produced from renewable energy (RE) projects [19]. By which, the investor can recover the different costs (capital, O&M, fuel, financing) while realizing a return on his investment that depends on the assumed financing costs.
LCoE has been utilized to assess the average lifetime costs of providing one MWh for a range of power production technologies or power savings. The cost elements comprising the LCoE include investment costs, fuel costs, operation and maintenance costs, environmental externalities and system costs for solar and wind power plants. LCoE is given by the following formula:

$$LCOE = \frac{\sum_{t=1}^{n}(I_t + Mt + Ft)}{\sum \frac{E_t}{(1+r)^t}} \quad (1)$$

In which:

I_t: investment cost by the year t
M_t: Operation and Maintenance cost by the year t
F_t: Fuel cost by the year t
E_t: Electricity production by the year t
r: discount rate
n: project lifetime (year)

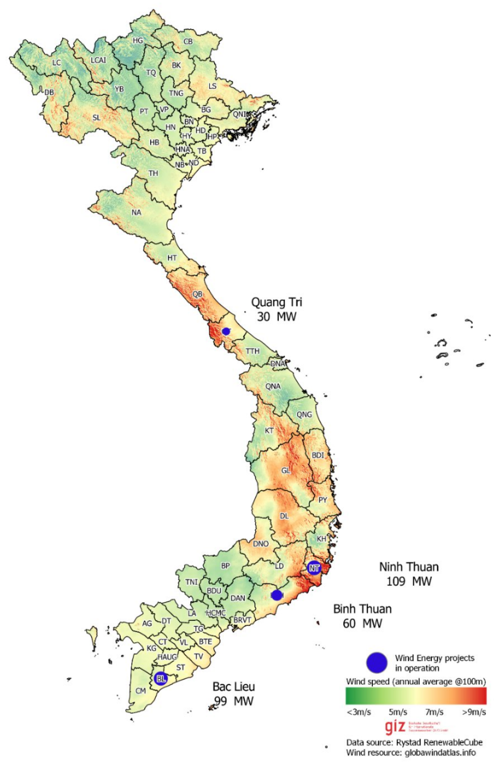

Fig 4. Installed wind power capacity in Vietnam [6]

2.5. Results

The key parameters are used for the calculations are shown in Table 1.

Table 1. Input parameters

Parameters	Ground-mounted PV power	Onshore wind power	Offshore wind power

Initial Investment Cost ($)	25,278,015	53,892,216	66,723,695
Operations and Maintenance Costs ($)	126,390	1,077,844	1,334,474
O&M Growth Rate (%)	2	2	2
Capacity (MW)	30	30	30
Annual Electricity Output (MWh)	48,450*	73,584	86,724
Project Lifespan (years)	25	25	25
Discount Rate (%)	6	6	6

*Note: Power degradation of solar power is no more than 2.5% in the first year, thereafter 0.7% per year until 25th year.

The LCOE or minimum FIT of major renewable electricity sources in Ninh Thuan (onshore wind power, offshore wind power, solar power) is evaluated in Table 2.

Table 2. Economic indicators calculation

Parameters	Ground-mounted PV power	Onshore wind power	Offshore wind power
Net present value (NPV) ($)	27,074,753	69,214,650	84,046,360
LCOE (centsUS/kWh)	5.1	7.9	8.2

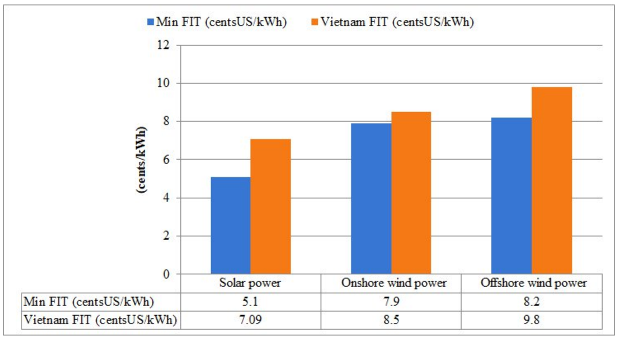

Fig 5. Minimum FIT versus Vietnam FIT

Figure 5 presents the comparison results between minimum FIT of onshore wind power, offshore wind power, solar power projects in Ninh Thuan with existing Vietnam FIT of these projects in Vietnam. The min FIT of onshore wind power in Ninh Thuan is closer with Vietnam FIT than solar power and offshore wind power.

3. Generation expansion planning

The planning models are the traditional tool to analyse future developments in the energy sector. The capacity planning problem in the power systems has been divided into demand forecasting, distribution expansion planning, transmission expansion planning, and generation expansion planning (GEP). For each capacity planning problem, the time horizon can be divided into long-term, medium-term, or short-term studies [20]. Short-term planning is associated with day-to-day system operation. Medium-term planning involves the maintenance of system assets. Long-term planning relates to new capacity additions [21].

GEP is a power plant mix problem that identifies types, location, and construction time of new generation technologies, which should be added to the existing system in order to meet the power demand over a specific planning horizon [20, 22]. The contemporary, systematic, and robust GEP should consider [23]:

- Integration of electric vehicles in power systems,
- Integration of short-term operational aspects into decision making,
- Power and fossil fuel systems interdependence,
- Energy storage and demand-side impacts on GEP,
- Policy implications on power investments, highlighting the role of supply of security.

The GEP models can be classified according to time horizon (static and dynamic), handling of uncertainties (deterministic and stochastic), network topology (the single-node or centralised and network constrained), and market structure (regulated and deregulated) [20].

The GEP is usually an optimisation problem in which the aim is to distinguish the optimal size, type of generation unit, and commitment time of new generating facilities so as to satisfy the power demand at least cost over a planning horizon [20].

3.1. Generation expansion planning with high share of renewable energy

The RE resources create for the power systems' operation some operational challenges for GEP due to the following feature of their stochastic nature [24-26]:

- RE variability requires flexible generation that can ramp up and down quickly,
- The intermittency makes the output from RE sources uncertain.
- Power quality and voltage stability issues connected with RE variability that needs to be assessed, controlled, observed and mitigated appropriately,

These three aspects (variability, intermittency, and grid stability issues) necessitate a paradigm change in GEP models that assess the impact of increased penetration of RE [27-29]. Traditional GEP models have mostly focused on the conventional power plant whose operation and planning can be easily conducted by varying fuel inputs to match variability on the load side [20, 30]. To address the operational challenges the grid might require additional levels of reserves [31-33]. Another way to mitigate these challenges is the adoption of storage units [34-36].

There are a lot of works that have included the integration of RE sources in GEP problem [37-42].

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3.3. Decision-making in energy planning

Most of the decisions to be made by energy sector decision-makers are fed by information which is usually subject to uncertainties [43]. There are different types of uncertainty: Gaussian noise, heavy-tailed distributions, bursts, rare events, temporal uncertainty, lagged information processes, and model uncertainty [44]. The combination of the uncertainty types with decisions that may be binary, discrete, continuous or categorical, scalar or vector creates a virtually unlimited range of problems [45].

There are much uncertainty handling methods developed for dealing with uncertain parameters: stochastic, possibilistic, hybrid and etc. The main difference between them is a way they choose to describe the uncertainty of the model's inputs. And they are similar in the attempt to quantify the influence of inputs on model's outputs [46].

3.3.1 Problem formulation

Our approach for solving GEP problem is based on the stochastic optimization framework [45, 47] that divides decision-making into the following five components: states, actions, exogenous information, transition function and objective function. Similarly to [48, 49], the proposed approach presents the optimization of operational decisions in GEP as a Markov decision process. It uses a stochastic base model that optimizes a deterministic lookahead model. The first model applies the stochastic search to optimize the operation of power sources and the second model captures hourly variations of RE over a year.

The simplified structure of the energy sector of Vietnam is represented as a network $G=(N,A)$, where N is the set of the nodes and A is the set of arcs. The node $i \in N$ represents a point of demand and/or supply of energy, and the arc $(i,j) \in A$ is a transmission line.

A set of power generation technologies O consists of two subsets: fossil fuel-fired facilities and RE sources. R denotes the RE subset. The fossil fuels constitute the set F. $q \in O$ is a power generation technology and $k \in F$ is a fossil fuel. T is the number of periods (hours) in the planning horizon where $t \in T$ is a time period.

3.3.2 The base model

The base model is intensively based on the work [50]. The additional objectives and constraints are adopted from studies [51-53].

The current state of the Vietnamese energy sector in the period *t* may be represented as

$$s_t = (d_{it}, h_{iqt}, b_{kt}, o_{kt}, p_t)\ i \in N, q \in R, k \in F, t \in T \quad (5)$$

where d_{it} is the load/demand (MW) at the node i in the period t, h_{iqt} is the corresponding hourly capacity factor for each RE technology q in the node i during the period t, b_{kt} is the local production (kTOE) of the fuel k in the period t, o_{kt} is the cost ($/kTOE) of the fuel k import in the period t, $p_t = (d_{it'}, h_{iqt'}, b_{kt'}, o_{kt'})$ is forecast for $t' > t$.

The decisions variables in the period t may be represented as

$$x_t = (g_{iqt}, x_{ijt}, v_{it})\ i \in N, (i,j) \in A, q \in O, k \in F, t \in T \quad (6)$$

where g_{iqt} is the generation amount (MW) of the technology q at the node i in the period t; x_{ijt} is the flow (MW) through the arc (i,j) in the period t, and

v_{it} is the unmet demand (MW) at the node i in the period t.

The set of feasible decisions in the period t is defined by the following constraints:

- Node power balance equation: the generation plus flow from other nodes is equal to the sum of demand, shortage and flow to other nodes at the node $i \in N$ in the period :

$$\sum_{(j,i)\in A} x_{jit} - \sum_{(i,j)\in A} x_{ijt} + \sum_{q\in O} g_{iqt} = d_{it} + v_{it} .\quad(7)$$

- Fossil fuels demand in the period t: The fuel k will be either imported or taken from local markets

$$\sum_{i\in N}\sum_{q\in O} w_{qt} g_{iqt} \le u_{kt} + b_{kt}; k \in F, t \in T ,\quad(8)$$

  where w_{qt} is the consumption of fuel (kTOE/MW) for the technology q in the period t.

- Power generation limit on each conventional technology in the node during the period :

$$g_{iqt} \le y_{iqt}; i \in N, q \in O \setminus R, t \in T .\quad(9)$$

  where y_{iqt} is the total capacity (MW) of the technology q at the node i in the period t.

- Power generation limit on each RE technology q in the node during the period :

$$g_{iqt} \le h_{iqt} y_{iqt}; i \in N, q \in R, t \in T .\quad(10)$$

- Power transmission limit on each arc (i, j) in the period :

$$x_{ijt} \le p_{ijt}; (i,j) \in A, t \in T .\quad(11)$$

- Nonnegativity: no negative values are permitted for the decision variables

$$g_{iqt}, x_{ijt}, u_{kt}, v_{it} \ge 0, \quad(12)$$

  where $i \in N$, $q \in O$, $(i,j) \in A$, $k \in F$, and $t \in T$.

The transition from the state s_t to the successor state s_{t+1} is determined by the function s^M

$$s_{t+1} = s^M\left(s_t, x_t, w_{t+1}\right); t \in T , \quad(13)$$

where w_{t+1} is uncontrolled exogenous process defined as the random variables that capture the stochastic updating of wind, solar, demand and cost forecasts. The w_t is modeled as changes of d_{it}, h_{iqt}, b_{kt}, and o_{kt}.

The total cost of the energy sector functioning s_t over the period t consists of operation and transmission costs, environmental impact, imports of fuel, and unmet demand cost:

- Operational and transmission costs: this objective function is defined as the total present value sum of the operation and maintenance costs

$$f_1(t) = \sum_{i\in N}\sum_{q\in O} q_{iqt} g_{iqt} . \quad(14)$$

  In this objective, q_{iqt} is the operation and maintenance cost (\$/MW) of the technology q at the node i in the period t.

- Fossil fuel import: the goal is to minimize the total amount of fuel imports

$$f_2(t) = \sum_{k\in F} o_{kt} u_{kt} . \quad(15)$$

- Unmet demand: the goal is to minimize the total power shortage

$$f_3(t) = \sum_{i\in N} l_t v_{it} , \quad(16)$$

  where l_t is the cost (\$/MW) of not satisfying the demand in the period t.

The total cost over the period t may defined as

$$c(s_t, x_t) = \sum_{l=1}^{3} f_l(t) . \quad(17)$$

The policy π represented by the function $x_t^{\pi}(s_t)$ makes hourly planning decisions and returns the feasible decision x_t for any system state s_t. The overall goal of the stochastic base model is to find the best policy. Since s_t is a random variable, the objective function would be written as the minimization of the expected sum of total cost over the entire time horizon T

$$\min_{\pi} e \sum_{t\in T} c\left(s_t, x_t^{\pi}(s_t)\right). \quad(18)$$

3.3.3 The lookahead model

The deterministic model is the policy $x_t^{LA}(s_t \mid \theta)$ with the lookahead horizon as the tunable parameter [49]. It determines the decisions by solving the optimization problem

$$\arg\min_{x_t} \sum_{t'=t}^{t+\theta}\sum_{l=1}^{3} f_l(t'), \quad(19)$$

where the set of feasible decisions x_t is defined by constraints (5)-(19) for each t' with $t \quad t' < t + \min(T - t, \quad)$.

The solving the lookahead model in (19) is not an optimal policy but it helps obtain robust behaviour by tuning using the base model.

3.4. Parallelization

Finding the optimal solution of the GEP problem can require running some hundreds evaluations of the total yearly cost [48]. Each evaluation is expensive computationally, since it solves a linear program that looks into the future for each hour in a year (i.e. 8760 rather big linear programs).

The future implementation of the proposed approach for solving GEP problem will use parallelization as a base feature to provide these evaluations. The approach will be implemented on the top of PARMONC - the library of easy-to-use programs that was implemented on high-performance clusters of the Siberian Supercomputer Center. The main features of the PARMONC are as follows:

- it is suitable for the massively parallel stochastic simulation for a wide range of applications,
- it is a software framework to parallelize stochastic simulation to be applied without knowledge of MPI language.

The PARMONC effectively launches stochastic simulation on supercomputers with different architectures. Also, it is scalable from current supercomputers to more powerful ones up to future exaflop supercomputers.

For example, each yearly assessment can be represented as 12 separate monthly evaluations, if a special distributed computing environment with parallel generator of pseudorandom numbers [54] is used.

4. Conclusions

In this study, the potential of solar power and wind power in Ninh Thuan province were presented with the annual average solar radiation of about 5.5 kWh/m^2.day and wind speed of 6.4 - 9.6 m/s.

The economic indicators calculation shows that the minimum FIT of onshore wind power, offshore wind power, solar power projects in Ninh Thuan were lower than current Vietnam FIT. The gap between minimum FIT and Vietnam FIT of onshore wind power was smaller than offshore wind power, solar power projects.

The proposed generation expansion planning approach presents the optimization of operational decisions in different power generation technologies as a Markov decision process. It uses a stochastic base model that optimizes a deterministic lookahead model. The first model applies the stochastic search to optimize the operation of power sources. The second model captures hourly variations of renewable energy over a year.

The approach helps to find the optimal generation configuration under different market conditions. Also, the approach takes into account the following types of constraints: flow balance constraints in the network with demand covering, power generation and transmission limit, availability of local fossil fuels production, system reliability requirements, maximum and minimum shares of RE resources, and energy supply security requirements.

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Flicker control in mains with distributed generation plants

Yuri Bulatov[1,*], *Andrey* Kryukov[2,3], and *Nguyen* Van Huan[3]

[1]Bratsk State University, Bratsk, Russia
[2]Irkutsk State Transport University, Irkutsk, Russia
[3]Irkutsk National Research Technical University, Irkutsk, Russia

Abstract. The use of distributed generation (DG) plants in power supply systems is a rapid development line. However, the impact of DG on power quality is multivalued. On the one hand, the presence of DG allows to reduce voltage losses. On the other hand, a phenomenon called flicker and associated with rapid voltage fluctuations is possible. This effect is usually manifested at an abrupt voltage drop in the DG generator connection unit. The processes taking place in the network when flicker occurs in networks with DG have not been sufficiently studied. The article presents results of the flicker modeling in a network equipped with DG plants, implemented on the basis of synchronous generators. The results obtained indicated that with sharp disturbances caused by switching on and off an additional load, flicker is observed in networks with unregulated generators, accompanied by voltage and frequency fluctuations. Based on the wavelet transformation and spectral analysis methods, it was found that the power spectral density of the generated flicker-noise is inversely proportional to the frequency. The use of look-ahead control algorithms to control the excitation and rotors rotational speed of the DG plants generators, as well as concordant adjustment of their controllers, increases stability and removes flicker completely.

1 Introduction

Distributed generation (DG) plants are broadly used nowadays to develop and upgrade power supply systems (PSS), but there are power sources which are located in close proximity from the consumers and whose operation is based on the different technologies: wind power generators, solar batteries, fuel cells, gas turbine power plants, mini- and micro-HPPs, etc.

Distributed power generation is a counterpart of Smart Grids concept [1-3] and can be used for mains load shedding, power and energy losses reduction and enhancing PSS reliability and survivability. New electrical power markets can be generated using DG plants [4]. It should be noted the distributed generation can produce unambiguous effect on PSS power quality. DG plants allow to maintain the required voltage levels in the mains nodes [5, 6], reduce unsymmetry and harmonic distortions in PSS [7]. However, low-power generators can cause voltage fluctuations which cause flicker in some cases [4, 8-10]. This can occur in case of an abrupt voltage drop in the connection node of DG plant. Incorrectly adjusted automatic voltage regulators (AVR) and automatic speed regulators (ASR) of DG plants can enhance the occurring flicker [10]. The processes taking place in DG plants mains on the background of arising flicker, have not been sufficiently studied. A broader study of the DG plants based on AVR and ASR generators require a precise assessment of their affect on PSS to eliminate power quality deterioration. The problems of flicker assessment and elimination in PSS using the controlled DG plants are undoubtedly of urgent character.

The work provides the study results of PSS working modes with DG plants implemented based on synchronous generators with AVR and ASR. To analyze flicker-noise in the network under study, spectral analysis and wavelet transformation methods were used.

2 Description of the network under study and synchronous generator regulators used

The study was carried out in MATLAB system based on PSS models with DG plants. Diagram of the PSS under study is represented in fig. 1. A PSS was simulated with a total consumer load of $5 + j2.4$ MV·A connected to supplying electrical energy system (EES) (110 kV System unit in fig.1) through a 110/35/6 kV transformer. The PSS consisted of DG plants, implemented on the basis of two turbine generators (Synchronous Machine units) with a rated power of 3.125 MV·A each and 6.3 kV voltage. The generators were simulated by the Synchronous Machine pu Fundamental units included in the SymPowerSystems library. Fig. 2 provides a structural diagram of the used steam turbine model (Steam turbine unit in fig. 1). The following turbogenerator parameters were used for modeling: the reactance of the machine along the longitudinal axis $X_d = 2.34$ r.u.; generator EMF $E_q = 1.25$ r.u; constant of the generator mechanical inertia $Tj = 8.669$ s, etc.

* Corresponding author: bulatovyura@yandex.ru

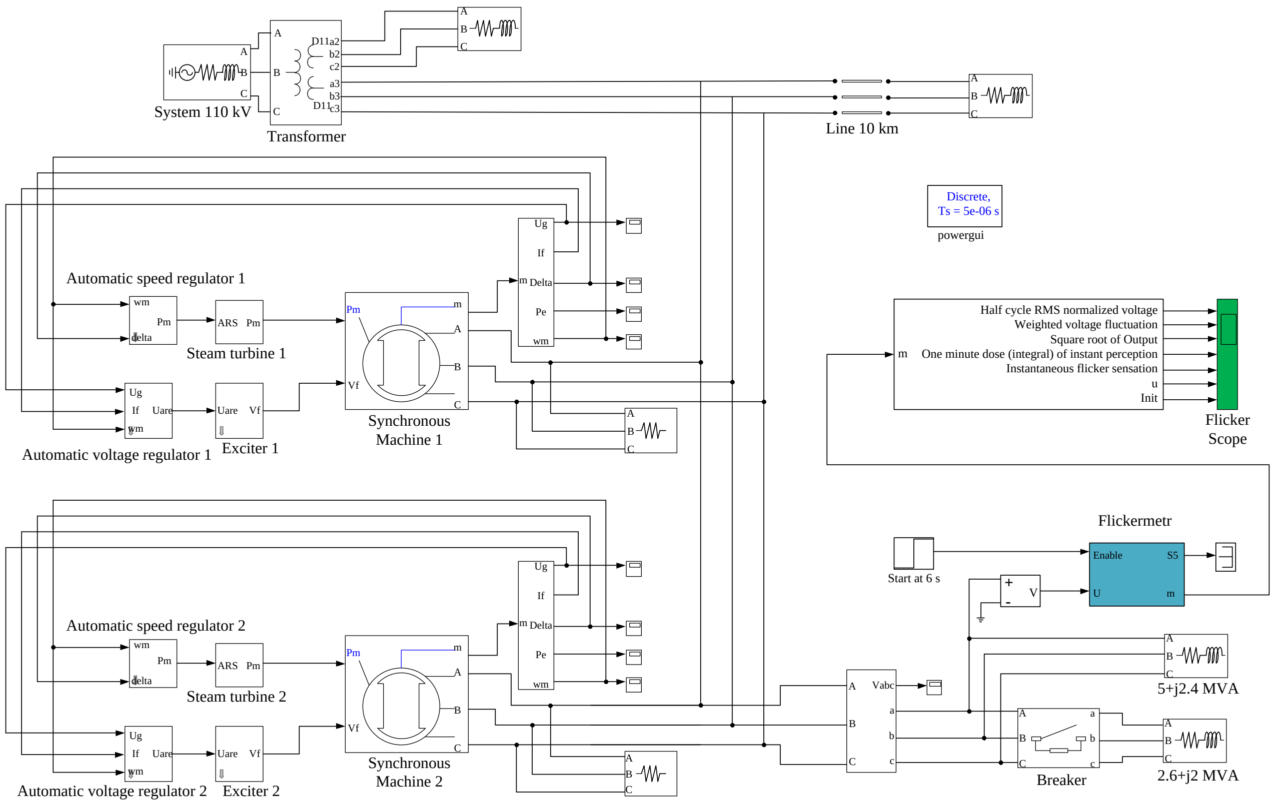


Fig. 1. The study model diagram in MATLAB.

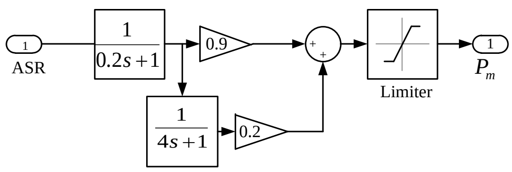


Fig. 2. Structural diagram of the used steam turbine model.

Models of thyristor excitation systems (Exciter1 and Exciter2 units) are implemented based on the equations provided in [11]. To control the rotor rotational frequency and voltage of the DG plants generators, the AVR and ASR models were used, which implement proportional-integral-differential (PID) control laws and are represented by the following transfer functions:

1) Automatic speed regulator unit:

$$\left(k_p + \frac{k_i}{0.1s} + \frac{k_d s}{s+1}\right)\cdot\frac{1}{0.01s+1},$$

where k_p, k_i, k_d – ASR adjustment coefficients; s – Laplasian operator;

2) Automatic voltage regulatoe unit:

$$\frac{1+0.5s}{0.5s}\cdot\left(k_{0u} - \frac{0.02\,k_{1u}s}{0.06s+1} + \frac{2\,k_{0\omega}s}{(2s+1)(0.02s+1)} + \frac{0.05\,k_{1\omega}s}{0.05s+1}\right)$$

where k_{0u}, k_{1u}, $k_{0\omega}$ and $k_{1\omega}$ – coefficients of AVR channels adjustment.

The model also used look-ahead control algorithms a detailed description of which is provided in [12, 13]. The structural diagram of auto prognostic ASR is provided in fig. 3 [13]. It included the following units:

– PID controller whose mathematical description is provided above;

– two links connected in parallel with a transfer function $\frac{K_a s}{T_a s+1}$ (K_a=1; T_a=0.001 s);

– unit for calculating *Tp* time constant of the linear forecasting link, which depends on the angle between the voltage and the generator EMF δ.

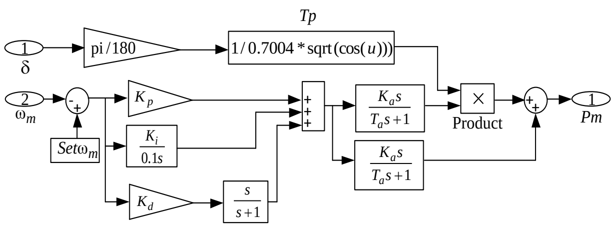


Fig. 3. Structural diagram of auto prognostic ASR.

Measurements of voltage and frequency fluctuations were performed using oscilloscopes. The modes leading to the occurrence of flicker were created by short-term connection to the node with additional load DG plants with a power of 2.6 + *j*2 MV·A.

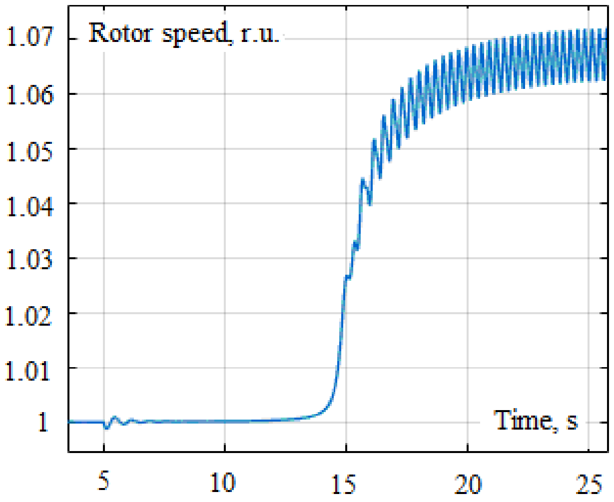
The model used a standard Flickermetr unit (fig. 1), which implements a digital flickermeter in accordance with the international standard IEC 61000-4-15. It allowed measuring the following parameters: root-mean-square voltage for each half cycle; weighted voltage fluctuation obtained after passing through a special filter; integral one-minute flicker dose; instant flicker sensation (instant flicker dose).

* Corresponding author: bulatovyura@yandex.ru

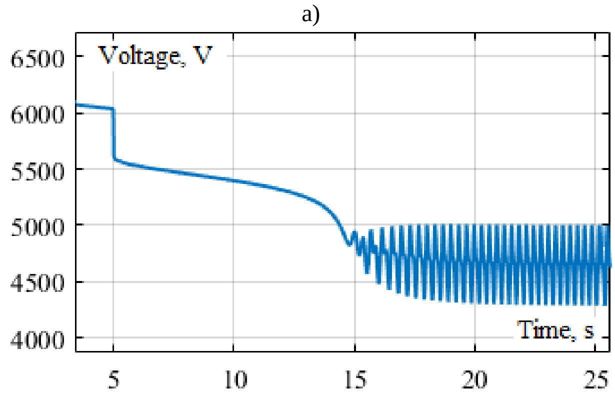
3 Description of the study results

The studies were carried out for the following operating modes of DG plants generators: without regulators; with concordantly and non-concordantly configured AVR and ASR; using predictive algorithms in AVR and ASR.

The computational experiments carried out on the model indicated that in case of operation of small turbine generators without AVR and ASR, there is a high probability of stability loss and the occurrence of an asynchronous run when an additional load is connected, which causes a decrease in voltage in the DG plants connection assembly. In this case, fluctuations of the generator rotor speed (fig. 4a) and the voltage on the 6 kV buses (fig. 4b) occur. These fluctuations can propagate across the entire network. It should be noted that Flickermetr shows the presence of flicker (fig. 5).



a)



b)

Fig. 4. Oscillograms of rotor speed (a) and voltage (b) of generator without regulators when additional load is connected in the node.

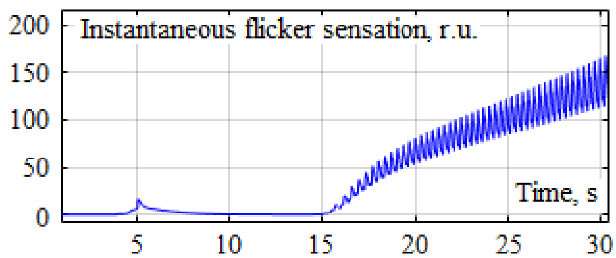


Fig. 5. Flickermeter reading (instantaneous flicker dose).

The resulting noise was selected from the signal of the effective voltage in the assembly with DG plants using the wavelet transformation. The user-selected noise is shown in fig. 6.

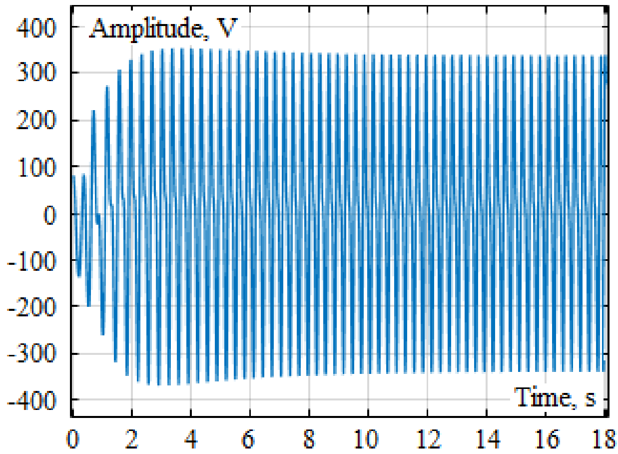


Fig. 6. User-selected noise.

The analysis results proved that the power spectral density of the selected noise is inversely proportional to the frequency. Dependences of spectral power density *Spd* on frequency at various scales, obtained using the Berg method [14], are provided in fig. 7, 8. Processing the results obtained indicates that

$$Spd \sim \frac{1}{f^{\beta}},$$

where $\beta = 3.59$ the spectrum shape index. Thus, the user-selected noise can be attributed to flicker-noise [15, 16].

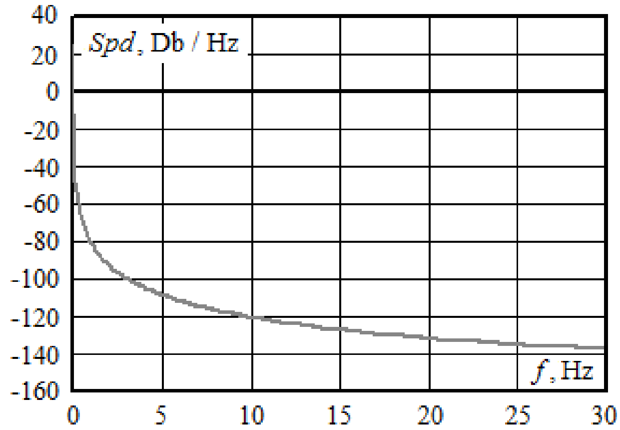


Fig. 7. Dependence of *Spd* (Db/Hz) on frequency.

The reason for the flicker-noise appearance in the system under study can be attributed to low-frequency fluctuations in the rotational speed of the rotors of DG plants generators when a sharp disturbance occurs in the assembly of their connection. Similar effects are observed with non-optimal adjustment of the DG plants regulators. Fig. 9 shows the corresponding oscillograms of the rotor speed and the generator voltage with non-concordantly adjusted AVR and ASR.

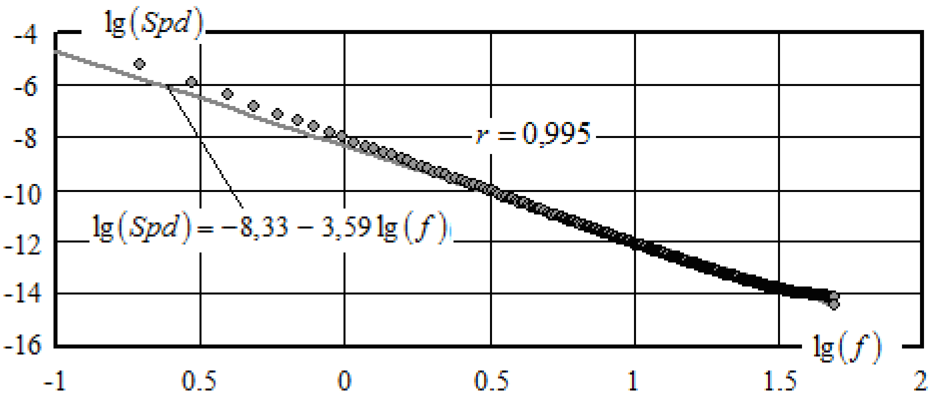


Fig. 8. Dependence of log(*Spd*) on frequency logarithm: *r* – correlation coefficient.

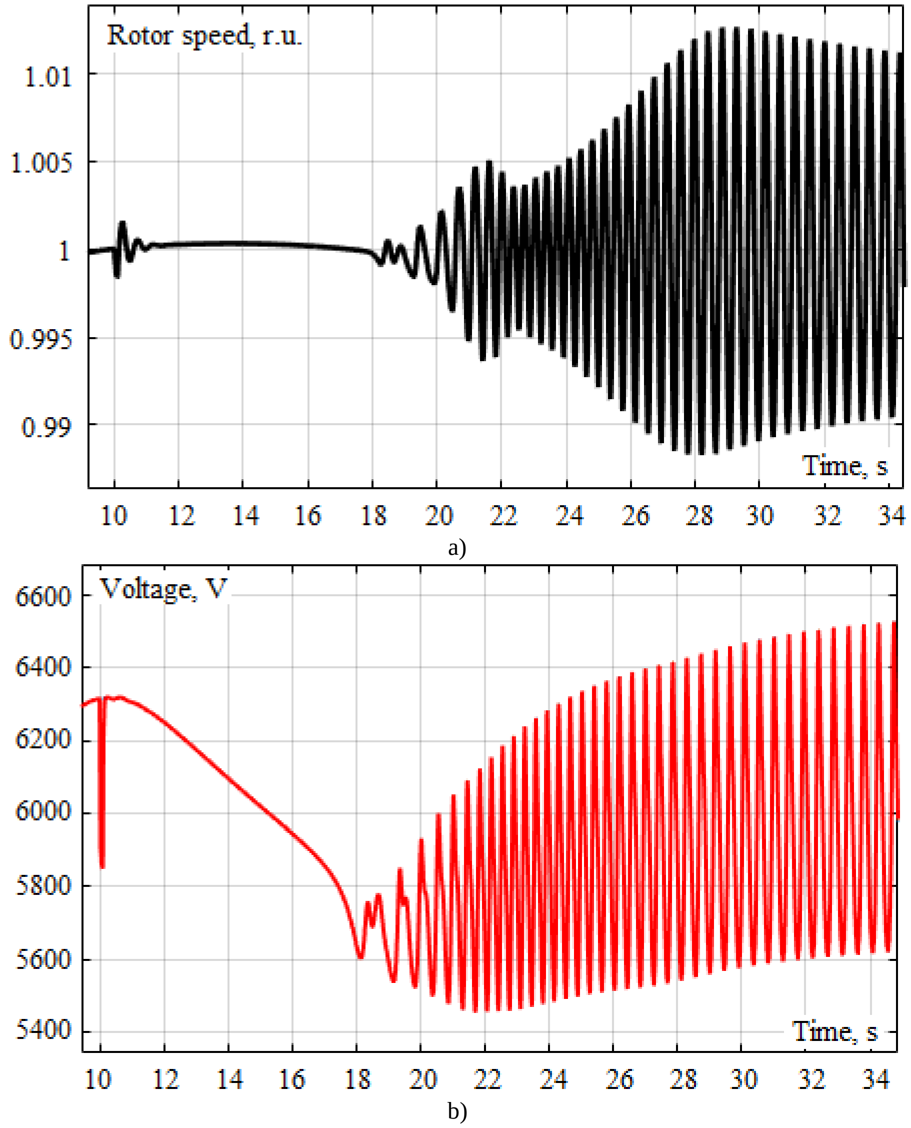


Fig. 9. Oscillations of the rotor speed (a) and voltage in the DG plant connection assembly (b) when a powerful load is switched on and off after 0.1 s. Non-concordantly adjusted AVR and ASR were used.

It should be noted that the issues of flicker removal can be solved by correctly adjusting the DG plants regulators using standard techniques. More complex cases may require system measurements to evaluate voltage fluctuations and determine how controls can be adjusted or modified to reduce flicker-noise.

The studies conducted have proved that the use of look-ahead control algorithms to control the rotor speed and excitation of the DG plants turbine generators allows to increase stability and completely removes the occurrence of flicker even without using the regulators adjustment procedure. The corresponding oscillograms of the voltage and rotor speed of one of the generators with a sharp change in the consumer load are shown in fig. 10 and 11. The use of procedure for AVR and ASR concordant adjustment of synchronous generators [5],

* Corresponding author: bulatovyura@yandex.ru

and look-ahead control algorithms helps to solve flicker occurrence issue. In this case, the quality indicators of transient processes in PSS equipped with DG plants are significantly improved. Oscillograms of the voltage and the generator rotor speed in case of a sharp change in the consumer load, as well as the readings of the flickermeter, confirming these conclusions, are shown in fig. 12 and 13.

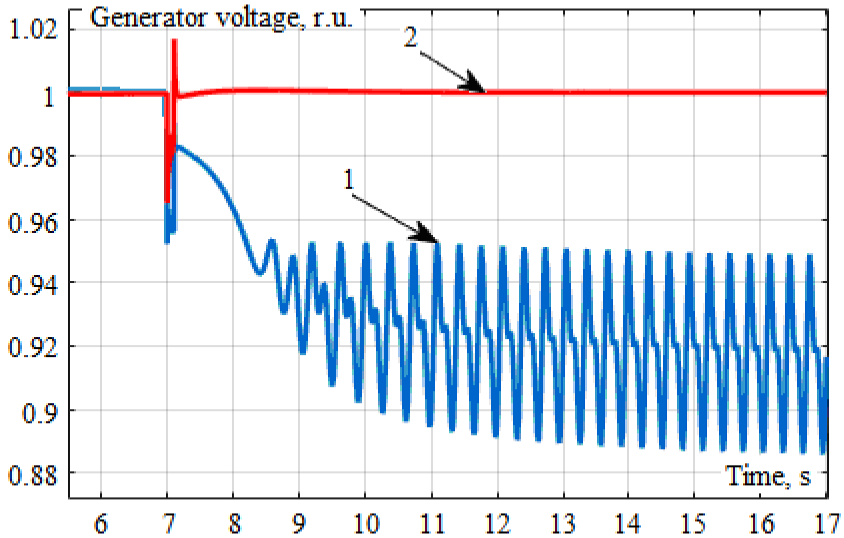


Fig. 10. Turbogenerator voltage oscillograms: 1 – generators were operated without AVR and ASR; 2 – generators were operated with the use of prognostic AVR and ASR.

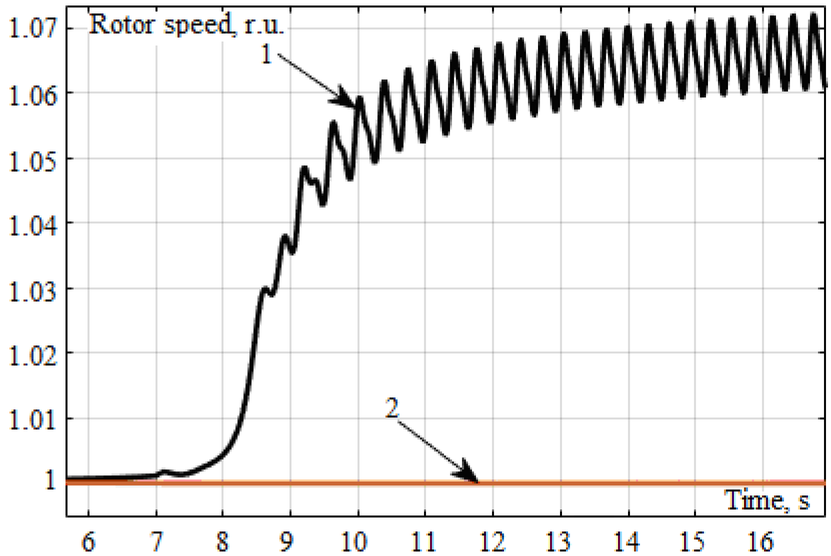


Fig. 11. Oscillograms of the turbogenerator rotor speed: 1 – generators were operated without AVR and ASR; 2 – generators were operated with the use of prognostic AVR and ASR.

