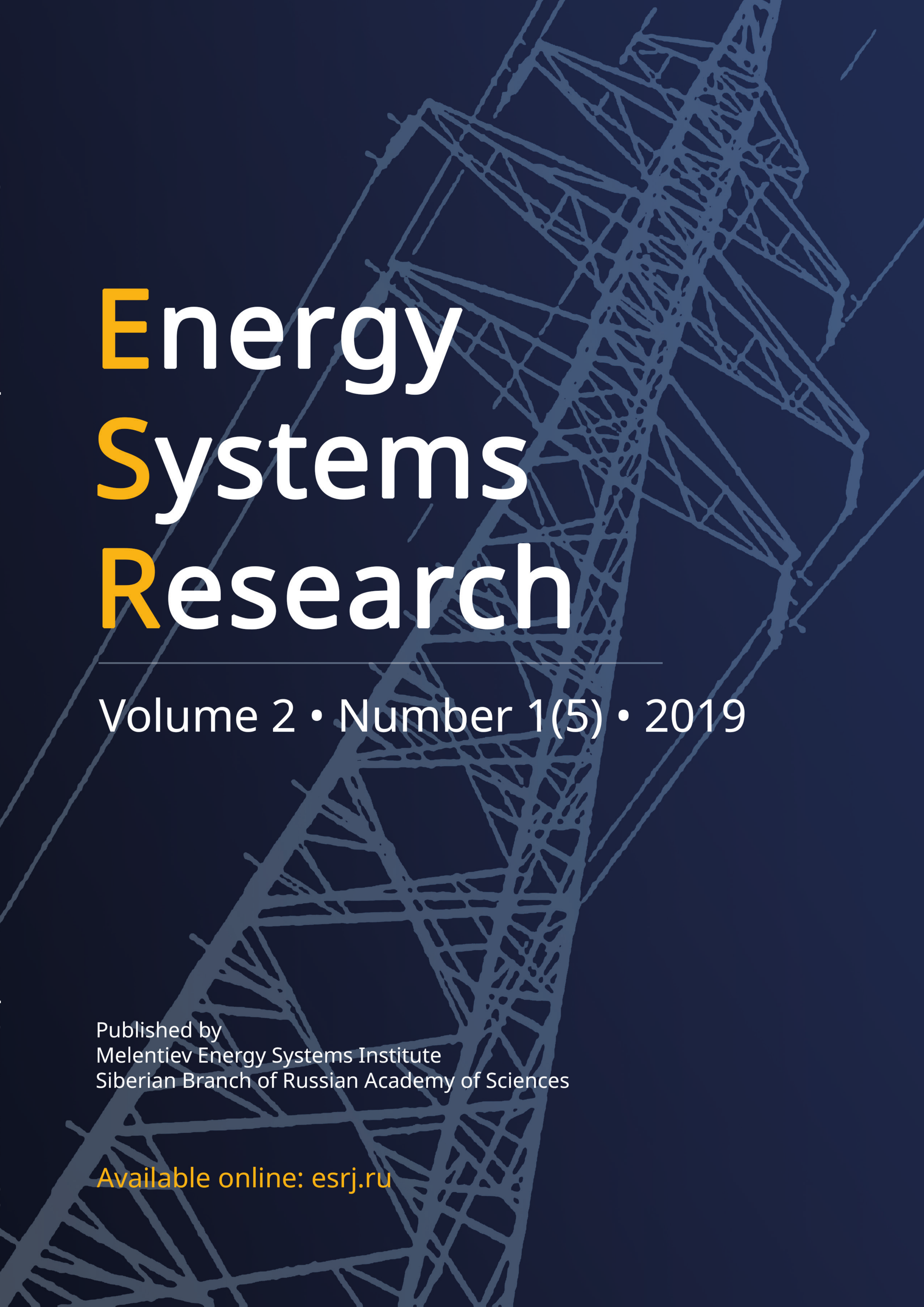

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Energy Systems Research is an international peer-reviewed journal addressing all the aspects of energy systems, including their sustainable development and effective use, smart and reliable operation, control and management, integration and interaction in a complex physical, technical, economic and social environment.

Energy systems research methodology is based on a systems approach considering energy objects as systems with complicated structure and external ties, and includes the methods and technologies of systems analysis.

Within this broad multi-disciplinary scope, topics of particular interest include strategic energy systems development at the international, regional, national and local levels; energy supply reliability and security; energy markets, regulations and policy; technological innovations with their impacts and future-oriented transformations of energy systems.

The journal welcomes papers on advances in heat and electric power industries, energy efficiency and energy saving, renewable energy and clean fossil fuel generation, and other energy technologies.

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Contents

An Approach to the Modeling of Decentralized Integrated Energy Systems with Renewable Energy Sources

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***Abstract* — New conditions for the development of energy systems, the growing consumer involvement in energy demand management, the expansion of energy supply services, the adoption of highly efficient technologies for energy production, transportation, and distribution both for large-scale systems and small-scale distributed generation, whose share is increasing, on the one hand, have already built a certain level of mutual integration of various systems, and, on the other hand, facilitate their even greater integration at the level of control of their expansion and operation. The paper presents an approach based on the long-term meteorological observation data. A chronological method for the calculation of operating conditions of integrated energy systems is presented.**

***Index Terms* — Decentralized integrated energy system, elements of the concept, mathematical modeling, long-term meteorological observation data, renewable energy source**

I. Introduction

The modern energy sector represents an infrastructural complex including fuel, electricity, heat and cooling systems. Despite various kinds of services rendered by the systems, their common goal is to create comfortable living and working conditions for the population and to effectively facilitate the development of the national economy. To perform their functions, each of the systems has its production, transportation and distribution structure connecting them with consumers. They often interact and compete in the existing market for energy services. This, in particular, refers to the electricity, heat, and gas systems. Despite their certain functional independence, these systems can interact with one another under normal and emergency conditions, at the level of interchangeable primary energy resources and use of energy carriers. This is indicative of their natural integration which gets even stronger in the course of the formation of intelligent, information and telecommunication systems. In combination, all of them represent a new structure in the form of a metasystem. This metasystem combines certain independence of the systems that constitute it and their coordinated participation in accomplishing the main goal to provide social and economic activity. Coordination of the accomplishment of this goal is ensured by the information system that represents an infrastructural framework of the metasystem.