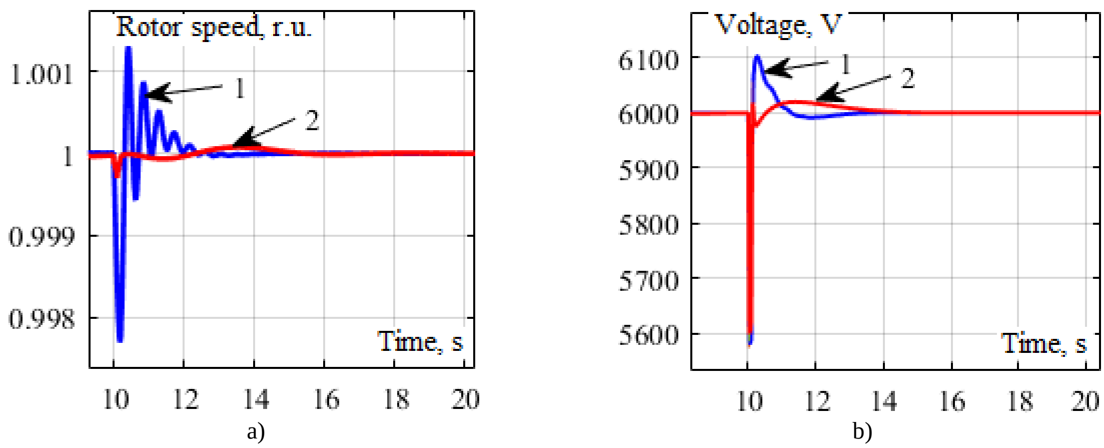
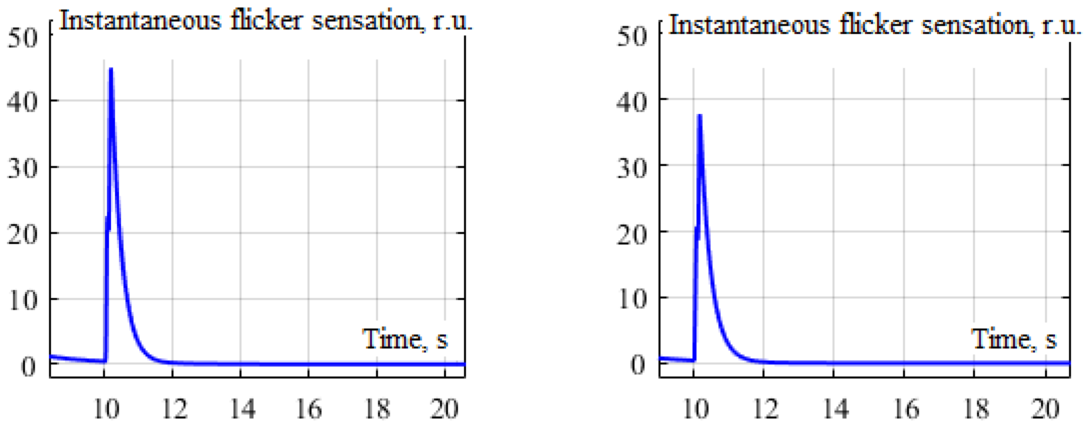


Fig. 12. Oscillograms of the generator rotor speed (a) and the voltage in the DG plant connection assembly (b): 1 – the generators worked with AVR and ASR with concordant adjustment; 2 – the generators were operated using prognostic concordantly adjusted AVR and ASR



a) b)

Fig. 13. Flickermeter reading (instantaneous flicker dose): a) the generators were operated with AVR and ASR with concordant adjustment; b) the generators were operated using prognostic concordantly adjusted AVR and ASR.

4 Conclusion

Based on study conducted, the following conclusions can be made:

1. At sharp disturbances caused by switching on and off an additional load, a flicker effect is observed in networks with unregulated DG plants operating based on synchronous generators. Based on the wavelet transformation and spectral analysis methods, it was found that the power spectral density of the generated flicker-noise is inversely proportional to the frequency.

2. The use of look-ahead control algorithms to control the rotor speed and excitation of the DG plants turbine generators makes it possible to increase stability and completely eliminates the occurrence of flicker even without using the regulators adjustment procedure.

3. The combined use of the procedure for concordant adjustment of regulators of synchronous generators and look-ahead control algorithms makes it possible to solve the issue of flicker occurrence in case of sharp disturbances in the DG plants connection assemblies. In this case, the quality indicators of PSS transient processes with DG plants are significantly improved.

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Simulation of Electromagnetic Fields Occurring at Intersection of Traction Networks and Multicircuit Power Lines

Natalia V. Buyakova[1,*], *Andrey V.* Kryukov[2, 3], *Dmitriy A.* Seredkin[3,*], and *Le Van* Thao[2].

[1]Angarsk State Tech-nical University, 665835, Angarsk, Russia
[2]Irkutsk State Transport University, 664074, Irkutsk, Russia
[3]Irkutsk National Research Technical University, 664074, Irkutsk, Russia

Abstract. Traction networks (TN) 25 kV generate higher electromagnetic fields (EMF) with frequency 50 Hz, whose strengths at a standardized height of 1.8 m, as a rule, do not exceed the permissible norms for electrical personnel. In places where railroads routes intersect with high voltage overhead power supply lines (OPL), interference of fields, generated by the traction network and OPL, occurs. This can lead to an increase in strengths and a complication of the EMF spatial structures. The article presents simulation results performed for a complex intersection, while 25 or 2 x 25 kV TN is crossed by a three-circuit 110-220 kV overhead power line at 90 degrees angle. Fazonord software application was used for simulating EMF strengths in points of traction networks and OPL intersection. Based on modeling results the following conclusions have been made: at intersection points of 1x25 kV traction network with a three-chain 110 - 220 kV power transmission line, the electrical field strength does not exceed the value acceptable for electrical personnel and reaches 4.2 kV/m; at the intersection with 2 x 25 kV traction network, this parameter decreases to 2.7 kV/m; the maximum amplitude of the magnetic field at the intersection points increases slightly.

1 Introduction

High-voltage overhead power lines (OPL) and electrified AC 25 kV railroads are sources of industrial frequency electro-magnetic field (EMF). Electromagnetic fields with high strength levels can generate interference causing disturbances of electrical and electronic devices' normal functioning [1–4] and result in serious accidents when operations are conducted on disconnected power supply lines or communication lines when personnel is subject to induced voltage.

25 kV traction networks (TN) generate higher electromagnetic fields (EMF) with frequency 50 Hz, whose strengths at a standardized height of 1.8 m, as a rule, do not exceed the permissible norms for electrical personnel. In places where rail-roads routes intersect with high voltage overhead power supply lines (OPL), interference of fields, generated by the traction network and OPL, occurs. This can lead to an increase in strengths and a complication of the EMF spatial structures [4].

In works [2, 15-20], a method was proposed for determining the fields of multi-wire systems, including traction net-works and power lines, based on preliminary calculation of the electrical network operating mode, which may contain mul-ti-wire lines, single-phase and three-phase transformers of various types, traction AC networks and moving traction loads. Fazonord software application [15] designed in Irkutsk State Transport university, combines possibilities for modes simulation in phase coordinates and simultaneous calculations of EMF strengths.

This article is a further development of ideas represented in work [16], which performs a detailed analysis of electro-magnetic field structure at a point of overhead power line and a railroad perpendicular intersection.

2 Simulation methods

Fazonord software application was used for simulating EMF strengths in points of traction networks and OPL intersection which was conducted in four stages:

1. The calculation of OPL traction networks in phase coordinates, the results of which were used to determine potentials and currents of all wires [15];
2. Calculation of vertical and horizontal components of electrical and magnetic fields of traction networks and OPL in their own coordinates.
3. Calculation of total EMF voltages components.
4. Calculation of strengths amplitude values $E_{\max}, H_{\max}$ with provision for possible fields elliptical polarization [2, 16].

3 Simulation results

The simulation was performed for a case of intersection of 1x25 and 2x25 kV traction networks with three-circuit 110–220 kV OPL. Spatial location of the conductive parts is shown in fig. 1. It was assumed that AC-300

* Corresponding author: dmitriy987@mail.ru

wires are mounted on OPL pylons. The diagram of OPL wires transposition is shown in fig. 2. The length of the transposed OPL divided into three sections is assumed to equal to 100 km. Loads on 220 kV circuits receiving end were equal to 20 + *j*10 MVA, circuits 110 kV - 6 + j3 MVA per phase. A power transit of 8 + *j*8 MVA was transmitted via the overhead catenaries of each 2 km long traction network. The calculation was carried out for the intersection of the traction network with the first segment of the transposed OPL.

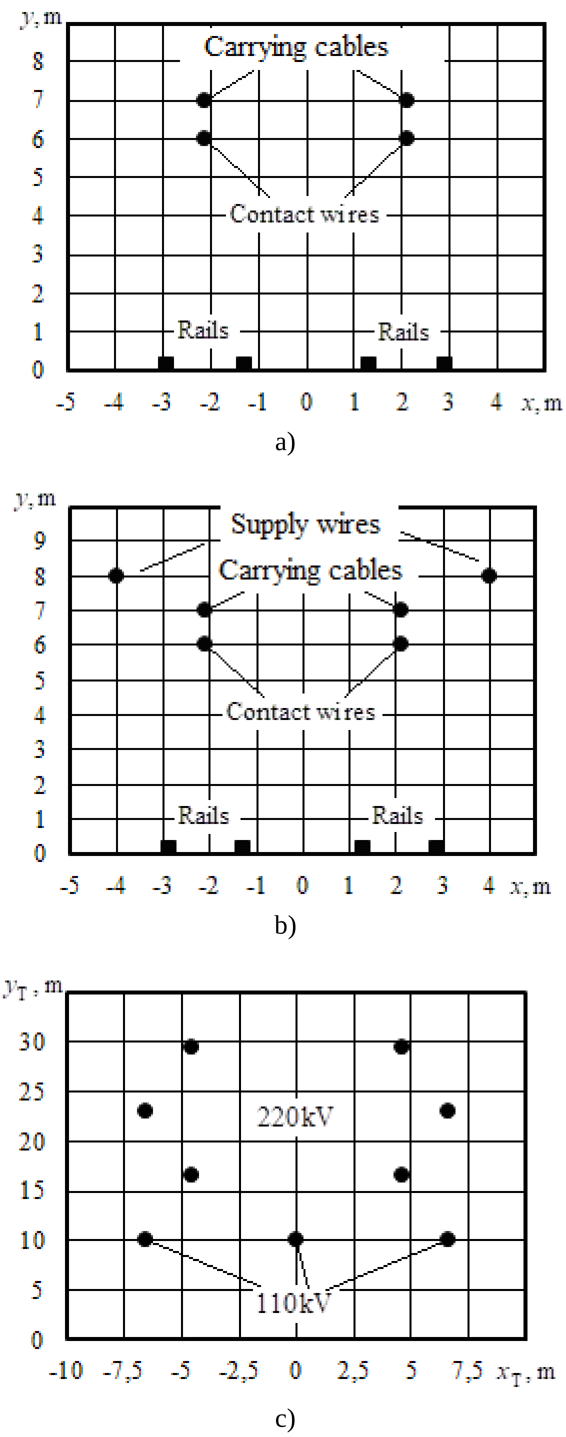


Fig. 1. Wires arrangement: a – 25 kV TN; b – 2x25 kV TN; c – three-circuit OPL

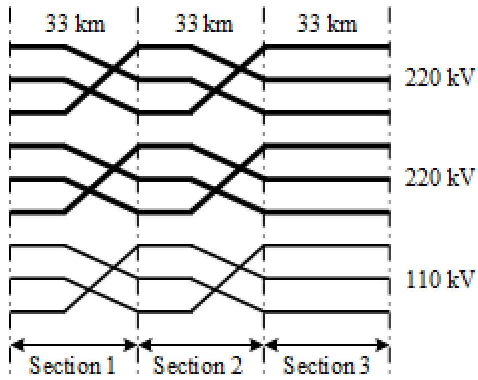


Fig. 2. OPL scheme of transposition

Table 1. Font styles for a reference to a journal article.

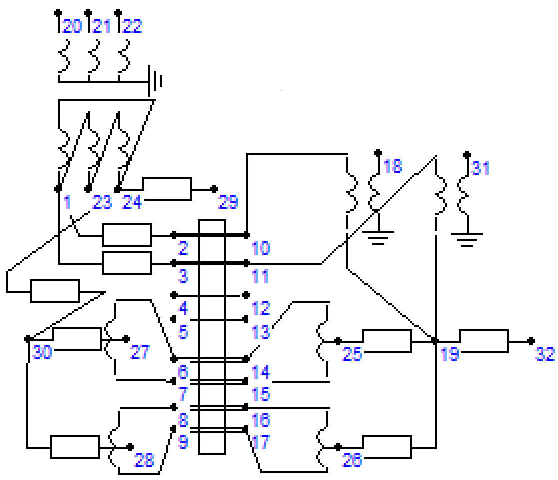
OPL	Phase	*U*, kV	*U*, degr.	*I*, A	*I*, degr.
Left 220 kV	A	133	0	160.6	–18.4
	B	133	–120	160.5	–138.3
	C	133	120	160.5	101.7
Right 220 kV	A	133	0	160.9	–18.6
	B	133	–120	160.9	–138.5
	C	133	120	160.9	101.5
110 kV	A	65	0	100.7	–21.1
	B	65	–120	100.6	–141
	C	65	120	100.6	99.2

Table 2. Voltages and currents of 1x25 kV traction network

Path	*U*, kV	*U*, degr.	*I*, A	*I*, degr.
1	25.6	–5.6	450	–51
2	25.6	–5.6	450	–51

Table 3. Voltages and currents of 2x25 kV traction network

Path	Place of measuring	*U*, kV	*U*, degr.	*I*, A	*I*, degr.
1	Overhead catenary	25.8	26.2	246.2	–21.2
2		25.8	26.2	246.2	–21.2
1	Power cord	26.5	–153.3	198.7	164.2
2		26.5	–153.3	198.7	164.2



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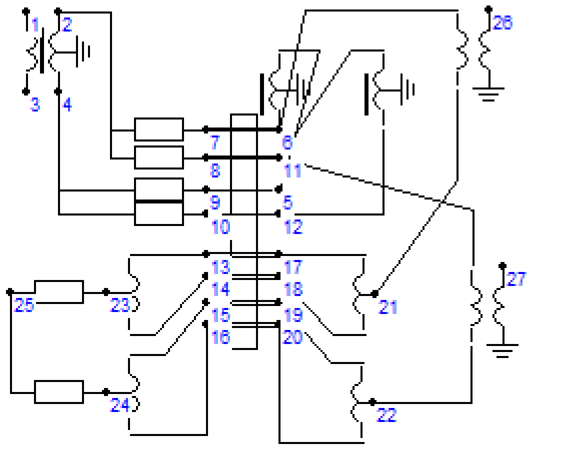

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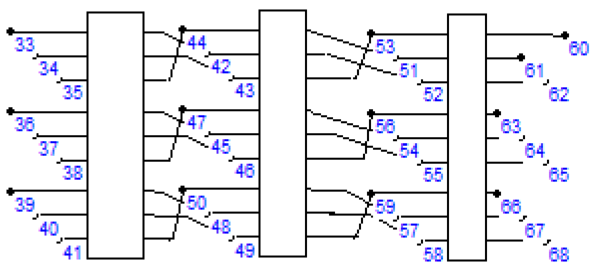
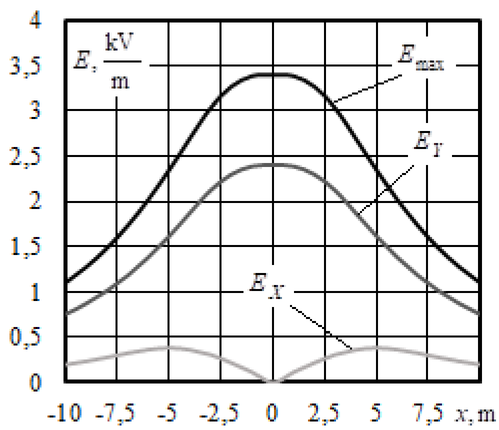


c)

Fig. 3. Fazonord PSW design models schemes: a – TC 1x25 kV; b – TC 2x25 kV; c – OPL 110-220 kV

Calculated electrical and magnetic fields strengths in their own coordinates of traction networks and OPL at a height of 1.8 m are provided in fig. 4–6.



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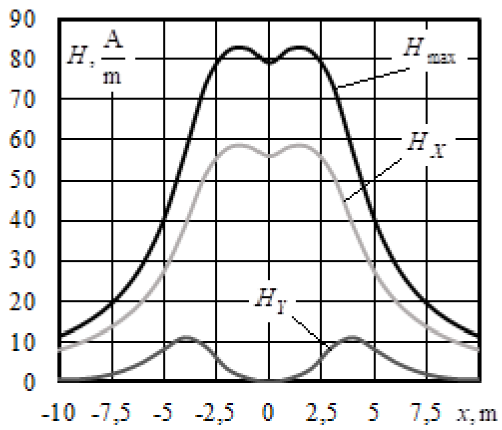

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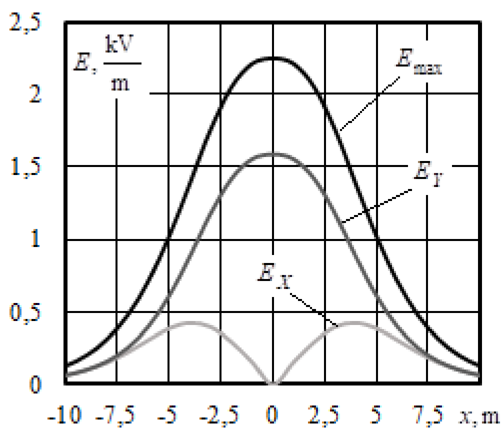
Fig. 4. Electrical (a) and magnetic field (b) strengths of 25 kV traction network at a height of 1,8 m.



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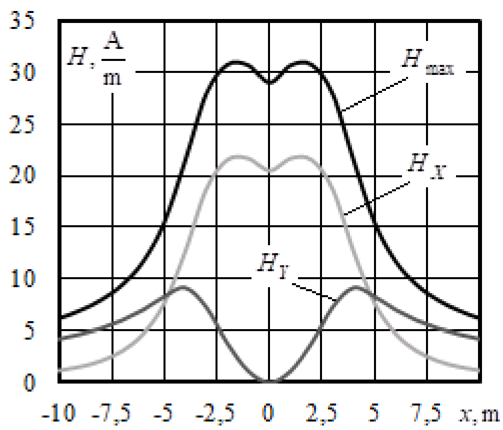

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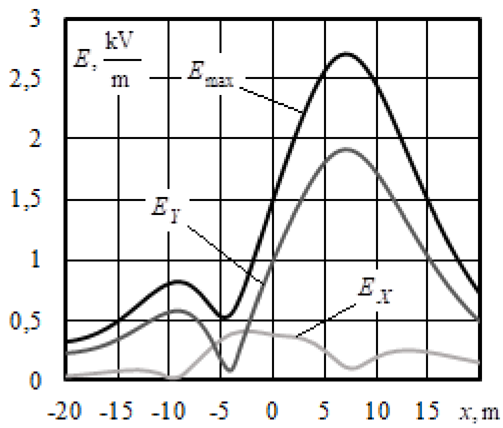
Fig. 5. Electrical (a) and magnetic field (b) strengths of 2x25 kV traction network at a height of 1,8 m.



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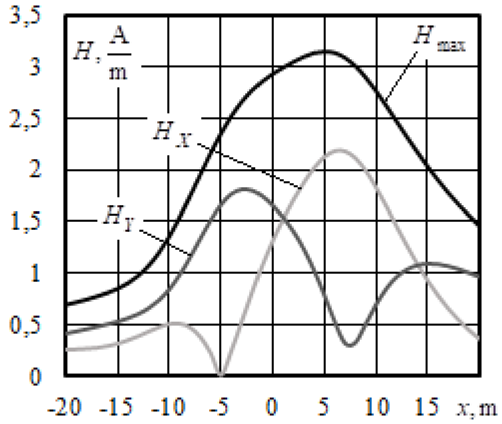
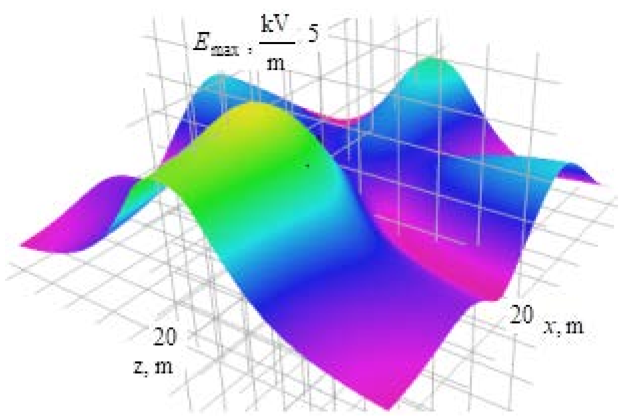


b)

Fig. 6. Electrical (a) and magnetic field (b) strengths of OPL at a height of 1,8 m.

Volumetric diagrams of the resultant strengths of electric and magnetic fields at the intersection of traction networks and OPL at a height of 1.8 m are shown in Fig. 7, 8. Figure 9 shows the hodographs of the resultant strengths vectors. Table 4 represents maximal values of electrical and magnetic fields strengths at intersection points.



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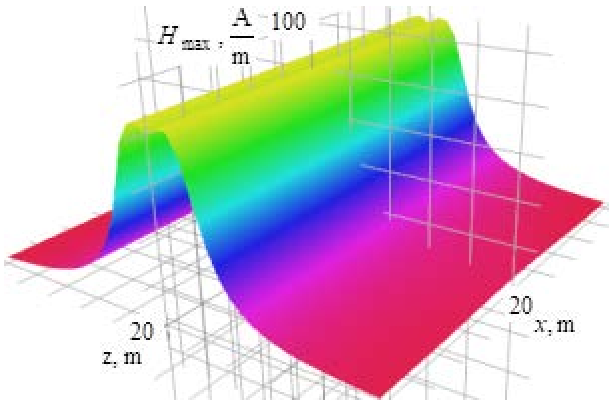
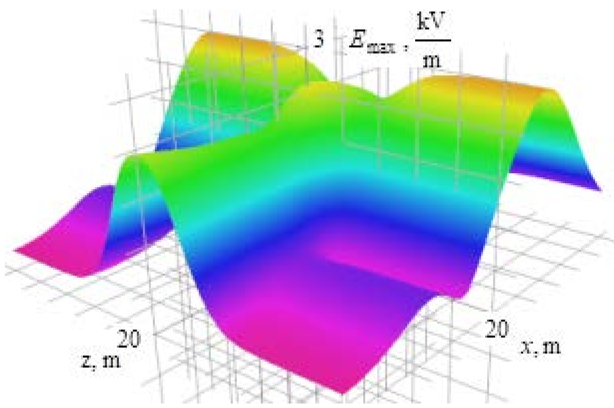


b)

Fig. 7. Amplitude values of EMF strengths at the point of 2x25 kV traction network OPL intersection: a – electrical field; b – magnetic field



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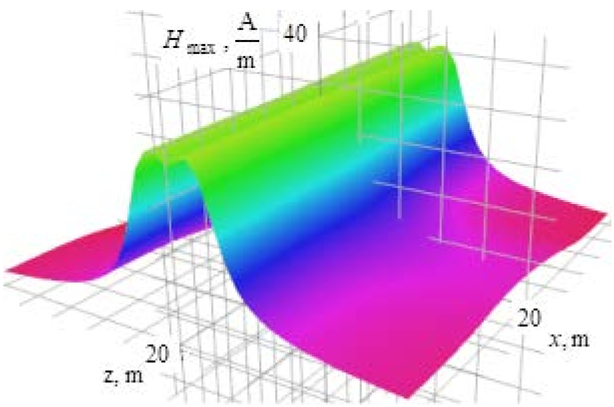
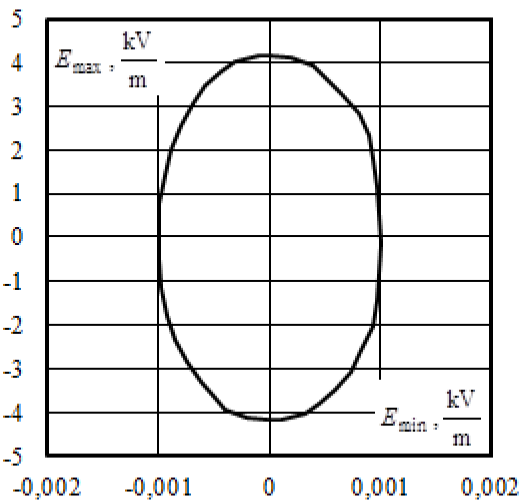


b)

Fig. 8. Amplitude values of magnetic field strengths at the point of 2x25 kV traction network and 220 kV OPL intersection: a – electrical field; b – magnetic field



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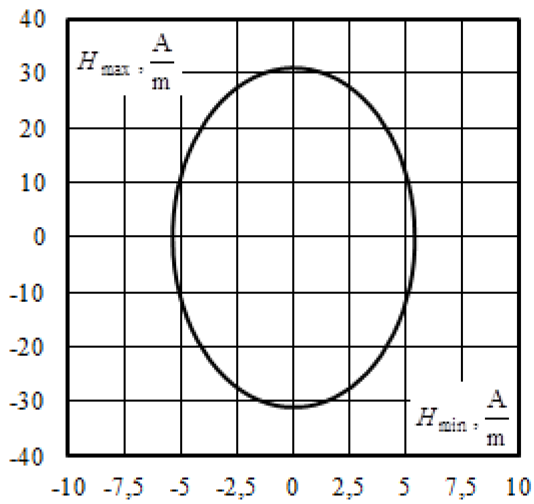

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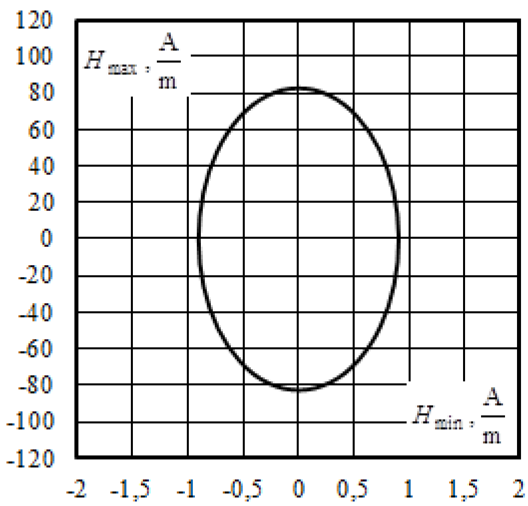

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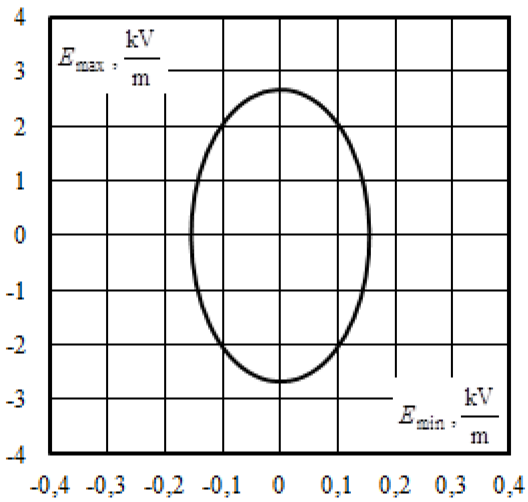

c)

Fig. 9. Hodographs of resultant vectors at points with maximal values of electrical (a, c) and magnetic (b, d) fields strengths for crossing TN 25 kV (a, b) and 2x25 kV (c, d) with OPL: a – point $x = 0$ m, $z = 9$ m; b – point $x = 1$ m, $z = 0$ m; c – point $x = –18$ m, z = –7 m;d – point $x = 2$ m, z = 3 m

Table 4. Maximum values of electrical and magnetic fields strengths

Parameter	TN 1x25 kV	TN 2x25 kV	Three-circuit 110-220 kV OPL	TN and OPL intersection		Difference, %	
				1x25 kV	2x25 kV	Between columns 2 and 5	Between columns 3 and 6
1	**2**	**3**	**4**	**5**	**6**	**8**	**9**
E_{max},. kV/m	3,4	2,3	2,7	4,2	2,7	19	15
H_{max}, A/m	83	31	3,1	83	31	0	0

4 Conclusion

Based on simulation results, the following conclusions can be made:

1. When separately modeling, the electric field strengths at a standard height of 1.8 m, do not exceed the permissible standards of 5 kV/m for electrical personnel both for traction networks and OPL. The magnetic field strength of 1x25 kV traction network exceeds the permissible value of 80 A/m. A similar parameter for the 2x25 kV traction network is reduced to 30 A/m, which is associated with the mutual compensation of the magnetic fields generated by overhead catenaries and power wires.

2. At the intersection points of 1x25 kV traction network with a 220 kV three-circuit OPL, the electrical field strength does not exceed the value permissible for electrical personnel and reaches 4.2 kV/m. When crossing a 2x25 kV traction network, this parameter is reduced to 2.7 kV/m.
3. The magnetic field strength at the intersection of power lines with 25 kV traction network reaches 83 A/m. For 2×25 kV TN, a similar parameter is reduced to 31 A/m.
4. At the intersection of 1x25 and 2x25 kV traction networks with OPL, the maximum amplitude of the magnetic field increases insignificantly.

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Methods of intelligent protection from asymmetrical conditions in electric networks

Guliyev H.B*[1], Tomin N.V.[1], Ibrahimov F.Sh[1].

[1]Azerbaijan Scientific-Research and Designed-Prospecting Institute of Energetics, "Azerenergy" JSC, Baku, Azerbaijan
[2]Melentiev Energy Systems Institute SB RAS, Irkutsk, Russia

Abstract. Possible cases of non-fulfilment of the requirements of the necessary sensitivity and the selectivity of the existing protection against incomplete-phase and asymmetric modes in the electrical network under conditions of uncertainty of the initial data are determined. The paper considers the issue of intellectualization of protection from asymmetric modes based on theories of fuzzy logic, as well as machine learning models, and offers a structural diagram and an algorithm for the functioning of protection. The results of the synthesis of intelligent protection and an approach to modelling and control for controlled drive systems based on reinforcement learning are presented.

1 Introduction

The system of three-phase voltages applied in the nodes of the electrical network with complex loads, including the stator windings of synchronous and asynchronous motors used in the auxiliary systems of power plants and substations, their symmetry is violated with an uneven distribution of single-phase loads between phases, as well as in emergency modes in electrical networks. As the boundary state of unbalance, it is possible to show out-of-phase modes due to voltage loss in one of the phases, for example, in the event of a break in one phase of the supply line, fuse blowing in one phase, etc. Because of these and other reasons, the likelihood of the occurrence of incomplete-phase modes at the nodes of the complex load is significantly high and amounts to 40% of all emergency shutdowns of elements of distribution electrical networks (DN) [1].

Research has shown that with a voltage unbalance ratio of 4%, the service life of three-phase asynchronous motors is halved in comparison with the service life in symmetrical mode, and with a current unbalance ratio of 10% or more, the insulation service life of power transformers decreases by 16%. Certain parts of violations occur due to unbalanced currents, which, in addition to the above, are the cause of other undesirable negative effects, such as the occurrence of harmonics of currents and voltages, distortion of current curves, changes in power factor, etc. [2].

The results of scientific research on the analysis of the operation of a node with an asynchronous load [3], carried out when one phase is broken, suggests that, depending on the degree of asymmetry, under conditions of uncertainty in the initial data, non-selective operation of existing protection and false actions of automation are possible. Therefore, to improve the reliability of protection in conditions of asymmetry of currents and voltages, the development of appropriate technical means or measures is a necessary and urgent issue.

In DC distribution grids, distributed generation control issues are greatly simplified. For example, in wind generators with variable rotation speed, for operation on a DC voltage network, the converter can be simplified by reducing its weight and dimensions. But, in practical applications, the motor often shall run at different velocities and, thus, the input voltage is not constant. To achieve variable input voltages, a power electronic converter is used in between the electric motor and the DC link (i.e. the supply voltage which could be a battery or a rectified grid supply). At the same time, voltage is supplied to the motor from the inverter, which is regulated both in magnitude and in frequency. The inverter is powered either through a rectifier from an AC voltage or directly from a DC voltage.

Modern drives also provide smooth start-up with reduced starting currents, which greatly facilitates the operation of the supply network in comparison with traditional starting schemes for asynchronous electric motors. At the same time, in asymmetric modes, for example, in case of failure of one of the phases in the power channel of the electric drive, the problem arises of ensuring the constancy of the electromagnetic torque, in particular for controlled systems based on a permanent magnet synchronous motor (PMSM) [4]. In this case, an effective solution can be the use of an autonomous bridge voltage inverter, which will allow the currents of the remaining phases to be formed so that the electromagnetic torque of the motor is stable. In such a setting, the development of optimal control strategies for voltage converters for controlled drive systems in normal and emergency modes can, among other things, be

* Corresponding author: huseyngulu@mail.ru

considered as a variant of protection against asymmetric modes.

The paper deals with the creation and implementation of intelligent protection against asymmetric modes operating on the basis of fuzzy sets and fuzzy logic, as well as machine learning models.

2 Fuzzy-based intelligent protection from asymmetric modes

2.1 Block diagram

The device proposed in [3] in its technical essence is an automated system for protection of detection and protection against partial-phase modes in DN, based on the use of digital filters of direct and negative sequence. Devices, which include a supply and an intersection switch, digital filters of current direct and negative sequence, an analog-to-digital converter, a microprocessor and an executive body, in the event of incomplete-phase modes, disconnects the supply and at the same time turns on the intersection switch, which ensures the normal full-phase mode of consumers.

Insufficient reliability and low sensitivity of protection of the motor load against phase failure, as well as overloads from reverse sequence currents, is a disadvantage of this system. These disadvantages are eliminated when a fuzzy controller (FC) is included in the protection device, which, as you know, consists of a fuzzifier, a decision-making mechanism and defuzzifier. The FC output is connected to the input of the executive body.

Figure 1 shows a block diagram of the proposed device for protection against an asymmetric mode based on FC. The intelligent system with FC consists of the following elements: current transformers 1-4; current sensors 5-10; analog-to-digital converter - 14; switch - 15; calculation block ratio of positive and negative sequence currents -16; fuzzy controller -17; fuzzifier - 18; decision-making mechanism -19; defuzzifier -20; executive body -21.

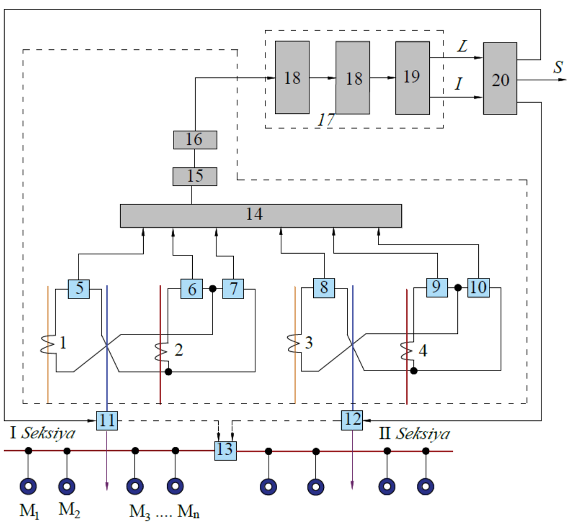


Fig. 1. The system of intelligent protection from modes against asymmetrical conditions in DN

2.2 Main parameters

The problem of the synthesis of intelligent protection against asymmetric mode in Matlab using modeling using the Fuzzy Logic Toolbox [5-8] is considered. The output linguistic variable is "Asymmetry" and the linguistic output parameters are "Delay" and "Control". The obtained membership functions (MF) of the terms of the linguistic variables input and output of the FC as a result of modeling are shown in Fig. 2 and Fig. 3.

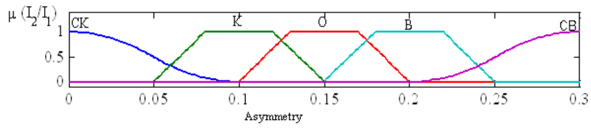


Fig. 2. Graphical representation of the FP terms of the input linguistic variable - "Asymmetry"

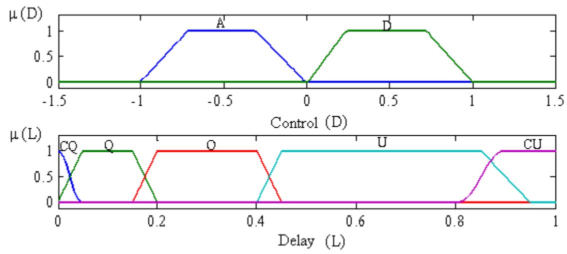


Fig. 3. Graphical representation of MF terms of output linguistic variables - "Control" and "Delay"

In Fig. 4 shows a block diagram of the FC synthesized on the basis of simulation modeling. As can be seen, to ensure the operation of FC with one input and two outputs according to the Mamdani algorithm, a logical inference mechanism with fuzzy rules is obtained. This mechanism is structured as follows. Using a simple fuzzy linguistic model, it is possible to synthesize an FC with one input and two outputs

$$\text{IF } X = A_i, \text{ THEN } Y = B_j \text{ AND } \quad Z = C_k \qquad (1)$$
$$i = \overline{1,n}, j = \overline{1,m}, k = \overline{1,l}$$

where X, Y are state variables, respectively, Z is a control parameter; A, B, and C - linguistic values (terms) of variables X, Y and $\underline{Z}$ on universal sets E_1, E_2 and E_3, that is $\forall x\ A \in E_1$, $\forall y\ B \in E_2$ and $\forall z\ C \in E_3$.

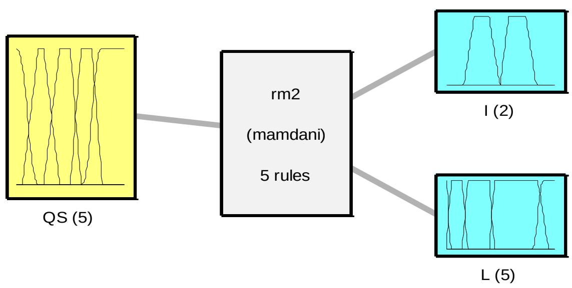


Fig. 4. Structural diagram of AC

In accordance with the above, the FC functioning algorithm is expressed as follows:

$$
\begin{aligned}
&IF \quad X = A_1 \quad THEN \quad Y = B_1 \quad AND \quad Z = C_1 \\
&ELSE \\
&IF \quad X = A_2 \quad THEN \quad Y = B_2 \quad AND \quad Z = C_2 \\
&ELSE \\
&IF \quad X = A_3 \quad THEN \quad Y = B_3 \quad AND \quad Z = C_3 \\
&ELSE \\
&IF \quad X = A_4 \quad THEN \quad Y = B_4 \quad AND \quad Z = C_4 \\
&ELSE \\
&IF \quad X = A_5 \quad THEN \quad Y = B_5 \quad AND \quad Z = C_5
\end{aligned}
\tag{2}
$$

The term-subsets of the linguistic variable "Asymmetry" is described as $T_i(QS)$, where $QS_i \in E_{1i}$ c $i = \overline{1,5}$:

$$
\begin{array}{lll}
E_{11} = SB & \text{(Very big)} & \underline{\Delta}(QS, \mu_{11}(QS)) \\
E_{12} = B & \text{(Big)} & \underline{\Delta}(QS, \mu_{12}(QS)) \\
E_{13} = M & \text{(Medium)} & \underline{\Delta}(QS, \mu_{13}(QS)) \\
E_{14} = S & \text{(Low)} & \underline{\Delta}(QS, \mu_{14}(QS)) \\
E_{15} = N & \text{(Natural)} & \underline{\Delta}(QS, \mu_{15}(QS))
\end{array}
\tag{3}
$$

The term-subsets of the linguistic variable "Delay" is described as $T_j(L)$, where $L_j \in E_{2j}$ and $j = \overline{1,5}$:

$$
\begin{array}{lll}
E_{21} = Max & \text{(Maximum)} & \underline{\Delta}(L, \mu_{21}(L)) \\
E_{22} = B & \text{(Big)} & \underline{\Delta}(L, \mu_{22}(L)) \\
E_{23} = M & \text{(Medium)} & \underline{\Delta}(L, \mu_{23}(L)) \\
E_{24} = S & \text{(Low)} & \underline{\Delta}(L, \mu_{24}(L)) \\
E_{25} = Z & \text{(Very low)} & \underline{\Delta}(L, \mu_{25}(L))
\end{array}
\tag{4}
$$

The term-subsets of the linguistic variable "Control" is described as $T_k(D)$, where $D_k \in E_{3k}$ and $k = \overline{1,2}$:

$$
\begin{array}{lll}
E_{31} = AC & \text{(Stop)} & \underline{\Delta}(D, \mu_{31}(D)) \\
E_{32} = QC & \text{(Open)} & \underline{\Delta}(D, \mu_{32}(D))
\end{array}
\tag{5}
$$

where $\mu_{1i}(QS)$, $\mu_{2j}(L)$, $\mu_{3k}(D)$ – respectively, the MF of term-subsets of linguistic variables QS, L, and D, which are defined in the unversimums E_{1i}, E_{2j} and E_{3k}.

Table 1 shows the forms and parameters of the terms of linguistic variables. As can be seen from (2), the fuzzy linguistic model consists of five simple implications and the general fuzzy relationship *R* can be defined by combining the fuzzy relations

$$
R = \bigcup_{i=\overline{1,5}} R_i = \bigcup_{i=\overline{1,5}} E_{1i} \times E_{2i} \tag{6}
$$

In this case *R*, the FP of fuzzy relations is determined as follows:

$$
\mu_R(QS, D, L) = \max \begin{cases} \min\left[\mu_{E_{11}}(QS), \mu_{E_{21}}(L), \mu_{E_{31...2}}(D)\right], \min\left[\mu_{E_{12}}(QS), \mu_{E_{22}}(L), \right. \\ \left. \mu_{E_{31...2}}(D)\right], \ldots, \min\left[\mu_{E_{15}}(QS), \mu_{E_{25}}(L), \mu_{E_{31...2}}(D)\right] \end{cases} \tag{7}
$$

For defuzzification, you can apply the centroid method [4-7]:

$$
z_0 = \frac{\int_\Omega z \mu_\Sigma(z) dz}{\int_\Omega \mu_\Sigma(z) dz} \tag{8}
$$

where n-the number of output quantization level.

Table 1. Terms, MF and parameters of input and output linguistic variables

Terms	MF	Parameters
Asymmetry, K_I		
Very low	Z - shaped	[0 0,02]
Low	Trapezoidal	[0,05 0,2 0,25 0,4]
Medium	Trapezoidal	[0,25 0,4 0,5 0,6]
Big	Trapezoidal	[0,5 0,6 0,7 0,8]
Very big	S - shaped	[0,7 1]
Control, I		
Stop	Trapezoidal	[-1,006 -0,7164 -0,3066 -0,0064]
Open	Trapezoidal	[0,0086 0,2376 0,7196 1,0026]
Delay, L		
Zero	Z - shaped	[0 0,05]
Low	Trapezoidal	[0 0,05 0,15 0,2]
Medium	Trapezoidal	[0,15 0,2 0,4 0,45]
Big	Trapezoidal	[0,4 0,45 0,85 0,95]
Maximum	S - shaped	[0,8 0,9]

2.2 Simulation results

On the basis of the above algorithm, computer modeling calculations of the proposed intelligent protection against asymmetric mode based on FC have been carried out. For this purpose, a Simuling-model of protection is built and is shown in Fig. 5, which consists of an FC (rm), an executive body (subsystem) and recording measuring devices. In Fig. 6 shows a fragment of the FC decision-making procedure. On this fragment, a decision is made ($I = 0{,}00555$) disconnecting the circuit with a time delay $L = 0{,}226$ sec in accordance with the asymmetry values $K_I = I_2/I_1 = 0{,}175$.