The expansion of distributed generation encourages the modification of the existing centralized energy systems and their integration with the distributed generation systems. This is based on a considerable approach of energy generation sources to consumers which in turn causes a change in the topology of the distribution networks that have a multi-loop structure but are operated according to the open circuit principle; an expanded use of cogeneration, in particular on the basis of electric boiler plants with the use of heat storage devices; and a considerable increase in the number of devices for metering and processing the data on the conditions of generation, network and consumption facilities.

One of the options of describing the integrated energy system with distributed generation is its representation as a set of autonomous or interacting subsystems (microgrids). The boundary of each subsystem is known and it is invariable. The determination of this boundary provides the possibility of maintaining the energy balances as well as meeting the requirements for the energy supply quality

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and reliability. Each subsystem can interact with the neighboring subsystems in the cases when contingencies occur in the subsystem and when energy supply conditions are optimized.

It is also important to solve the problem of planning the operating condition which optimizes the implementation of balance relationships and requirements for quality and reliability during the control cycle.

A specific character of planning under the presence of distributed energy generation is determined by the online control of the operation. The question about the length of time intervals for both monitoring and measurement of different parameters as well as generation of control actions is important. This is related to the fact that the time characteristics differ for electric and heat processes.

II. Concept of intelligent integrated energy systems

Intelligent integrated energy systems have a multi-dimensional structure of functional characteristics and expansion properties. They combine a great number of components, intelligence, efficiency, reliability, controllability, flexible use of technologies for energy conversion, transportation, storage, and the load-controlled consumer [1,2]. Conceptually, the integration is carried out in three aspects:

- A system aspect which represents the integration of systems by their type (electricity, heat/cooling and gas systems);
- A scale aspect which reflects the size of the systems with their differentiation into super-, mini- and microsystems;
- A functional aspect which determines the functions of the system (its purpose), including energy (technological); communication, control and decision making.

In terms of the system aspect, the intelligent integrated energy system is represented by the key infrastructural energy systems that can be highly integrated with respect to the functional tasks, mutual redundancy, technological interrelations at various hierarchical levels, etc.

In terms of the scale aspect, we distinguish the following interrelated systems:

- super-systems, i.e. traditional centralized energy systems that consist of large-scale electricity and heat sources, gas fields, underground gas storages, electrical, gas and heat networks;
- mini-systems, i.e. decentralized (distributed) systems including mini electricity and heat sources (including those nonconventional and renewable), which are connected to the distribution electrical, heat and gas networks, and these networks themselves;
- micro-systems, i.e. individual systems with nonconventional and renewable electricity and heat sources as well as house electrical, heat and gas networks.

Functional aspects of the intelligent integrated energy system include the following constituent functions:

- the energy functions that represent production, transportation, distribution and consumption of electricity, heat/cooling, gas at all levels and scales;
- the communication and control functions that represent measurement, processing, transfer, exchange, and visualization of information, control of operating conditions and expansion of the metasystem;
- the decision-making functions, i.e. the metasystem intelligence which includes models and methods for planning the expansion of the integrated energy systems as well as settings for their control.

All the functional properties of the intelligent integrated energy system have strong interrelations with one another in terms of input and output state variables, the structure of forecasts both at the level of operation and at the level of expansion. They form a totally new technological architecture which defines the organization of the metasystem implementing the design solutions of its components, their interactions with one another and with the external environment, as well as the principles of the evolutionary development of such a multi-component structure.

III. Literature review

Various energy systems, such as electric, gas, heating and other systems were normally designed and operated independently of one another. The advances in technologies and equipment, the emergence of new conditions and opportunities, however, make the interaction between different types of energy systems much stronger, which leads to a considerably increasing interest in the research on joint operation of these systems. A widely applied approach to study the integrated systems is based on consideration of such systems in the form of an energy hub. For example, in [3] the authors suggest a method for optimal energy generation and conversion in the integrated energy system with different energy carriers, which involves the energy hub conception. This method is widely applied in the studies related to optimal operation and design of integrated energy systems [4-7].

The problem of an optimal load of generating equipment lies in obtaining an optimal schedule of generating equipment startup and shutdown to meet the expected demand, given costs and constraints of a system. In the context of the integrated energy systems, this refers to the optimal startup and shutdown of each generating unit to meet the demand for several types of energy. The authors of [8] propose a solution to the problem of optimal loading of generating equipment based on the energy hub concept. For solving this problem, it is very important to consider the energy storage possibility. The authors in [9] consider the planning of electricity and heat storage as part of the problem of optimal loading of generating equipment. The authors of [10] present a comparison of energy approach and exergy-based approach to solving the problem of optimal use of generating equipment.

The problem of the integrated energy system control can also be solved by determining optimal power flow. The determination of optimal power flow is reduced to the load distribution among energy sources, which meets the constraints of the energy transmission system in terms of cost minimization. Solving the problem of optimal power flow in the integrated energy system should allow for several energy types. Consequently, several energy sources and devices for energy conversion are required. The optimal power flow in an integrated electric and gas system was investigated in [11]. To this end, the authors developed a mathematical model in which the objective function is determined by a set of points for various components that are characterized by the minimum operation cost of the electric and gas systems and do not violate the constraints of the electric and gas transportation system. A method for calculation of optimal power flow for the integrated electricity, gas and heating system is presented in [12]. The method is focused on the power flow and optimality condition of Kuhn-Tucker for the case with several energy resources.

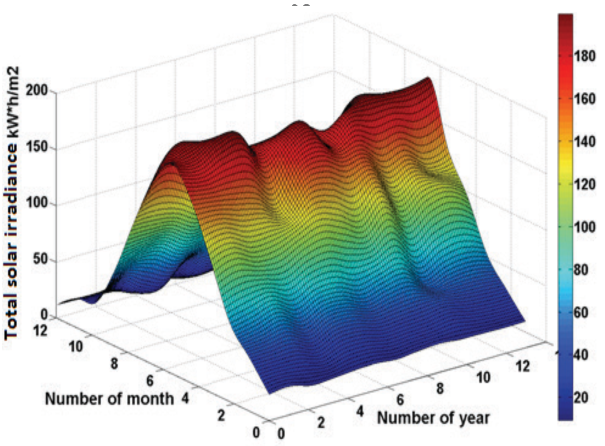
The problem of the optimal power flow calculation for several periods of time is related to the planning of the energy system operation for a set time horizon. In [13], the authors present modeling of an optimal power flow coordinated in time for electric and gas system for the case of distributed energy resources. Due to relatively slow flow speeds and specific features of storage in the gas and heating systems, it is important to take into account the dynamic behavior of these energy systems during several periods of time to solve the problems of control and scheduling of the systems. The authors of [14] study a method for calculation of optimal power flow and scheduling for integrated electric and gas systems with a transient model for the natural gas flow. The calculations were performed to compare the solutions obtained with stationary and transient models of natural gas transmission systems. A model of optimal power flow for several time periods was developed to study combined electricity and gas networks in Great Britain [15, 16].

Some of the studies aim to investigate the control of integrated systems with a focus on centralized and decentralized control. In [17], the authors present the findings of the research into centralized control, which involves an approach to the control with projection models for integrated energy systems. The central controller determines the actions for each energy hub to ensure better efficiency in terms of stability of the transportation system, use of storage devices and forecasts of loads and prices. In [18], the authors propose a hierarchical centralized control of an integrated microgrid. The controller receives the data on transient characteristics of the natural gas flow and operation of energy converters. To take into consideration the dynamic characteristics of different systems, the controller was divided into three layers: slow, medium-speed and fast. The study is focused on the control of executive mechanisms when the renewable generation fluctuates, the start of a conditioner, start of a microturbine, demand response and filling of energy storage. Further, the results of this research were extended to the control of an integrated energy system [19]. A strategy of real-time control of the integrated electric and heating system was proposed in [20]. The strategy of control has a hierarchical centralized architecture and is designed to maintain the frequency of a power supply system at a level of 50 Hz and a temperature of district heating water equal to 1000C. An approach to solving the scheduling problem is presented in [21], where optimization is performed for a time period of 24 hours, and a strategy of real-time control compensates for a gap between a scheduled load and a real load by control actions.

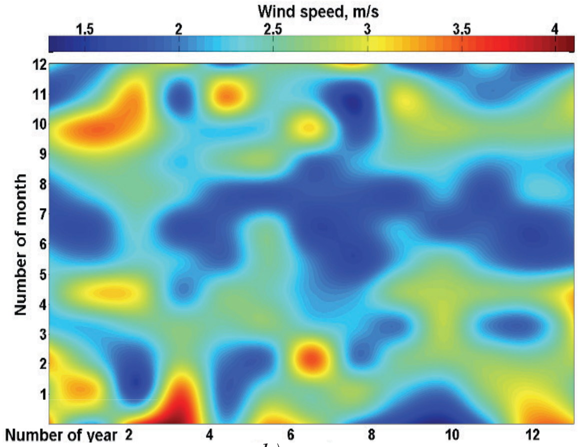
Although the centralized architecture of control can provide the best total energy system performance, its complexity limits its wide practical application. The distributed control architecture divides the common optimization and control problem into subproblems that are solved with individual models. The local control action to be performed, however, depends on the actions of neighboring controllers and should be coordinated. In [22], the authors propose a distributed control system for combined electricity and natural gas systems. The system consisting of several interrelated energy hubs was controlled by corresponding control agents. In [23], these results were extended to the studies of distributed control based on projection models and the use of storage devices in gas systems.

The integration of electric and heating systems is most pronounced in cities and populated areas, and manifests itself: in combined electricity and heat generation; the use of energy storage systems to ensure flexibility of cogeneration operation; and the use of electric equipment for heat production, transport and distribution. The joint operation and scheduling of electric and heating systems based on cogeneration are discussed in [24]. The interaction between electric and heating systems in the view of the need to ensure the required demand response was considered in [25]. Various electricity and heat supply options were compared when solving the problems of operation and scheduling in terms of techno-economic and environmental indices in [26, 27].

The sources of combined electricity and heat generation interconnect electric, heating and gas systems. In [28], the authors applied Sankey diagrams to illustrate energy flows through the electricity-heat-gas networks when considering several scenarios for the involvement of a cogeneration power plant and heat pumps. The research was also focused on the impact of different technologies



a)



b)

***Fig. 1.** – a) total solar irradiance; b) – wind speed (10 m).*

Figure 1 shows the total solar irradiance and wind speed.