The input fuzzy parameter "Asymmetry" is expressed as , and the numerical values are obtained using the simulation of the Monte Karlo method and are graphically presented in Fig.7. As can be seen from Fig. 7, a, the value of the variable changes in the interval . In this case, the obtained values for the variable "Delay" using the Simuling-model are generated on the interval . For various values of "Asymmetry", the diagram of the protection system is shown in Fig. 7, b. As you can see from these figure, the FC does not make any decisions with the aim of disconnecting the circuit to an unbalance value of 0,2. But when the unbalance value exceeds 0.2, the FC generates a control signal to turn off the circuit with a delay of 2 seconds.

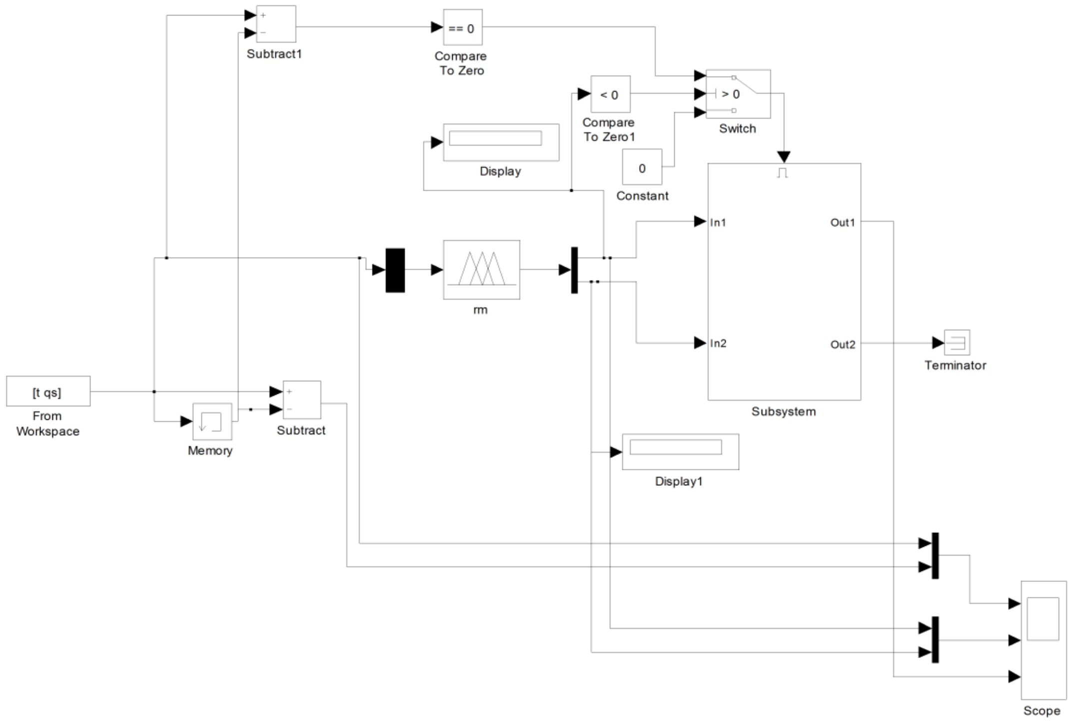


Fig. 5. Simulation Simulink-model of intelligent protection

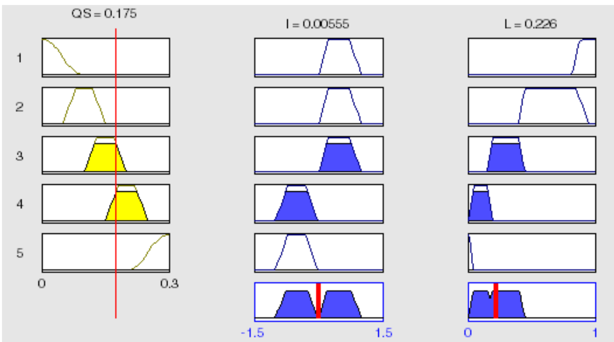
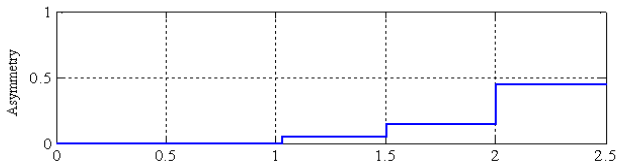
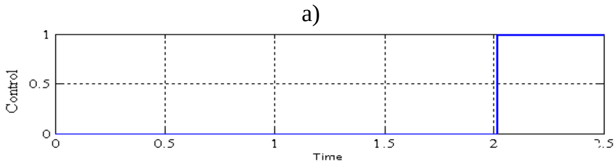


Fig. 6. Fragment of decision making



a)



b)

Fig. 7. Meaning of "Asymmetry" and "Control" in time: a - for "Asymmetry"; b - for "Control"

For another case, the diagram of the system is shown in Fig. 8. As can be seen for different levels of asymmetry, the NC makes a similar decision.

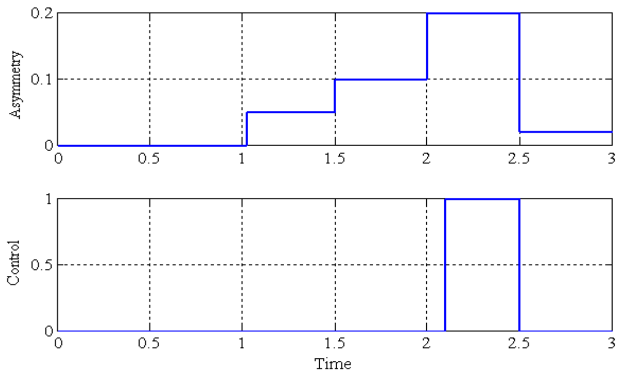


Fig. 8. Operation diagram of the FC

As a result of the calculations, fuzzy dependences $L=\tilde{f}(K_I)$ and $I=\tilde{\varphi}(K_I)$ were obtained. Fig. 9 shows the dependencies of the change $L=\tilde{f}(K_I)$ for creating a delay during the protection operation. As you can see, when the asymmetry value is set $QS=0\div0{,}05$, the "Delay" variable takes on the value $L=0{,}25\div0{,}9$ sec, when it turns $QS=0{,}25\div0{,}3$ out, and when practically the protection is triggered instantly $(L=0)$.

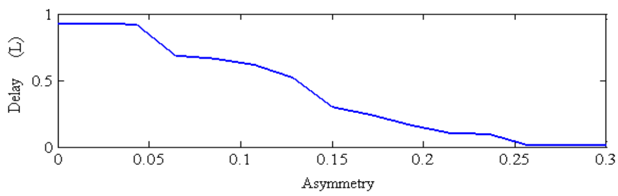


Fig. 9. Fuzzy dependence $L=\tilde{f}(K_I)$

Fig. 10 shows the dependence that expresses the dependence $I = \tilde{\varphi}(K_I)$ of the "Direction" on the degree of asymmetry. As you can see, with the value $QS = 0 \div 0{,}15$ of "Asymmetry" the protection does not work, with $QS = 0{,}15 \div 0{,}22$ FC it delays the operation of the protection with a time delay $L = 0{,}1 \div 0{,}3\sec$, and with $QS = 0{,}22 \div 0{,}3$ FC it generates a control action to disconnect the circuit and is triggered almost instantly.

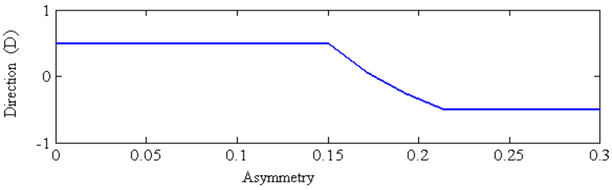


Fig. 10. Fuzzy dependence $I = \tilde{f}(K_I)$

Fig. 11 shows the steps of changing the variables "Control" (I) and "Delay" (L), as well as a diagram of smart protection operation, with random changes in the values of "Asymmetry" obtained with Monte Carlo simulation. As can be seen from the figure, in accordance with the value of the input variable "Asymmetry" ($K_I = I_2/I_1$), the FC makes an adequate decision and instantly or with a time delay generates a control signal for actuating the executive body or blocks it.

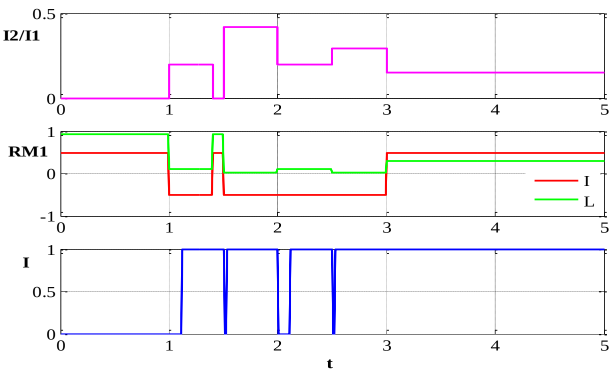


Fig. 11. Diagrams of decision making and triggering of FC protection

3 Reinforcement learning-based controller to protect and control synchronous motor

3.1 Technical background

Some asymmetric conditions, caused phase imbalances, phase rotation faults and open phasing, are associated with AC motors. But if a DC motor is powered by a DC converter, this controller protects the motor from these conditions. However, these converters present an enhanced fault tolerance capability, but an open-circuit fault can leads to ripple beyond load requirements. Поэтому разработка новых средств моделирования и управления DC converters позволяет фактически реализовать эффективную защиту и надёжную работу DC motors. The paper also is shown the example of using an intelligent controller example based on the deep deterministic policy gradient algorithm (DDPG), which controls a three-phase permanent magnet synchronous motor (PMSM) is presented and compared to a cascaded PI-controller as a baseline for future research [9]. The circuit diagram of the phases for PMSM is similar to each other and the armature circuit of the externally excited motor (Figure 12) [10].

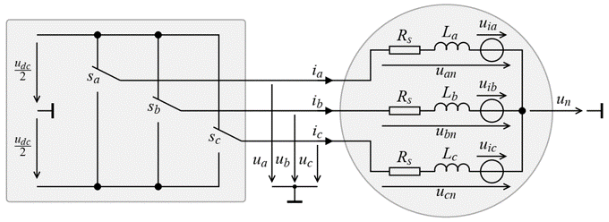


Fig. 11. The circuit diagram of the phases for PMSM

In practical applications, power electronic converters are used in between the motor and a DC link to provide a variable input voltage. Various converters provide different output voltage and current ranges, which affect the control behavior, which can include in the simulation as well as a mechanical load model. Usually, the motor often shall run at different velocities and, thus, the input voltage is not constant. Typical controllers provide either a desired output voltage or a duty cycle in a normalized form. This continuous value needs to be mapped to a switching pattern over time.

A novel approach is to use reinforcement learning (RL) to have an agent learn electric drive control from scratch merely by interacting with a suitable control environment. The controller acts as DDPG-agent and an environment includes the motor model and the reference trajectories. The DDPG-agent receives a reward depending on how close the motor is following its reference trajectory. We used RL-based motor environment, developed in [9], which simulate combinations of converter, electric motor and load, depicted in Fig. 12.

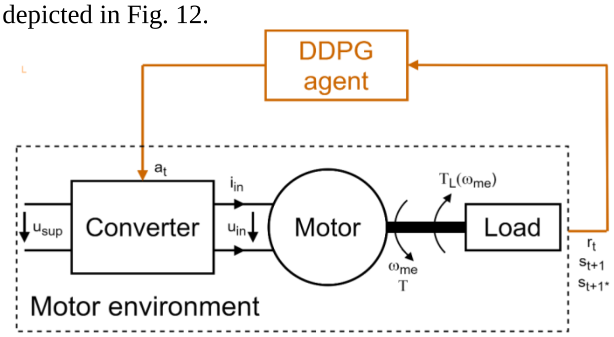


Fig. 12. Scheme of converter, motor, load and control flow from an action to a new observation

The control action at is converted to an input voltage u_{in} of the motor. Then, the next state s_{t+1} is calculated using an ODE solver, according ODE system for PMSM (eq.9).

$$\begin{pmatrix} \frac{di_{sd}}{dt} \\ \frac{di_{sq}}{dt} \\ \frac{d\omega_{me}}{dt} \\ \frac{d\varepsilon_{me}}{dt} \end{pmatrix} = \begin{pmatrix} \frac{1}{L_d}(u_{sd} - R_s i_{sd} + L_q \omega_{me} p i_{sq} \\ \frac{1}{L_q}(u_{sd} - R_s i_{sq} - \omega_{me} p(L_d i_{sd} + \psi_p)) \\ \frac{1}{J}(T - T_l(\omega_{me})) \\ \omega_{me} \end{pmatrix} \quad (9)$$

where i_{sd}, i_{sq} and u_{sd}, u_{sq} are d-axis and q-axis currents/voltages for rotor fixed coordinates d and q;$T$is torque produced by the motor; T_l is torque from the load; ψ_p is permanent linked rotor flux; $J$is moment of inertia; $R_s$is stator resistance; $L_q, L_d$are d-axis and a-axis inductance;ε_{me} is the mechanical angle. A PMSM may have more than one pole pair, thus$p > 1$. In this case the electrical angular velocity $\omega$is$\omega = p\omega_{me}$.

This solver uses the motors differential equations including the load torque (eq.10).

$$T_l(\omega_{me}) = sign(\omega_{me})(c\omega_{me}^2 + sign(\omega_{me})b\omega_{me} + a) \quad (10)$$

with a constant load torque a, viscous friction coefficient b and aerodynamic load torque coefficient c. These parameters as well as a moment of inertia of the load J_{load} can be freely defined by the user to simulate different loads.

Afterwards, the reward r_{t+1} is calculated based on the current state and current referencess_{t+1} *. If a state exceeds the specified safety limits, the limit observer stops the episode and the lowest possible reward is returned to the agent to punish the limit violation.

4.2 Limit observation and motor damage protection

The typical operation range of electric motors is limited by the nominal values of each variable. However, the technical limits of the electric motor are larger. Those limits must not be exceeded to prevent motor damage, which might be inflicted due to excessive heat generation. Motors are stopped if limits are violated in real applications, including in the event of dangerous situations due to asymmetric modes in the converter. For safety agent training, we can specify the nominal values and safety margin ξ

$$x_{limit} = \xi x_N \quad (11)$$

An important task for the control is to hold those limits. Consequently, learning episodes will be terminated if limits are violated as in real applications, and a penalty term can be chosen that is affecting the final reward to account for those cases.

4.2 Test example

In this example, we used the proposed approach to train a DDPG-agent using the open-source Python package [10]. The agent learns to control the current of a PMSM with a continuous action space. Motor and load parameters are compiled in Tab. 2.

Table 1. Example's motor and load parameter

Variable	Value
Stator Resistance, R_s in Ohm	4.9
d-axis inductanceL_d in Henry	0.079
q-axis inductanceL_q in Henry	0.113
Moment of inertia of the rotor, J	0.00245
Permanent linked rotor flux, ψ_p	0.165
Pole pair Number, p	2

The reward function is the shifted weighted sum of absolute error with reward weight 1 on the current i and 0 otherwise. The training consists of 75000 simulation steps partitioned in episodes of length 1000.

$$r_t = 1 - \sum_{k=0}^{N} \omega_{\{k\}} \left| s_{\{k\}t} - s_{\{k\}t}^* \right| \quad (12)$$

The testing process is depicted in Fig. 13. At the beginning, the MAE is 229.15 and decreases to 83.04 at 75 000 steps. The control behavior during the training and afterwards is visualized in Fig. 1. The agent does perform well. This shows that the RL control approach for electric motors reaches control quality similar to a state-of-the-art controller, and that RL is a highly promising approach for electric motor control. The control quality of the DDPG-agent might be improved with an optimization of the DDPG-parameters and architecture in future research.

4 Conclusions

1. An analysis of the existing protection and developments against asymmetric and incomplete-phase modes was carried out and it was determined that with the uncertainty of the initial information, depending on the degree of asymmetry, the requirement of selectivity and sensitivity is not met. To reduce failures and increase the reliability of protection, a new protection method based on the theory of fuzzy logic is proposed.
2. A block diagram and an algorithm for triggering intelligent protection against asymmetric conditions based on fuzzy controller with one input and two output parameters are proposed. The terms, types and parameters of their membership functions are determined.
3. The results of fuzzy controller synthesis are presented and the results of the calculated implementation of the protection actuation algorithm are obtained. The obtained results of computational experiments show that with a change in asymmetry in the interval 0-1.0, the selectivity and reliability of protection against asymmetric modes are fully ensured.
4. An approach to modeling and control for controlled drive systems with PMSM based on RL is proposed, which allows finding optimal policies for controlling voltage DC converters in normal and emergency conditions. The resulting learning models can be considered as a option of protection against asymmetric conditions arising in a DC converter.

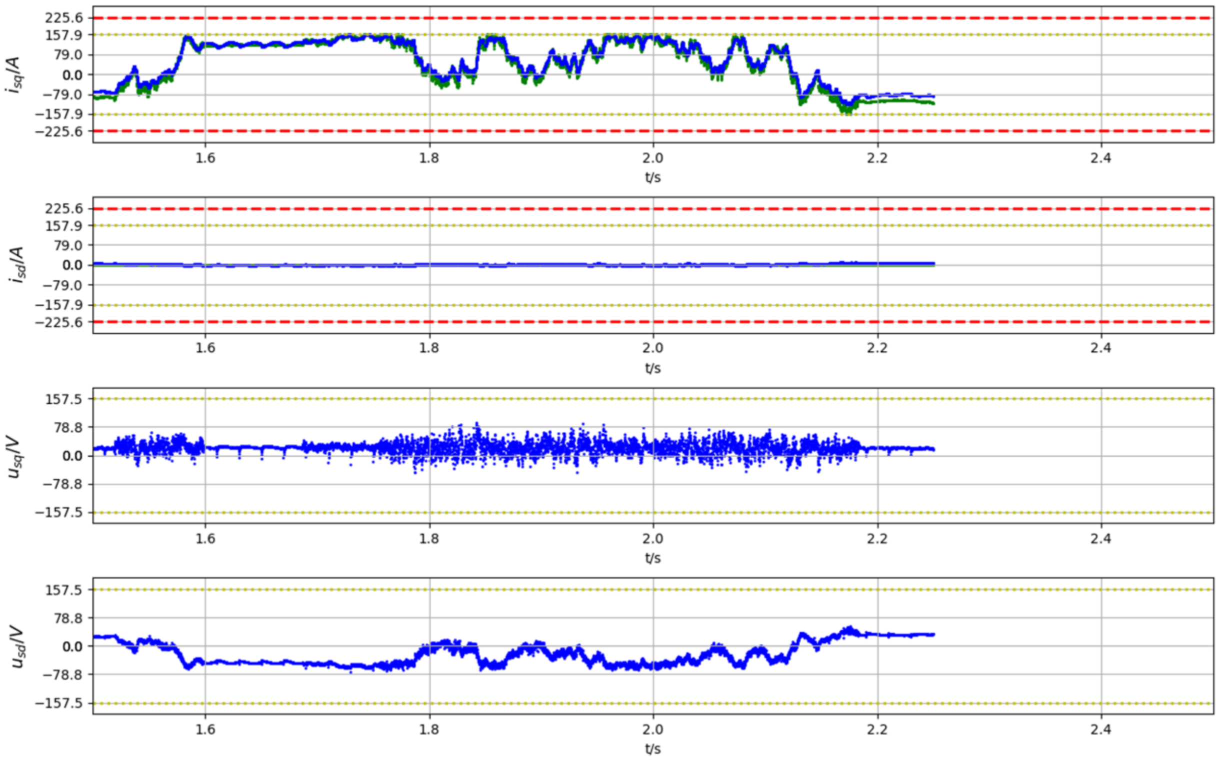


Fig.13. Trajectories of learned RL-agent and (blue) and current reference (green).
The nominal values (dotted-yellow) and limits (dashed-red) aredrawn.

Acknowledgment

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Development of an Adaptive Module for Control of Energy Supply of the Consumer in the Distributive Electrical Network 0,4 kV for Elimination of the Phase Load Unsymmetry

Yu.A. Klimenko[1,*], A.P. Preobrazhensky [1]

[1] Voronezh Institute of High Technologies »ANOO VO, Voronezh, Russia

Annotation. The paper considers the possibility of modeling the process of controlling the power supply of the consumer in the lower levels of network organizations to improve the quality indicators of electrical energy in the distribution electrical networks of 0.4 kV. The analysis of the process of control of indicators of the quality of electricity in the supply of energy to consumers. The block diagram of the adaptive power supply control module of the consumer and the algorithm of the control process are presented. A consumer power supply control module in 0.4 kV distribution networks is proposed.

Introduction

Improving production efficiency depends on the supply of energy resources to consumers in accordance with the requirements of the Laws of the Russian Federation [1], GOST [2,3], industry and other regulatory documents [4,5]. New scientific developments in this field of energy should be aimed at improving the network economy of energy suppliers [6,7], modernizing the technological equipment of electricity consumers [8,9].

The purpose of this work is to develop a model of the consumer's power supply control process in the adaptive system [10] of the power quality control and management complex [11,12] in the 10 / 0.4 kV power distribution network [13,14] and to solve the optimization problem [15] of the control technological process quality of electrical energy (EE) [16,17] by developing an algorithm for monitoring and control.

1 Adaptive control system.

An adaptive control system to eliminate the asymmetry of the phase load will be used in the concept of creating a complex for monitoring and managing the quality of the EE of a section of a 10 / 0.4 kV electrical distribution network (Fig. 1). The control complex for the section of the distribution network for monitoring and managing the quality of energy efficiency is a symbiosis of electrical and telecommunication networks, technological equipment, software and consists of a central management complex (CMC), control measuring complexes of 10 kV (CMC-10 kV) and 0.4 kV (CMC-0.4 kV), remote measuring points (RMP), adaptive power supply control modules of consumers (CAM) (Fig. 1).
The result of the use of the adaptive control system is the uniform distribution of the single-phase load over the phases of the three-phase network, increasing the energy characteristics of the network.
A diagram of a section of a 10 / 0.4 kV electrical distribution network using an adaptive control system is shown in Fig. 2.

The control system includes a CMC -0.4 kV, a RMP, CAM. CMC are located at 10 / 0.4 kV substations.

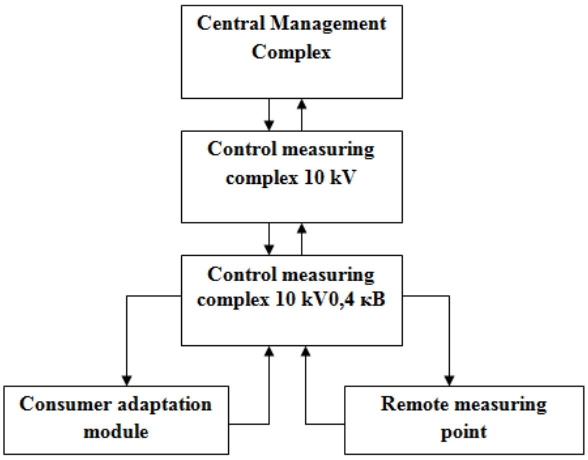

Fig. 1. Scheme of the complex for monitoring and managing the quality of electricity in the 10 / 0.4 kV electrical distribution network section.

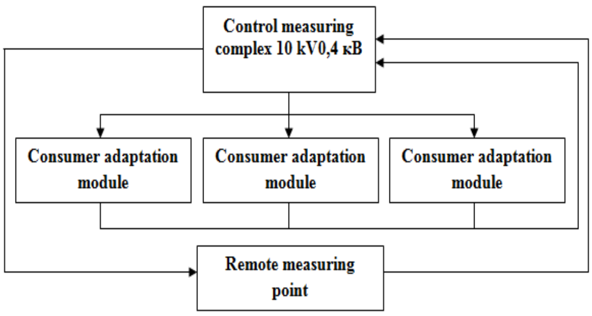

Fig. 2. Diagram of an adaptive control system for eliminating phase asymmetry of a 10 / 0.4 kV electrical distribution network section.

RMP is located on the end supports of the overhead line-0.4 kV. CMC, RMP and CAM perform the following main functions: monitoring EE parameters; collection, processing, transmission of data to the CMC.

* Corresponding author: klm71165@mail.ru

2 Adaptive power supply control module

The 0.22 kV consumer power management adaptation module (CAM) is part of an adaptive control system for eliminating the load asymmetry of the phases of the 0.4 kV power grid [18], which will be used in the concept of creating a complex for monitoring and controlling the quality of electric power in the 10/0 distribution network section , 4 kV. CAM is intended for uniform distribution of a single-phase load over the phases of a 0.4 kV three-phase network. AM contains input terminals L1, L2, L3, N for connecting the mains and output terminals L and N for connecting the load, and also includes a measuring device (MD), a device for selecting phases (switch) (PSD), a device control and data transmission (CDTD), communication device (CD) (Fig. 3).

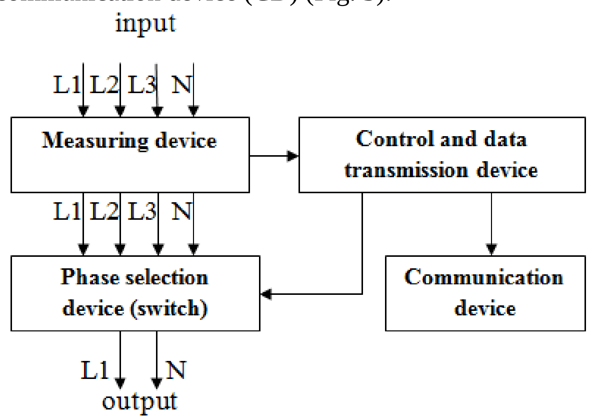

Fig. 3 Consumer power management adaptation module.

The task of the CAM device is to achieve balancing of phase currents (loads) of a three-phase distribution network of 0.4 kV, reducing the volume and cost of hardware, ensuring the realization of the goal of balancing phase currents (loads).

This CAM works as follows. Power supply to each consumer is carried out through the CAM, which is installed on the support of the power transmission line at the point of connection of the branch of the overhead line (OHL) of 0.4 kV. Power is supplied to the CAM input contacts in phases. The measuring device (MD) determines the magnitude of the parameters of the power grid for each of the phases: voltage, current load, power factor, electric power consumption of electricity (full, active, reactive) and others. The MD sends data on the state of the power grid to the CDTD for data analysis. The CDTD of each CAM transmits data on the state of the electric network at each specific point of the 0.4 kV overhead line through the CD to the measuring control complex to process the measurement data and decide on switching certain consumers to balance the loads along the phases of the power line, as well as sends control commands to a specific CAM for switching and load balancing. CDTD processes the received information, makes a decision and sends a command to the PSD to switch a certain consumer to a phase that meets the specified requirements. Having received a command, the PSD switches the consumer's power supply to a predetermined phase and reports information on the switching performance to the control unit and the control unit.

The implementation of this device eliminates the use of additional hardware for regulating the asymmetry of the phase parameters of the 0.4 kV network.

3 Algorithm of the consumer energy supply control process

The block diagram of the algorithm of the process of managing the power supply of the electricity consumer to eliminate the phase voltage asymmetry and phase voltage deviations is shown in Fig. 4. The description of the operation of the algorithm is presented point by point.

1. Beginning of the algorithm.
2. Entering the technical characteristics of the power transmission line (PTL). The following technical characteristics are introduced: the total length of the power lines , the number of power line wires , the cross-sectional area of the power line wires , the distance from the starting point of the power line to the point of connection of each AM to the power line , the specific resistance of the power line conductors, maximum transmission capacity of power transmission lines , maximum power of electrical equipment of consumers connected to power lines.
3. Enter restriction parameters for the network. It is necessary to introduce the following basic restrictions: the tolerance for the maximum permissible deviations of the voltage value is not more than ± 10% of the nominal voltage , the tolerance for the value of the voltage unbalance factor between the phases of a three-phase four-wire electrical network is not more than ± 4% of the nominal voltage , tolerance to exceed the amount of power consumed by the consumer's electrical equipment relative to the declared maximum power determined by the terms of the power supply agreement.

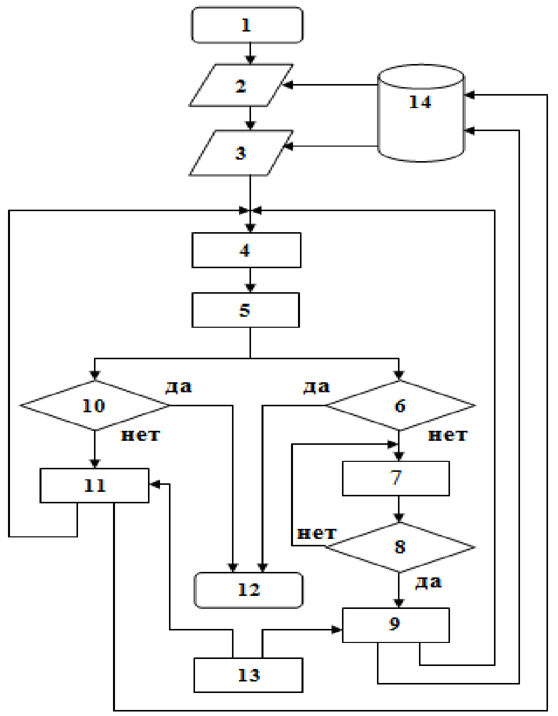

Fig. 4 Algorithm of the process of energy management of the consumer.

4. Measurement of the electrical parameters of the network at the points of CAM connection to the power transmission line. To calculate the symmetry of electrical loads and voltages in phases of a three-phase electrical network, the following parameters are recorded: electric current flowing in the circuit I, electric voltage U , active power factor , reactive power factor, electric active power P, electric reactive power Q.

5. Calculation and analysis of asymmetry of phase voltages and values of maximum deviations of phase voltages and values of power consumption. This is necessary to determine the configuration of the distribution of the connection of CAM consumers in the phases of power lines. The values of phase voltages should be equal to each other, i.e. it is necessary to fulfill the relation

$$U_1 = U_2 = U_3 \quad , \qquad (1)$$

where, U1, U2, U3 - electric voltages of phases L1, L2, L3 respectively.

The deviation of the voltage levels of the phases of the three-phase four-wire electrical network should be no more than ± 10% according to paragraph "3" of the algorithm:

$$U_{MIN} < U_i < U_{MAX} \quad , \qquad (2)$$

where, U_i - is the voltage value of phase *i;* U_{MIN} , U_{MAX} - minimum and maximum voltage values.

Next, we check the ratios of the phase voltage deviations among themselves:

$$|U_1 - U_2| < \Delta\,?;|U_2 - U_3| < \Delta\,?;|U_3 - U_1| < \Delta\,? \quad (3)$$

If relation (3) is not satisfied, then the transition to step "6" of the algorithm occurs. To determine the correspondence between the consumed and allowed capacities, the average active power consumed by the electrical equipment at the point of connection of the consumer CAM to the power transmission line is calculated:

$$P_{потреб} = U_i \cdot I_i \cdot cos\varphi_i \quad , \qquad (4)$$

where, $P_{потреб}$ - active power consumption; U_i , I_i , $cos\varphi_i$ - network parameters of the i phase.

The condition for matching the capacities is checked when moving to paragraph "10" of the algorithm.

6. The choice of the algorithm action based on the analysis of the asymmetry of the mains phase voltages and the maximum deviations of the mains phase voltages. If the voltages U1, U2, U3 have equal values in phases L1, L2, L3 of the network according to the tolerance requirement for voltage unbalance and maximum voltage deviations specified in paragraph "3" and the condition:

$$(|U_1 - U_2| < \Delta) \land (|U_2 - U_3| < \Delta) \land (|U_3 - U_1| < \Delta) \qquad (5)$$

then, no actions are taken to switch the load on the phases of the power transmission line and the transition to point "12" "End of the algorithm" is performed. If the voltages U1, U2, U3 have unequal values in phases L1, L2, L3 of the network in accordance with the tolerance requirement for voltage unbalance and maximum voltage deviations specified in paragraph "3" and condition (2) and (5) is not met, then actions are taken to switch the consumer load to the power transmission line phase, which meets the requirements specified in paragraph "3" and proceeds to paragraph "7" of the algorithm.

7. Determination of the configuration of the optimal connection of the consumer's CAM to the phases of the transmission line. The voltage regulation method can be carried out by distributing the power of consumers over the phases of the network to equalize the voltage level and switching the load of the consumer to the phase of the network, which meets the requirements of relation (5).

8. Decision-making on the distribution of the connection of CAM consumers taking into account the indicators of electric voltage at the points of connection to the power transmission line. the decision is made on the basis of determining the most optimal variant of the distribution of CAM consumers by phases.

9. Automatic switching of CAM consumers to selected network phases. Switching selected CAM consumers to other phases of power lines is carried out in compliance with relation (2).

10. The choice of the algorithm based on an analysis of the comparison of power consumption with the allowed (declared). If the condition for limiting the permitted power for the consumer is met and the power consumed by the electrical equipment does not exceed or equal to the allowed:

$$P_{потреб} \leq P_{разреш} \qquad (6)$$

then, you go to "12" "End of algorithm". If the condition for limiting the permitted power for the consumer is not met and the power consumed by the electrical equipment exceeds the permitted:

$$P_{потреб} > P_{разреш} \qquad (7)$$

then proceeds to step "11".

11. Temporary limitation of the consumption of electrical energy through the consumer's CAM. At present, exceeding the maximum power is a violation of consumer obligations under an electricity supply agreement, for which a restriction on the consumption regime is introduced [14].

12. End of the algorithm execution.

13. Controlling influence of the adaptive control system. An adaptive system for controlling electrical loads as part of a control measuring complex and an adaptive module for controlling energy supply of a consumer eliminates uneven distribution of electrical loads in phases, asymmetry of currents and phase voltages for monitoring and controlling the quality of electricity in a section of a distribution electrical network.

14. Database for receiving, storing transmission of information.

4 Results of modeling the operation of the algorithm of the consumer's power supply control process

The adaptive power supply control module of the consumer, using the operation of the control process algorithm, analyzes the parameters of the network phases according to the magnitude of the voltage level [18,19]. When the voltages U1, U2, U3 have equal values in phases L1, L2, L3 of the network according to the tolerance requirement meets the specified limitation conditions, the action of the algorithm is performed to move from point "6" to point "12" of the algorithm and the optimization process is not performed. If the voltage value exceeds the limits of the limits, a transition is made to point "7" of the algorithm, then the optimization process is performed on the choice of the electric phase for powering electrical appliances, which corresponds to the specified conditions of the limits [20] .

Let us consider an example of calculating the problem of optimizing the operation of an adaptation module using linear programming when the voltage in the supply phase of the network drops below a given level under the conditions of restrictions.

Let the consumer's electrical equipment through the adaptation module be powered from phase A of the electrical network. The voltage values of the phases of the network L1, L2, L3 are 190 V, 200 V, 230 V, respectively. The voltage value of phase A is lower than the level specified by the condition-limitation of item "3" and the conditions (2) and (5) of the algorithm are not met.

Let us solve this problem using the dual simplex - the method [21] of linear programming using a simplex table.

The objective function is as follows:

$$F(X) = 190x_1+220x_2+230x_3 \quad (8)$$

Let us determine the minimum value of the objective function under the following constraint conditions:

$$190x_1+220x_2+230x_3 \le 242 \quad (9)$$
$$-190x_1-220x_2-230x_3 \le -198 \quad (10)$$

To construct the first reference plan, the system of inequalities is reduced to a system of equations by introducing additional variables [22]. We introduce the basic variables X4, X5.

The coefficient matrix A = a (ij) of this system of equations has the form:

$$A = \begin{pmatrix} 190 & 220 & 230 & 1 & 0 \\ -190 & -220 & -230 & 0 & 1 \end{pmatrix}$$

Let's solve the system of equations for the basic variables: X4, X5.

The initial version of the simplex table is shown in able 1.

Table 1

Basis	B	x_1	x_2	x_3	x_4	x_5
x_4	242	190	220	230	1	0
x_5	-198	-190	-220	-230	0	1
F(X0)	0	-190	-220	-230	0	0

After performing the transformations, the simplex table acquires the final version (table 2).

The optimal plan can be written as follows:

$$x_1 = 0,\ x_2 = 0,\ x_3 = {}^{99}/_{115} \quad (11)$$
$$F(X) = 190*0 + 220*0 + 230*{}^{99}/_{115} = 198 \quad (12)$$

Table 2

Basis	B	x_1	x_2	x_3	x_4	x_5
x_4	44	0	0	0	1	1
x_3	$^{99}/_{115}$	$^{19}/_{23}$	$^{22}/_{23}$	1	0	$^{-1}/_{230}$
F(X1)	198	0	0	0	0	-1

The optimal plan can be written as follows:

$$x_1 = 0,\ x_2 = 0,\ x_3 = {}^{99}/_{115} \quad (11)$$
$$F(X) = 190*0 + 220*0 + 230*{}^{99}/_{115} = 198 \quad (12)$$

We will also determine the maximum value of the objective function (8) under the above conditions-constraints (9).

The initial version of the simplex table is shown in Table 1. After performing the transformations, the simplex table acquires the final version (Table 3).

Table 3

Basis	B	x_1	x_2	x_3	x_4	x_5
x_5	44	0	0	0	1	1
x_3	$^{121}/_{115}$	$^{19}/_{23}$	$^{22}/_{23}$	1	$^{1}/_{230}$	0
F(X2)	242	0	0	0	1	0

The optimal plan can be written as follows:

$$x_1 = 0,\ x_2 = 0,\ x_3 = 1{}^{6}/_{115} \quad (13)$$
$$F(X) = 190*0 + 220*0 + 230*1{}^{6}/_{115} = 242 \quad (14)$$

We see that the condition for limiting the voltage value in phase A of 198 V was not met. To fulfill this condition, it is necessary for CAM to switch the power supply to phase B or C, which satisfy the condition for limiting the voltage value in the range of variation of the objective function from 198 V to 242 V according to expressions (12), (14). That is, as a result of solving the optimization problem, the control process is carried out for the selection of the supply phase for the power supply of the consumer.

Conclusion

The presented article discusses the issues of modeling the process of managing the energy supply of the consumer. As a result, a structural diagram of the adaptive module for controlling the consumer's power supply, an algorithm for the process of controlling electrical loads in a three-phase 0.4 kV electrical distribution network was developed. Also, a study was carried out to simulate the operation of the algorithm for the control process of electrical loads based on the use of the dual simplex method of linear programming. As a result, simulation modeling of the state of the network and the operation of the algorithm for changing the configuration of the consumer's connection was carried out to achieve a uniform distribution of power over the phases of the network and the magnitude of permissible voltage deviations.

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Resonance Modes at Harmonics Frequencies in Electrical Networks

Lidiia I. Kovernikova[1,*]

[1] Melentiev Energy Systems Institute SB RAS, Irkutsk, Russian Federation

Abstract. Resonance modes at harmonic frequencies in electrical networks are a serious problem. They arise due to the availability of electrical equipment with capacitive and inductive elements. The values of the harmonics of currents and voltages increase at resonances. The voltage quality indices in resonant modes exceed the limit values. Harmonics cause energy losses in electrical equipment, reduce its service life, create economic damage. Capacitor banks are often damaged by resonances. Network nodes with resonant circuits and resonant harmonics can be determined using the frequency characteristics of the nodal reactance (susceptance). The paper presents an algorithm and HARMONICS software for the analysis and forecasting of resonance modes, the results of studies of resonance modes in the high-voltage networks of Eastern Siberia.

1 Introduction

Resonance modes at harmonics frequencies in power grids have been [1-5] and remain a big challenge [6-10]. They occur due to availability of equipment with capacitance and reactive elements [11, 12]. The hazard of resonance modes lies in the fact that if a non-sinusoidal current with harmonic components multiple to the main frequency (harmonics) and/or non-multiple to the main frequency (interharmonics) on which the resonance circuit occurred, runs in the grid, then current and voltage surge may occur at those harmonics. Current and voltage harmonics cause additional power losses in the electric equipment; they damage it, reduce its service life and thus cause economic losses. To avoid negative consequences of resonance modes, standardization documents provide for the occurrence of resonances.

"Guidelines for monitoring and analyzing the power quality in public power supply system" [4] that were in force in Russia in 2002-2008 stated that "non-sinusoidal nature of voltage in the point of common connection (PCC) may be caused both by distorting utilities of consumers connected directly to PCC and by equipment of power supply companies operating in the modes favoring the occurrence of non-sinusoidal nature of their volt-ampere characteristics or occurrence of resonance modes". In 2003 in the Project Technological rules for the wholesale electricity market [5] it was noted that "network companies during their operation are responsible for network modes unfavorable or hazardous for equipment and consumers (resonance modes...)". In 2019 a document "Unified technical policy in the power grid complex of Rosseti" [13] mentioned that "Usage of a capacitor is allowed subject to avoidance of resonance phenomena in all the operating conditions of a network". It was also noted that "when selecting the power factor correction unit (PFCU) containing capacitor banks (CB) for the network section where frequent distortions of current and voltage curves occur, PFCU shall be checked (CB in particular) for possible overloading by harmonic currents".

The paper offers an algorithm for determination of resonance nodes, harmonics and interharmonics on the base of analysis of the results of calculations made using HARMONICS software. HARMONICS software was developed in ESI SB RAS [14]. The analysis allows identification of network sections and harmonics with the presence of resonance modes or modes close to them. The paper presents the results of studies on the resonance modes in the high-voltage networks in the East Siberia. An algorithm and HARMONICS software can be used for forecasting the resonance modes for power quality control in the course of networks operation.

2 An algorithm for analysis of resonance modes

Theoretical foundations of electric power engineering [11] state that two types of resonance modes may occur in the electrical circuit: series resonance, i.e., voltage resonance, and parallel resonance, i.e., current resonance.

Voltage resonance occurs in case of series connection of resistance, inductive reactance and capacitive reactance. Circuit reactance at resonance equals zero. Circuit impedance is active and reaches its lowest value. Current and voltage at the circuit entry match in phase. Current has the highest value. If value of inductive and capacitive reactances exceeds that of resistance, then value of voltage on the capacitive and inductive reactances will exceed voltage at the circuit entry.