Figure 2 shows the relationship between climate data and energy systems modeling.

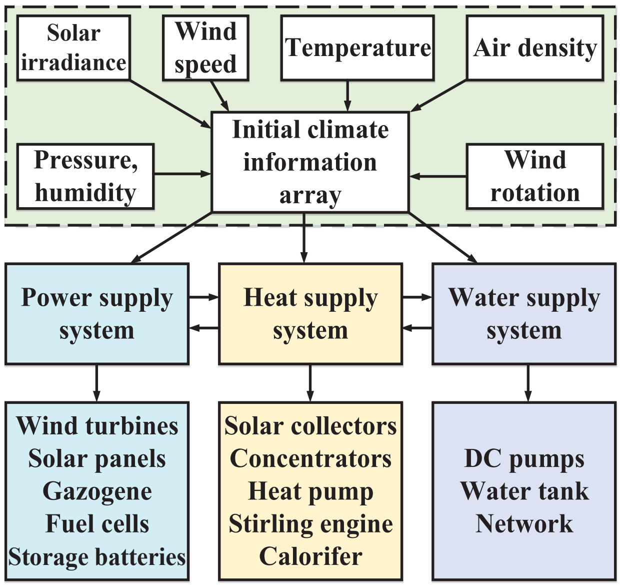


***Fig. 2.** Relationship between climate data and energy systems modeling.*

on the operation of each network. The implications of switching from hydrocarbon fuel to renewables in the electric system for the district heating systems and gas network were studied in [29, 30].

IV. Climate indicators and their role in research

Integrated microsystems often comprise different types of power generation equipment using renewable energy sources. Solar panels, wind turbines, gas generators, battery units, and fuel cells can be used for electrical supply. Solar collectors, concentrators, heat pumps and thermal storage units can be used for heat supply. An integrated power system can consist of different combinations of the above-mentioned equipment.

The common feature for all of these installations is the use of renewable energy sources such as solar and wind power, low-potential heat, waste substances and so on.

Consequently, detailed information on the following natural and climatic factors is required when examining energy systems involving renewable energy sources: solar irradiance, wind speed and direction, temperature, humidity, pressure, and air density.

To increase the accuracy of research findings, climate indices have to approximate real values as much as

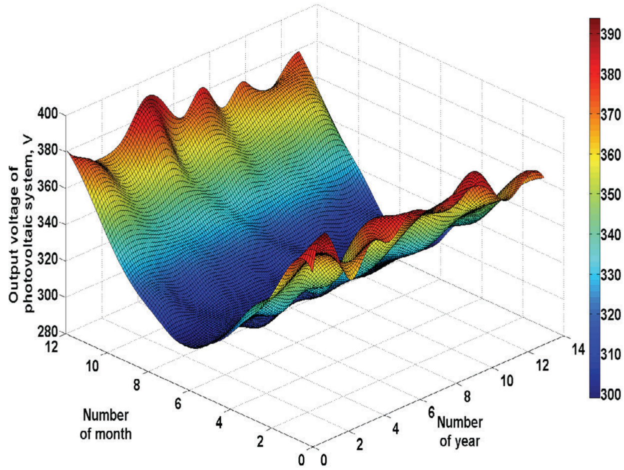


***Fig. 3.** The output voltage of the photovoltaic system.*

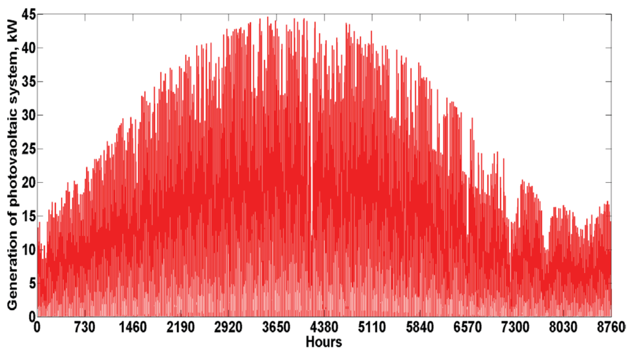


***Fig. 4.** Power output of the photovoltaic system (50 kW) during the year.*

possible. To this end, the study follows the method of reproducing natural and climate indices by using the year-long meteorological series, available in the public domain.

These meteorological series record, line by line, the major climate indices such as wind speed and direction, air temperature, pressure, humidity and assessment of total cloud cover.

A combination of Iqbal and Kasten-Czeplak mathematical models is used to calculate the total solar irradiance. In the calculation of the total solar irradiance for each day, sunrise, zenith and sunset times are determined based on geographic coordinates and time zones. In the first stage, solar irradiance is determined under clear sky conditions. In the second stage, the solar irradiance attenuation quotient is determined based on cloud cover, cloud composition, the percentage of bad weather clouds and so on.

These data can be directly used for modeling solar panels, collectors, concentrators and wind generators.

V. Modeling the integrated energy systems with renewable energy sources

What is special about the integrated microsystem is its direct relationship with the centralized energy system. Besides, various heat and electric power generation techniques should be taken into consideration as modeling these systems is a challenging task.

The chronological calculation method is used to model the integrated systems. This method involves the determination of the system's basic operating parameters with regard to every discrete step of the considered period. Importantly, this calculation method is fully consistent with the year-long meteorological series which, by their very nature, respect the continuity of changes in meteorological indices. Of special importance is the fact that the data collected directly from weather stations are used to reproduce natural and climate conditions. All of the above makes it possible to accurately model the operating conditions of the integrated systems using renewable energy sources.

Figure 3 shows the output voltage of the photovoltaic system.