* Corresponding author: kovernikova@isem.irk.ru

Current resonance occurs at parallel connection of resistance, inductive and capacitive reactances. Circuit susceptance at resonance equals zero. Circuit admittance reaches its minimum value. Current and voltage in the unbranched part of the circuit match in phase. The value of current happens to be the lowest. Values of currents in parallel branches with inductive and capacitive reactances may exceed current in unbranched part of the circuit.

For analysis of the network modes at harmonic frequencies the electric network is represented by a current source and admittance relative to any node. Modes are calculated by solving the system of equations

$$\boldsymbol{U_h} = \boldsymbol{Z_h I_h}, \qquad (1)$$

where $\boldsymbol{h}$ - harmonic order; $\boldsymbol{U_h}$ - column matrix of nodal voltages of the h-th harmonic that are to be determined; $\boldsymbol{I_h}$ - column matrix of nodal currents of the h-th harmonic that are generated by non-linear loads; $\boldsymbol{Z_h}$ - matrix of self- and mutual impedances of the network nodes, which is obtained as result of inversion of the nodal admittance matrix $\boldsymbol{Y_h}$ [15].

Data of the system of equations (1) for analysis of resonance conditions in any node are used for computation of the following parameters: $K_{U(h)}$ - the h-th harmonic factor; I_h – current value of the h-th harmonic; $y_h = 1/z_h = 1/\sqrt{r_h^2 + x_h^2}$ – admittance of the network node; $g_h = r_h/\sqrt{r_h^2 + x_h^2}$ – conductance of the network node; $b_h = x_h/\sqrt{r_h^2 + x_h^2}$ – susceptance of the network node. $K_{U(h)95\%}$, $K_{U(h)100\%}$ are limit values of the index $K_{U(h)}$ used in the analysis for 95% and 100% of measurement time specified in [16]. Resonance harmonics can be adjusted by computing the frequency characteristics for y_h, g_h, and b_h. For a large-dimensionality network it is a sophisticated problem that requires account of a large number of network elements, significant time for calculating and analysis of frequency characteristics. Experience of studying the harmonics conditions allowed development of an algorithm for searching the resonance conditions on the base of the results of calculations using HARMONICS software that facilitates determination of nodes and harmonics with resonance modes. The modes are initially calculated for 3, 5, 7, 9, 11, 13, 17, 19, 23, and 25-th harmonics. Measured values of indexes $K_{U(h)}$ on the listed harmonics in the electric networks, as a rule, exceed the limit values specified in [16]. For adjusting the resonance harmonics the range of harmonics is then changed.

An algorithm for determination of resonance nodes and harmonics includes provisions listed further.

1) Computation of mode parameters and nodal parameters on harmonics 3, 5, 7, 9, 11, 13, 17, 19, 23, 25 for determination of values $K_{U(h)}$, I_h, y_h, g_h, and b_h.

2) Analysis of parameters as per Item 1) for the nodes where values $K_{U(h)}$ exceed the limit values $K_{U(h)95\%}$, $K_{U(h)100\%}$.

In the course of the analysis it should be kept in mind that index $K_{U(h)}$ exceeds the limit value not only in the resonance mode but at high value of current I_h in the node as well.

Since susceptance in the resonance mode equals zero, conductance and admittance are equal in value, then combinations of these values are searched for determination of nodes with resonance on the computed harmonics.

Nodes where modes are close to resonance conditions are also identified. Numerical values of conductance and admittance are rather close, whereas the value of susceptance is much lower than conductance and admittance.

For identification of resonance modes or modes close to them the signs of susceptance on the adjacent harmonics are analyzed. Change of the sign evidences availability of the resonance mode on the interval of harmonics. Susceptance sign of the node may change several times, which evidences availability of the resonance modes on several harmonics simultaneously.

As a result of Item 2) the nodes, harmonics or harmonics intervals are determined where resonance modes or modes close to them occur.

3) Analysis of parameters as per Item 1) for the nodes where values $K_{U(h)}$ do not exceed the limit values $K_{U(h)95\%}$, $K_{U(h)100\%}$.

For finding the resonance modes, the values of admittances are analyzed for searching the nodes and harmonics with low values of admittances. Susceptances are further analyzed in the nodes with low values of admittances for identification of the sign change.

As a result of Item 3) the nodes, harmonics or harmonic intervals are determined where resonance modes or modes close to them occur.

4) Determination of the number of the resonance harmonic or interharmonic on the interval of harmonics obtained in Items 2) and 3).

For identification of the number of a resonance harmonic the frequency characteristic of susceptance is computed from 50 Hz on the harmonics interval at a step of 0.5%. The frequency characteristic curve is constructed. The harmonic or interharmonic number at which the susceptance sign changes, i.e., resonance occurs, is determined using frequency characteristic.

For adjusting the number of a resonance harmonic the harmonic interval is reduced with account of the results of above calculations, and frequency characteristic is computed anew from the presumed resonance harmonic at a step of 0.2%. The obtained frequency characteristic of susceptance is used for adjusting the number of a resonance harmonic. If necessary, calculations are repeated at a lesser step.

5) Determination of resonance harmonics in the node at different changes in the network. Connection and disconnection of transmission lines, capacitors, passive

filters, and changing loads can lead to resonant modes. For assessing of occurrence of resonance modes in the node in case of changes in the network, Items 1) - 4) of the algorithm shall be fulfilled.

3 Results of the analysis of resonance modes in the networks of East Siberia

3.1 An example of using the algorithm for searching the resonance modes in one of the nodes of the calculated scheme

Analysis of the mode parameters when searching for the resonance modes in Node 2401 of the calculated network whose fragment is shown in Fig. 1 is given as an example.

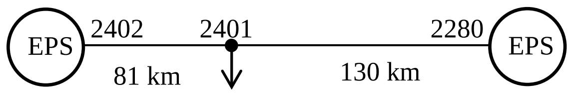

Fig. 1. Fragment of the calculated network with Node 2401.

Parameters as per Item 1) for the analyzed node are given in Table 1 and Table 2.

Table 1. Mode parameters of harmonics 3, 5, 7, 9, 11

Harmonic	3	5	7	9	11
I_h, A	21.35	10.70	7.30	2.78	7.39
y_h, p.u.	5.02	2.15	1.01	0.92	1.39
g_h, p.u.	0.69	0.37	0.76	0.76	1.22
b_h, p.u.	-4.97	-2.11	-0.67	-0.52	0.67
$K_{U(h)}$, %	0.98	1.15	**1.67**	**0.69**	**1.22**
$K_{U(h)95\%}$, %	1.5	1.5	1.0	0.4	1.0
$K_{U(h)100\%}$, %	2.25	2.25	1.5	0.6	1.5

Table 2. Mode parameters of harmonics 13, 17, 19, 23, 25

Harmonic	13	17	19	23	25
I_h, A	9.70	2.48	4.61	2.91	0.78
y_h, p.u.	1.29	3.19	4.76	2.88	1.4
g_h, p.u.	1.29	2.16	4.75	2.27	1.16
b_h, p.u.	-0.04	2.34	-0.16	-1.76	-0.78
$K_{U(h)}$, %	**1.72**	0.18	0.22	0.23	0.13
$K_{U(h)95\%}$, %	0.7	0.5	0.4	0.4	0.4
$K_{U(h)100\%}$, %	1.05	0.75	0.6	0.6	0.6

Index $K_{U(h)}$ exceed the limit values $K_{U(h)95\%}$ on the 7, 9, 11 and 13-th harmonics, and $K_{U(h)100\%}$ on the 7, 9 and 13-th harmonics (in bold).

Conductance and susceptance on the 7-th harmonic are close in value. Index $K_{U(7)}$ is high due to higher value of current on the 7-th harmonic. The value of all the conductances on the 9-th harmonic is of the same order, which evidences the lack of resonance in the vicinity of the 9-th harmonic. Susceptance on the interval of harmonics 9-11 changes from “minus” to “plus”, which evidences the resonance of voltages. Admittance and conductance on the 11-th harmonic are close in value, whereas susceptance is half the admittance and conductance. So far as the value of susceptance is of the same order as admittance, we can assume that there is no resonance in the vicinity of the 11-th harmonic, and $K_{U(11)}$ exceeds the limit value due to high value of current on the 11-th harmonic. For adjusting the number of a resonance harmonic the frequency characteristics of susceptance shall be used. On the interval of harmonics 11-13 the susceptance sign changes from “plus” to “minus”. Admittance and conductance on the 13-th harmonic are close in value, whereas susceptance is rather low as it has no impact on admittance. Thus, current resonance occurs on the interval of harmonics 11-13. For adjusting the number of resonance harmonic the frequency characteristic of susceptance shall be used. Susceptance sign on the interval of harmonics 13-17 changes from “minus” to “plus”, which evidences the presence of the resonance of voltages. Values of all the conductances on the 17-th harmonic are of the same order. Comparison of the values of susceptances on the 13-th and 17-th harmonics evidences the voltage resonance on the harmonic close to the 13-th harmonic. Susceptance on the interval of harmonics 17-19 changes from “plus” to “minus”, which evidences the resonance of currents. Admittance and conductance on the 19-th harmonic are close in value, whereas susceptance is rather low. We can conclude that current resonance occurred on the harmonic close to the 19-th harmonic.

Frequency characteristics of admittance, conductance and susceptance were computed on the harmonics intervals 3-25 using HARMONICS software. From Fig. 2 it follows that frequency characteristics of susceptance intersects abscissa four times changing the sign: between 9-th and 10-th harmonics; two times between 12-th and 13-th harmonics and between 18-th and 19-th harmonics, which evidences the occurrence of four resonances. Results of the analysis of frequency characteristics of susceptance are given in Table 3. They correspond to activated state of lines in Fig. 1.

Disturbances that may cause change in the number of resonances and resonance harmonics in Node 2401 include disconnections of transmission lines connected to Node 2401. Frequency characteristics of susceptances of Node 2401 of transmission lines in Fig. 3 are given for comparison. It is obvious that the number of resonances and numbers of resonance harmonics for each state of a transmission line are different.

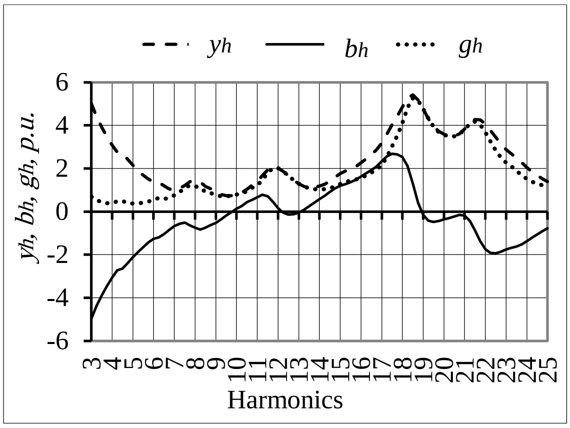

Fig. 2. Frequency characteristics of admittance, conductance and susceptance on the harmonics intervals 3-25.

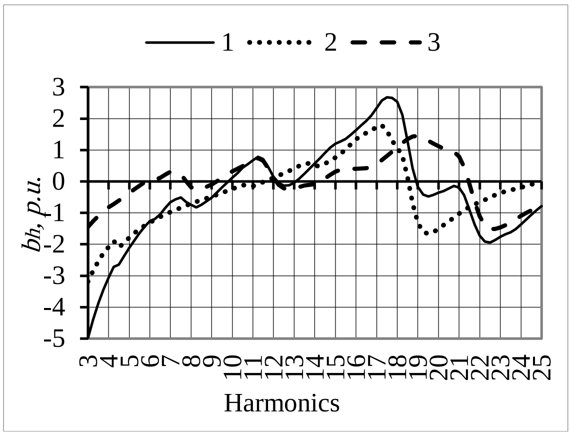

Fig. 3. Frequency characteristics of susceptance of Node 2401: 1 - two lines are turned on; 2 - line 2401–2402 is turned on, line 2401–2280 is turned off; 3 - line 2401–2402 is turned off, line 2401–2280 is turned on.

Table 3 gives intervals of harmonics where there is a resonance harmonic and the values of susceptances corresponding to the interval of resonance harmonics for three states of transmission lines.

Table 3. Results of analysis of frequency characteristics of susceptance

State of transmission lines	Interval resonant harmonics and interharmonic	Interval values b_h, p.u.
Both lines are turned on	9.75 – 10.00	(-0.03) – (0.13)
	12.00 – 12.25	(0.16) – (-0.05)
	13.00 – 13.25	(-0.04) – (0.09)
	18.75 – 19.00	(0.42) – (-0.16)
2401–2402 is turned on, 2401–2280 is turned off	11.50 – 11.75	(-0.02) – (0.05)
	18.50 – 18.75	(0.12) – (-0.72)
2401–2402 is turned off, 2401–2280 is turned on	5.75 – 6.00	(-0.03) – 0.06
	7.75 – 8.00	(0.02) – (-0.18)
	9.00 – 9.25	(-0.10) – (0.04)
	12.00 – 12.25	(0.11) – (-0.10)
	14.00 – 14.25	(-0.01) – (0.10)
	21.00 – 21.25	(0.44) – (-0.07)

3.2 Impact of a capacitor bank on occurrence of resonance conditions

Fig. 4 shows a fragment of the calculated network where a 50 MVAr capacitor bank owned by a power supply company is connected to Node 1980. Capacitor bank is activated for maintaining the voltage at the main frequency in conformity with requirements of standardizing documents. A traction substation is connected to Node 1981. Values $K_{U(3)}$ and $K_{U(5)}$ measured in three phases of Node 1981 before and after activating the capacitor bank are given in Figs. 5 and 6. Capacitor bank was activated after the 19-th minute. It is obvious those after activating the capacitor bank the values $K_{U(3)}$ and $K_{U(5)}$ increased. They exceeded the limit values specified in [16].

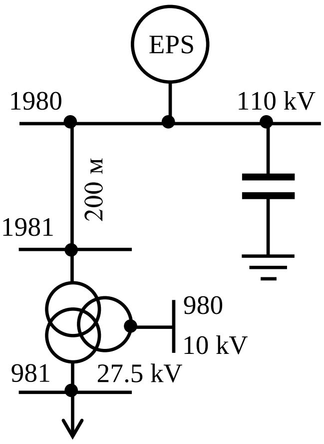

Fig. 4. Fragment of the calculated network with capacitor bank.

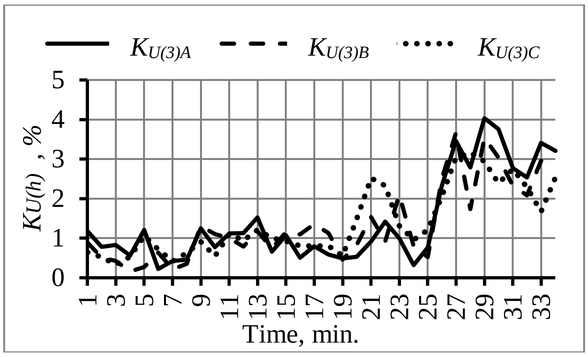

Fig. 5. $K_{U(3)}$ measured in three phases.

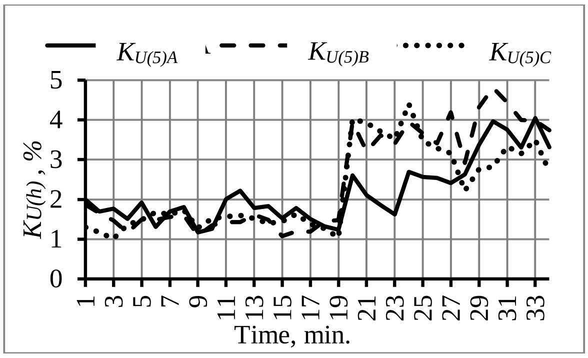

Fig. 6. $K_{U(5)}$ measured in three phases.

Values $K_{U(h)}$ for harmonics 7, 9, 11, 13, 17, 19, 23 and 25 are given in Figs. 7 and 8. After activating the capacitor bank the values of all the listed harmonics decreased. Their values are less than half of the limit ones.

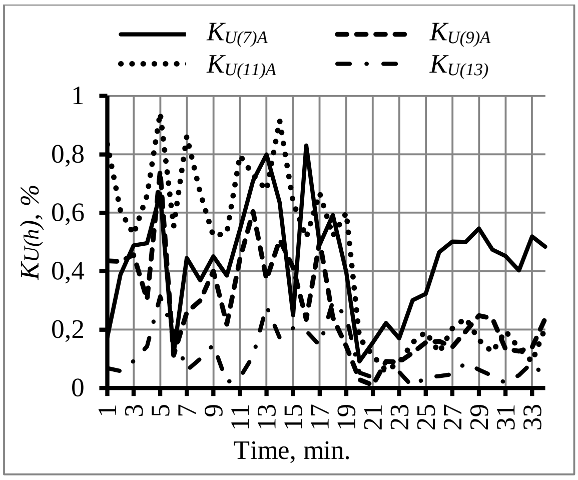

Fig. 7. $K_{U(7)}$, $K_{U(9)}$, $K_{U(11)}$, $K_{U(13)}$ measured in phase A.

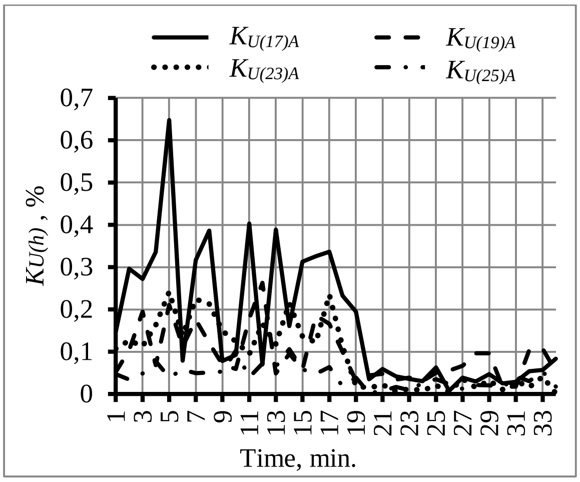

Fig. 8. $K_{U(17)}$, $K_{U(19)}$, $K_{U(23)}$, $K_{U(25)}$ measured in phase A.

For analysis of the impact of capacitor bank on the network mode at the harmonics frequencies, mode parameters in Node 1981 without a capacitor bank were calculated using HARMONICS software, and they were calculated after the bank activation. Results of calculations are given in Table 4.

Table 4. Parameters of the node and mode

Parameter	Harmonic	
	3	5
g_{hN}, S	0.0046	0.0092
g_{hCB}, S	0.0	0.0
g_{hN+CB}, S	0.0046	0.0092
b_{hN}, S	-0.0116	-0.0125
b_{hCB}, S	0.0076	0.0127
b_{hN+CB}, S	-0.0039	0.0003
y_{h+CB}, S	0.0060	0.0092
$K_{U(h)}$, %	1.14	**1.75**
$K_{U(h)CB}$, %	**2.36**	**2.96**

Notations in the Table: g_{hCB} – conductance of a capacitor bank; g_{hN} – conductance of a node; g_{hN+CB} – a sum of conductance of capacitor bank and of node; b_{hCB} – susceptance of capacitor bank; b_{hN} – susceptance of node; b_{hN+CB} – a sum of susceptance of capacitor bank and susceptance of node; y_{hN+CB} – admittance of a capacitor bank and node; $K_{U(h)}$ – value of the index before activation of a capacitor bank; $K_{U(h)CB}$ – value of the index after activation of a capacitor bank. Data in the table demonstrate that susceptance of the node before activation of a capacitor bank (b_{hN}) had a "minus" sign on the 3-rd and 5-th harmonics. After activation of a capacitor bank the susceptance (b_{hN+CB}) of the 5-th harmonics changed the sign to "plus". Change of susceptance sign evidences the voltage resonance on the interval of harmonics from 3-rd to 5-th. As a result, the values $K_{U(3)}$ and $K_{U(5)}$) increased and exceeded the limit values specified in [16]. .

3.3 Resonance modes in the 220 kV network

Fig. 9 shows a fragment of the calculated 220 kV network from Node 2012 to Node 2880. The distance between nodes is about 840 km. The 220 kV network powers more than 20 traction substations.

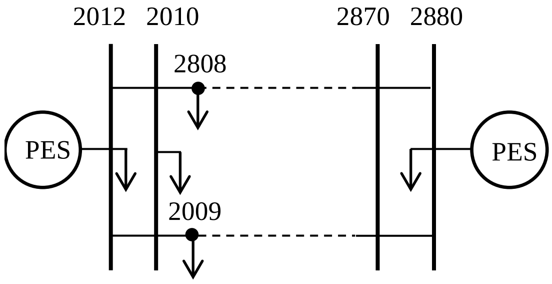

Fig. 9. Fragment of the calculated 220 kV.

Parameters of modes and nodes of the network for 3, 5, 7 and 11-th harmonics were calculated using HARMONICS software. Results of calculations are presented in the form of graphs in Figs. 10-13.

Fig. 10 shows computed parameters for the 3-rd harmonic.

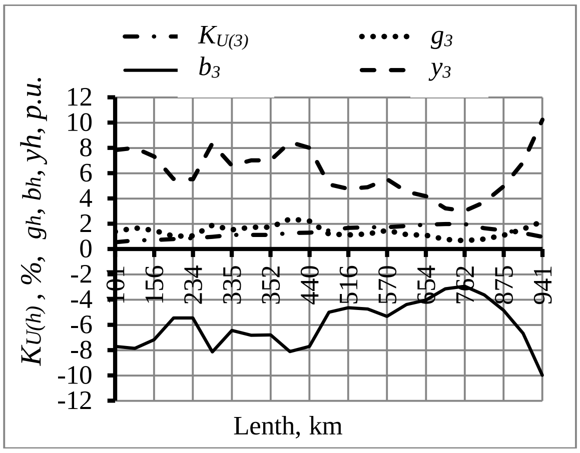

Fig. 10. Parameters of nodes and mode on the 3-rd harmonic.

The susceptance curve does not intersect the abscissa, which means that there are no resonances on the 3-rd harmonic. The value $K_{U(3)}$ increases with decrease of admittance.

On the 5-th harmonics (Fig. 11) the resonances occur at a distance of 400 - 700 km from Node 2012. Susceptance changes its sign four times. Two serial and two parallel resonances occur in the network. The value of susceptance in the neighbourhood of resonance harmonics reduces; values of admittance and conductance are also reduced and become close in value. Index $K_{U(5)}$ increases. In the vicinity of resonances it reaches its maximum that exceeds the limit value $K_{U(5)95\%}$.

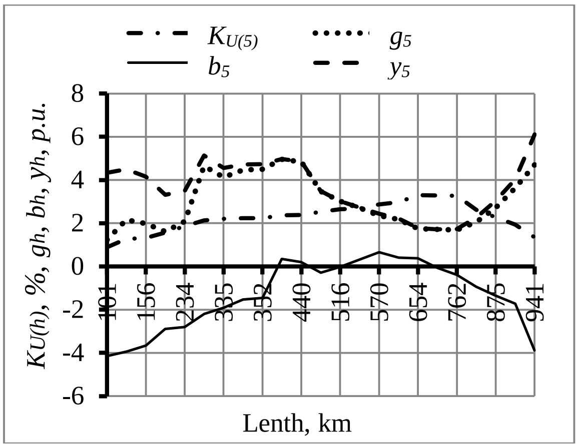

Fig. 11. Parameters of nodes and mode on the 5-th harmonic.

Resonance circuits on the 7-th harmonics were formed from the point of 234 km to 941 km (Fig. 12). Susceptance changes its sign four times. Two voltage resonances and two current resonances occurred in the network. The values of $K_{U(7)}$ exceeded $K_{U(7)95\%}$ but it turned out to be lower than the limit value $K_{U(7)100\%}$.

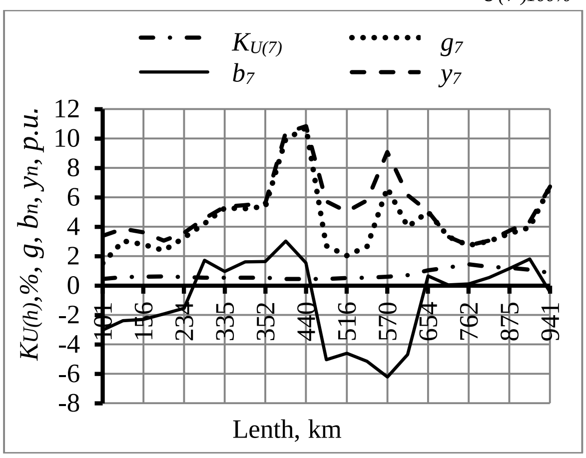

Fig. 12. Parameters of nodes and mode on the 7-th harmonic.

Resonance circuits on the 11-th harmonic were formed throughout the network. Susceptance changes the sign nine times. Nine resonance circuits occurred in the network, five of which correspond to voltage resonance and four correspond to current resonance. Since currents of the 11-th harmonic of a traction station are negligible, index $K_{U(11)}$) does not exceed the limit value of $K_{U(11)100\%}$.

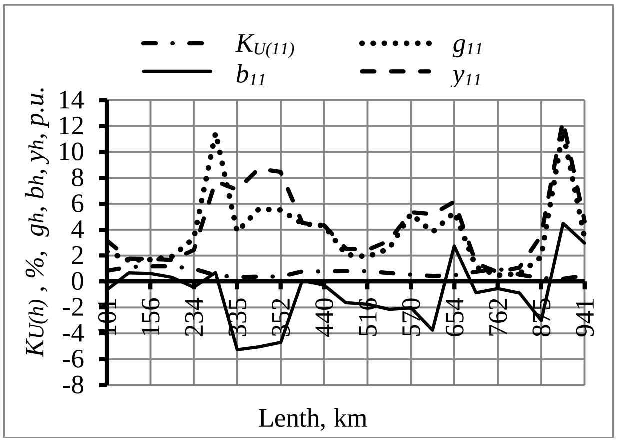

Fig. 13. Parameters of nodes and mode on the 11-th harmonic.

4 Conclusions

1. Resonance modes in the network nodes are of random nature, cover vast areas of the network and are caused by different changes in the network, very often at several harmonics and interharmonics simultaneously, and are among the causes why $K_{U(h)}$ exceeds the limit values specified in State Standard 32144-2013.

2. Tables generated using HARMONICS software reveal the mechanism of voltage harmonics occurrence in the network nodes and together with frequency characteristics of conductance, susceptance and admittance identify resonance modes.

3. The algorithm proposed for analysis of resonance conditions at the harmonics frequencies together with HARMONICS software can be applied for power quality control during networks operation for the purpose of forecasting the resonance conditions.

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Dispatch's decision-making support during operational voltage control in control stations

Andrey Ostanin[1*], *Dmitriy* Lotsman[1], *Alexey* Vasilyev[2], and *Vladislav* Fomenko[2]

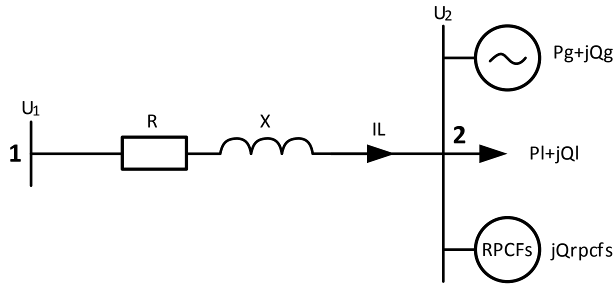
[1] Siberian department of «System Operator of the United Power System», Joint-stock Company, Kemerovo, RF
[2]National Research Tomsk Polytechnic University, Tomsk, RF

Abstract. Voltage and reactive power mode control is performed by dispatcher for the purpose of ensuring required reserves on steady state stability and load stability as well as permissible voltage operating conditions of electric grid equipment. The decision made by dispatcher engaged in controlling reactive power and voltage modes is founded on instructional materials developed in advance for each voltage control station (CS) with focus on data about typical modes of power system or energy area operation. The actual efficiency of reactive power compensation facilities depends on many factors (the composition and operation of grid elements, the composition and operation of generating equipment, etc.). To make final and balanced decision, in some cases, it is necessary to perform some estimation calculations, which take more time for decision making. To minimize and reduce the time required by dispatcher for their decision making and improve its accuracy when involved in voltage and reactive power mode control, it is reasonable to develop software able to determine the efficiency of reactive power compensation facilities in real time.

Voltage and reactive power mode control is one of the critical goals and responsibilities of dispatch control in accordance with [1] and [2]. Voltage and reactive power mode control performed by the dispatch control is aimed at ensuring required reserves of steady state stability and load stability as well as permissible voltage modes of electric grid equipment operation.

Dispatcher involved in voltage and reactive power mode control takes decisions on the need to change operating conditions and modes of reactive power compensation facilities (RPCFs) and generating equipment. The decision made by the dispatcher is based on instructional materials developed in advance for each voltage control station (CS). When developing guidance materials, the estimation of the RPCF and generating equipment efficiency intended for voltage regulation of each CS is determined under typical modes of power system and energy area operation. The actual RPCF and generating equipment efficiency, in most cases, will differ from that specified in recommended guidance materials. These differences can be explained, first of all, by inconstancy of factors that determine the voltage at initial and final stages of power transmission.

Let us consider the relation of voltages without taking into account its shunt admittance and external connections features (see Fig. 1). To cope with the specified task, a transmission line is used as a simplified example.



U_1 – voltage at the beginning of the transmission line (node 1);
U_2 – voltage at the end of the transmission line (Node 2);
R , X – active resistance and inductance of the transmission line;
I_L – current flowing through the transmission line;
P_l , Q_l – active and reactive load power in node 2;
P_g , Q_g – active and reactive power of a generator in node 2;
Q_{rpcfs} – reactive power produced by RPCFs.

Fig. 1. Equivalent circuit of the transmission line without shunt admittance adjacent to the power system node.

According to [3], the voltage at the beginning of the U1 branch depends on the voltage at the U2 end and transmission line parameters. This relation can be described by the following expression:

$$U_1 = \sqrt{U_2^2 - \left[\sqrt{3}\left(I_L^{'}X - I_L^{''}R\right)\right]^2} - \sqrt{3}\left(I_L^{'}R + I_L^{''}X\right) \quad (1)$$

* Corresponding author: andrey@osib.so-ups.ru

Real and imaginary parts of the overhead line current I can be found from the following expression:

$$I_L = I_L^{'} - jI_L^{''} = \frac{P_l - P_g}{\sqrt{3}U_2} - j\frac{Q_l - Q_g - Q_{rpcfs}}{\sqrt{3}U_2} \quad (2)$$

From expressions (1) and (2) the following conclusion can be drawn: voltage in CS depends on the composition and operating modes of its network elements, the composition and operating modes of generating equipment, RPCFs and the power of consumers. In the case when the specified transmission line functions as a part of a complex power system, the relation of the above mentioned elements becomes much more complicated.

When controlling the electrical mode, the dispatcher do not have up-to-date information on the RPCF and generating equipment performance efficiency, which can lead to unfounded decisions. In some cases, to make a balanced decision on the feasibility to use the appropriate RPCFs or generating equipment for voltage regulation, the dispatcher need to perform some operational calculations for steady-state modes using software systems. This can take more time for decision-making.

As an example, let us consider the efficiency of the operating mode impact of some RPCFs and generating equipment on the voltage in the CS of busbar of 500 kV Barabinskaya substation. The following factors may have a significant impact on the utilization efficiency of PECFs and generating equipment involved in voltage regulation in the considered CS depending on the current circuit conditions:

1. Reactive load capacity of the controlled RPCFs in operation:
   1.1. Controlled shunt reactor R-532 at 500 kV Barabinskaya substation;
   1.2. Controlled shunt reactor UShR-1-500 at 500 kV Voskhod substation;
   1.3. Controlled shunt reactor 2R-500 at 500 kV Tavricheskaya substation;
   1.4. Static thyristor compensator STK-1 at 500 kV Zarya substation.
2. The state of the 500 kV Barabinskaya - Voskhod and 500 kV Zarya - Barabinskaya transmission lines, as well as the active-power flow according to the data of the 500 kV power transmission line data;
3. The state of 1AT 500/220 kV 500 kV CS Barabinskaya and AT-1 500/220 kV 500 kV Voskhod substations;
4. Availability of reactive power reserves at power plant generators of the power system in Novosibirsk and Omsk regions.

Table 1 shows a list of actions with RPCFs and generating equipment which use is the most effective for voltage regulation in the considered CS indicating their maximum and minimum efficiency performance determined for the operating modes in July and December 2019.

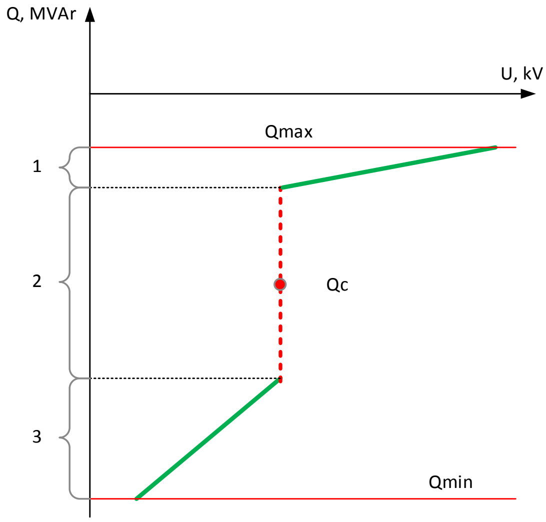
Table 1. Efficiency performance of RPCFs for voltage regulation in the CS of busbar 500 kV Barabinskaya substation

№	Actions with RPCFs for voltage regulation in the CS of busbar 500 kV Barabinskaya substation"	Efficiency of RFCF performance	
		Minimum	Maximum
1.	Changes in reactive power consumption by a controlled shunt reactor		
1.1.	R-532 at the 500 kV Barabinskaya substation	14 MVAr/kV	10 MVAr/kV
1.2.	Controlled Shunt Reactor (CSR) -1-500 at the 500 kV Voskhod Substation	–[1]	35 MVAr/kV
1.3.	2R-500 at the 500 kV Tavricheskaya substation	–[1]	55 MVAr/kV
2.	Consumption and reactive power output variations by a static thyristor compensator STK-1 at 500 kV Zarya substation	–[1]	75 MVAr/kV
3.	Change of the shunt reactor state		
3.1.	R-534 at the 500 kV Barabinskaya substation	10 kV	20 kV
3.2.	R-2-500 or R-3-500 at the 500 kV Voskhod Substation	1 kV	5 kV
3.3.	1R-500 at the 500 kV Tavricheskaya substation	–[1]	3 kV
3.4.	R-532 at the 500 kV Zarya substation	–[1]	4 kV
4.	Total reactive power load variation of power plant generators		
4.1.	Power system of Novosibirsk oblast	500 MVAr/kV	20 MVAr/kV
4.2.	Power system of Omsk oblast	–[1]	185 MVAr/kV

[1] – the sign «–» means that for a given RPCF, the efficiency characteristic of the impact of its reactive power load variation on the voltage in the considered CS is in the ineffective regulation zone.

The utilization efficiency of the RPCF used for voltage regulation is a complex parameter expressed as the dependence of the voltage in the CS on the consumption / reactive power output of a step-controlled or continuously variable RPCF. The efficiency characteristic of the impact of the continuously adjustable RPCFs in the general case consists of a section, where the variation in the output / consumed reactive power of RPCFs does not cause significant voltage regulation in the CS (hereinafter referred to as the ineffective regulation zone) and a section where the change in the output / consumed reactive power leads to significant voltage regulation in the CS (hereinafter referred to as the effective regulation zone).

In the effective regulation zone, the dependence of the voltage on the RPCF reactive power is close to linear; accordingly, it can be represented by a constant efficiency value. Figure 2 shows an example of a generalized efficiency characteristic of the controlled shunt reactor impact on the voltage in the CS.



1 – effective regulation zone by the decrease of the CSR reactive power consumption;
2 – ineffective regulation zone;
3 – effective regulation zone by the increase of the CSR reactive power consumption;
Qc – CSR reactive power consumption in current operation state.

Fig. 2. Efficiency characteristic of a controlled shunt reactor impact on voltage in CS

The availability of an ineffective regulation zone is due to the presence of a reserve of reactive power for loading or unloading of continuously adjustable RPCFs, which ensure the voltage maintenance directly in the CS. For different RPCFs, the width of the ineffective regulation zone and the characteristic slope in the effective regulation area are in the general case different. These parameters are also not constant for the same RPCFs operating in various circuit-mode situations. The lack of information about the availability of an ineffective regulation zone can also significantly complicate the dispatcher decision-making.

The development of automation technology intended for dispatching control makes it possible to increase the relevance and reliability of information provided to the dispatcher, reduce the decision making time required by this personnel for controlling the power system voltage performance and minimize unreasonable decisions making. Software is being developed in the Siberian department of «SO UPS», JSC in cooperation with Tomsk Polytechnic University. The developed software allows determining in real time the efficiency of the RFCF performance for voltage regulation in the CS using information on the current circuit-mode situation in the power system.

For the software being developed, the initial data are:

1. File with information about the current balanced steady-state electrical mode (hereinafter referred to as the File);
2. List of CS;
3. List of the RPCFs and generating equipment used for voltage regulation in each CS;
4. Information concerning connection of CS, RPCFs and generating equipment to the computational power system model.

The information on the current steady-state electrical mode is formed by an algorithm state estimation in accordance with [4] and [5], whose input receives information from the operational information complex of a dispatch center about the current electrical mode in the form of telemetering signals. This information is generated in the form of a file as a software format for calculating steady-state electrical modes, which is fed to the input of the algorithm for determining the RPCF efficiency for voltage regulation in the CS. An enlarged algorithm for determining the RPCF efficiency for voltage regulation in the CS is shown in Figure 3.

After completing the calculation cycle, the information on relevant efficiency of all RPCFs intended for voltage regulation in CS is displayed in special output forms for each control station. In these forms for each CS, all RPCFs and generating equipment are ranked according to the degree of their application efficiency for voltage regulation. After that, the information is transmitted to the operational information complex for its analysis by the dispatcher during the actual control of the electric power voltage mode.

Table 2. Actual efficiency of actions with RPCFs for voltage regulation in the CS

№	Actions with RPCFs for voltage regulation in the CS of busbar of the 500 kV Barabinskaya substation	Efficiency of RPCF utilization for loading/unloading
1.	Variations in reactive power consumption by a controlled shunt reactor	
1.1.	R-532 at the 500 kV Barabinskaya substation	13,7/13,8 MVAr/kV
1.2.	CSR -1-500 at the 500 kV Voskhod Substation	38,2/–[1] MVAr/kV
1.3.	2R-500 at the 500 kV Tavricheskaya substation	–/–[1]
2.	Variation in consumption and reactive power output by a static thyristor compensator STK-1 at 500 kV Zarya substation	–/–[1]
3.	Changes in the the shunt reactor state	
3.1.	R-534 at the 500 kV Barabinskaya substation	11,4 kV
3.2.	R-2-500 or R-3-500 at the 500 kV Voskhod Substation	1,5 kV
3.3.	1R-500 at the 500 kV Tavricheskaya substation	–
3.4.	R-532 at the 500 kV Zarya substation	0,6 kV
4.	Total reactive power load variation of power plant generators	
4.1.	Power system of Novosibirsk oblast	24,1/53,3 MVAr/kV
4.2.	Power system of Omsk oblast	–[1]

[1] – the sign «–» means that for a given RPCF, the efficiency characteristic of the impact of its reactive power load variation on the voltage in the considered CS is in the ineffective regulation zone.

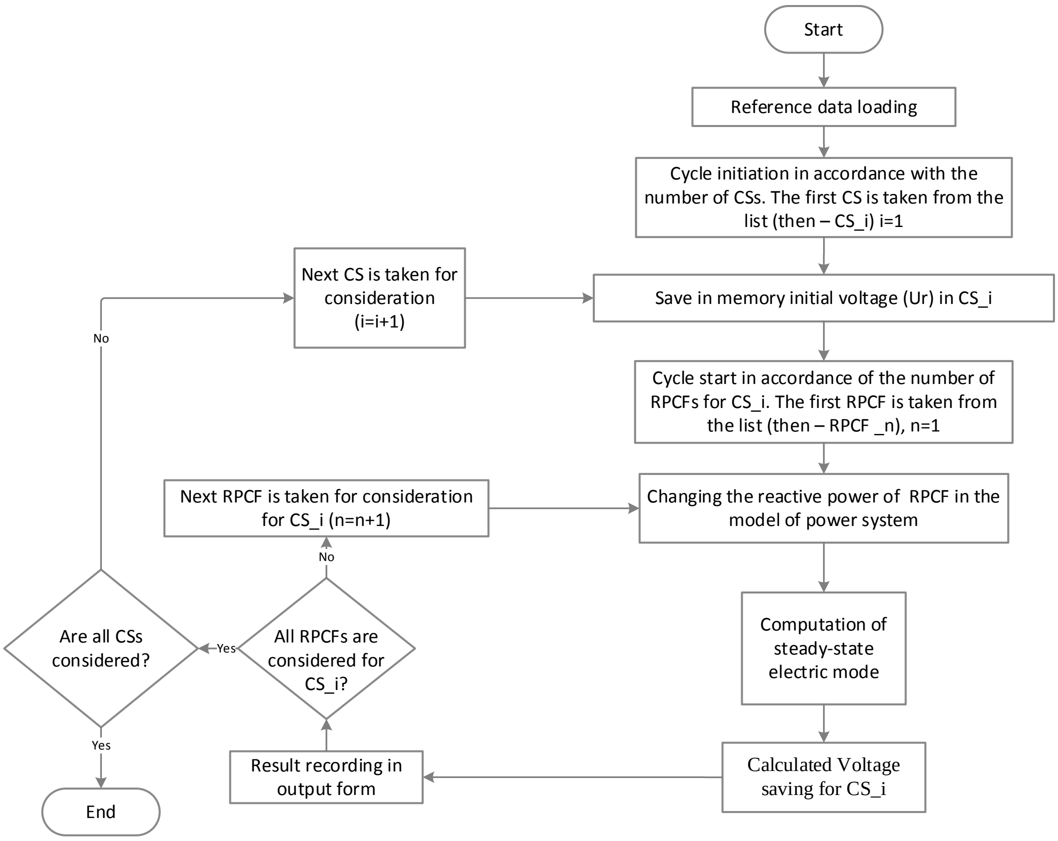


Fig. 3. Block-diagram of an enlarged algorithm for evaluating the RPCF efficiency for voltage regulation in the CS

For the above-mentioned CS of busbars of the 500 kV Barabinskaya substation, Table 2 shows the actual efficiency of actions with RPCFs for voltage regulation in the CS, as well as the information about ineffective voltage regulation zones in the CS in the mode on 28.12.2019.