Modeling is performed for a period of up to 20 years according to real climate data. These climate data are a chronological sequence of events. Moreover, these data can be applied to various components of the integrated system.

VI. Conclusions

The organization of the coordinated process of energy system operation and consideration of different energy system types as a single integrated energy system will allow us to considerably increase their security, reliability, cost-effectiveness and environmental friendliness. An inevitable expansion of the distributed generation on the basis of unconventional and renewable energy sources both at the level of energy systems and directly at consumers', as well as their integration in the centralized systems require the implementation of new principles for the construction of these systems and establishment of intelligent systems to control them on the basis of developed information-communication support. The potential advantages of the decentralized integrated energy system with renewable energy sources can be easily implemented through the correctly selected integration mechanisms. Such advantages can include:

- Energy saving and reduction in the emission of harmful substances.
- The decrease in energy transmission and distribution losses.
- Stabilizing the stochastically varying power output.
- Increasing flexibility of energy supply.
- Participation of end users in both electricity market transactions and energy system control.
- Transition to the intelligent energy system concept.

Further research will focus on the development of the concept of integrated energy systems with renewable energy sources.

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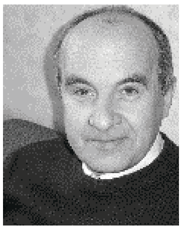

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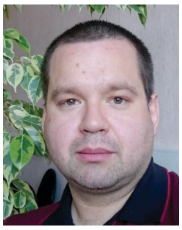

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Dispersed Renewable Generation In The Power Supply System Of An Industrial Enterprise: Technical Feasibility And Economic Effectiveness

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***Abstract* — This paper is concerned with the possibility of using renewable energy sources for power supply to an industrial enterprise (a mechanical plant). We assessed the climatic conditions of the area and explored if it is possible to install renewable energy facilities (solar panels and wind turbines) at this plant. The assessment of climatic conditions in Irkutsk revealed that the use of wind turbines is not reasonable due to the weak wind activity in the city. However, this area has a relatively high potential of solar energy. The paper presents an in-depth analysis of the integration of solar panels into the power supply system of a mechanical plant. Their actual output depending on solar activity was calculated. Based on the area of the buildings roofs, the number of solar modules, inverters and other equipment pieces connected to them was calculated. The payback period of installed equipment was determined to assess the economic effectiveness. According to the assessment results, the economic effectiveness of their use is currently quite low. However, with the expected reduction in the equipment cost and an increase in electricity prices, renewable energy sources will become more cost-effective in the future.**

***Index terms* — Cost-effectiveness, energy potential, integration, power supply systems, renewable energy resources, solar, wind.**

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I. Introduction

In many developed and developing countries of the world, the share of renewable energy sources (RES) in energy balances is quite considerable and further increasing. The transition from conventional energy sources to renewable energy resources is gaining momentum and becoming increasingly global. According to the results of various studies, a gradual transition to renewable energy sources is expected in the near future. Despite the global trends, renewable energy in Russia is still in the early stages of development, although the formation of the renewable energy industry can have a significant positive impact on the Russian economy. For example, RES can foster the creation of new companies and jobs, and provide new opportunities for meeting the consumer loads in off-grid areas [1-4].

This study examines the integration of renewable energy sources into the power supply system of a mechanical plant. According to the project, the plant is located in Irkutsk, and climatic features of the area are taken into account. The input data contain the layout of the plant, including the shops located on the territory of the plant, and a statement of electrical loads of the plant with detailed information about consumers. The renewable energy sources are considered as complementary power sources. The paper describes in detail the integration of renewable energy sources into the power supply system of a mechanical plant, and presents the assessment of their economic effectiveness.

II. Assessement of renewable energy potential in Irkutsk

Many regions in our country (and the Irkutsk region is no exception) are promising in terms of the use of renewable energy, especially the energy of the sun. This is confirmed by the fact that the level of solar radiation in Irkutsk (located at a latitude of 52 degrees north) reaches 1340 kWh/m2, which is a fairly good indicator. The data on

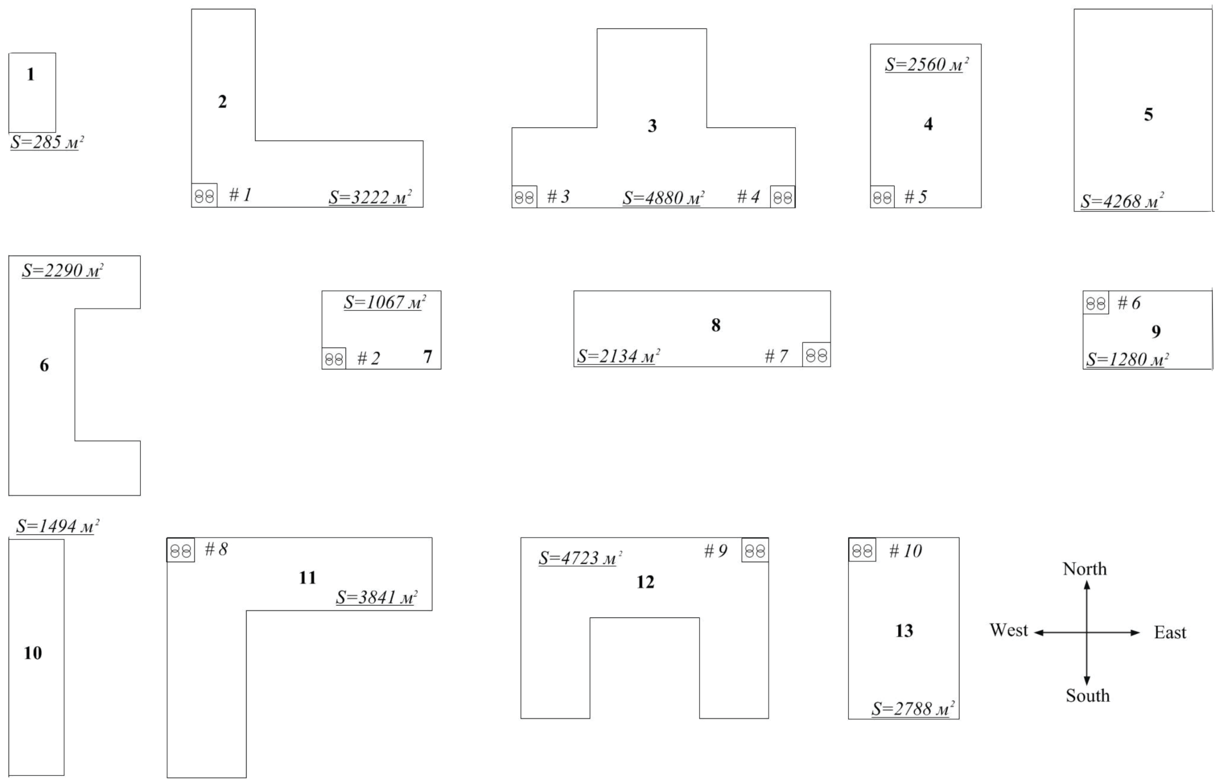

Fig.1. Layout of the mechanical plant shops

the amount of direct solar radiation falling on a horizontal surface under a clear sky in Irkutsk are given in [5]. The highest solar activity is achieved in June at noon in clear weather and it is 2.81 MJ/m2 per hour. The rest of the time, this activity varies depending on the season, weather and time of the day. Thus, the Irkutsk region has a relatively good potential for the development of solar energy, which means that the use of solar panels at the plant is relevant.

In addition, Russia has a huge potential for wind energy. The large territory of the country and a wide climatic diversity foster the development of wind energy. The main indicator of the wind power potential is the annual average wind speed. Despite the wide climatic diversity, the annual average wind speed in most of the Irkutsk region does not exceed 3-4 m/s [6]. When the speed is less than 4 m/s, the use of wind turbines is not advisable, since the speed required for the normal operation of most wind turbines is 10 m/s. Consequently, it was decided not to consider wind turbines in the study.

III. Conditions for the use of solar panels at a mechanical plant

In this section, we analyze the possibilities of using solar panels at a mechanical plant, with the view to meeting demand for electricity by environmentally friendly energy sources.

Solar modules will be mounted only on the roofs of the shops and other buildings because other possible places for their installation in the territory of the plant can be occupied by access routes, warehouses and other facilities. The roofs of the buildings are assumed to be horizontal and, therefore, the roof area will be equal to the area of the building. In addition, placement of solar panels on the ground may be inefficient, since in this case, shadows from fences and shops located nearby may fall on the panels and decrease their effectiveness. Therefore, the installation of solar panels on the roofs of the shops will provide the maximum possible output. Figure 1 shows the layout of the mechanical plant shops, and the area of the buildings.

There are two groups of buildings at this plant:

- energy-intensive production shops with their transformer substation;
- non-production buildings which consume much less power and do not have their own transformer substation.

The solar panels are supposed to be mounted on the entire surface of the roofs of industrial shops. This will allow installing as many solar panels as possible and covering a significant part of the electrical load. At the same time, we need to bear in mind that the power generated by solar panels must not exceed the power load of the shop in order not to feed excess power back into the grid. Daily load curves of the shops are taken into account for this purpose. Such a constraint is imposed not to break the existing relations in the electricity and power market when its participants have a certain established status of electricity consumer or supplier. Moreover, reverse power