For the mode under consideration as can be seen in Table 2, measures 1.1 and 3.1 have the highest efficiency for voltage regulation in the CS of busbars 500 kV Barabinskaya substation. These measures are associated with the shift in the reactive power balance directly in the CS, while the application of measures 1.3., 2, 3.3. and 4.2 is unreasonable.

In the course of practical calculations employing the developed software for real modes, the following issues were resolved:

1. Means with the highest efficiency intended for voltage regulation in the CS have been determined;
2. Ineffective means for voltage regulation in the CS have been identified;
3. Fast response and high speed of balanced decision made by the dispatcher when dealing with voltage regulation in the CS have been ensured.

In this paper, an efficient algorithm is developed and analyzed. The developed algorithm ensures an efficient performance assessment of facilities used for voltage regulation in control stations in the real-time mode utilizing information on real circuit conditions and power system operating parameters. Moreover, the proposed algorithm offers the best compromise to dispatcher in terms of accuracy and optimal decision-making time when using control means for voltage regulation in control stations.

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* Corresponding author: andrey@osib.so-ups.ru

A method of power system simulation model reduction for transmission grid frequency response analysis

Valery Solodovnikov [1,*], *Vladimir* Tulsky[1], and *Roman* Shamonov[2]

[1]NRU “Moscow Power Engineering Institute”, Moscow, Russian Federation
[2]PJSC “FGC UES”, Moscow, Russian Federation

Abstract. Application of the frequency scan method for the determination of resonant conditions in a transmission power grid requires great effort since the harmonic power system simulation model needs to be developed. This process is rather complicated since the original model used for fundamental frequency load-flow analysis is built with respect to certain assumptions and, thus, intolerable errors are introduced when frequency-domain properties of the power system are investigated. To strike a balance between inputs needed for the development of such model (time, data amounts) and accuracy of the results, it is proposed to employ a method which makes it possible to represent dead-end, double-ended and tapped 110-220 kV substations as a single frequency-dependent equivalent so that the harmonic power system model is reduced. Such an element essentially is a series *R-L* or *R-L-C* shunt, parameters of which vary with frequency. The algorithm for the evaluation of its parameters is proposed and the test case for a real 110 kV grid area is discussed. Results of the method application show that it can be used in practice.

1 Introduction

Frequency scan (FS) is regarded as one of the most widely used methods for the investigation of harmonic voltage level variation trends, which consists in the estimation of the frequency response of power system positive (negative) sequence impedance as seen from the nodes of an electrical grid and subsequent identification of resonant frequencies [1-4]. As outlined in [1, 4, 5], development and verification of a power system simulation model is by far the most time- and labor-consuming stage of the investigation when 220 kV and above transmission grid is of concern. It is due to the fact that 110-220 kV grid areas, which do not have a significant impact on a power system fundamental frequency load-flow, are usually modelled as equivalent power take-offs, while valid frequency response can only be obtained if such areas are fully incorporated into a power system model [1, 4]. For this reason, considerable enhancement of the original fundamental frequency power system model is required in order to perform FS, resulting in drastic increase in its size defined by the number of nodes and branches. Therefore, maintenance and practical use of the derived harmonic model becomes rather difficult, which makes the assurance of acceptable K_U (voltage total harmonic distortion) and $K_{U(n)}$ (n^{th} harmonic voltage factor) levels in a transmission grid a rather complicated task.

Since over-limit voltage harmonic distortion is a topical issue for Russian grid utilities [6], a method of power system simulation model reduction is proposed in this article. The method makes it possible to represent dead-end, double-ended and tapped 110-220 kV substations as frequency-dependent equivalents (FDEs) when FS is performed at the 110 kV and above buses of the transmission grid substations.

2 Frequency-dependent equivalents of 110-220 kV substations

2.1 Use of frequency-dependent equivalents for frequency response analysis: motivation

Frequency response of the driving-point impedance as seen from the nodes of a 220 kV and above transmission grid strongly depends on the actual topology of adjacent distribution grids (primarily 110 and 150 kV) as well as on the parameters of their elements, which makes it necessary to incorporate them into harmonic power system model [1, 4]. On the other hand, power system models used for the load-flow analysis at the fundamental frequency (i.e. for the purposes of transmission grid operational control) are usually developed with the following simplifications taken into account:

- 110 (150) kV dead-end grid fragments can be modelled as equivalent power take-offs provided that bus voltage levels and line ampacity do not exceed permissible values during both normal operation and contingencies;
- 110-220 kV substations can be represented as equivalent loads referred to HV side in case no reactive power compensators are installed or their output is relatively small;

* Corresponding author: valerysol@yandex.ru

- 110-220 kV substations can be represented as equivalent loads referred to HV side unless generation units are connected to MV or LV buses either directly or via dead-end grid fragments.

Therefore, harmonic power system model can be built on the basis of existing fundamental frequency model, but the latter needs to be expanded significantly so that the valid FS results could be obtained. It is thus proposed to represent dead-end, double-ended and tapped 110-220 kV step-down substations as FDEs in order to minimize harmonic model size increase.

2.2 Composite harmonic model of a 110-220 kV substation

Composite harmonic model of 110-220 kV step-down substations include the following elements:

- power transformer;
- load;
- reactive power compensation units and filters.

Power transformers in the frequency range from 2nd to 40th harmonic are represented as an equivalent circuit consisting of resistive and inductive elements connected in series or series-parallel manner; excitation circuit is usually neglected [1-4].

In accordance with [1, 3-5], actual load composition must be taken into account when performing harmonic assessments in power systems. However, gathering such information for composite loads fed from 110-220 kV substations is a challenging task since standard-form connection contracts and technical specifications stated by [8] impose no customer obligations regarding provision of contracted capacity disaggregated by receiver type during connection procedure. For this reason, aggregate load models are used for FS.

Such models proposed in [1-5] are essentially passive one-ports, parameters of which can be evaluated given the fundamental frequency voltage at the connection point, active power demand and two consolidated values, namely electronic and motor fractions of the total active power demand. Besides, reactive power demand can be used for evaluation of parameters in case motor fraction is less than 10%. It is also noteworthy that load model proposed in [4] also accounts for the total capacitance of outgoing 6-35 kV feeders.

Driving-point impedance frequency response is also heavily influenced by reactive power compensation units and filters in service. Such devices are represented in a harmonic power system model as a shunt inductance or capacitance [1-4, 7].

Hence, a 110-220 kV step-down substation feeding composite load can be modelled as a passive one-port in the frequency range of interest. The impedance of such a one-port is determined by its topology and parameters of the constituent elements and, in return, can be associated with a series *R-L* shunt in case of a substation feeding lagging load. If reactive power compensation units installed at the substation are in service and/or distribution grid feeders' capacitance is taken into account, the model can be extended to *R-L-C* shunt (see Fig. 1). Generally, parameters of the equivalent shunt are frequency-dependent.

Representation of 110-220 kV substations in a harmonic power system model as FDEs of such a specific topology is required in case impedance with reversal imaginary part cannot be modelled as a single element by means of a software tool used for FS.

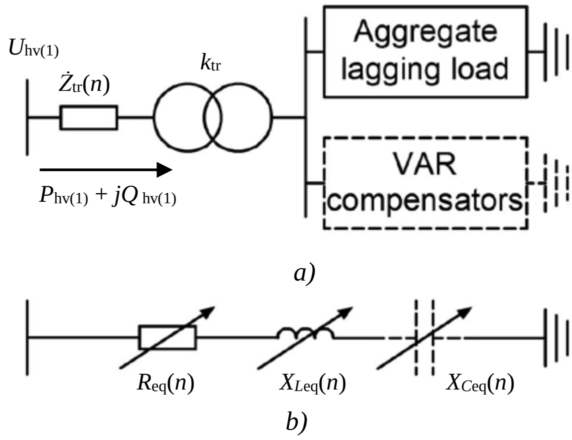


Fig. 1. Frequency-dependent equivalent of a 110-220 kV single-transformer step-down substation: a) – original two-port; b) – equivalent shunt.

2.3 Description of the proposed method

According to recommendations given in [4], frequency response assessment of the driving-point impedance as seen from transmission grid nodes is usually performed under the assumption that a power system is perfectly balanced in terms of both circuit and state parameters, which makes it possible to employ single-phase approach. In that respect, since the fundamental frequency steady-state of the original substation one-port is determined by the voltage and apparent power flow at the transformer HV side, parameters of an FDE can be calculated by means of the method described below (see Fig. 2 for the algorithm flowchart).

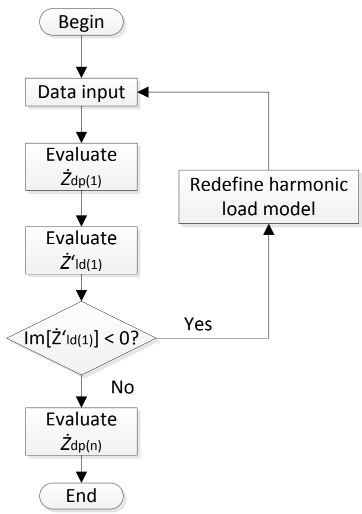


Fig. 2. Flowchart of the algorithm for the evaluation of parameters of a 110-220 kV substation frequency-dependent equivalent.

The input data are as follows:

- Fundamental frequency load-flow parameters:
  - phase-to-phase voltage at the HV bus $U_{\text{hv}(1)}$;
  - three-phase apparent power demand referred to the HV side $P_{\text{hv}(1)} + \text{j}Q_{\text{hv}(1)}$.
- Transformer parameters:
  - OLTC tap position;
  - fundamental frequency impedance at the given tap position $\dot{Z}_{\text{tr}(1)}$;
  - turns ratio at the given tap position k_{tr}.
- Load parameters:
  - fraction of the electronic load K_{E};
  - fraction of the motor load K_{MT} (if considered);
  - total capacitance of outgoing 6-35 kV feeders (if considered).
- Reactive power compensator parameters:
  - total reactance of reactive power compensators in service (if any).

Bus voltage and apparent power at the fundamental frequency are obtained on the basis of the preliminary load-flow analysis. Transformer parameters are defined given its nameplate data. It is also recommended to use actual data on load composition; however, average K_{E} and K_{M} values presented in [7, 9] can be used if such information is unavailable.

Additional information is needed in case three-winding and split-winding transformers are installed at the substation:

- HV, MV and LV transformer branch impedance at the given OLTC and DETC tap positions;
- active and reactive power demand ratio on the MV and LV sides respectively (can be assumed with respect to check measurements).

For simplicity, the algorithm is further described for a substation with a single two-winding transformer as an example.

Step 1. Equivalent driving-point impedance of the substation one-port is calculated by the formula (1):

$$\dot{Z}_{\text{dp}(1)} = (P_{\text{hv}(1)} + jQ_{\text{hv}(1)}) \cdot \frac{U^2_{\text{hv}(1)}}{P^2_{\text{hv}(1)} + Q^2_{\text{hv}(1)}} \qquad (1)$$

Step 2. Fundamental frequency load impedance referred to the HV side is evaluated. If no reactive power compensation units are in service, the impedance can be obtained from equation (2):

$$\dot{Z}'_{\text{ld}(1)} = \dot{Z}_{\text{dp}(1)} - \dot{Z}_{\text{tr}(1)} \qquad (2)$$

In presence of reactive power compensators load impedance can be found by the formula (3), where $X_{\text{vcu}\Sigma}$ is the total reactance of compensators referred to the HV side:

$$\dot{Z}_{\text{dp}(1)} - \dot{Z}_{\text{tr}(1)} = \frac{\dot{Z}'_{\text{ld}(1)} \cdot jX_{\text{vcu}\Sigma}}{\dot{Z}'_{\text{ld}(1)} + jX_{\text{vcu}\Sigma}} \qquad (3)$$

Step 3. If the reactive power demand is used for the evaluation of the load model parameters, the value of the imaginary part of $\dot{Z}'_{\text{ld}(1)}$ is then analyzed. A negative value indicates that either a more sophisticated load model is required to determine FDE parameters or the adjacent area of the 35 kV and below distribution grid needs to be represented in the harmonic power system model.

It is essential to test this condition since models proposed in [1, 5], parameters of which are derived from the reactive power, are valid in case of the inductive load. In real operation, a load might be capacitive due to the following reasons:

- motive load operating conditions (i.e. synchronous motors with a leading power factor);
- presence of the capacitor banks in the downstream distribution grid;
- light-load conditions and/or significant capacitance of outgoing 6-35 kV feeders.

Step 4. FDE parameters are evaluated in the frequency range of interest. Design formulae are determined by load and power transformer models as well as presence of reactive power compensators. For instance, if models presented in Fig. 3 and proposed in [1] are adopted and no compensators are installed, equivalent parameters at the n^{th} harmonic frequency can be found from equations (4) and (5):

$$R_{\text{eq}}(n) = \frac{1}{1 - K_{\text{E}} - K_{\text{MT}}} \cdot \frac{\left|\dot{Z}'_{\text{ld}(1)}\right|^2}{\text{Re}[\dot{Z}'_{\text{ld}(1)}]} \cdot \frac{n^2 K_1^2}{1 + n^2 K_1^2} + R_{\text{tr}(n)} \qquad (4)$$

$$X_{L\text{eq}}(n) = \frac{1}{1 - K_{\text{E}} - K_{\text{MT}}} \cdot \frac{\left|\dot{Z}'_{\text{ld}(1)}\right|^2}{\text{Re}[\dot{Z}'_{\text{ld}(1)}]} \cdot \frac{n K_1^2}{1 + n^2 K_2^2} + X_{\text{tr}(n)} \qquad (5)$$

Capacitive reactance $X_{C\text{eq}}$ is set to zero since chosen load model does not account for the impact of outgoing feeders. Transformer parameters at the n^{th} harmonic frequency and K_1 factor can be calculated as follows:

$$R_{\text{tr}(n)} = R_{\text{tr}(1)} + R_{\text{tr}(1)} \cdot \frac{10n^2}{100 + \left(\dfrac{nR_{\text{tr}(1)}}{X_{\text{tr}(1)}}\right)^2} \qquad (6)$$

$$X_{\text{tr}(n)} = \frac{100 \cdot X_{\text{tr}(1)} \cdot n}{100 + \left(\dfrac{nR_{\text{tr}(1)}}{X_{\text{tr}(1)}}\right)^2} \qquad (7)$$

$$K_1 = \frac{X_{\text{M}} \cdot (1 - K_{\text{E}} - K_{\text{MT}})}{K_{\text{MT}} \cdot K_m} \qquad (8)$$

Names of the variables in the last equation are assumed in accordance with [1].

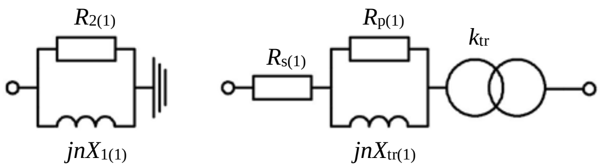


Fig. 3. Examples of load and two-winding power transformer harmonic models: IEEE 'Induction motors' load model (left), Electra-167 transformer model (right).

It should be noted that each one-port consisting of a power transformer as well as loads and reactive power compensation units connected to it are replaced with its own FDE. Therefore, it is reasonable to represent multiple-transformer substation in the harmonic power system model as a single equivalent. Its parameters are estimated in the frequency range of interest as the total impedance of equivalent shunts connected in parallel.

As a result, dead-end, double-ended and tapped 110-220 kV step-down substations can be represented as FDEs by means of the proposed method. The advantages of the method are as follows:

- FDE parameters are determined directly from the load-flow parameters on the HV side, which makes it possible to build harmonic power system model with minimum adjustment of the original fundamental frequency model and, therefore, to simplify its development, practical use and maintenance;
- representing FDEs as series *R-L* (*R-L-C)* shunts facilitates application of the method since such elements are basic for harmonic analysis software tools.

3 Simplified representation of the 110-220 kV substations

Under certain conditions, simplified representation of 110-220 kV substations in the harmonic power system model is possible due to the frequency-domain properties of load and transformer models.

According to [5], an aggregate load can be modelled as a series *R-L* shunt if the motor fraction is small (less than 10%). If reactive power compensation units are not installed at the substation, a transformer can be excluded from the original 'transformer + load' one-port given the specific combination of load-flow parameters at the fundamental frequency. Therefore, the original one-port can be replaced by the series *R-L* shunt; its parameters are estimated given the HV bus voltage and apparent power on the HV side at the fundamental frequency.

It must be emphasized that the discussed conversion can be regarded as equivalent in terms of electric circuit theory only at the fundamental frequency. Thus, conversion acceptance criteria were defined. The criteria (9) state that the impedance modulus relative difference for the original and converted one-ports (amplitude-frequency response, AFR) as well as impedance angle difference (phase-frequency response, PFR) does not exceed 5% in the frequency range of interest:

$$\begin{cases} \delta_{\mathrm{AFR}} = \dfrac{\left\| \dot{Z}^{\mathrm{conv}}_{\mathrm{dp(n)}} \right| - \left| \dot{Z}^{\mathrm{orig}}_{\mathrm{dp(n)}} \right\|}{\left| \dot{Z}^{\mathrm{orig}}_{\mathrm{dp(n)}} \right|} \cdot 100 \le 5\% \\ \delta_{\mathrm{PFR}} = \dfrac{\left| \arg(\dot{Z}^{\mathrm{conv}}_{\mathrm{dp(n)}}) - \arg(\dot{Z}^{\mathrm{orig}}_{\mathrm{dp(n)}}) \right|}{\left| \arg(\dot{Z}^{\mathrm{orig}}_{\mathrm{dp(n)}}) \right|} \cdot 100 \le 5\% \end{cases} \quad (9)$$

It is then possible to assess permissibility of the simplified representation of 110-220 kV substations under given load-flow conditions at the fundamental frequency. Based on the above-stated criteria, a set of load-flow parameters can be divided into regions where the simplification is and is not justifiable.

As an example, such regions are presented in the Fig. 4 for the substations with a single 110-220 kV split-winding transformer installed. Frequency-dependence of the transformer impedance is taken in accordance with IEEE-399 [10], loads connected to secondary windings LV1 and LV2 are assumed to be linear.

Simplified substation representation is allowed if the transformer operating point lies below the border drawn in the 'p.u. transformer load – maximum tgφ of LV1 and LV2 loads' plane. Boundaries presented in Fig. 4 are valid under the following conditions:

- transformers are manufactured in accordance with regulations [11, 12];
- fundamental frequency voltage at the HV bus is within the range of $0.8U_{\mathrm{nom}}$ to maximum operating voltage based on the requirements [13].

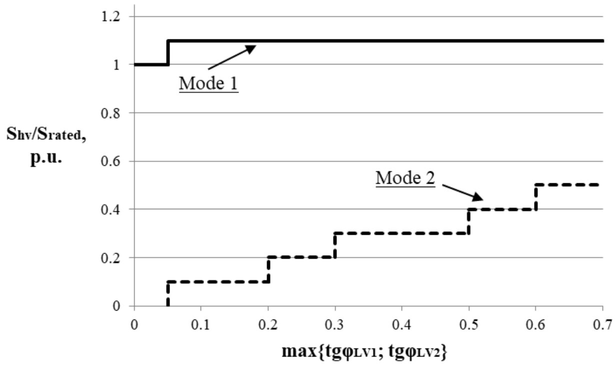


Fig. 4. Simplified representation regions for the substations with a single 110-220 kV split-winding transformer installed.

Since AFR and PFR of the original one-port impedance are heavily influenced by the ratio between loads connected to transformer secondary windings, boundaries are defined for two operating modes:

- **Mode 1**: even load distribution ($S_{\mathrm{LV1}} = S_{\mathrm{LV2}}$; $\mathrm{tg}\varphi_{\mathrm{LV1}} = = \mathrm{tg}\varphi_{\mathrm{LV2}}$; solid line);
- **Mode 2**: uneven load distribution ($S_{\max}/S_{\min} \le 2$; $\mathrm{tg}\varphi_{S\max}/\mathrm{tg}\varphi_{S\min} \le 1{,}5$; dashed line).

It can be seen from Fig. 4 that load ratio has a significant impact on the permissibility of the simplified representation of substations in a harmonic power system model. If loads are distributed evenly between transformer secondary windings, a simplification can be implemented over the wide range of transformer load (from no-load operation to $1.0\text{-}1.1S_{\mathrm{rated}}$) and tgφ (from 0 to 0.7) values. On the contrary, the allowable region shrinks if loads are unequal: a conversion can be performed in case transformer load does not exceed $0.3\text{-}0.5S_{\mathrm{rated}}$ (the former value corresponds to the $\mathrm{tg}\varphi_{S\max}$ between 0.05 and 0.4, the latter – between 0.6 and 0.7).

It should be noted that if the impact of transformer outages on the transmission grid frequency response is of interest, the assessment of simplified representation permissibility for 110-220 kV substations with 2 or more transformers installed should be performed in case of an outage due to increase in power flow through the transformers left in operation.

4 Test of the method: a real-life 110 kV grid area case study

The proposed method was tested for an area of a 110 kV grid; its simplified one-line diagram is presented in Fig. 5. Power is supplied from the 220 kV substation K, which is electrically close to 500 kV transmission grid facilities. The area of interest consists of dead-end fragments connected to substation K 110 kV buses and interconnector between substations K and A, which feeds tapped and double-ended 110 kV substations. The interconnector is normally open-circuited (substation 15 110 kV bus coupler and line circuit breakers at the substation C are open). Total length of the interconnector is 302 km; the section between substations K and 15 is 117 km long.

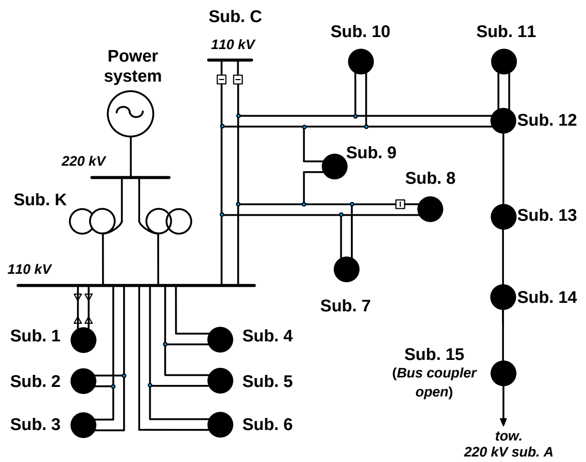


Fig. 5. Simplified one-line diagram of the 110 kV grid analysis area for the test of the proposed method.

FS was performed to obtain AFR and PFR of the driving-point impedance as seen from the 110 kV bus of substation K. This grid point is of interest since it defines a boundary between areas of responsibility of regional distribution and transmission grid operators.

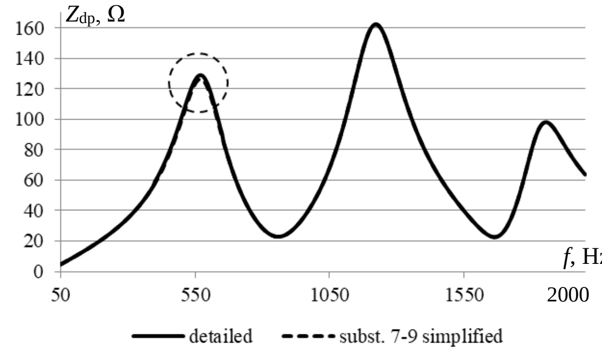
Driving-point impedance AFR and PFR curves as at 10:00 06/20/2018 (Moscow time zone, summer check measurement day) are presented in Fig. 6. Total area load demand amounted to 67.8 + *j*27.6 MVA. Curves are plotted for three types of a harmonic power system simulation model:

- detailed model (all the 110 kV transformers are represented) – 106 nodes, 141 branches;
- FDE representation – 50 nodes, 64 branches;
- simplified representation of 110 kV substations 7-9.

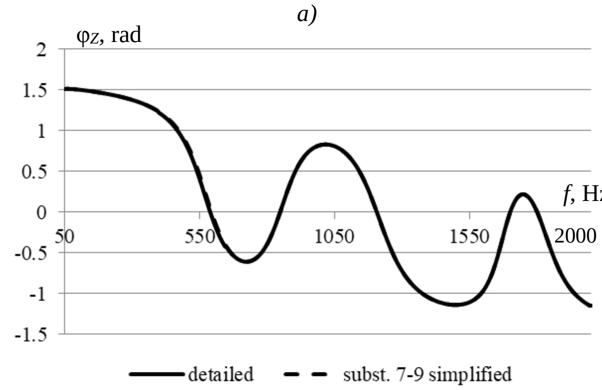
It should be noted that curves are plotted only for the first and the last case since FDE representation is strictly equivalent in the frequency range of interest. Therefore, AFR and PFR curves for the first and second case are essentially the same (relative deviation does not exceed 0.05% and is caused by rounding errors).

At the same time, simplified representation of substations 7-9 causes moderate decrease in impedance modulus close to the first resonant frequency (less than 2%, circled in the Fig. 6) and introduces slight upwards shift (5 Hz) of such frequency.

It can be seen that application of the proposed method makes it possible to cut down number of nodes and branches more than by half (from 106 down to 50 and from 141 to 64 respectively) with the same computational accuracy. Simplified representation introduces light errors; however, they are offset by input data reduction since gathering and processing of the 110-220 kV transformer data is not required in this case, which, eventually, makes it possible to speed up the transmission grid frequency response analysis.



a)



b)

Fig. 6. Positive (negative) sequence driving-point impedance frequency response as seen from the 110 kV buses of the 220 kV substation K: a) – AFR curve; b) – PFR curve.

5 Conclusions

Based on the foregoing, the following conclusions can be made:

1. Development and verification of a power system simulation model is the most time- and labor-consuming stage of the harmonic voltage trend investigation when the transmission grid is of concern since 110-220 kV grid areas, which do not have a significant impact on a power system fundamental frequency load-flow, are usually modelled as equivalent power take-offs, while valid frequency response can only be obtained if such areas are fully incorporated into a power system model.
2. Dead-end, double-ended and tapped 110-220 kV step-down substations can be modelled as frequency-dependent equivalents (FDE) unless generation units are connected to MV or LV substation buses either directly or via dead-end grid fragments. The FDE is a series *R-L* or *R-L-C* shunts with frequency-dependent parameters. Such a specific representation is required in case impedance with reversal imaginary part cannot be modelled as a single element by means of a software tool used for FS.
3. A method of harmonic power system model reduction is proposed, which makes it possible to employ FDEs for the purposes of FS instead of the full

substation representation. FDE parameters are estimated on the basis of the fundamental frequency load-flow parameters at the beginning of a transformer branch. Therefore, the size of a harmonic power system model can be reduced, which simplifies its development, practical use and maintenance.

4. It is demonstrated that if aggregate load fed from the substation is modelled as a series *R-L* shunt, simplified representation of such a substation is allowed under certain fundamental frequency conditions. In this case, substation as a whole can be modelled as a series *R-L* shunt; its parameters are evaluated given the HV bus voltage and apparent power flow; transformer impedance is neglected. Permissibility analysis is performed on the basis of plots which reflect the possible transformer operating conditions: if the operating point lies below the border defined according to permissibility criteria, a substation can be represented in a simplistic manner.

5. The proposed method of harmonic power system model reduction was tested for a real-life 110 kV grid area. It is shown that the number of nodes and branches can be reduced more than by half if FDEs are employed. Simplified representation introduces moderate errors, but, at the same time, data amount needed for the performance of FS is reduced, which speeds up the analysis.

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Thyristor Voltage Regulator Experimental Research

Elena Sosnina[1,*], *Aleksandr* Sevostyanov[1], *Evgeny* Kryukov[1], and *Rustam* Bedretdinov[1]

[1]Nizhny Novgorod State Technical University n.a. R.E. Alekseev, Department of Electric Power Engineering, Power Supply and Power Electronics, Nizhny Novgorod, Russia

Abstract. The article is devoted to the thyristor voltage regulator (TVR) development. The TVR purpose is to control power flows and regulate voltage in 6-20 kV distribution electrical networks (DEN). The principle of TVR operation is based on the plus EMF (or minus EMF) introduction into power line when the shared use of longitudinal (change of magnitude) and transverse (change of phase) voltage regulation. The description of the TVR prototype is given. The TVR prototype consists of a 0.4 kV thyristor switches, power transformers (shunt and serial) and a 6 kV switchgear. The TVR has a two-level control system (CS). The TVR prototype experimental research was conducted in four stages: check of power equipment, first level CS research, second level CS research, prototype tests as a whole. The connection diagrams (thyristor switches unit, transformer and measuring equipment) and contact connections reliability were checked when the power part was tested. A qualitative characteristic of the input and output signals was obtained when testing the first level CS. It is found that the thyristor control pulses are formed according to the developed algorithm. The correctness of control system algorithms, executed and transmitted commands, passed and received data was confirmed as a result of the second level CS tests. The TVR research results indicate that the prototype provides the smoothness and specified accuracy of voltage regulation in all modes. The control range of the output voltage relative to the input was ±10%. The discreteness of regulation did not exceed 1.5%. The range of change in the shift angle of the output voltage relative to the input was ±5˚. Research confirmed the TVR ES operability and its readiness for trial operation.

1 Introduction

The electric power industry development and its transition to a new technological level are connected with implementation of Internet of energy concept [1, 2]. This technology is aimed at converting electric networks from a passive device for transporting and distributing electricity to an active one that ensures energy security and power supply quality [3, 4]. The interaction of distributed electricity sources, its accumulators and active consumers will be carried out on the basis of "horizontal" connections and multi-party services. This approach will preserve the advantages of both centralized and decentralized power supply systems [5, 6].

Two important tasks must be solved when building distribution electrical networks (DEN) that operate on the Internet of energy principle: power flows control and power quality ensuring [7]. These tasks can be solved using devices that implement D-FACTS (Distributed Flexible Alternative Current Transmission Systems) technologies. D-FACTS include such devices as an unified power flow controller (UPFC) [8], an interline power flow controller (IPFC) [9], a distributed static series compensator (DSSC) [10], a thyristor controlled phase angle regulator (TCPAR) [11], a thyristor switched series capacitor (TSSC) [12], etc. Currently, these devices are either in development or at the stage of trial operation.

Low power quality in the MV DEN is often caused by voltage deviations. Load tap changers (LTCs) [1-16] and step voltage regulators [17, 18] are used to regulate the voltage levels. Booster transformers (BT) are widely used [19]. The main BT disadvantage is their low response which makes them inefficient in electric networks with a dynamic load.

A thyristor voltage regulator (TVR) prototype which was developed by scientists of Nizhny Novgorod state technical university n. a. R.E. Alekseev allows to provide the power flow controlling and to ensure power quality [20].

The principle of TVR operation is based on the shared use of longitudinal (change of magnitude) and transverse (change of phase) voltage regulation. Adding EMF in the line under longitudinal regulation allows to change the voltage level on the consumer's buses. The

* Corresponding author: sosnyna@yandex.ru

change in phase of the output voltage under transverse regulation allows to control active and reactive power flow.

The TVR favorably differs in response, switching resource and smooth regulation compared to electromechanical regulators.

The article is devoted to research of TVR prototype operability, the effectiveness of control system, and the readiness of the prototype for trial operation.

2 Operation principle of thyristor voltage regulator

Fig. 10 shows a schematic circuit of the thyristor voltage regulator.

The TVR is based on longitudinal and transverse control thyristor modules, shunt and series transformers. The primary windings of the shunt transformer T1 are delta-connected. The secondary windings of each three phases T1 are made in the form of three galvanically isolated sections.

The sections with EMF1 (e_{1A}, e_{1B}, e_{1C}) form a three-phase voltage system for power supply the transverse control module (TS1-TS4).

The sections with EMF2 (e_{2A}, e_{2B}, e_{2C}) form a three-phase voltage system for power supply the longitudinal control module (TS5-TS8).

The transverse and longitudinal control modules of each phase are made according to the reversible AC bridge scheme. The bridges diagonals are series connected and form a power supply circuit for the primary windings of serial transformers (T2).

The secondary windings of T2 are included in the phase dissection of DEN lines. Their voltages are summed with the TVR input voltage.

Thyristor switches placed in the secondary windings of circuit T1 are under low potential. This significantly reduces the requirements for their isolation from constructional elements.

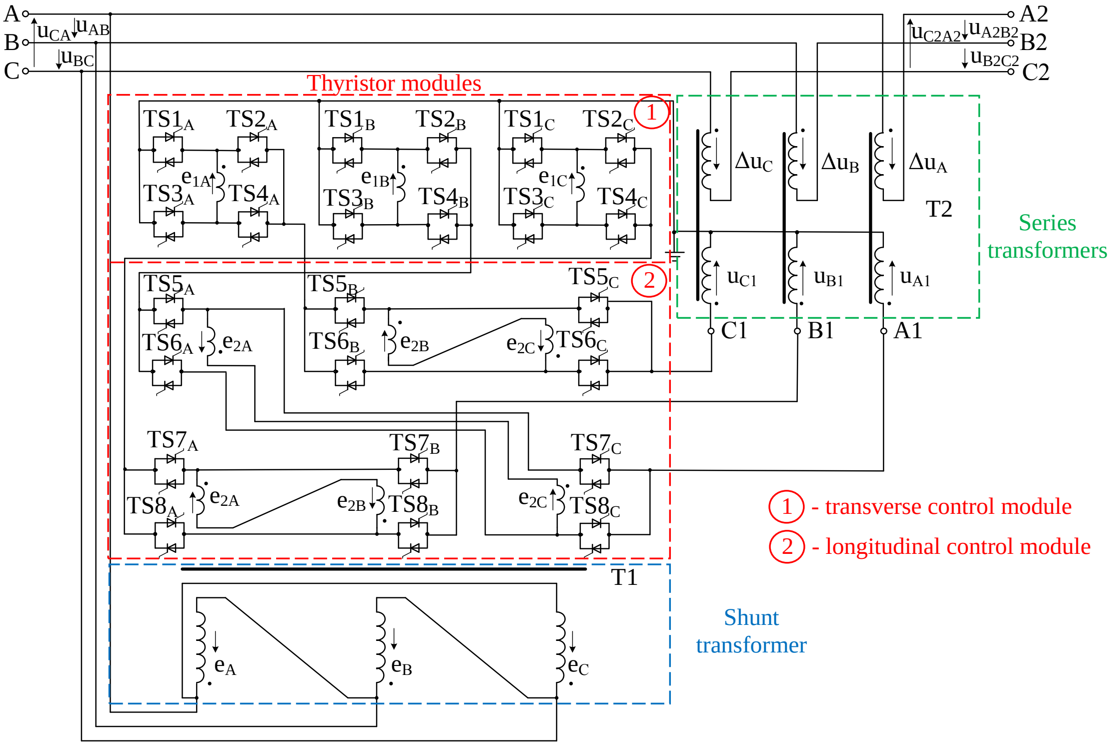

Fig. 1. Schematic diagram of the TVR power part .

It should be noted that using the pulse-phase control principle allows to regulate the value and phase of the TVR output voltage smoothly.

The direct transmission mode of input voltage to the TVR output is implemented when the TS3, TS4 and TS6, TS8 of all phases are switched on. In this case, all secondary windings T2 are excluded from the supply circuit T1, and the primary windings T2 are shorted to neutral, and their voltage, as well as the voltage of the secondary windings Δu, is zero.

As a result, the TVR output voltages are equal to the corresponding input voltages:

$$u_{A1B1} = u_{A2B2};$$
$$u_{B1C1} = u_{B2C2};$$
$$u_{C1A1} = u_{C2A2}.$$

The phases of the output voltage are changed by transverse regulation. This allows to control the active and reactive power flows in the power line. In this case voltages are formed shifted by 90° relative to the phase voltages of the network.

It is possible to implement the delay and advance modes of the TVR output voltage relative to the input. The delay mode is activated when switches TS2, TS3 and TS6, TS8 of all phases are on. At the same time, EMF e_{1A}, e_{1B}, e_{1C}, are introduced into the power supply circuit of the primary windings T2 which differ from the input voltages of the TVR in proportion to the transformation ratio of the transverse control stages T1 (k_{11}). It should be noted that the EMF of phase B (e_{1B}) is used for phase A. The EMF of phase B (e_{1B}) is in antiphase with the line voltage u_{B1C1}. Similarly, the EMF of phases C (e_{1C}) and A (e_{1A}) are used for the B and C phases voltages, respectively. These EMFs are in antiphase with the input line voltages u_{C1A1}, u_{A1B1}. Accordingly, the addition voltages of the secondary windings $\Delta u_{Aпп}$, $\Delta u_{Bпп}$, $\Delta u_{Cпп}$ are introduced into the line. These additional voltages differ from the voltages of the primary windings u_{A1}, u_{B1}, u_{C1} in proportion to the transformation ratio (k_2) T2:

$$\Delta u_{Aпп} = k_2 \cdot u_{A1} = k_2 \cdot e_{1B} = - k_{11} \cdot k_2 \cdot u_{B1C1};$$

$$\Delta u_{Bпп} = k_2 \cdot u_{B1} = k_2 \cdot e_{1C} = - k_{11} \cdot k_2 \cdot u_{C1A1};$$

$$\Delta u_{Cпп} = k_2 \cdot u_{C1} = k_2 \cdot e_{1A} = - k_{11} \cdot k_2 \cdot u_{A1B}.$$

The vector diagram of the input and output line voltages for the delay mode is shown in Fig. 2. From the presented diagram it follows that the introduction of a transverse regulation step into the line of each phase allows to obtain linear voltages at the TVR output, lagging in phase relative to the input voltages by an angle α.

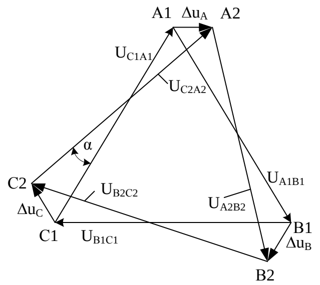

Fig. 2. Voltage vector diagram for the delay mode.

It can be shown that EMF e_{1A}, e_{1B}, e_{1C} are reversed when switches TS1-TS4 and TS6-TS8 of all phases are turned on. Due to this, the mode of advancing the TVR output voltage relative to the input voltage is also realized on the angle α.

Change of phase of the output voltage relative to the input one allows to regulate an active and reactive power flows transmitted through the AC power line between two nodes of the DEN which are determined by the formulas:

$$P = \frac{U_1 \cdot U_2}{x_{PL}} \cdot \sin\delta \,;$$

$$Q_1 = \frac{1}{x_{PL}} \cdot \left(U_1^2 - U_1 \cdot U_2 \cdot \cos\delta \right);$$

$$Q_2 = \frac{1}{x_{PL}} \cdot \left(U_2^2 - U_1 \cdot U_2 \cdot \cos\delta \right),$$

where U_1 and U_2 – voltages of a power line (PL) initial and in the end; Q_1 и Q_2 – reactive power of a PL initial and in the end; x_{PL} - power line reactance; δ – angle between the U_1 и U_2 voltage.

The longitudinal control modules are powered by secondary windings T1 with EMF values e_{2A}, e_{2B}, e_{2C}. Moreover, the EMF of the secondary windings e_{2A}, e_{2B}, e_{2C} are in antiphase with the input line voltages of the TVR u_{A1B1}, u_{B1C1}, u_{C1A1} and differ from them in magnitude in proportion to the transformation ratio (k_{12}).

When the switches $TS6_A$, $TS7_C$ and TS3, TS4 of all phases are switched on, the EMF difference of the longitudinal control stages e_{2C}-e_{2A} is introduced into the power supply chain of phase A of the primary winding T2. Accordingly, when the switches $TS8_A$, $TS7_B$ and $TS6_B$, $TS5_C$ are turned on, the differences in the EMF e_{2A}-e_{2B} and e_{2B}-e_{2C} are introduced in the supply circuit of phases *B* and *C* T2. Thus, the voltage additions of the secondary windings Δu_{Alon}, Δu_{Blon}, Δu_{Clon}, which differ from the specified geometric difference in proportion to the T2 transformation ratio k_2, are introduced into the series of the TVR line:

$$\Delta u_{Alon} = k_2 \cdot u_{A1} = k_2 \cdot (e_{2C} - e_{2A}) = k_{12} \cdot k_2 \cdot (u_{A1B1} - u_{C1A1});$$

$$\Delta u_{Blon} = k_2 \cdot u_{B1} = k_2 \cdot (e_{2A} - e_{2B}) = k_{12} \cdot k_2 \cdot (u_{B1C1} - u_{A1B1});$$

$$\Delta u_{Clon} = k_2 \cdot u_{C1} = k_2 \cdot (e_{2B} - e_{2C}) = k_{12} \cdot k_2 \cdot (u_{C1A1} - u_{B1C1}).$$

The voltage vector diagram for the voltage reduction mode is shown in Fig. 3.

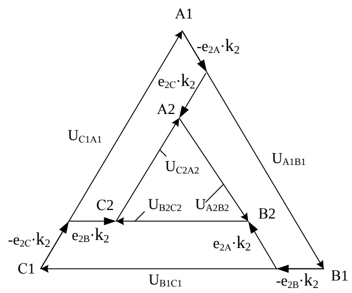

Fig. 3. Voltage vector diagram for the voltage reduction mode.

The mode of increasing the TVR output voltage is activated when the switches $TS5_A$, $TS8_C$, $TS5_B$, $TS6_C$, $TS7_A$, $TS8_B$ and switches TS3, TS4 of all phases are turned on. In this case, the EMF (e_{2A}, e_{2B}, e_{2C}) supplying the primary windings of the series transformer are reversed.

The shared use of longitudinal and transverse control modules allows to make a longitudinal-transverse regulation of the TVR output voltage.

The developed technical and circuit solutions formed the basis for the TVR prototype.

3 Thyristor voltage regulator prototype

The main technical characteristics of the TVR prototype are given in table 1.

Table 1. Technical characteristics of the TVR .