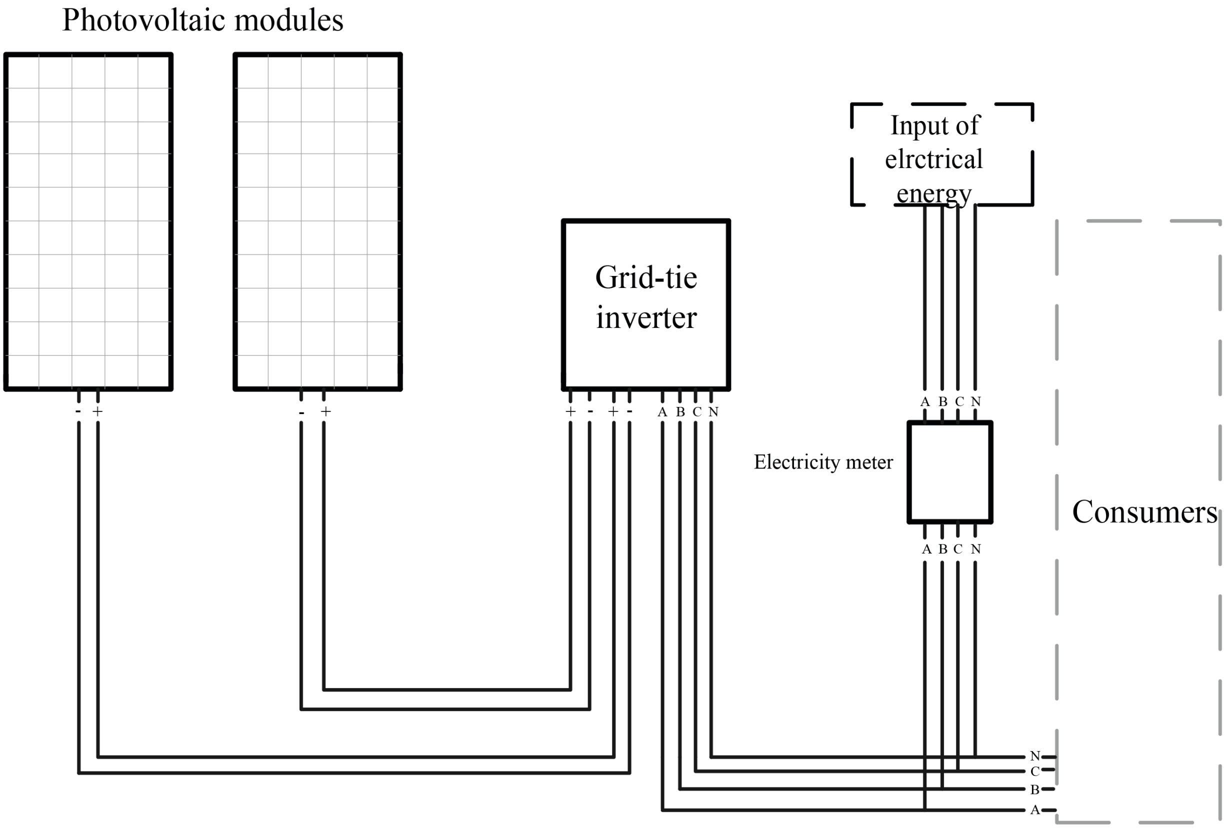

Fig. 2. A scheme of solar panels connection to consumers

Table 1. Actual output of one solar panel depending on the hour of the day and the season in Irkutsk (Wh)

Hours	Month											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
0-1												
1-2												
2-3												
3-4						1.5						
4-5					8.1	14.8	9.6	1.5				
5-6				10.3	30.2	39.8	33.9	19.2	1.5			
6-7			6.6	37.6	58.3	70.1	65.6	43.5	17.0	1.5		
7-8		8.9	30.2	70.1	90.7	104.0	104.0	77.5	50.9	22.9	0.7	
8-9	9.6	37.6	67.9	104.0	126.1	139.4	137.9	115.1	81.1	50.9	14.8	5.2
9-10	28.0	62.0	101.8	135.0	162.3	171.9	166.0	146.8	115.1	78.9	39.8	19.2
10-11	43.5	82.6	124.7	162.3	190.3	194.0	188.8	169.7	141.6	104.0	60.5	33.9
11-12	54.6	94.4	137.9	177.0	203.6	207.3	201.4	179.2	154.9	112.9	70.1	43.5
12-13	54.6	94.4	137.9	177.0	203.6	207.3	201.4	179.2	154.9	112.9	70.1	43.5
13-14	43.5	82.6	124.7	162.3	190.3	196.2	188.8	169.7	141.6	104.0	60.5	33.9
14-15	28.0	62.0	101.8	135.0	162.3	175.6	166.0	146.8	116.5	78.9	39.8	19.2
15-16	9.6	37.6	67.9	104.0	128.3	143.1	137.9	115.1	82.6	50.9	14.8	5.2
16-17		8.9	30.2	70.1	92.2	105.5	104.0	77.5	48.7	22.9	0.7	
17-18			6.6	37.6	60.5	70.1	65.6	43.5	17.0	1.5		
18-19				10.3	31.7	39.8	33.9	19.2	0.7			
19-20					8.1	14.8	9.6	1.5				
20-21						1.5						
21-22												
22-23												
23-24												
Diurnal	271	571	938	1393	1747	1896	1815	1505	1124	742	372	204
Monthly	8409	16007	29063	41750	54143	56872	56282	46619	33710	23014	11138	6344
Yearly	383350.93											

Table 2. The results of calculation of solar panels area

Shop #	S_{shop}, m^2	S, m^2
1	285	312.6
2	3222	3352.18
3	4880	5361.03
4	2560	2813.37
5	4268	4688.95
6	2290	2377.9
7	1067	1172.24
8	2134	2344.47
9	1280	1406.68
10	1494	1641.13
11	3841	3889.34
12	4723	4962.97
13	2788	3063.45

flows may require changes in the relay protection and automation organization in the power supply system of the plant, in the supply substation, and in the grid itself. Thus, the shops with low electricity consumption and non-production buildings should be equipped with a limited number of solar panels to meet the above constraint.

With a decrease in the power supplied from the grid due to the power received from solar panels, the previously selected transformer capacity, cable carrying capacity and switching devices were not revised. This slightly worsened the economic effectiveness of solar panels, however, was necessary because solar energy is unpredictable, it cannot be considered as firm and, therefore, it requires full redundancy. In this case, the grid plays a role of such a backup source. On the other hand, due to the connection of the solar panels to the centralized grid, it was decided not to use electric power storage for solar panels as an additional backup source. This will significantly reduce the cost of solar systems.

To synchronize and connect the solar panels to the power supply system of the plant we use grid-tie inverters. Grid-tie inverters are devices that convert DC voltage from renewable energy sources to AC voltage. They have a distinctive feature – the presence of synchronization of the output voltage and current with a stationary network. Thus, the grid-tie inverter converts direct current from solar panels to alternating current, with the appropriate values of its frequency and voltage phase for the connection with a stationary network. In our study, we use a three-phase inverter. In contrast to single-phase inverters, three-phase inverters evenly distribute energy received from solar panels between phases. In the case of three single-phase inverters, the output power of each inverter will fluctuate depending on the output of the solar panel connected to its input. If the power of solar panels is different and /or each solar panel is oriented or lit differently, then, accordingly, the power supplied by different phases will be different [7].