Parameter	Value
Nominal voltage (supply voltage)	6 kV ±10%
Variation range of the angle voltage phase α	± 5°
Measurement resolution of the phase shift voltage α	1.5°
Range of regulation voltage	± 10%
Regulation discreteness of the voltage amplitude	≤ 1.5%
Load power	≤ 630 кVA
Shunt-wound transformer power	106 kVA
Series transformer power	3×28 kVA

The TVR prototype is a container-type 6 kV substation, consisting of 0.4 kV longitudinal and transverse control thyristor modules, three-phase shunt and three single-phase series transformers and a 6 kV switchgear. Fig. 4 – 6 show the prototype appearance.

The TVR control system (CS) is two leveled. The first level CS (CS1) implements the physical execution of commands for the operational control of thyristors [21], carried out by the pulse-phase method. The CS1 is based on the algorithm of two-zone alternate regulation [22]. This method provides an output voltage change in the positive and negative power directions intervals, and also does not require the use of a current sensor. That allows to maintain the regulating properties of the TVR with a significant change in the value of the load current, as well as at idle.

Fig. 4. TVR prototype

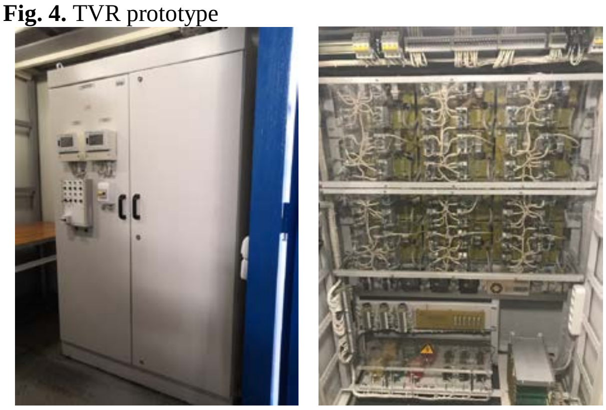

Fig. 5. Thyristor switch cabinet.

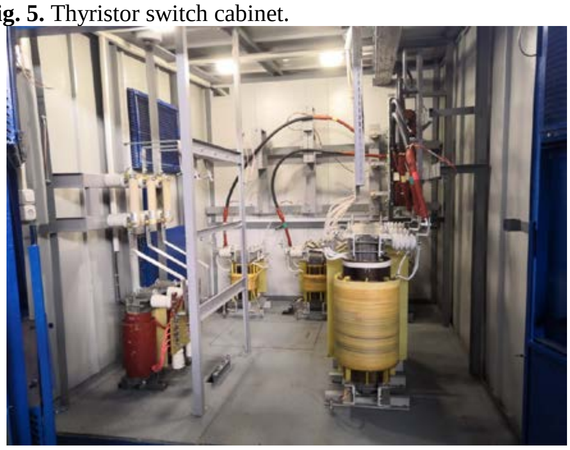

Fig. 6. Power transformer compartment.

The CS1 software part is implemented in the *LabVIEW* with *Real Time* and *FPGA* modules. Executable files provide the operation of the controller with a field programmable gate-array (FPGA), which generates and transmits control pulses to the TVR thyristors in the modes of transverse, longitudinal and longitudinal- transverse regulation.

Fig. 7 shows the main blocks of the CS1 software part.

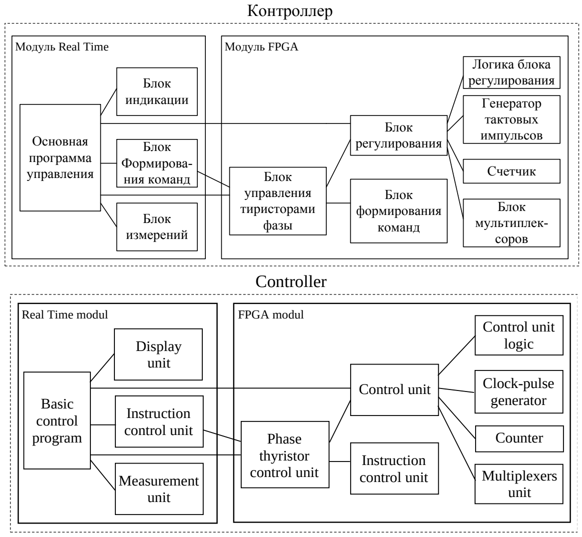

Fig. 7. Structure scheme of the CS1 software part

The CS1 hardware was implemented on three *NI myRIO* controllers. This was necessary to increase the speed of data processing. The controller carries out interaction between phases, as well as receiving and transmitting information to any external adaptive control system. The *Real Time* module provides measurements of frequency, power, *RMS* voltages and currents. The *FPGA* is the second hardware layer.

External commands as control actions are sent to the controller, which transmits them to the FPGA. Synchronizing pulses are formed at the FPGA level from the obtained voltage values of the high-voltage winding of the transformers. These pulses are generated at the moment of voltage polarity change when it crosses zero and are differentiated into four main synchronizing signals U_0, U_+, U_-, U_{0+}. Due to the commands received from the controller, pulses are formed in the FPGA to control the TVR thyristors. At the FPGA level, zero crossings are isolated from the incoming sinusoidal signal, analyzed when the sine is in a positive and negative state, and synchronizing pulses are formed when the sign changes from minus to plus U_{0+}.

Fig. 8 shows the control unit implementation.

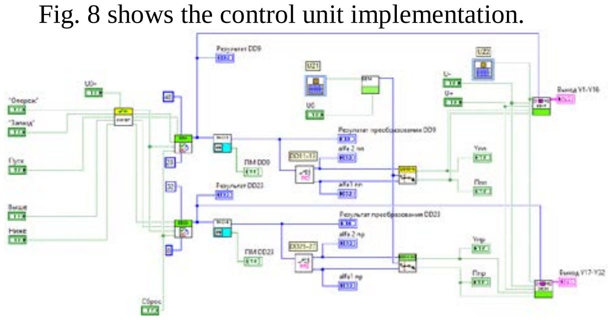

Fig. 8. Control unit of the CS1

The TVR is controlled through a specialized interface of the control panel. The control panel is shown in Fig. 9.

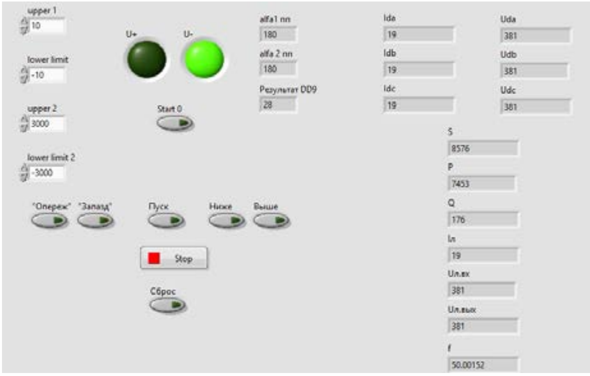

Fig. 9/ Control panel appearance of the CS1

The second level CS (CS2) performs the functions of centralized control and monitoring with the subsequent development of control commands for the CS1, as well as storage, transmission and remote access to information [23].

Fig. 10 shows CS2 functional diagram.

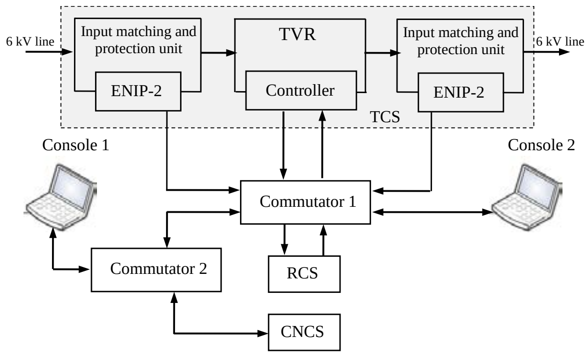

Fig. 10. Functional diagram of the CS2.

To the TVR prototype input and output measuring devices ENIP-2 are connected, it allows to calculate the RMS voltage, current and phase. The monitored parameters are transmitted to CS2 at a specified frequency using the *Modbus TCP* protocol.

The CS2 performs the functions of storage, processing of the received data and further transfer of analyzed parameters to the operator.

In addition, control actions are formed for the CS1. To do this, a connection is established between the CS1 and CS2 controllers via their own data transfer interface.

The CS2 contains two subsystems – CNCS (centralized network control system) and RCS (regulator control system). *XML-RPC* acts as a protocol for exchanging data and control signals in the RCS-CNCS network. The RCS console is used to control RCS configuration parameters.

The CNCS collects and processes information received from the RCS. The stored information can be visualized in the CNCS client and used to form control actions on the CS1.

The devices included in the CS2 are connected to a local area network with a switch via a high-speed *Ethernet* connection. The CNCS system may be remote. For this, a communication channel was organized between the two commutators.

The operation of CS2 is based on the following algorithms:

- data aggregation algorithm received from RCS;
- network state determination and message delayed transmission algorithm;
- emergency situation tracking algorithm by threshold exceeding.

Experimental research was carried out to check the TVR prototype power equipment, control system and the device as a whole.

4 Experimental research of thyristor voltage regulator prototype

TVR prototype research was carried out according to the developed program and methods in four stages: power part testing, CS1, CS2 and prototype as a whole.

4.1 Tests of the TVR prototype power equipment

The following operations were performed when the TVR prototype power equipment testing:

- checking the connection diagrams (transformer and measuring equipment, thyristor switch unit);
- checking the integrity of conductors and semiconductor elements, as well as the reliability of contact connections (checking the insulation of conductors, the integrity of thyristor bodies, circuits of pulse amplifiers);
- checking the supply voltage polarity and magnitude of the boards of the pulse amplifiers;
- checking the local control console.

The following was found based on the results of power unit check:

- 6 kV switchgear insulation resistance is at least 1000 MΩ, 0.4 kV network insulation resistance is at least 1 MΩ;
- 6 kV and 0.4 kV switchgear insulating strength with power frequency test voltage complies with the standards;
- no breakdowns and failures of the main circuits equipment were detected, the electrical circuits are functioning properly, the interlocks are in good order, and no damage has occurred that impedes their further work;
- contact resistance of detachable connections does not exceed 75 μOhm;
- resistance of bolted or welded busbar joints does not exceed 1.2 times the resistance of a busbar section of the same length without joints.

4.2 Tests of the CS1 TVR prototype

The CS1 test consisted in checking the correctness of implementing the thyristor control algorithm and its functioning.

The all control signals tracing was checked. The settings for the main and auxiliary modules of the program were calculated and stored in the read-only memory. Debugging of program blocks in case of emergency situations was performed.

The correctness of switching on thyristors in the transverse, longitudinal and longitudinal-transverse voltage regulation modes was checked.

The correctness of the control pulses formation at the moment of voltage zero crossing was checked.

Fig. 11 shows oscillograms of digital signals on thyristors during testing.

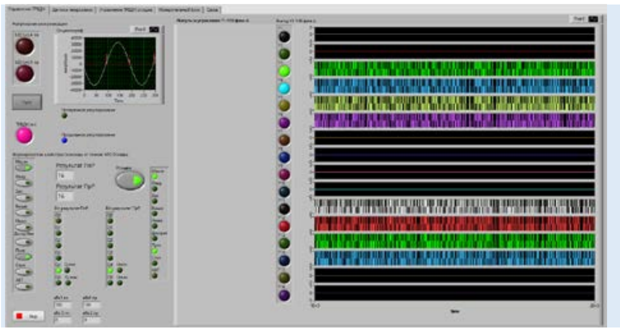

Fig. 11. Control panel of the CS1 controller during testing.

As a result of the research carried out, it was found that in the longitudinal and transverse regulation modes, control pulses by the control system are fed only to the thyristors which are embedded by the algorithm, it indicates the correct operation of the control system.

Fig. 12 shows an example of a control pulse shaping oscillogram.

Research has shown that a synchronizing pulse generated by a high voltage sensor appears at the moment the voltage sine wave crosses zero, which also corresponds to the control algorithm.

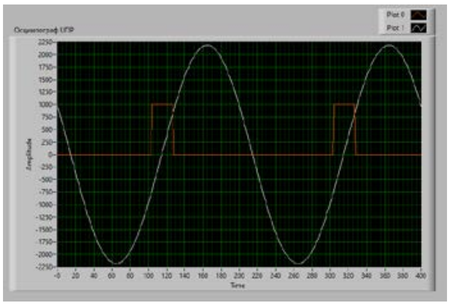

Fig. 12. Synchronizing pulses generated by the high voltage sensor when the voltage sine wave crosses zero from minus to plus.

4.3 Tests of the CS2 TVR prototype

The following was checked when CS2 testing:

- the main subsystems of the actions logic;
- interaction with an external monitoring and control system;
- user interaction;
- centralized collection, storage and processing of data; tracking equipment failures and communication channels;
- notifications of system users about failures;
- protection and authentication.

The signal generators were connected to the appropriate lines and generated signals with the parameters of voltage, current, phase shift within the range of acceptable values. On the service laptop, the console in which the values of the TVR parameters were monitored was launched, and control commands were sent to the CS1.

As a tests result the correctness of CS2 algorithms, the correctness of the executed and transmitted commands, as well as the transmitted and received data, were confirmed. The correctness of displaying the equipment status and communication lines was confirmed.

During the experiments, the correctness of the transmitted alarm messages, the ability to comment, acknowledge, filter, navigate from the message to the object that generated it were confirmed. The functions of displaying and exporting the history of archived alarms and creating sound and mail notifications about emergency events were also confirmed. The correctness of the receipt of sound and mail notifications about failures in communication channels and in equipment was confirmed.

4.4 TVR prototype tests as a whole

Experimental research of TVR prototype as a whole was carried out in the longitudinal, transverse and longitudinal-transverse voltage regulation modes.

Fig. 13 shows an example of the thyristor control pulses shaping oscillogram in the longitudinal regulation mode. When switching the TVR mode numbers, the duration of the control pulses changes, and the filling frequency of the pulses themselves is 10 kHz, which ensures the stability of the thyristor opening process.

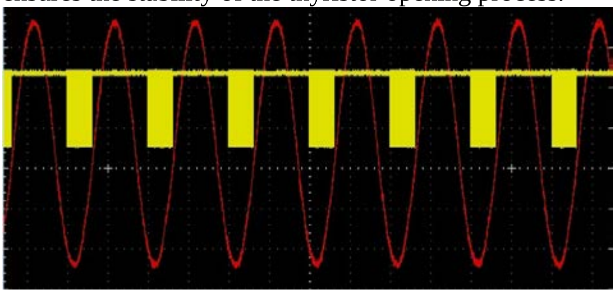

Fig. 13. Oscillogram of forming control pulses for thyristors and synchronizing voltage of *A* phase in longitudinal regulation mode.

Fig. 14 shows the example of the TVR output voltages oscillogram in the longitudinal regulation mode. The analysis of the results showed that the regulation range of the output voltage relative to the input was ± 10%. The regulation discreteness of does not exceed 1.5%.

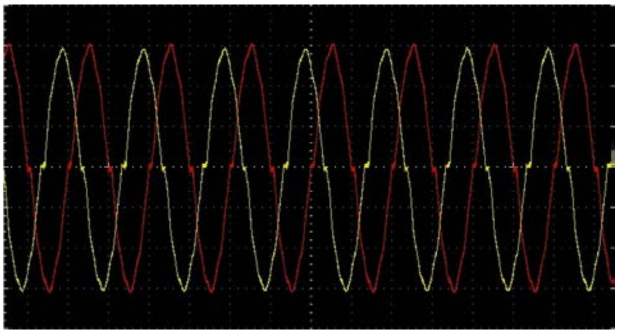

Fig. 14. Output voltages oscillogram of *A* and *C* phases in the longitudinal regulation mode (voltage reduction mode).

Fig. 15 shows the example of the TVR output voltages oscillogram in the transverse regulation mode. The Analysis of the results showed that the output voltage shift angle variation range relative to the input was ± 5˚.

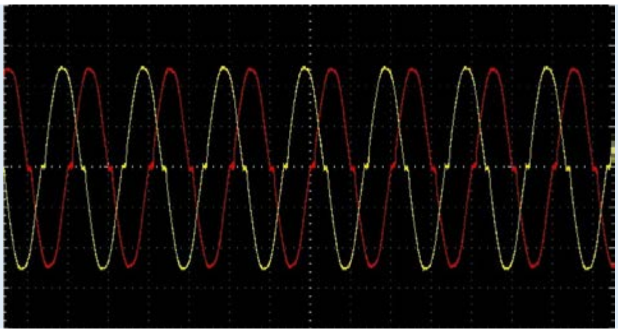

Fig. 15. Output voltages oscillogram of *A* and *C* phases in transverse regulation mode (delay mode).

Fig. 16 shows the example of the TVR output voltages oscillogram in the longitudinal-transverse regulation mode.

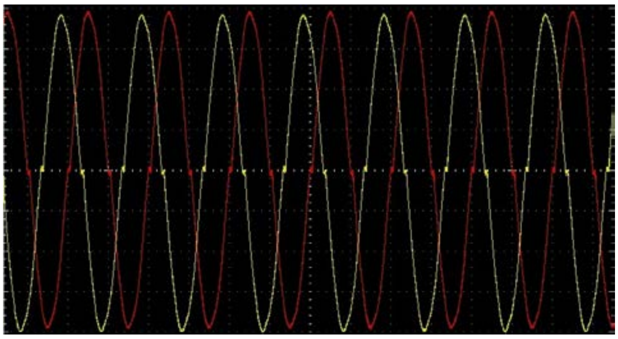

Fig. 16. Output voltages oscillogram of *A* and *C* phases in longitudinal-transverse regulation mode (reduction and delay mode).

The research results have shown the correctness of supplying thyristor control pulses in full accordance with the developed algorithm. It was found that the TVR ES provides smoothness and specified accuracy of voltage regulation in all modes.

5 Conclusion

The electric power systems building on the Internet of energy principle is accompanied by the need to implement flexible flow distribution in networks with a multi-circuit configuration and multiple power sources. The use of a thyristor voltage regulator allows this function to be carried out in 6-20 kV power distribution networks.

The prototype of thyristor voltage regulator has been developed and manufactured, which makes it possible to exercise voltage control in the distribution electrical network, both in magnitude and in phase. It makes possible to redistribute power flows and optimize voltage at the load nodes.

Experimental research of power equipment, first and second level control systems (CS1 and CS2) and TVR prototype as a whole has been carried out.

The power equipment tests showed the correctness of the assembled connection schemes (thyristor switch unit, transformer and measuring equipment), as well as the reliability of contact connections.

A qualitative characteristic of the input and output signals was obtained when the CS1 testing. It was found that the thyristor control pulses were formed according to the developed algorithm.

The correctness of control system algorithms, executed and transmitted commands, transmitted and received data was confirmed as a result of the CS2 tests.

The TVR prototype research results indicated that the device provides smoothness and specified accuracy of voltage regulation in all modes.

The experimental research confirmed the TVR prototype operability and algorithms for its functioning, as well as the prototype readiness for trial operation

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Application of ETAP™ eTraX™ software package for digital simulation of distribution network that feeds an AC traction power supply system.

Vladimir Tulsky[1], Maxim Shevlyugin[2], Aleksei Korolev[2,*], Kamil Subhanverdiev[2], Alexander Murzintsev[1], Ksenia, Zhgun[1], Maksim Silaev[1], Nikita Khripushkin[1], Rashid Baembitov[3]

[1]NRU "Moscow Power Engineering Institute", Moscow, Russian Federation
[2]Russian University of Transport (RUT(MIIT), Transportation Power Systems Department, Moscow, Russia
[9]TEXAS A&M UNIVERSITY, College Station, TX

Voltage unbalance in power systems feeding AC traction power systems is a worldwide known problem. One of the main aspects of this problem is the negative effect of voltage unbalance on motor loads causing operating problems and economic damage. It is necessary to perform unbalanced power flow studies and calculate voltage unbalance indexes to assess this negative effect of voltage unbalance and the develop of compensating measures during the design stage. Usually, calculations of the AC traction power supply system and the distribution network feeding it are carried out separately during the design of new lines of railways electrified by alternating current (AC) and reconstructing of existing ones. This approach is a source of deviations in the power flow studies because the lack of consideration of mutual influences between the traction power system and the distribution power system. In this paper, we compare a digital model in which the traction power supply system and the distribution network are modeled separately with a model that considers mutual influences between the traction and external power supply systems, including power flows through the traction network caused by the distribution network (transit currents). For digital modeling of these processes, authors used ETAP™ software with eTraX™ package. It allows to run unbalanced power flow studies when the generation and load are being changed over time, including train movement. During a separate simulation of the traction power system and distribution network, traction network was modelled using the equivalent sources connected to traction substation buses and the distribution network was modeled taking into account the fact that traction load was given from the simulation of the traction power system. The traction load was considered as lumped loads connected to the traction substation buses.At the same time, in both cases, the unbalanced power flow study was carried out by the phase domain method. Based on the results of two models comparison, it was concluded that the combined model containing a traction power supply system and distribution network, is more effective in terms of improving the accuracy of assessment voltage unbalance in accordance with current regulatory and technical documents on power quality.

1 Introduction

Voltage unbalance is the well-known worldwide important in power grids feeding AC traction power systems. AC traction power system trains are 1-phase loads with huge power consumption causing unbalanced power flows through traction substations. It causes voltage unbalance at all buses of the power system. According to Russian national standard [1] negative voltage unbalance factor (VUF2) should be lower than 2% during 95% of the period of measurement (one week) and lower than 4% at any moment of the same period. According to recent work [2] VUF2 value does not provide the full scope of information to analyze the negative influence of AC traction power system on the other loads in upstream power system including induction motors. It makes necessary to improve the methodology of AC traction power system modeling. In this paper authors compares the traditional way of AC traction power system modeling with equivalent sources with the way using the detailed model of the upstream power system. All results were given using made in ETAP™ software with eTraX™ based on Current Injection method described in [3]. In Russian papers this

* Corresponding author: alex.a.korolev87@gmail.com

approach is described in [4]. The software package is certified under [5]. The idea of detailed consideration of the upstream power system in AC traction power system analysis is known and the examples of the models are described in [6,7]. Consideration of the detailed upstream power system provides the possibility to see power flows of non-traction power through AC traction power system. The traditional models with equivalent sources at each AC traction substation cannot provide these results. The main purpose of this paper is to show the benefits of the co-simulation of AC traction power and the upstream power system and the difference between these two approaches of AC traction power system modeling for design and operation.

2 AC traction power system modeling approaches

2.1 Traditional approach of AC traction system modelling

The design of AC traction power system has a long history of many decades. The implementation of AC traction was necessary to improve the capacity of railway lines to transfer more freight sand to increase the speed of passenger trains. According to limited capabilities of computational devices engineering companies used simplified models to size the equipment of traction substations and find the minimal value of the pantograph voltage. That approach was based on the idea that the power system could be replaced by equivalent sources. Each equivalent source is being represented as a voltage source and the impedance calculated from the fault current at the input bus of the traction substation. All voltage sources have the rated voltage and the same phase zero angle. That model (Fig. 1) makes the feeding of all substations independent without any power flows between substations at the side of the upstream power systems (grid).

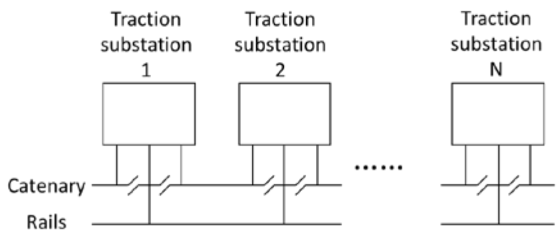

Fig.1. The traditional model of AC traction power system.

2.2 Combined model of AC traction power system and the grid.

The necessity of co-simulation of AC traction power system and the grid could be shown using a simple example (Fig.2) made in ETAP.

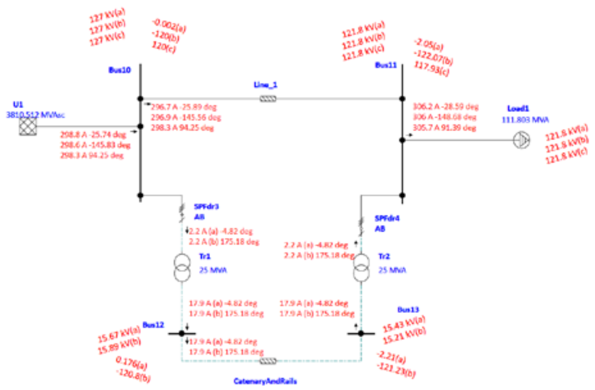

Fig.2. The simple model showing transit currents in the AC traction power system.

This effect is also known as transit currents. This example consist of:

- U1 - Equivalent 220 kV power grid source with 10 kA 3-phase fault current and 12 kV 1-phase fault current. The operation voltage is 100%.
- Line_1 - transmission line with 50 km length, R1=9 Ohm, X1 = 21 Ohm, Y1 = 0.000135 S, R0=16 Ohm, X0 = 70 Ohm, Y0 = 0.000067 S (lumped parameters)
- Single-phase traction transformers 220/27.5 kV Tr1 and Tr2 with 25 MVA, Z=10%, X/R=20 connected to AB.
- CatenaryAndRails – catenary and rails with 50 km length, R=11 Ohm, X=37 Ohm (lumped parameters).
- Load1 – 100% constant power lumped load at the end of the line with 100 MW, 50 Mvar.

This simple example shows that even at no load conditions catenary is an additional transmission line for grid power. The current at 27.5 kV is 17.9 Amps. It is not quite big for the grid (2.2 Amps) but it is important in traction substations modeling. Of course this example does not show the real transit currents and voltage unbalance. It is described in the test case below.

3 Test case description

3.1 Railway, train parameters and train schedule data

The modeling of the traction power system starts from the railway and trains. The volume of freight transportation is being increased. The test case is related to high-load freight railways in Russia. The current typical configuration of a freight train in Russia is 7100 tons driven by 3S5K Yermak locomotive. It has the following rated parameters:

- Rated traction motors power - 9840 kW
- Maximum traction effort - 1017 kN
- Maximum speed – 110 km/h

•Average speed – 49.9 km/h

•Mass – 288 tons.

The traction effort curve added to ETAP library for modeling is shown in Fig.3

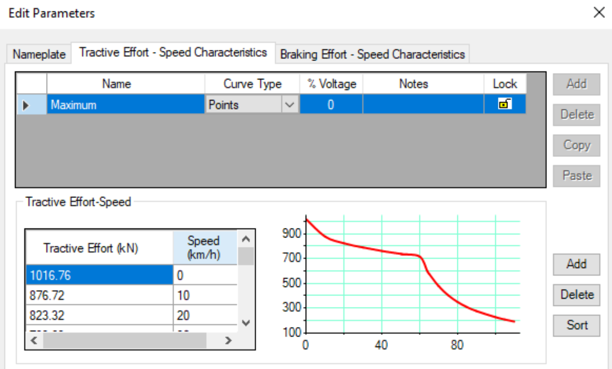

Fig.3. Traction effort curve of Yermak locomotive.

The railway modelled in this test case is two-way 150 km line with 3 stations (at the ends of the line and in the middle) with 5 substations (Fig.4). The elevation profile is assumed as flat.

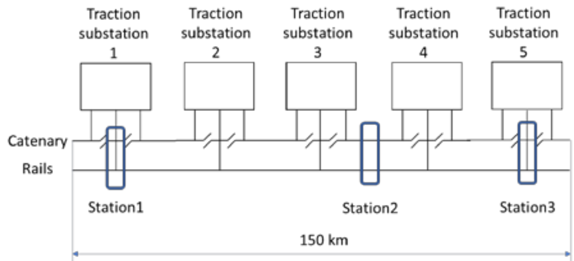

Fig.4. Railway and substations.

The modelled train schedule is 10 min headway and 5 min dwell time (Fig.5).

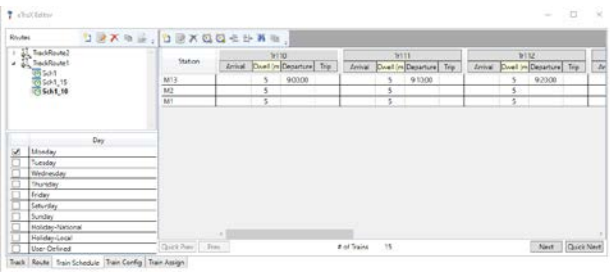
Fig.5. Train schedule.

The modelled configuration of the train is:

•1 3S5K Yermak locomotive (288 tons);

•84 freight cars (85 tons and 7140 tons in total).

Fig.6 shows this configuration.

Order	Quantity	Type	Manufacturer	Model	Weight	% Loaded	Length	Library
1	1	Locomotive	АС Грузовой	3ЭС5К Ермак	288	100	52.5	...
2	84	Passenger	Passenger	Груз.рол_новый	85	100	14	...

Fig.6. Train configuration.

The limit of acceleration was assumed as 0.5 m/s^2. The limit of deceleration was assumed as 1 m/s^2.

The model of the moving train is based on solving of differential equations using numerical integration. The results are:

•Traction effort, kN

•Acceleration, m/s^2

•Speed, km/h

It provides the mechanical power of the train and it is being recalculated to the active and reactive power. These values are being substituted to the location of the train as the constant power load. The model of the constant power load is a good assumption for traction power system analysis because the purpose of the driver and locomotive automation systems is to keep the speed fixed the specific location. Thus we get the necessity to keep the mechanical power as the fixed value regardless of the pantograph voltage level.

3.2 Substations and grid data

All 5 substations has 2 3-phase 3-winding transformers with the following parameters:

•40 MVA rated power

•Rated voltages of windings 230 kV (primary) 27.5 kV(secondary) and 10 kV (tertiary)

•Z_{PS}=17.5 %, Z_{PT}=9.97 %, Z_{ST}=6.68 %

•X/R = 19

Each traction substation also has 3 MVA non-traction load (signaling systems and other loads).

In the normal conditions only one transformer at each substation feeds the catenary.

The modelled grid is 11 bus 220 kV grid with 2 slack bus sources.

Impedance data is presented in Table 1. Load and generation data is presented in Table 2. Fig.7 shows the graphical view of the grid with traction substations. All impedances of lines are considered as lumped values. Bus SS2 also contains shunt reactor with 60 Mvar rating. All traction substation buses (TSS1-TSS5) does not have specified load power because its load is the result of moving trains analysis.

#	Branch ID	Start bus ID	End bus ID	R, Ohm	X, Ohm	Y, µS
1	Z_SS2-3	SS2	3	3.7	16.6	100
2	Z_SS2-4	SS2	4	4.3	19	100
3	Z_SS2-TSS3	SS2	TSS3	1.8	8	50
4	Z_SS2-TSS4	SS2	TSS4	6.5	29	180
5	Z_SS3-2	SS3	2	9.5	40	250
6	Z_TSS2-SS3	TSS2	SS3	4.5	20	120
7	Z_TSS3-SS1	TSS3	SS1	10	48	280
8	Z_TSS4-TSS5	TSS4	TSS5	6	27	160
9	Z_TSS5-1	TSS5	1	10.3	46.1	280

Table 1. Branch data

#	Bus ID	Type	Vmag, % of 220 kV (rated)	Vang, deg.	P, MW	Q, Mvar
1	1	Slack	103.39	-0.25	-	-
2	SS1	Load	-	-	4.3	2
3	3	Load	-	-	11	7
4	4	Load	-	-	10	6
5	SS2	Load	-	-	40	-40
6	TSS1	Load	-	-	Result of analysis	Result of analysis
7	TSS2	Load	-	-	Result of analysis	Result of analysis
8	TSS3	Load	-	-	Result of analysis	Result of analysis
9	TSS4	Load	-	-	Result of analysis	Result of analysis
10	TSS5	Load	-	-	Result of analysis	Result of analysis
11	2	Slack	102.55	-7.93	-	-

Table 2. Bus load and generation data

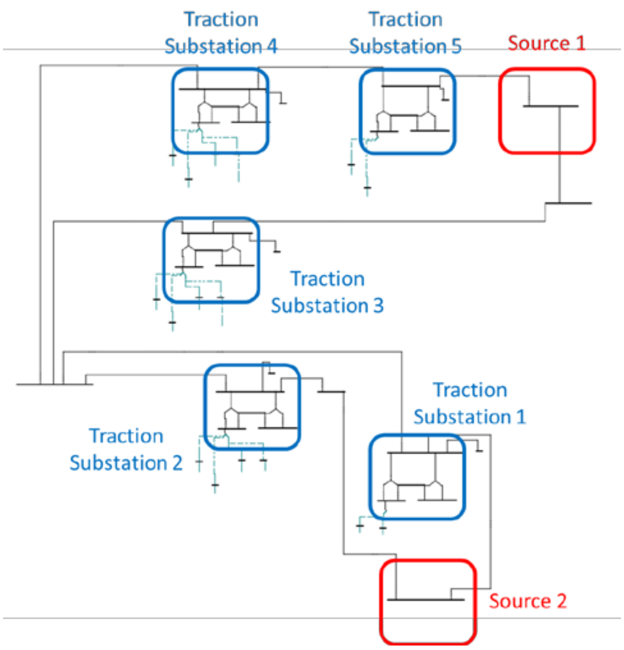

Fig.7. Visual representation of the modeled system

3.3 Equivalent sources modelling

The standard way to calculate equivalent source parameters is to calculate 3-phase and 1-phase faults at the selected bus. It has been done using StarZ module of ETAP. Its main advantage is consideration of prefault power flow. All currents calculated at traction substations buses are shown in Table 3.

#	Bus ID	3-phase fault current, kA	3-phase fault X/R	1-phase fault current, kA	1-phase fault X/R
1	TSS1	4.657	14.78	4.595	14.22
2	TSS2	4.828	14.93	4.522	13.84
3	TSS3	5.131	12.8	4.773	11.93
4	TSS4	3.995	8.98	3.838	8.77
5	TSS5	4.03	7.133	3.942	7.07

Table 23. Equivalent sources data

4 Results analysis and comparison

4.1 Train output results

The result of moving train shows the following curves of Mw and Mvar for one train (Fig.8,9). The simulated time is 3 h 30 mins. Axis X shows time in seconds.

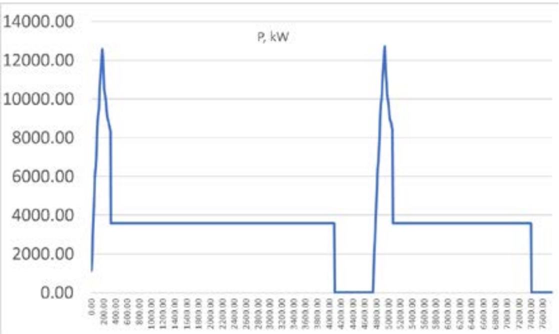

Fig.8. Train active power consumption

Fig.9. Train reactive power consumption.

It shows that the considered train configuration is a high load for the power system. The assumption of the flat elevation profile provides a possibility to compare the energy required to accelerate the train from 0 to 80 km/h and the power need to maintain the speed without additional resistances considering:

- Track elevation
- Track bend radius

In the real case with elevation profile and bend radius of track Mw and Mvar curves of trains will be more complicated and will have more impacts related to acceleration after changing of slope.

Results at Fig.8 and Fig.9 are independent from the upstream grid because it is constant power model but the voltage at the pantograph. But if we compare the current of any train we get the difference shown on Fig. 10. The current in the model with equivalent sources is higher because of the lower source voltage.

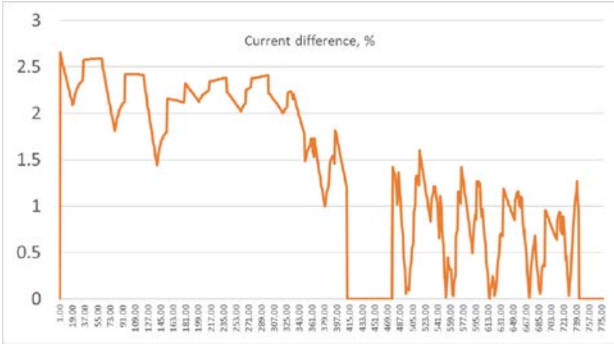

Fig.10. The relative difference between the locomotive current in the equivalent source model and the model with the detailed grid.

4.1 Power system response on traction load

The design and operation of traction power system require assessment of transformers power rating and power quality factors. The kVA function as the sum of power of 3 phases for the 4th substation is shown on Fig.11. This result has been calculated in the model with the detailed grid.

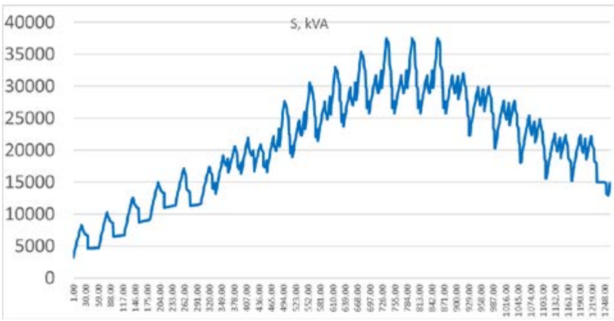

Fig.11. 3-phase kVA versus time for the 3rd substation calculated in the model with the detailed grid.

The calculation in the case with equivalent sources at each traction substation. The Fig. 12 shows the relative difference between P, Q and S calculated in the model with the detailed grid and the model with equivalent sources for the same substation.

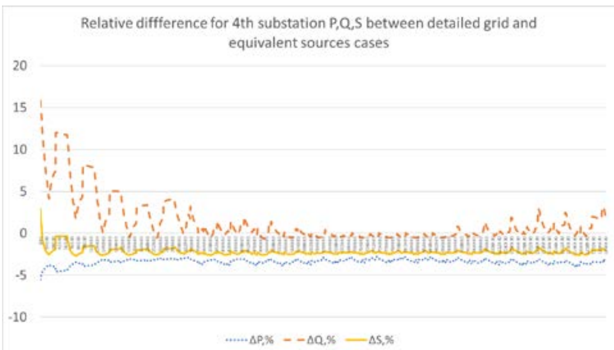

Fig.12. Relative difference between P, Q, S calculated in the model with the detailed grid and model with the equivalent sources.

The difference for this specific substation shows that active power is higher, the reactive power is lower, and the complex power is lower. The result could be different for other grid and other traction power system.

VUF2 in % is one of the most important factors need to be calculated in any unbalance load flow study including AC traction power system analysis. In Russia the limits of this factor are described in the standard [1]. The values of VUF2 calculated for the first substation are shown on the Fig.13.

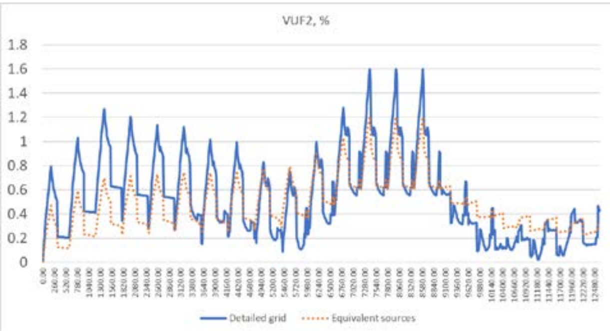

Fig.13. VUF2 calculated at 220 kV bus of 1st substation for the model with the detailed grid and the model with equivalent sources.

This plot shows that the model with equivalent sources provides underestimated values of VUF2. The results for peak loads differs more almost 3 times.

Plots for other substation (Fig.14-17) shows the same effect – VUF2 is higher for the model with the detailed grid.

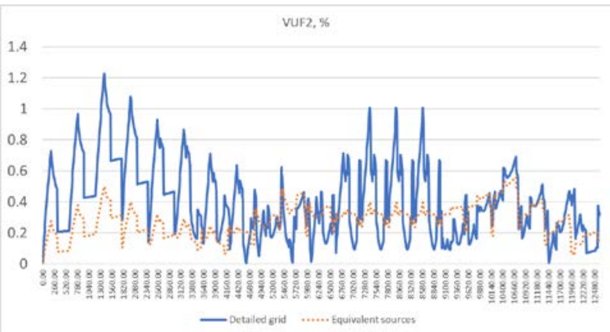

Fig.14. VUF2 calculated at 220 kV bus of 2nd substation for the model with the detailed grid and the model with equivalent sources.

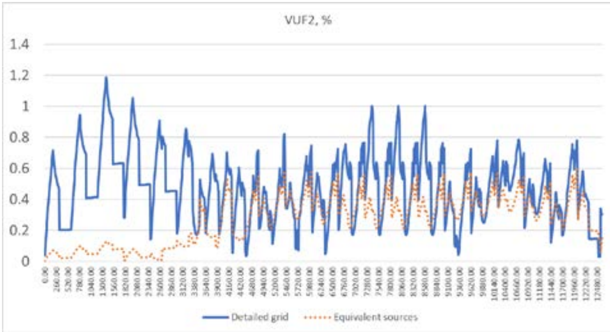

Fig.15. VUF2 calculated at 220 kV bus of 3rd substation for the model with the detailed grid and the model with equivalent sources.

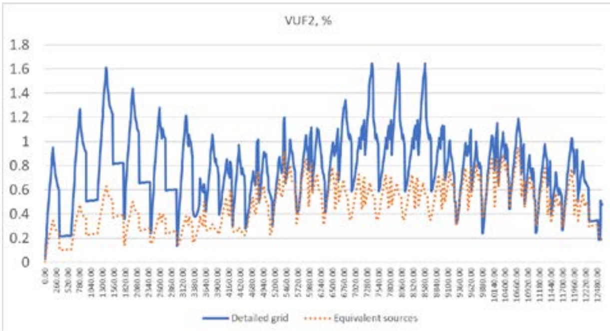

Fig.16. VUF2 calculated at 220 kV bus of 4th substation for the model with the detailed grid and the model with equivalent sources.

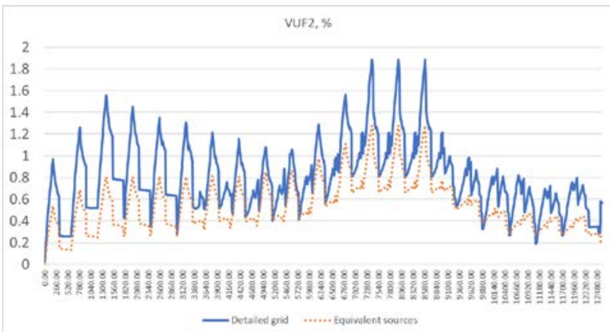

Fig.17. VUF2 calculated at 220 kV bus of 5th substation for the model with the detailed grid and the model with equivalent sources.

Fig.13-17 concludes that the model with equivalent sources underestimates voltage unbalance. The SVC sized using those results will not compensate unbalanced currents in the appropriate state.

It is need also to mention that recent researches described in [2] shows that it is need to consider the relative phase angle between the negative and the positive sequence of voltage at any bus feeding induction motors.

The model with the detailed grid provides the possibility to see values the difference between phase angles of negative and positive sequence of voltage. Fig. 19 shows the function of that angle for Substation 2 (SS2) 220 kV bus (see Fig.18).

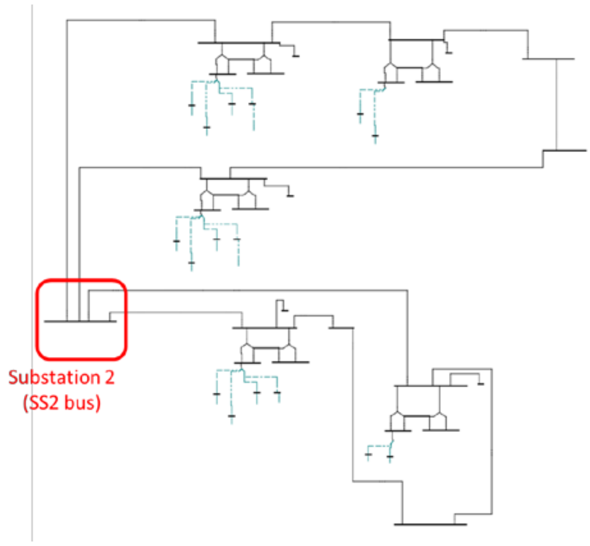

Fig.18. Substation 2 in the model with the detailed grid.

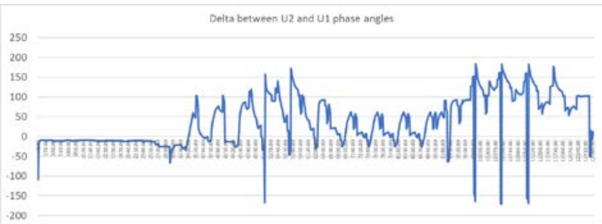

Fig.19. The relative angle between positive and negative sequence of voltage at 220 kV bus of Substation 2 (SS2).

This value also is a good example for comparison of the model with detailed grid to the model with equivalent sources. Fig.20 describes the difference between the relative phase angle between negative and positive sequences.

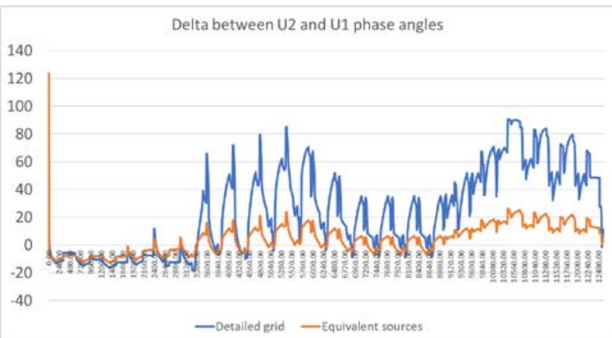

Fig.20. The relative angle between negative and positive sequence of voltage at 220 kV bus of Traction Substation 2 (TSS2).

5 Conclusions

Based on the foregoing, the following conclusions can be made:

1. There is the difference between train current calculated for the compared models with the detailed grid and the equivalent sources at the input bus of traction substations.
2. The compared models show the difference in power flows versus time for each traction substations. It could affect the sizing of traction substations transformers.
3. The model with equivalent sources shows underestimated value of VUF2. It could cause to incorrect sizing of SVC devices.
4. The model with the detailed grid provides the possibility to analyze the value of the relative phase angle between the negative and the positive sequence of voltage at any bus in the system. It is important due to recent studies including [2].
5. The model with equivalent sources shows the lower the value of the relative phase angle between the negative and the positive sequence of voltage at buses of traction substations.
6. The model with the detailed grid is recommended for all studies related to substation transformer and SVC sizing.

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On the power quality of electrical energy supplied to joint stock company “Aleksandrovsky mine”

Oleg V. Zapanov[1], *Lidiia I.* Kovernikova[2,*]

[1]JSC “Aleksandrovsky Mine”, Trans-Baikal Territory, Mogochinsky district, Davenda village, Russian Federation
[2]Melentiev Energy Systems Institute SB RAS, Irkutsk, Russian Federation

Abstract. Joint Stock Company (JSC) “Mine Aleksandrovsky” is located in the Mogochinsky district of the Trans-Baikal Territory. “Mine Aleksandrovsky” concluded an energy supply agreement with JSC “Chitaenergosbyt” for the purchase of electric energy from it. In accordance with the contract, the electric energy supplier undertakes to supply electric energy that meets the requirements of the current legislation of the Russian Federation. The power quality in the Trans-Baikal Territory in most regions does not meet the requirements of State Standard 32144-2013. Suppliers and the network organization are responsible to consumers for the reliability of its electric energy supply and its quality within the boundaries of their electric networks. Despite the obligations of the contract, the electric energy supplied to “Mine Alexandrovsky” does not meet the requirements. In 2017 the ball mill engine in the shredding department of the gold recovery factory failed as a result of power outages and the supply of low power quality through the 6 kV line. The article provides information on interruptions in power supply over the years of operation of the enterprise, the results of analysis of the power quality, information on damage to electrical equipment caused by low power quality, and economic damage.

1 Introduction

In Russia, there is a big problem with the power quality [1]. Before the Law “On Electric Power Industry” was enforced in 2003 [2], the country had had an economic mechanism for managing the power quality. It was presented in three documents [3-5] and obliged both the utility and consumers of electrical energy to deal with its quality. According to these documents, in the event of non-compliance with the requirements of the state standard for the power quality, utilities and consumers would have to incur additional financial costs in the amount of discounts/surcharges to the electricity rates [5]. After the adoption of the Law “On Electric Power Industry”, these documents [3-5] were canceled. New mandatory regulatory and technical documents governing the relationship between the utility and consumers in the field of power quality have not been developed, although the law states that all entities of the electric power industry are obliged to supply consumers with electrical energy, the quality of which corresponds to “technical regulations and other mandatory requirements”. As regards the power quality, the law has not been complied with since it entered into force and is not being implemented at present. After the adoption of the law, market relations began to take root in the power industry. The issues of power quality turned from a technical problem into commercial terms between the consumer of electrical energy and the last resort supplier, which are recorded in the contracts for energy supply and sale/purchase of electrical energy. There are still no regulatory-technical and legal documents that would necessarily regulate the relationship between the consumer and the utility in the field of power quality [1]. The entities of the electric power industry engaged in the power supply to consumers do not want to deal with the power quality themselves, because it is unprofitable, and, as a result, consumers suffer by buying low power quality [6, 7].

2 Description of the Joint Stock Company “Aleksandrovsky Mine”

One of the consumers, which has suffered many times from the poor power quality, is the JSC “Aleksandrovsky Mine”. Its founder is the JSC “Zapadnaya Mining Company” [8]. The JSC “Aleksandrovsky Mine” was founded in 2008 for the development of the Aleksandrovskoye gold-ore deposit in the Mogochinsky district of the Trans-Baikal Territory by open-pit mining. After conducting geological prospecting, a project was developed for the ore extraction and processing, which entailed the construction of the gold recovery plant, hydraulic structures, an ore transportation road, and a rotational camp. In September 2013, the first Aleksandrovsky gold was smelted. It is worth noting that the processing of the mined ore is carried out at the gold recovery plant, where the most efficient beneficiation technologies are adopted

* Corresponding author: kovernikova@isem.irk.ru

and modern equipment supplied under the contract is used [9]. The extraction of gold is 92-93%. The gold recovery plant was constructed according to the documentation prepared by the CJSC "TOMS Engineering" [10]. The company has a year-round continuous operation. It has created more than 650 jobs. By investing money in the organization of production, creating jobs, manufacturing products, paying taxes to the state budget, the company contributes to the development of the country's industry and economy. However, from the very beginning of its work, the plant began to experience difficulties due to the low quality of the supplied electrical energy, and, as a result, numerous stoppages in the production process and long downtime of the gold recovery plant.

3 Power quality problems at the JSC "Aleksandrovsky Mine"

3.1. On the power quality in the agreement for energy supply

The supplier of electricity to the JSC "Aleksandrovsky Mine" is the JSC "Chitaenergosbyt". The JSC "Chitaenergosbyt" in the Trans-Baikal Territory is the last resort supplier, which has to supply (sell) electricity to consumers under the purchase/sale agreements.

A power supply (electricity purchase/sale) contract has been concluded between the JSC "Aleksandrovsky Mine" and JSC "Chitaenergosbyt" [11]. The clause of the contract "Obligations of the Supplier" indicates that the Supplier (the JSC "Chitaenergosbyt") undertakes to "Supply electrical energy (power) under the terms of this contract. The quality and other parameters of the supplied electricity (power) must comply with the requirements of the current legislation of the Russian Federation, including the current technical regulations, and the requirements of State Standard 13109-97 unless the relevant technical regulations come into force. At the time of the contract conclusion, the applicable standard for the power quality was the State Standard 13109-97" [12]. On July 1, 2014, it was replaced by the State Standard 32144-2013 [13], which is the current standard for the power quality. The clause of the contract "Consumer Rights" states that the Consumer (the JSC "Aleksandrovsky Mine") has the right to "receive electrical energy (power) of proper quality under the terms of this contract", and "require maintenance of quality indices of electrical energy at the point of its supply following the requirements of the current legislation of the Russian Federation, including the current technical regulations, and the requirements of the State Standard 13109-97 unless the relevant technical regulations come into force". The contract [11] also indicates that the JSC "Aleksandrovsky Mine" has the third category of power supply reliability.

Consumers in the Mogochinsky District receive electrical energy from the networks of the JSC "Chitaenergo", a branch of the PJSC "IDNC of Siberia". The JSC "Chitaenergosbyt" and the JSC "Chitaenergo" signed an agreement for electricity transmission services [14]. Under the agreement, the JSC "Chitaenergo" undertakes to supply consumers with electrical energy, the quality of which complies with the technical regulations and other mandatory requirements, including State Standards. The JSC "Chitaenergo" also undertakes "to ensure the transmission of electricity received into its network from points of reception to the points of delivery, the quality and parameters of which must comply with technical regulations, State Standard ...". The JSC "Chitaenergo" also undertakes to transfer electrical energy by the agreed reliability category. Under the agreement, the JSC "Chitaenergo" is responsible for "deviation of power quality indices above the values established by the mandatory requirements adopted under the legislation of the Russian Federation". The obligations on the quality of power supply declared by both the JSC "Chitaenergosbyt" and the JSC "Chitaenergo" have not been fulfilled since the time of the JSC "Aleksandrovsky Mine" connection to the JSC "Chitaenergo" networks.

3.2 Consequences of the poor power quality for the JSC "Aleksandrovsky Mine"

Table 1 provides information on the downtime of the gold recovery plant from January 2014 to September 2017, caused by the poor power quality.

Table 1. Information on the plant downtime.

Year	Number of downtimes	Loss of working time, hour:min
2014	130	159:23
2015	140	216:03
2016	133	141:43
2017from January 1 to August 13	691	332:53

Under the power supply agreement [11], the permissible number of shutdown hours for the third category of power supply reliability is 72 hours per year but no more than 24 hours in a row, including the period of power supply restoration. The analysis of the downtime shown in the Table indicates that the permissible number of hours of the power outage was exceeded each year. In 2017, in 7.5 months, it was exceeded 3.9 times. In August 2017, a 35 kV power transmission tower No. 238 fell. The network company was notified of a possible fall in advance, but the repair team arrived at the scene of the accident one and a half days after the notification. As a result, the plant downtime due to just one power interruption was 43 hours 58 minutes, i.e., from 00:10 h: min on August 11 to 19:08 h: min on August 12.

The plant outages were caused by equipment relay trips due to unacceptable voltage rises and drops, and equipment damage. In 2014, the bearings of the 2.2 MW ball mill electric motor were replaced three times. The front bearing was replaced once and the rear bearing - twice. The third replacement of the rear bearing also involved welding the shaft. The cause of bearing damage is voltage imbalance, which causes the rotor vibration and, as a result, accelerated wear of the bearings [15, 16]. In 2015, due to short-term voltage rises, the resistance of the discharge circuit of the high-voltage frequency converter of the 2.3 MW mill was damaged three times. In April 2017, during another unexpected power outage, the asynchronous motor of the ball mill failed.

3.3 Results of the electrical energy tests

In 2015 and 2017, by the decision of the Administration of the JSC "Aleksandrovsky Mine", the power quality indices [17-23] were measured at the point of its transmission from the JSC "Chitaenergo" to JSC "Aleksandrovsky Mine". The point of transmission is located on the border of the responsibility of electrical networks under the contract for technological connection [24]. The electricity transmission points are cable lugs on outgoing feeders in ten 6 kV indoor switchgear cells at the 35/6 kV "Fabrika" substation. In 2017, the power quality indices were measured at cells no. 11 and no. 12. The measurements were carried out by the electrical laboratory of the JSC "IRMET". The measurement results are shown in Tables 2-6. Indices exceeding the standard values [13] are shown in bold in the Tables. As seen in Tables 2 and 3, at both points of electric power transmission, the limits of the indices $\delta U_{(-)}$, $\delta U_{(+)}$, K_U, $K_{U(n)}$, P_{st}, P_{lt}, K_{2U} are exceeded. The values of the measured indices indicate that the voltage deviations in the phases exceed the established norms, the fluctuations in the voltage values exceed the permissible ones, and that the voltage is significantly unbalanced and nonsinusoidal. The measured values of indices K_U, $K_{U(n)}$, K_{2U} exceed the limits established in [13], both for 95% of the measurement time and for 100% of the measurement time.

Table 2. Measured indices of the power quality in cell no. 11.

Index	Cell no. 11			Limit
	Phase A	Phase B	Phase C	
$\delta U_{(-)}$	7.50	**11.40**	**10.30**	10.00
$\delta U_{(+)}$	**10.10**	5.50	9.20	10.00
$K_{U95\%}$	**12.03**	**15.02**	**12.88**	5.00
$K_{U100\%}$	**20.46**	**40.60**	**37.17**	8.00
$K_{U(3)100\%}$	**14.00**	**24.44**	**16.64**	4.50
$K_{U(5)100\%}$	**18.97**	**38.50**	**36.55**	6.00
$K_{U(7)100\%}$	**10.00**	**7.43**	**11.12**	1.50
$K_{U(9)95\%}$	**1.64**	**1.83**	**1.83**	1.00
$K_{U(9)100\%}$	**2.88**	**3.19**	**3.67**	1.50
$K_{U(11)95\%}$	1.97	**2.26**	**2.12**	2.00
$K_{U(11)100\%}$	**3.08**	**3.96**	2.57	3.00
$K_{U(17)95\%}$	1.26	**1.56**	1.21	1.50
$K_{U(27)95\%}$	**0.60**	**0.80**	**0.61**	0.20
$K_{U(27)100\%}$	**1.07**	**1.54**	**0.86**	0.30
P_{st}	**2.65**	**1.75**	**1.72**	1.38
P_{lt}	**1.30**	0.88	0.84	1.00
$K_{2U95\%}$	**4.87**			2.00
$K_{2U100\%}$	**10.01**			4.00

Table 3. Measured indices of the power quality in cell no. 12.

Index	Cell no. 12			Limit
	Phase A	Phase B	Phase C	
$\delta U_{(-)}$	7.80	**10.60**	**11.30**	10.00
$\delta U_{(+)}$	9.70	6.70	9.50	10.00
$K_{U95\%}$	**11.71**	**15.16**	**12.40**	5.00
$K_{U100\%}$	**23.69**	**41.92**	**41.40**	8.00
$K_{U(3)100\%}$	**15.71**	**25.95**	**18.19**	4.50
$K_{U(5)100\%}$	**20.18**	**38.62**	**40.88**	6.00
$K_{U(7)100\%}$	**9.85**	**8.00**	**10.51**	1.50
$K_{U(9)95\%}$	**1.51**	**1.87**	**1.76**	1.00
$K_{U(9)100\%}$	**2.63**	**3.38**	**3.51**	1.50
$K_{U(11)95\%}$	1.84	**2.27**	**2.27**	2.00
$K_{U(11)100\%}$	2.82	**3.72**	2.94	3.00
$K_{U(17)95\%}$	1.13	**1.59**	1.30	1.50
$K_{U(27)95\%}$	**0.51**	**0.85**	**0.62**	0.20
$K_{U(27)100\%}$	**0.90**	**1.77**	**0.86**	0.30
P_{st}	**3.18**	**2.08**	**1.50**	1.38
P_{lt}	**1.30**	0.87	0.72	1.00
$K_{2U95\%}$	**4.96**			2.00
$K_{2U100\%}$	**8.34**			4.00

The data in Tables 4-6 indicate that at both points of the electrical energy transmission there were a large number of overvoltages and voltage dips.

Table 4. Number of overvoltages

Voltage U, % U_O		Duration of overvoltage Δt, seconds		
		$5 \geq \Delta t > 1$	$20 \geq \Delta t > 5$	$60 \geq \Delta t > 20$
Cell no.11	$120 \geq U > 110$	5	35	50
	$140 \geq U > 120$	2	1	0
Cell no.12	$120 \geq U > 110$	4	30	55
	$140 \geq U > 120$	2	1	0

Table 5. Number of voltage dips

Voltage U, % U_O		Duration of voltage dip Δt, seconds		
		$0.2 \geq \Delta t > 0.01$	$0.5 \geq \Delta t > 0.2$	$1 \geq \Delta t > 0.05$
Cell no.11	$90 > U \geq 85$	27	19	17
	$85 > U \geq 70$	2	5	7
	$70 > U \geq 40$	6	0	0
Cell no.12	$90 > U \geq 85$	22	33	6
	$85 > U \geq 70$	2	2	4
	$70 > U \geq 40$	6	0	0
	$40 > U \geq 10$	5	0	0

Table 6. Number of voltage dips

Voltage U, % U_O		Duration of voltage dip Δt, seconds		
		$5 \geq \Delta t > 1$	$20 \geq \Delta t > 5$	$60 \geq \Delta t > 20$
Cell no.11	$90 > U \geq 85$	16	51	84
	$85 > U \geq 70$	9	4	8
	$70 > U \geq 40$	2	0	0
Cell no.12	$90 > U \geq 85$	25	62	78
	$85 > U \geq 70$	9	6	6
	$70 > U \geq 40$	1	0	0
	$40 > U \geq 10$	0	0	0

In addition to the listed violations, the devices measuring the power quality indices recorded a power supply failure at both cells. The graphs of active and reactive powers in Figs. 1 and 2 show that at about 10 minutes past 9 pm, the values of active and reactive power are zero, which means that on April 12, 2017, there was a power outage at the gold recovery plant.

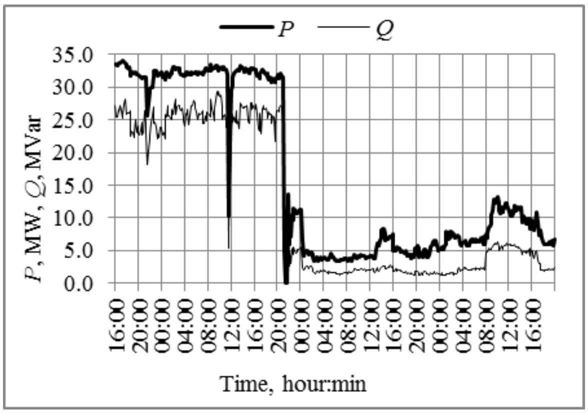

Fig. 1. Graphs of active and reactive powers at cell no.11.

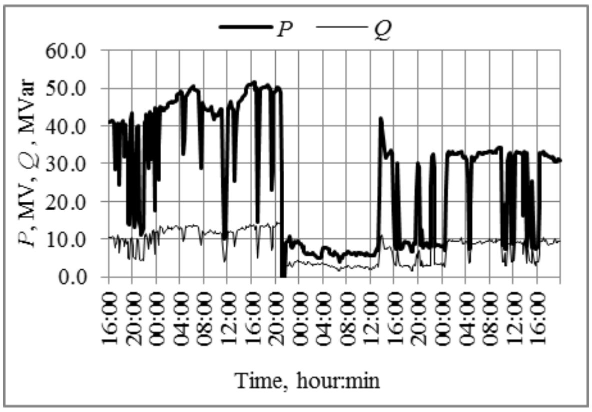

Fig. 1. Graphs of active and reactive powers at cell no.12.

3.4 Economic damage caused by poor power quality

The company calculated the economic damage for the time of lost working hours, shown in Table 1, in the form of lost revenue. The damage assessment results are shown in Table 7.

Table 7. Economic damage.

Year	The average productivity of metal, g/hour	The amount of underproduced metal, g	Lost revenue, thousand roubles
2014	40	6360	9406
2015	112	24192	50924
2016	157	22137	59416
2017 from January 1 to August 13	157	52124	119885
Total		68703	239631

In addition to the losses due to lost revenues, the JSC "Aleksandrovsky Mine" had financial losses in the form of the cost of equipment that was installed instead of the damaged one. The company also incurred the costs to cover the repair of the 35 kV power transmission tower after the fall. The JSC "Chitaenergo" repair team that arrived at the scene of the accident did not have the technical tools to eliminate the accident. The JSC "Aleksandrovsky Mine" was forced to provide them with its equipment, including a bulldozer, an excavator, and two mining dump trucks. The costs of the company amounted to 233 435 rubles.

3.5 Complaints of the JSC "Aleksandrovsky Mine" about the poor power quality

Due to the grave consequences caused by the low power quality supplied to the JSC "Aleksandrovsky Mine", the administration of the company has repeatedly addressed complaints and requests for assistance in improving the power quality to various authorities of the Trans-Baikal Territory since the JSC "Aleksandrovsky Mine" was connected to the JSC "Chitaenergo" electrical networks, i.e., since 2013. Letters about the low power quality have been repeatedly sent to the governor of the Trans-Baikal Territory, the chairman of the government, the first deputy chairman of the government, the minister of natural resources and industry, the director of the JSC "Chitaenergo", the director of the JSC "Chitaenergosbyt". The issues of the power quality supplied to the JSC "Aleksandrovsky Mine" have been repeatedly discussed at the meetings of the Center for Ensuring the Safety of Power Supply in the Trans-Baikal Territory. As a result of the appeals, all the governing bodies of the Trans-Baikal Territory acknowledge the existence of the problem of poor quality, and the fact that that its source is the electrified railway. Railway traction consumers cause voltage imbalance, non-sinusoidality and fluctuations. As a result, the power quality at the consumers receiving electrical energy from a network shared with traction load does not meet the established requirements [13].

The JSC "Aleksandrovsky Mine" is not the only consumer that suffers from the poor quality. The meetings of the Center for Ensuring the Safety of Power Supply on the Territory of the Trans-Baikal Territory have repeatedly considered the issue of the negative impact of voltage imbalance spreading throughout the entire electrical network from the network supplying the railway on the reliability of generating equipment, primarily the Kharanorskaya condensing power plant. The voltage imbalance in the electrical network, to which the plant is connected, leads to the disconnection of power units of the plant by relay protection devices against negative sequence currents, and to the consumer load disconnection by the emergency control devices.

The letter from the director of the JSC "Chitaenergosbyt" to the Federal Antimonopoly Service for the Trans-Baikal Territory dated 11.23.2015 [25] contains the complaints about the poor power quality received by the JSC "Chitaenergosbyt' in 2014 and

2015, from residents of the town of Mogocha, the village of Ust-Karsk, OJSC "Priisk Ust-Kara", LLC RSO "Teplovodokanal", and others. In December 2017, the website of the newspaper "Zabaikalsky Rabochy" reported that "At night from December 9 to December 10, 17 motors and 1 pump at boiler houses and water supply facilities failed in several populated areas of the Mogochinsky District due to power variation. An emergency state was declared in the district" [7].

In August 2017, the JSC "Aleksandrovsky Mine" appealed to the Arbitration Court of the Trans-Baikal Territory with a statement of claim against the JSC "Chitaenergosbyt" to recover the cost of low power quality supplied in April 2017 under the power supply agreement and to compensate for the amount of damage associated with the need to restore the damaged ball mill motor. The statement also contained a claim against the PJSC "IDNC of Siberia" on the company's obligation, within three calendar months from the date of entry into force of the decision of the Arbitration Court, to install a STATCOM (a device for regulating reactive power) on the buses of the 110/35/6 kV "Verkhnyaya Davenda" substation or the 35/6 kV "Fabrika" substation to improve the power quality. In August 2020, three years have passed since the consideration of the case by the Arbitration Court.

4 Conclusions

1. The JSC "Aleksandrovsky Mine" has been facing the problem of the electrical energy quality since its connection to the electrical networks of the JSC "Chitaenergo", i.e., since 2013. The company incurs financial losses due to the poor power quality. Yearslong numerous appeals of the Administration of the JSC "Aleksandrovsky Mine" to higher authorities turned into long-term correspondence and rarely found efficient support and assistance.

2. In Russia, there is no legal mechanism regulating the relationship between the consumers and suppliers of electrical energy in terms of its quality. Last resort suppliers are monopolists in the areas to which they sell electricity. They dictate their terms to consumers but do not fulfill their obligations stipulated in the energy supply agreement.

3. There is no governmental control over such monopolists. The state does not protect the interests of the consumers. In this regard, it is necessary to create an organization of specialists, provided with the required technical tools, which would have the right to conduct expert assessments. Moreover, this organization should be capable of providing legal support to the consumers and deal with the problems of electrical energy quality.

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PASSIVE FILTER DESIGN FOR POWER SUPPLY SYSTEMS WITH TRACTION LOADS

Valery Dovgun[1] , *Denis* Shandrygin[1], *Natalia* Boyarskaya[2] and *Valentina* Andyuseva[1]

[1]Siberian Federal University, 26 Kirensky St., Krasnoyarsk, 660074, Russia.
[2]Krasnoyarsk State Agricultural University, 90 Mira prospect. Krasnoyarsk, 660049, Russia.

Abstract. The purpose of the investigation is to analyze resonant modes in electric power systems that feed the traction load, to study the mutual influence of the traction network and the external power supply system. Simulation model of the power supply system with traction load, implemented with the Matlab/Simulink software package, is considered. The proposed model is used to study the influence of various parameters of the power supply system on resonant modes, including the length of lines, the short-circuit power of the external power supply system, and the spectral composition of locomotive currents. It is shown that the study of resonant modes should consider the traction power supply system and the external network as a single system. Its frequency characteristics depend on both the parameters of the traction network and the parameters of the external power supply system.
The ways to improve technical characteristics of passive filtering systems (PFS) for traction railway networks due to the sustainable choice of passive filter configurations have been investigated. Different PFS that provide compensation for voltage distortions in both the traction and external network have been proposed. They provide the suppression of powerful low-frequency harmonics and the resonant mode damping in the traction network – transformer – external network system. Broadband filters of the 3-5 orders have been proposed to control the characteristics of the traction power supply system.

Introduction

Power electronic converters are the main sources of harmonic current pollution in industrial power networks. Many railway electrification systems (RES) are loaded with conventional AC thyristor-based locomotives, which produce substantial amount of third, fifth and seven harmonic currents [1-4]. Current harmonic distortions can cause overvoltage problems in the locomotive pantograph. Voltage total harmonic distortion in railway traction networks reaches 20 ... 45%.

RES traction substations are supplied by three-phase 220/110 kV power grid. The traction network and power grid are two coupled resonant systems with distributed parameters. Their frequency characteristics have resonance maxima, the frequencies and amplitude of which depend on length of the traction and utility networks, traction transformer impedance, etc [1, 2, 5].

The critical factors negatively affect the traction power supply system efficiency are significant voltage drop at the end of long feeder section, current and voltage harmonics, overvoltages caused by resonant phenomena in the catenary network, and loss of average voltage [1, 3, 4, 6]. Actual values of power quality parameters go beyond the existing standards in the traction network, and in some cases in the utility supply system.

The classical means of reactive power compensation and harmonic distortion attenuation in railway electrification systems are passive and active power filters. Due to their simplicity and reliability, passive filters remain the main means of distortion compensation in HV and MV networks.

In the industrial systems, passive filters have various configurations that give different compensation characteristics. The comparative analysis of the topology and characteristics of passive filters for the industrial power systems was carried out in [7, 8]. However, railway electrification systems have significant differences from industrial ones. This fact is necessary to be considered when choosing compensating devices.

Passive filters for railway electrification systems must perform the following functions [3, 4, 9, 10]:
- reactive power compensation;
- average pantograph voltage increase due to the suppression of powerful low-frequency harmonics;
- damping of resonance phenomena in the traction network and the utility supply system.

This paper investigates the harmonic resonance problems in railway electrification systems. Possibility to improve the technical characteristics of passive filters for RES due to the rational choice of filter configurations is considered. Promising filter options have been selected that provide electromagnetic compatibility of non-linear loads with traction power supply system, as well as with utility supply system.

To study the modes of power supply systems with traction loads, simulation model has been developed in MATLAB/Simulink. Using the proposed model, the mutual influence of the utility supply system parameters and the parameters of traction network have been investigated.

Traction power supply system model

* Corresponding author: shandrigin2012@yandex.ru

The structural diagram of the MATLAB/Simulink model is shown in Fig. 1. It includes 220 kV utility supply system, a power traction transformer, 27.5 kV traction system. The locomotive converter is modeled by shunt connected current harmonic sources.

Utility supply system is modeled by Distributed Parameter Line from Sim Power Systems library. Utility power system is assumed as a pure sinusoidal system and does not contain harmonics. The parameters of utility supply system model are given in Table 1.

The catenary network is modeled as cascade connection of equivalent PI-type sections. Each section corresponds to the 10 km line and has longitudinal impedance and a shunt capacitance.

The parameters of the catenary network model are given in table II.

Table 1. Parameters of the utility supply system model

R, Om/Km	L, mH/Km	C, uF/Km
0,108	1,3	0,0086

Table 2. Parameters of the catenary network

R, Om/Km	L, mH/Km	C, uF/Km
1,33	6,5	0,029

The star-delta connected traction transformer has a rated voltage of 220 / 27.5 kV and the rated power of 40,000 kVA;

The proposed simulation model of the railway electrification system enables to study the influence of the traction network and the utility supply system parameters, the spectral content of the electric rolling stock currents on the level of voltage distortion both in the traction system and in the utility supply system.

RES frequency characteristics and harmonic modeling

Fig. 2 shows the frequency characteristics of the traction network impedance relative to the locomotive pantograph when changing the length of the utility system from 10 to 100 km.

The catenary network length is fixed at 30 km.

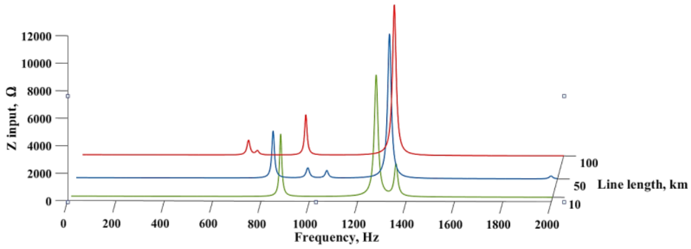

Fig. 2. Frequency characteristics of traction network impedance.

From Fig. 2 it follows that the frequency characteristics of the considered power supply system have resonance maxima in the range of 500 - 1000 Hz. Resonance phenomena can cause both the traction network and 220 kV bus voltage harmonic amplification. The maximum frequencies decrease with the increase of the 220 kV line length. It should also be taken into account that resonance frequencies are also affected by the changes in the utility power system modes.

Typical thyristor-based locomotive current spectrum (% of fundamental) is presented in Table 3. In Table 3 h is the harmonic number.

Table 3. Locomotive current spectrum

h	3	5	7	9	11	13
%	18,16	16,74	18,61	17,87	18,12	31,08

Figure 3 shows the locomotive pantograph voltage spectra. The voltage spectra on the primary side of traction transformer are shown in Fig. 4. In all cases, the harmonic frequencies close to the resonant frequency of the system show significant amplification. In this context, locomotive pantograph voltage total harmonic distortion may exceed 40%. Voltage total harmonic distortion on the primary side of traction transformer reaches 4.6%, which exceeds the maximum permissible values determined by Russian and international standards.

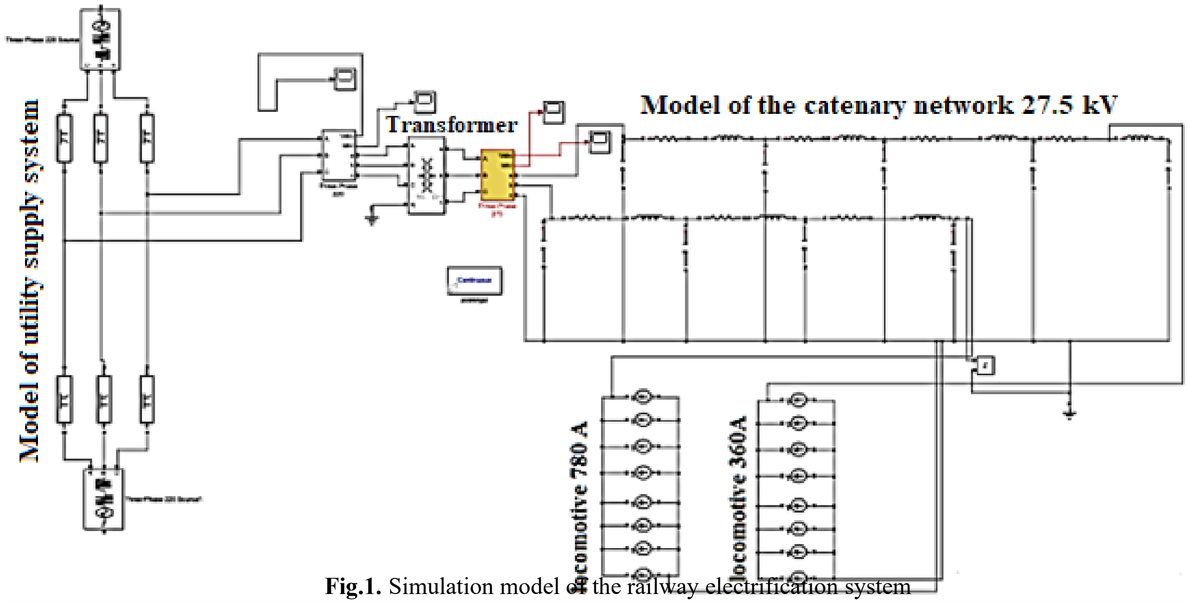

Fig.1. Simulation model of the railway electrification system

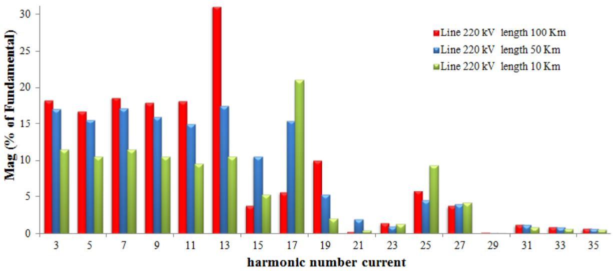

Fig.3. The voltage spectrum of the locomotive pantogaph.

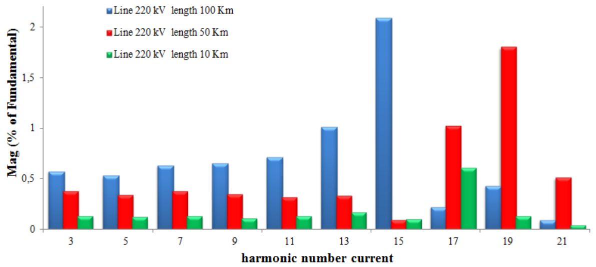

Fig. 4. Voltage spectrum on the primary side of the traction transformer

RES model simulations have shown that the utility supply system and traction network represent two coupled systems with distributed parameters. Resonance phenomena that occur in this coupled system affect both the traction network and the utility power system. Thus the key factors of the power quality normalization in the railway traction systems are the harmonic pollution mitigation and damping for harmonic resonance.

Filter design for railway electrification systems

Traditional means of reactive power compensation in AC RES feeding thyristor-based locomotives are single-tuned (narrow-band) filters tuned to a resonance frequency close to 150 Hz [5, 11]. This filter includes series connected capacitor bank and a tuning reactor. In some cases, two-resonance filters are used to provide reactive power compensation and suppress the most powerful 3rd and 5th harmonics of the traction load current [10]. The disadvantage of single-tuned filters is that they suppress low-frequency harmonics but do not damp the resonance maxima of the frequency characteristics. Another disadvantage of single-tuned filters is that they form parallel resonant circuits with traction system inductance, which leads to the additional resonant modes.

In RES, it is necessary to install more efficient compensating devices, which can suppress the most powerful low-frequency voltage harmonics and reduce overvoltage due to the resonant mode damping. Such devices are needed primarily for RES that are powered by weak power systems with low fault level. It is necessary to search for new, more efficient structures of passive filters that provide electromagnetic compatibility of traction system and utility supply system.

An alternative to narrow-band resonance filter is damping broadband filter (BBF). Fig. 5 illustrates the second-order broadband filter configuration. Filter impedance is given by the following expression

$$Z\left(j\omega\right) = R\frac{-\omega^2 + j\omega\frac{1}{RC} + \frac{1}{LC}}{j\omega\left(j\omega + \frac{R}{L}\right)} \qquad (1)$$

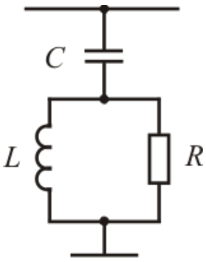

Fig. 5. Second-order broadband filter

Filter resonant frequency $\omega_0 = 1/\sqrt{LC}$. At frequencies above ω_0, the filter has low impedance. This provide resonance mode damping and high-frequency harmonic attenuation. The quality factor of the second order broadband filter is determined by:

$$Q = \frac{R}{\sqrt{L/C}} \qquad (2)$$

For a second-order BBF, typical values of Q vary in the range of 0.5-5.

The simplest broadband passive filters of the 1-2 order for RES are considered in [2, 3, 12]. The analysis conducted in [9, 10] showed that the use of broadband damping filters provides reducing the locomotive pantograph voltage total harmonic distortion, attenuate overvoltage due to the resonance mode damping and increase the average pantograph voltage value. Broadband filters are appropriate for randomly varying loads. The disadvantages of the simplest 1-2 order BBF are poor selectivity of the frequency characteristics and large fundamental frequency power losses.

To reduce losses, C-type broadband filters with zero fundamental frequency reactance are used [9, 13]. In C-type filter, an additional capacitor is connected in series with the reactor in the shunt branch (Fig. 6). The series circuit $L - C_2$ is tuned in resonance to the fundamental frequency. This decreases power losses in the damping resistor of the filter at the fundamental frequency.

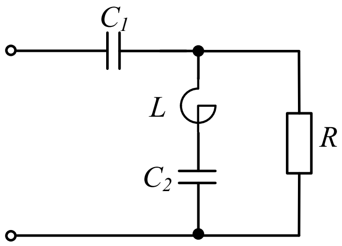

Fig. 6. C-type filter

C-type filter resonant frequency:

$$\omega_0 = \sqrt{(C_1 + C_2)/LC_1C_2} \qquad (3)$$

The main advantage of C-type filter compared to second-order broadband filter Fig. 5 is lower fundamental power losses. However, this leads to the large range of capacitors. Capacitors C_1 and C_2 in the circuit (Fig. 6) are related as follows

$$C_2 = C_1\left(n^2 - 1\right) \tag{4}$$

where n is number of the harmonic to which the filter is tuned. The large total capacity of the passive filter in Fig. 6 significantly increases the cost of the device. In addition, fundamental power losses are achieved if the series oscillatory circuit $L - C_2$ is precisely tuned to the fundamental frequency. The filter fundamental frequency losses increases significantly when changing the tuning frequency caused by a variations of the shunt branch inductance or capacitance.

Another way to reduce losses at the fundamental frequency can be implemented in ladder broadband filters [14]. Third- and fifth-order broadband filters are shown in Fig. 7. This filters are single-ended ladder LC two-ports. The advantage of such structures compared to the C-type filters is significantly lower total capacitance of the capacitors. In addition, ladder filters have lower sensitivity to parameter variations.

Analytical expressions for calculating the third and higher order filters are very cumbersome and only special cases can be designed. For example, author of [15] considered the condition C1 = C2. It is, therefore, logical to use optimization methods to determine the parameters of broadband damping filters.

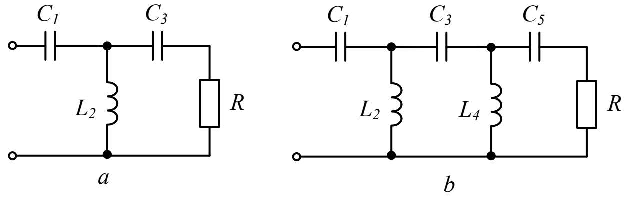

Fig. 7. 3-order broadband filter (a), 5-order broadband filter (b)

The BBF design problem is considered as an optimization problem with constraints, and may be written in the following form: find the values of the filter elements that provide a minimum of the objective function:

$$\Phi(\bar{x}) = \sum_{(k)} w_k \frac{\left|Z_c(j\omega_k)\right|^2 \left|Z_ф(j\omega_k,\bar{x})\right|^2}{\left|Z_ф(j\omega_k,\bar{x}) + Z_c(j\omega_k)\right|^2} J_k^2,\ k = 1,2,\ldots,\ \bar{x} \in \{L_i, C_i\} \tag{5, a}$$

Subject to:

$$\left(\mathrm{Re}\left\{\frac{1}{Z(j\omega_1,\bar{x})}\right\} \Big/ \mathrm{Im}\left\{\frac{1}{Z(j\omega_1,\bar{x})}\right\} \right) \le K_0 \tag{5, b}$$

In the formulas (5):

$Z_ф(\bar{x}, \omega_k)$ - input impedance of a BBF at the frequency ω_k;

$Z_c(\omega_k)$ - impedance of the catenary network at the frequency ω_k;

w_k - weighting factors considering the importance of k term. Constant K_0 determines the maximum value of the active to reactive filter power dependence at the fundamental frequency.

Inequality (5, b) determines the permissible value of the active to reactive PFS power ratio at the fundamental frequency.

Note that the proposed optimization procedure takes into account the spectrum of the current generated by the locomotive, as well as the RES frequency characteristics. The designed filter provides the minimum value of the pantograph voltage total harmonic distortion by suppressing low-frequency harmonics and the resonant mode damping.

Table 4 show the values of the BBF parameters calculated with the proposed optimization procedure. The filters reactive power is 4000 kvar.

Table 4. The element values of 3-5 order broadband filters

N	C_5, uF	L_2, mH	C_3, uF	L_4, mH	C_5, uF	$R_н$, Om
3	8,5	46,6	4,67	-	-	135
4	8,5	31,0	3,95	97,6	-	135
5	8,5	35.2	1.89	56.7	4.1	135

Case study

The proposed passive filtering system (PFS) consists of two sections. The low-frequency section represents a narrow-band filter tuned to a frequency close to the most powerful third harmonic (145 Hz). The second section is implemented by a broadband filter, which attenuates high-frequency harmonics ($h \ge 5$) and damps resonance phenomena in the RES.

Let's consider three options for broadband filters. Filter power is the same and equals 4036 kvar

Case 1. The PFS with third-order broadband filter. BBF parameters were calculated using the proposed procedure. PFS circuit is shown in Fig. 8. The values of the filter elements are given in Table.5.

Case 2. The PFS with C-type filter. PFS circuit is shown in Fig. 9. The values of the filter elements are given in Table. 5.

Case 3. PFS consists of two narrow - band filters tuned to 3rd and 5th harmonic. PFS circuit is shown Fig. 10.

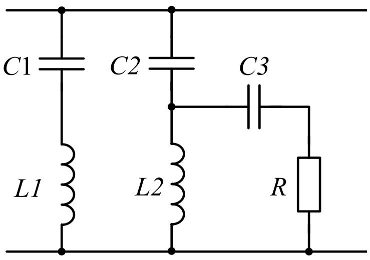

Fig. 8. PFS with 3-order BBF

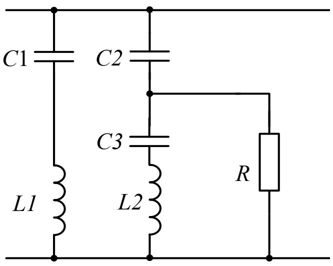

Fig. 9. PFS with C-type BBF

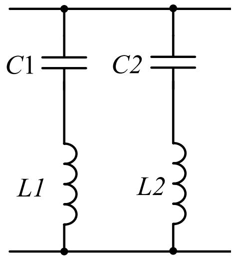

Fig. 10. PFS with two narrow - band filters

Table 5. Element values of PFS with 3-order BBF and PFS with C-type BBF

N	C_1, uF	L_1, mH	C_2, uF	L_2, mH	C_3, uF	R_H, Om
3	8,5	141,8	8,5	38,73	2,2	135
C	8,5	141,8	8,5	58	175	250

The frequency characteristics of the input impedance relative to the locomotive pantograph after the installation of compensating devices are shown in Fig.11.

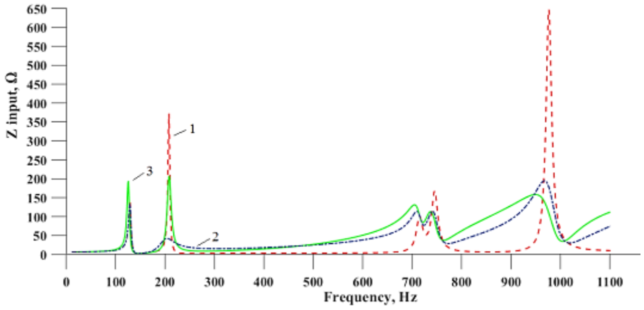

Fig. 11. Frequency characteristics of the RES input impedance after the installation of compensating devices: 1- PFS with two narrow - band filters, 2-PFS with C-type BBF, 3- PFS with 3-order BBF

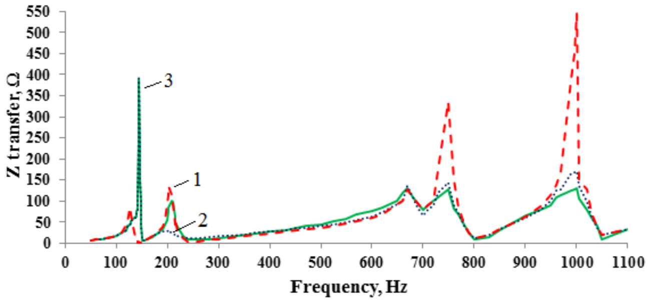

Fig. 12 Frequency characteristics of the RES transfer impedance after the installation of compensating devices: 1- PFS with two narrow - band filters, 2-PFS with C-type BBF, 3- PFS with 3-order BBF.

Figure 13 shows the locomotive pantograph spectra after the installation of compensating devices.

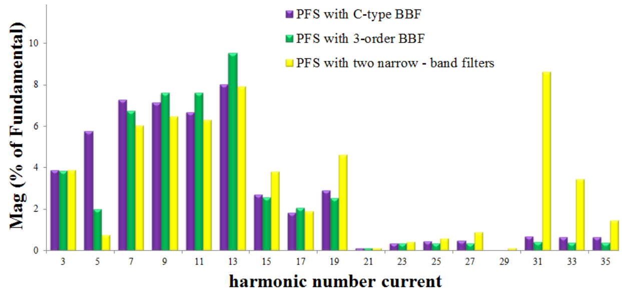

Fig. 13. Voltage spectrum on the primary side of the traction transformer.

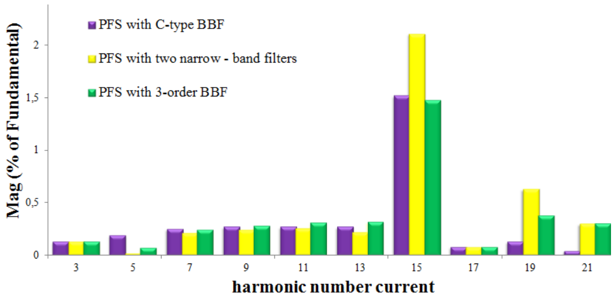

Fig. 14. Voltage spectrum on the primary side of the traction transformer.

Table 6 shows the values of the harmonic voltage coefficients when after the installation of compensating devices.

Table 6. The values of the harmonic coefficients 27,5 kV, %

Filter option	The values of the harmonic coefficients 27,5 kV, %							
	$K_{U(3)}$	$K_{U(5)}$	$K_{U(7)}$	$K_{U(9)}$	$K_{U(11)}$	$K_{U(13)}$	$K_{U(15)}$	K_U
Without PFS	18,16	16,74	18,61	17,87	18,12	31,08	3,87	52,64
PFS with C-type BBF	3,88	5,76	7,28	7,16	6,69	8,02	2,71	16,82
PFS with two narrow - band filters	3,88	0,76	6,05	6,49	6,30	7,93	3,82	18,11
PFS with 3-order BBF	3,86	2,01	6,75	7,61	7,63	9,54	2,59	17,03

Table 7. The values of the voltage harmonic coefficients on the primary side of the traction transformer 220 kV, %								
Filter option	The values of the harmonic coefficients 220 кV, %							
	$K_{U(3)}$	$K_{U(5)}$	$K_{U(7)}$	$K_{U(9)}$	$K_{U(11)}$	$K_{U(13)}$	$K_{U(15)}$	K_U
Without PFS	1,16	1,17	1,49	1,78	2,57	8,94	1,83	10,4
PFS with C-type BBF	0,13	0,19	0,25	0,27	0,27	0,27	1,52	1,64
PFS with two narrow - band filters	0,13	0,02	0,21	0,24	0,26	0,22	2,11	2,18
PFS with 3rd-order BBF	0,13	0,07	0,24	0,28	0,31	0,32	1,47	1,59

Comparison of the analysis results shows that PFS with broadband damping filters provide more effective voltage harmonic attenuation in the frequency range exceeding 250 Hz. Due to this, the negative impact of railway traction system on wired communication devices and signaling system is reduced.

Conclusion

In this paper power quality problems of railway electrification systems are considered. In is shown that railway traction network and external grid are coupled resonance systems. A passive filtering system for harmonic mitigation and resonance damping in RES is considered. System consists of parallel connection narrow-band third harmonic filter and a broadband section. The method for design of arbitrary order broadband filters is proposed. The proposed filtering system is effective for harmonic mitigation and resonance damping.

Modeling showed that PFS with the 3-5 order broadband filters have significant technical advantages over devices based on narrow-band sections and simple damping circuits. The proposed PFS provides more effective high-frequency voltage harmonic attenuation, has lower losses at the fundamental frequency and lower total capacitance.

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Estimation of Power Losses Caused by Supraharmonics

Alexander Novitskiy[1,*], *Steffen Schlegel*[1], and *Dirk Westermann*[1]

[1]Technische Universität Ilmenau, Department of Electrical Engineering and Information Technology, 98693 Ilmenau, Germany

Abstract. Nowadays increases the number of power electronic devices in distribution electrical networks rapidly. Modern generation and consumption units use high switching frequency power converters for the network connection and therefore cause the voltage and current distortion in the frequency range over 2 kHz (so-called "supraharmonics") in addition to conventional harmonics. Supraharmonics cause additional power losses in electrical equipment. The goal of the offered paper is the estimation of power losses caused by supraharmonics. The estimation is based on the measurement results obtained in a real MV/LV network in Germany.

1 Introduction

The increase in the number of power electronic devices in distribution electrical networks is the characteristic trend in the development of electric power supply during many years. Modern generation and consumption units use high switching frequency power converters for the network connection and therefore cause the voltage and current distortion in the frequency range over 2 kHz (so-called "supraharmonics") in addition to conventional harmonics.

The presence of harmonic and supraharmonic distortion in electrical networks has a direct influence on the power and energy losses in the electrical equipment. The harmonic and supraharmonic currents cause the additional Joule heating of conductors and therefore increase the total power losses in these conductors.

The conductor resistance grows with the growth of the frequency and therefore relative small harmonic or supraharmonic currents can cause notable power losses.

In [1-3] is shown that additional power losses in LV cables and HV transmission lines caused by conventional current harmonics can be up to 30% regarding the power losses at the fundamental frequency.

The influence of supraharmonics on the additional power losses can be illustrated using the simplified assumption that the values of the line conductor resistances are proportional to the root of the frequency [2-5]:

$$R_{sh} = R_1 \sqrt{h} \quad (1)$$

where R_{sh}, R_1 – resistance values at the supraharmonic frequency f_{sh} and at the fundamental frequency f_1 respectively, $h = f_{sh} / f_1$ is the harmonic order.

Using the calculation formula for the Joule heating and taking into account (1) the relative values of additional power losses caused by supraharmonics can be calculated as follows:

$$P_{Lsh} / P_{L1} = (I_{sh} / I_1)^2 \sqrt{h} \quad (2)$$

where P_{Lsh}, P_{L1} – power losses caused by the supraharmonic current I_{sh} at the frequency f_{sh} and by the current I_1 at the fundamental frequency f_1 respectively.

The dependences (2) are presented in Fig. 1 for some ratios of I_{sh} / I_1.

It can be seen from Fig. 1 that additional power losses caused by a supraharmonic can be e.g. 10% and more regarding the power losses at the fundamental frequency and therefore cannot be neglected in the calculation of total power losses in electrical networks. The exact values of additional power losses are depending on the supraharmonic frequency and on the ratio I_{sh} / I_1.

It must be noted that (1) and (2) are valid mainly for overhead transmission lines.

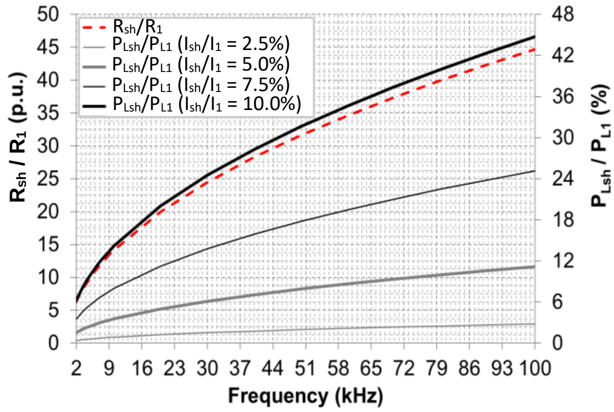

Fig. 1. Relative supraharmonic power losses (2) and the corresponding ratio R_{sh} / R_1

The estimation of power losses caused by supraharmonics in a cable feeder under real operating conditions is presented below. The estimation is based on the measurement results obtained in a real MV/LV network in Germany [6].

* Corresponding author: Alexander.Novitskiy@TU-Ilmenau.de

2 Measurements of supraharmonics

Results of the measurements carried out in the real MV/LV electrical network presented in Fig. 2 were used for the estimation of the impact of supraharmonics on the power losses in MV cable feeders.

The network supplies different settlments with mainly residential and commercial loads and contains a lot of decentralized renewable energy generating units. The network contains a MV wind plant and several solar parks (MV PV plants) distributed over the whole network and connected to the MV grid via dedicated transformers. Several powerful wind parks are located in the upstream HV network. Numerous LV PV power plants are connected in downstream LV distribution networks together with other power electronic devices using high switching frequency power converters like charging stations, consumer electronics, etc. via local area step-down MV/LV transformers.

Measurement devices SIRIUSi-HS [7] were located at the measuring points MP1 – MP3 and operated with the sampling rate 100 kHz. Supraharmonic voltage and current 200 Hz groups (according to [8, 9]) were recorded as 1 minute average values over the measuring interval of 2 weeks.

Power quality (PQ) parameters were measured at MP1 – MP3 in addition.

Instantaneous voltage values (sampling rate 10.240 kHz) and some PQ parameters as 1 sec average values were recorded at the measuring points W1-W24 (LV network) using measurement devices WeSense [10].

Influences of renewable energy sources on the supraharmonic distortion and the propagation of the supraharmonic distortion in the network under study were analysed in [6, 11, 12].

Power losses estimation in the supraharmonic frequency range can be done using the supraharmonic currents measured in the MV feeder at the distribution station. This is the measuring point MP2 (Fig. 2).

Measuring device at MP2 was connected to the secondary side of the instrument current transformer via current clamps. Current clamps were certified for the measurements in the frequency range up to 100 kHz.

The applicability of the standard MV instrument current transformer for the measurements in the supraharmonic frequency range was estimated taking into account IEC Technical Report 61869-103 [13] and investigation results [14, 15].

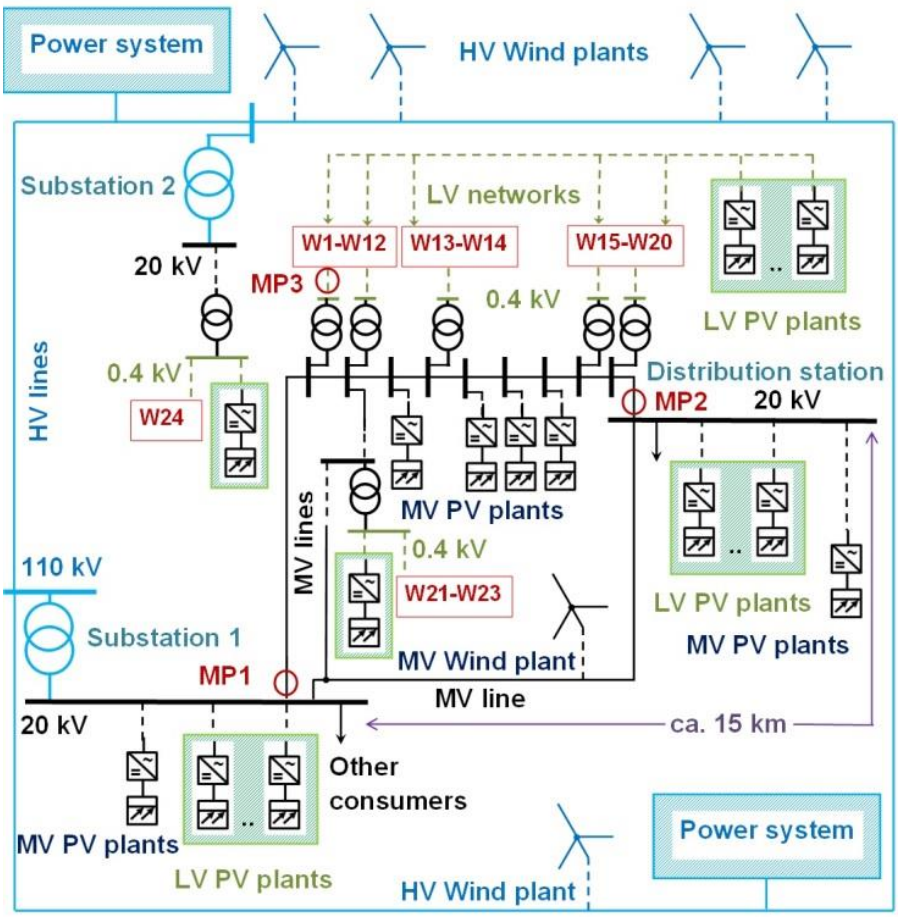

Fig. 2. MV/LV network under study and location of measuring devices

Supraharmonic frequency range is divided into a row of subranges. The supraharmonics in the frequency subrange up to 9 kHz are the subject of special consideration in the IEC standards for compatibility levels for conducted disturbances and signalling in public medium-voltage [16] and in low-voltage power supply systems [17]. Technical requirements for the connection and operation of customer installations to the MV network in Germany contains admissible values for the supraharmonic currents in the frequency range 2 to 9 kHz [18]. Therefore is necessary to pay special attention to the transfer characteristics of MV instrument current transformers in the frequency range 2 to 9 kHz.

In [13] is noted that inductive current transformers are suitable for the use in the supraharmonic frequency range 2 to 9 kHz. Taking into consideration the measured frequency dependences for ratio and phase errors of MV instrument current transformers presented in [14] and [15] it can be concluded that the supraharmonic currents can be measured using standard MV instrument current transformers with a sufficient accuracy (amplitude errors up to a few percent) for the simplified estimation of power losses in the frequency range 2 to 9 kHz.

Examples of measured current spectra in the MV feeder (MV distribution station, measuring point MP2) are presented in Fig. 3 and 4.

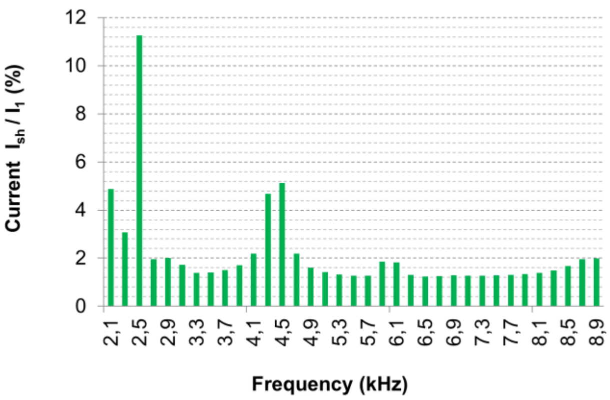

Fig. 3. Measured current spectrum, 95% quantiles of 1 min average values, 200 Hz groups, measurement time 24 h, MP2

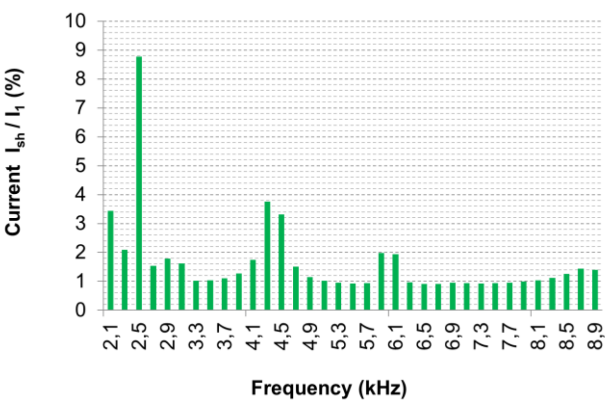

Fig. 4. Measured current spectrum, 95% quantiles of 1 min average values, 200 Hz groups, measurement time one week, MP2

It can be seen from Fig. 3 and 4 that the current spectra are characterized by the domination of the supraharmonic component 2.5 kHz. In [6, 12] is shown that the components 2.5 kHz in the network under study are mainly caused by the operation of the MV wind plant.

The components 5.9 and 6.1 kHz are caused by the daily operation of solar plants, the components 4.3 and 4.5 kHz are caused by the changes of operating points of connected units.

The measuring point MP2 is the connection point of the MV cable 3x1x150/25 to the busbar of the distribution station. This MV cable connection contains three single-core cables with aluminium conductors of 150 mm^2 and copper screens of 25 mm^2 for each cable.

Determination of the frequency dependences for the cable resistances is considered below.

3 Determination of the frequency dependences for the cable resistances

3.1. Analytic calculation method

Calculation of AC resistance of conductor is a part of the IEC standard [19]. In [19] is noted that the AC cable conductor resistance is depending on the skin and on the proximity effects. The following formula can be used:

$$R_{sh} = R'_{DC}\,(1+Y_S+Y_P) \qquad (3)$$

where R_{sh} –conductor resistance at the supraharmonic frequency f_{sh}, R'_{DC} – DC resistance of conductor at the maximum operating temperature θ, Y_S – skin effect factor, Y_P – proximity effect factor.
The values of Y_S and Y_P are depending on the values of the factors X_S and X_P as follows:

$$X^2_S = (1 / R'_{DC})\; 8\pi f_{sh}\; 10^{-7}\; k_S \qquad (4)$$

and

$$X^2_P = (1 / R'_{DC})\; 8\pi f_{sh}\; 10^{-7}\; k_P \qquad (5)$$

where k_S, k_P – coefficients, e.g. k_S = 1 and k_P = 1 for cables with copper or aluminium solid conductors[19].
The skin effect factor Y_S is given by the following equations [19]:

For $0 < X_S \le 2.8$

$$Y_S = (X^4_S / 192 + 0.8\, X^4_S) \qquad (6)$$

For $2.8 < X_S \le 3.8$

$$Y_S = -0.136 - 0.0177\, X_S + 0.056\, X^2_S \qquad (7)$$

For $3.8 < X_S$

$$Y_S = 0.354\, X_S - 0.733 \qquad (8)$$

The proximity effect factor Y_P according to [19] can be calculated only if the factor X_P does not exceed 2.8.

It can be seen from (4) and (5) that $X_P = X_S$ for the cables with solid conductors taking into consideration the assumption $k_S = k_P = 1$ [19].

The values of X_P and X_S calculated according to (4) and (5) for the cables with solid aluminium conductors are presented in Fig. 5 and 6. The values R'_{DC} in (4) and (5) were determined for each cross-sectional area according to [20] taking into account the standard formula [19]:

$$R'_{DC} = R_{DC}\,[1+\alpha_{20}\,(\theta\text{-}20)] \qquad (9)$$

where R_{DC} – DC resistance of conductor at 20°C, R'_{DC} – DC resistance of conductor at the maximum operating temperature θ, α_{20} is the constant mass temperature coefficient at 20°C per Kelvin.

The calculation results for the operating temperature 20°C are presented in Fig. 5, the calculation results for the maximum operating temperature 90°C are presented in Fig. 6.

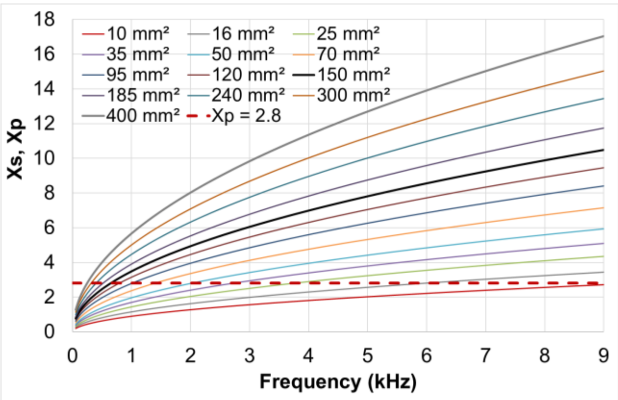

Fig. 5. Factors X_S and X_P for cable aluminium solid conductors at the operating temperature 20°C

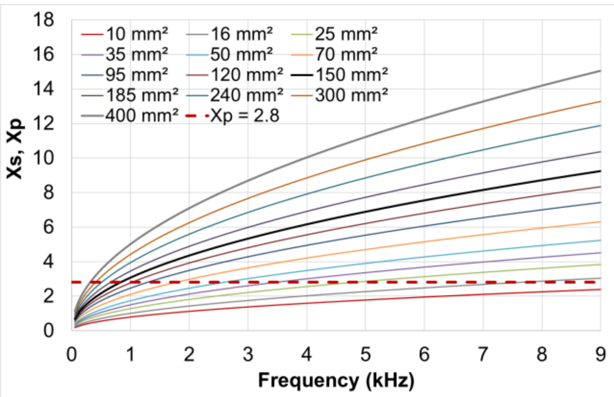

Fig. 6. Factors X_S and X_P for cable aluminium solid conductors at the operating temperature 90°C

It can be clearly seen from Fig. 5 and 6 that the cable aluminium solid conductors with the standard cross-sectional areas starting from 16 mm^2 and larger are characterized by the values of X_P higher than 2.8 at least at some frequencies in the frequency range 2 to 9 kHz.

Cable aluminium solid conductors with the standard cross-sections of 70 mm^2 and larger are characterized by the values of X_P higher than 2.8 in the full frequency range 2 to 9 kHz.

It means that the method for the analytic calculation of frequency-dependent cable resistances [19] is not applicable to the calculation of resistances at supraharmonic frequencies in many practical cases due to the constraints on the combination of parameters considered in [19].

More common analytic method for the calculation of frequency-dependent cable resistances is published in [21].

The analytic method for the calculation of the skin effect factor Y_S in [21] is identical with the method [19] described above.

The following formula is suggested in [21] for the calculation of the proximity effect factor Y_P for three single-core cables:

$$Y_P = m\,y^2\,G_P\,/(2 - 5\,y^2\,H_P\,/12) \qquad (10)$$

where m = 3 for three single-core circular cables, y – spacing ratio, G_P, H_P – coefficients.
The coefficients G_P, H_P are given by the following equations [21]:

For $0 < X_P \le 2.8$

$$G_P = 11\,X^4_P\,/\,(704 + 20\,X^4_P) \qquad (11)$$

For $2.8 < X_P \le 3.8$

$$G_P = -0.08\,X^2_P + 0.72\,X_P - 1.04 \qquad (12)$$

For $3.8 < X_P$

$$G_P = X_P\,/\,(4\sqrt{2}) - 1/8 \qquad (13)$$

For $0 < X_P \le 2.8$

$$H_P = (1/3)\,(1 + 0.0283\,X^4_P)\,/\,(1 + 0.0042\,X^4_P) \qquad (14)$$

For $2.8 < X_P \le 3.8$

$$H_P = 0.0384\,X^2_P + 0.119\,X_P + 0.095 \qquad (15)$$

For $3.8 < X_P$

$$H_P = (2X_P - 4.69)\,/\,(X_P - 1.16) \qquad (16)$$

The spacing ratio $y = d_c\,/\,s$, where s is the spacing between conductor axes, d_c is the diameter of an equivalent circular conductor.

The construction of the MV cable 3x1x150/25 means that each cable conductor is surrounded by a cable screen.

The AC currents flowing in the cable conductors cause the induced currents in the surrounding cable screens and therefore cause some additional power losses in the screens. It means the increase of equivalent cable resistances at the frequencies of the AC currents (fundamental frequency, harmonic and supraharmonic frequencies).

Therefore the formula (3) can be extended to consider the influence of the power losses in the cable screens on the conductor resistance as follows:

$$R_{sh} = R'_{DC} \left(1+Y_S+Y_P+Y_{SC}\right) \qquad (17)$$

where Y_{SC} – the screen losses factor.

It must be noted that each cable containing axial conductor surrounded by a cable screen can be considered as a pipe-type cable. Taking into account the relation given in [22] for the consideration of the increase in losses in the phase conductors due to the proximity of the pipe the following formula can be used for the screen losses factor:

$$Y_{SC} = 0.5 \left(Y_S+Y_P\right) \qquad (18)$$

These considerations are in compliance with the recommendation [19] for the calculation of AC cable conductor resistances for pipe-type cables. The following formula can be used according to [19]:

$$R_{sh} = R'_{DC} \left[1+1.5(Y_S+Y_P)\right] \qquad (19)$$

Using (4) – (16), (19) the values of the conductor resistances at the supraharmonic frequencies R_{sh} and the relations R_{sh} / R_1 can be analytic determined for the MV cable 3x1x150/25 under study.

3.2 Numerical calculation method

The use of the finite element method (FEM) is a popular approach for the numerical calculation of the frequency dependences for the cable resistances.

The advantages of this method are the exact modelling of the cable geometry, the simulation of the properties of the materials used in the cable construction and the simultaneous consideration of all influencing effects named above: the skin effect, the proximity effect, the influence of the cable screens and all other metallic elements (e.g. cable armour, pipes, ducts, trays, etc.) which can have an influence on the AC resistances of the cable conductors.

Using the FEM approach it is possible to calculate the current density distribution in all parts of the simulated cable construction. Taking into account the cable geometry and the electrical conductivities of simulated constructive materials the power losses in all elements of the cable construction can be determined.

The calculation of the equivalent AC resistance of the cable conductor R_{sh} at the supraharmonic frequency f_{sh} can be carry out taking into consideration the following formula:

$$P_{Lsh} = I^2_{sh}\, R_{sh} \qquad (20)$$

where P_{Lsh} – the average value of total power losses caused by the simulated supraharmonic conductor current I_{sh} at the frequency f_{sh} in each phase of the three-phase cable system.

In respect to the considered MV cable construction 3x1x150/25:

$$P_{Lsh} = P_{Lsh\ cond} + P_{Lsh\ sc} \qquad (21)$$

where $P_{Lsh\ cond}$ – the average value of the power losses in each phase conductor and $P_{Lsh\ sc}$ – the average value of the power losses in each conductor screen.

For the determination of the frequency dependence for the equivalent AC cable resistance it is necessary to carry out the row of the simulations at different frequencies. The frequency dependence can be determined from the following relations:

$$P_{Lsh} / P_{L1} = I^2_{sh}\, R_{sh} / I^2_1\, R_1 \qquad (22)$$

The values I_{sh} and I_1 can be taken e.g. from the measurement results.

Taking into account the FEM simulation of the heating processes the cable operating temperature can be determined and the influence of the temperature on the electrical conductivity can be considered additionally [23-25].

For the simplification of the calculations it is enough to assume $I_{sh} = I_1$. In this case is enough to calculate the power losses (21) for each frequency under consideration. The formula (22) will be simplified as follows:

$$P_{Lsh} / P_{L1} = R_{sh} / R_1 \qquad (23)$$

Using (23) the frequency dependence for the equivalent AC cable resistance can be determined.

It must be noted that the electrical conductivity of the cable insulation is very small in comparison with the conductivities of the cable conductors and metallic screens. Therefore it is enough to simulate only metallic parts of the cable configuration to simplified estimate the power losses (20) and to calculate the equivalent AC resistance of the cable conductor.

Fig. 7 presents a simulation example for the MV cable 3x1x150/25. The trefoil formation with the spacing between conductor axes of 40 mm was simulated. Both aluminium conductors and copper screens were simplified represented as solid objects.

The simulation was carried out using the software package FEMM [26].

The calculated current density distribution J in the aluminium cable conductors and in the copper cable screens is shown in Fig. 7. The supraharmonic phase conductor currents of I_{sh} = 0.54 A (r.m.s. value) at the frequency f_{sh} = 2.5 kHz were simulated as the origin of the magnetic field in the cable. This value of the conductor current was measured as 1 min value during the measurement campaign at the measuring point MP2.

The conductor currents were simulated as a three-phase set of balanced phasors with the difference of phase angles of 120° between two neighboring phasors.

Fig. 8 presents the line plot of the current density for the straight line contour crossing the centers of two neighboring conductors with screens. The coordinates of centers in the "position" axis are - 20 mm and + 20 mm respectively. The skin effect, the proximity effect, the influence of the cable screens can be clearly seen from Fig. 8.

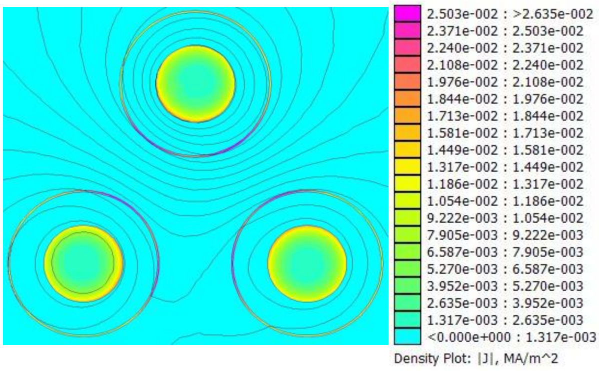

Fig. 7. Current density distribution J in the aluminium conductors and copper screens of the MV cable 3x1x150/25 caused by the supraharmonic current 0.54 A (r.m.s. value) at the frequency 2.5 kHz

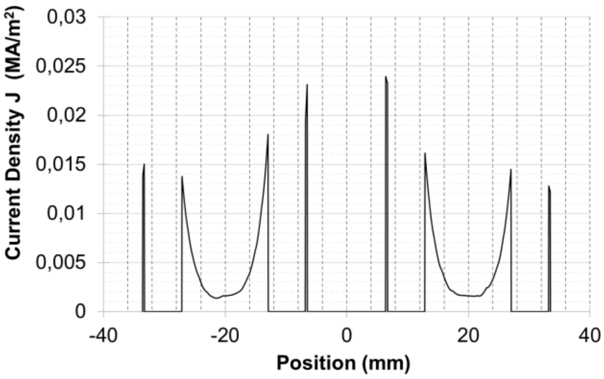

Fig. 8. Current density distribution J along the straight line crossing the centers of two neighboring conductors and screens of the MV cable 3x1x150/25 caused by the supraharmonic current 0.54 A (r.m.s. value) at the frequency 2.5 kHz

3.3 Calculated frequency dependences for the MV cable under study

The analytic calculated frequency dependences R_{sh} / R_1 for the MV cable 3x1x150/25 are presented in Fig. 9. It is the frequency dependence calculated taking into account only the skin effect (parameter Y_S), the frequency dependence calculated taking into account both the skin and the proximity effects (parameters Y_S and Y_P), the frequency dependence calculated taking into account the skin effect, the proximity effect and the influence of the power losses in the conductor screens (parameters Y_S, Y_P, Y_{SC}).

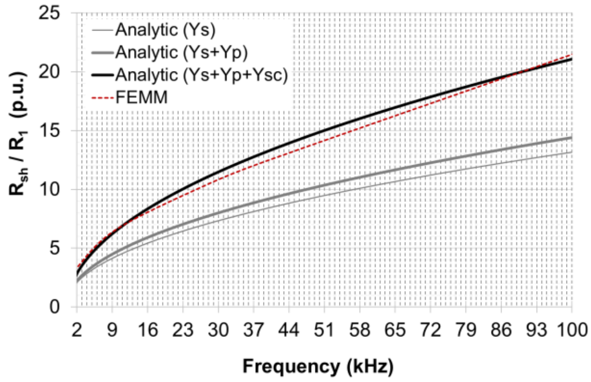

Fig. 9. Analytic and numerical (with the use of FEMM software) determined frequency dependences R_{sh}/R_1 for the MV cable 3x1x150/25 in the supraharmonic frequency range

The frequency dependence R_{sh} / R_1 determined with the use of the software package FEMM for numerical calculations is presented in Fig. 9 for the comparison.

The corresponding reference values R_{sh} / R_1 = 1 were calculated for each presented dependence taking into consideration the fundamental frequency 50 Hz.

It can be seen from Fig. 9 that the skin effect is the dominating factor in the increase of the equivalent AC resistance of the cable conductor R_{sh} with the increase of the frequency in the supraharmonic frequency range.

It can be seen from Fig. 9 that the influence of the power losses in the conductor screens on the increase of the equivalent AC resistance of the cable conductor R_{sh} with the increase of the frequency is much higher in comparison with the influence of the proximity effect for the MV cable under study.

It can be concluded from the comparison of the analytic and numerical calculated frequency dependences presented in Fig. 9 that the analytic formula (17) parametrized according to (18) or the direct formula (19) are most suitable for the analytic characterization of the increase of the equivalent AC resistance of the cable conductor R_{sh} with the increase of the frequency for the MV cable under study in the supraharmonic frequency range 2 to 100 kHz.

Taking into consideration the frequency dependence (1) presented graphically in Fig. 1 it can be concluded that the frequency dependences calculated by (19) or using FEM simulations for the MV cable under study are characterized by lower values of the relations R_{sh} / R_1 than the square root from the harmonic order $h = f_{sh} / f_1$.

For the supraharmonic frequency range 2 to 9 kHz the following formula can be suggested for the simplified representation of the frequency dependence of R_{sh} / R_1 for the MV cable under study:

$$R_{sh} / R_1 \approx 0.48 \sqrt{h} \quad (24)$$

Deviations of (24) from the FEMM calculation results do not exceed a few percent in the range 2 to 9 kHz.

4 Use of measurement results for the supraharmonic power losses estimation

Using (22) the supraharmonic power losses in the MV cable under study can be determined. For clarity (22) can be represented similar to (2) and rewritten as follows:

$$P_{Lsh} / P_{L1} = (I_{sh} / I_1)^2 R_{sh} / R_1 \quad (25)$$

Taking into consideration calculated frequency dependences R_{sh} / R_1 for the MV cable under study and the measurement results for the time rows I_{sh} / I_1 obtained during the measurement campaign the time rows for the relative values of supraharmonic power losses P_{Lsh} / P_{L1} can be determined.

Fig. 10 and 11 show the supraharmonic spectrums of relative power losses in the frequency range 2 to 9 kHz in the 20 kV cable feeder under study determined according to (25) for the measurement interval of 24 h (Fig. 10) and for the measurement interval of one week (Fig. 11).

The spectrums in Fig.10 and 11 are presented for the supraharmonic groups of 200 Hz in accordance with the obtained measurement results for the supraharmonic currents. For the center frequencies of each group the frequency dependences R_{sh} / R_1 calculated according to (19) were taken into consideration.

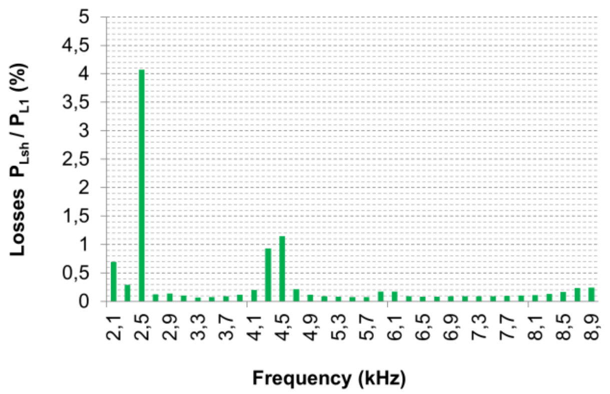

Fig. 10. Relative power losses in a 20 kV cable feeder, 95% quantiles of 1 min values, 200 Hz groups, measurement time 24 h, MP2

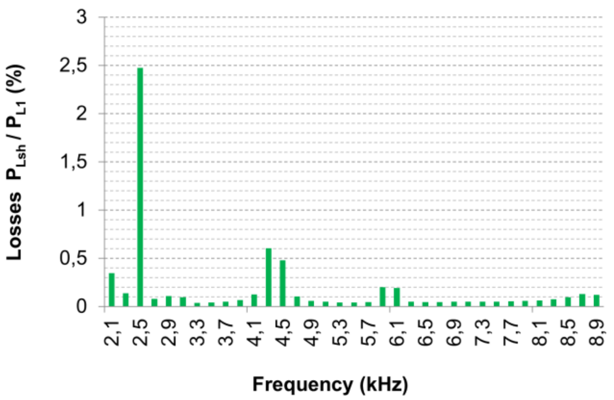

Fig. 11. Relative power losses in a 20 kV cable feeder, 95% quantiles of 1 min values, 200 Hz groups, measurement time one week, MP2

It must be noted that the sum of average values of 1 min relative harmonic power losses (harmonics 2nd to 40th) for this measurement day considered in Fig. 10 is 24.4%, the sum of average values of 1 min relative supraharmonic power losses in the range 2 to 9 kHz presented in Fig. 10 is 2.4%. The sum of average values of 1 min relative harmonic power losses for the complete measurement week considered in Fig. 11 is 12.9%, the sum of average values of 1 min relative supraharmonic power losses in the range 2 to 9 kHz presented in Fig. 11 is 1.6%.

It means that the supraharmonic power losses are present in modern distribution networks and can reach the values of several percent with respect to the power losses at the fundamental frequency. The results of the analysis show that supraharmonic power losses can exceed 10% regarding the power losses caused by conventional current harmonics in the MV cable under study. Therefore it can be recommended to consider supraharmonic power losses for a correct estimation of total power losses in modern distribution networks.

5 Summary

Method of the supraharmonic power losses estimation combining the analytic determination of AC cable resistances at the supraharmonic frequencies with the use of measurement results of supraharmonic currents in a real MV/LV cable network was considered in the paper.

Analytic calculation results of the determination of AC cable resistances at the supraharmonic frequencies were verified and precisized using the FEM simulations for a MV cable chosen for the investigation. A simplified formula for the estimation of the increase of the AC cable resistances with respect to the cable resistance at the fundamental frequency of the MV cable under study for the frequency range 2 to 9 kHz was suggested.

It was noted that supraharmonic power losses in MV networks in the frequency range 2 to 9 kHz can be simplified estimated using the measurement results obtained by conventional current measuring instruments.

It was shown that supraharmonic power losses in the MV cable under study operating in a real network can reach the values of several percent with respect to the power losses at the fundamental frequency and can exceed 10% regarding the power losses caused by conventional current harmonics.

It can be recommended to consider supraharmonic power losses for a correct estimation of total power losses in networks with high presence of power electronics.

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