Figure 2 illustrates the basic principle of connecting solar modules to a grid-tie inverter, and the joint operation of the inverter with a centralized grid.

IV. Calculation of the actual output of solar panel

To perform further calculations, we selected solar panels "Sila Solar" with an installed capacity of 250 W each [8]. These panels has a quite good output at a relatively low price in comparison with the panels of other producers.

The actual power of solar panels averages 75-85% of its rated power. This depends primarily on climatic factors, as well as the angle of inclination (the angle between the horizontal plane and the solar panel) and the orientation of these modules to the south (for the northern hemisphere). Solar panels achieve the highest efficiency when they are directed to the sun and their surface is perpendicular to the sun's rays. Solar panels are located on the roofs of the plant shops in a fixed position; therefore, they are not at a right angle to the sun's rays throughout the day. In this case, the tilt angle of the panels is selected so as to ensure that they are at right angles to the sun's rays during the longest time possible.

The optimum mounting angle of solar panels is chosen depending on the latitude of the area. In the city of Irkutsk, located at a latitude of 52 degrees, the optimum tilt angle is 36 degrees [9].

In this case, the solar panels located on the roofs of the shops are assumed to be south facing. As is seen from Fig. 1, such a geographical location of the panels provides the minimum deviation from the southern direction. With the deviation from the southern direction assumed to be equal to 5 degrees, the power output of solar panels is maximal [10].

To calculate the actual output of one solar panel, we use the formula [10]:

$$E = \frac{I \cdot V \cdot k_o \cdot k}{U}, \quad (1)$$

E – actual output of one solar panel, Wh;

I – amount of solar energy falling on a horizontal surface, kWh/m^2 (it is given in Table 1 with conversion to the specified units);

V – rated power of one solar panel, W (it is given in the technical characteristics of the solar panel "Sila Solar" 250 [6]);

k_o – correction factor depending on the tilt angle of solar panel and the deviation from the southern direction

Table 3. Energy produced by solar panels of shop No.2 (kWh)

	Months											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Diurnal	565	1189	1954	2899	3637	3949	3778	3133	2341	1545	774	424
Monthly	17508	33327	60512	86928	112730	118413	117184	97065	701188	47918	23191	13208
Yearly	798175.78											

Table 4. The calculated data on solar panels of the shops

Substation	Shop	Design power, kW	Number of panels, pcs.	Rated power of solar panels, kW	Generated power, MWh/year
#1	2	1431.08	2082	520.53	798.18
#2	7	1247.313	728	182.02	279.12
#3	3	1266.936	1845	461.13	707.1
#4	3	1248.182	1485	371.33	569.4
#5	4	2764.521	1747	436.86	669.88
#6	9	1147.897	874	218.43	334.94
#7	8	1830.188	1456	364.05	558.23
#8	11	1174.512	2416	603.93	926.08
#9	12	2789.062	3083	770.65	1181.71
#10	13	1737.349	1903	475.69	729.43
−	1	10.84	25	6.25	9.58
−	6	189.36	250	62.5	95.84
−	10	26.74	100	25	38.34
−	5	206.43	490	122.5	187.84
Total			18483	4620.87	7085.65

(it is taken from [9] according to the panel tilt angle and the deviation from the southern direction);

k – loss factor (it is assumed to be equal to 0.94 and includes losses associated with an increase in the panel temperature, with shading and pollution of solar panels, losses during the period of low solar radiation, and losses in shunt diodes);

U – solar radiation intensity at which solar panels are tested, kW/m^2 (it is given in the technical characteristics of the solar panel "Sila Solar" 250 [8]).

Formula (1) is used to calculate the actual output of solar panels. The calculation data are summarized in Table 1.

The calculation results indicate that the highest output of one solar panel will be achieved at 11.00-13.00, in June. The rest of the time, the actual power of one module will decrease in proportion to a decrease in the amount of direct solar radiation.

V. Calculation of energy Parameters of solar panels

The plant layout (Figure 1) indicates the geographical location which is taken into account to make the solar panels face south. Table 2 shows the dimensions of the plant buildings. Since the solar panels are fixed at an angle, their area will increase (comparing to underlying surface of the shop roofs), which will allow mounting more panels than on a horizontal surface.

Table 5. The equipment cost

Equipment	Price, thousand rub.	Quantity, pcs	Cost, thousand rub.
Sofar 11ktl 3- phase photovoltaic grid-tie inverter	120	394	47280
Cable Solarflex PV1-F NTS 10 mm^2	0.19	11820	2246
Solar panels “Sila Solar” 250 W	9.1	18483	168195
Total			217721

The area of solar panels given their tilt angle is calculated by the following formula:

$$S = 0.9\frac{l}{\cos\alpha}\cdot b \qquad (2)$$

l – building length, m;

α – solar panel tilt angle equal to 36^o;

b – building width, m;

0.9 – coefficient taking into account the area of technical passages for the maintenance of the solar panels.

The calculation data for the shops are summarized in Table 2.

The data from Table 1 are used to calculate the annual output of electricity produced by solar panels. By multiplying the data from the Table by the number of solar panels placed on the roof of the shop, we obtain the power and energy for a particular shop. Further, we calculate the total energy generated by solar panels of the shop for a year. Table 3 demonstrates an example of the calculation of power and energy of solar panels of shop No. 2 depending on the day and time of the year. From this Table we take the total value of the generated energy for the year. This value is necessary to calculate the economic effectiveness of the solar panels. The number of panels for each shop and the rated power of the entire solar system for the shop are also calculated. The calculation results are presented in Table 4.

VI. Selection of auxiliary equipment

The Sofar 11KTL 3-phase solar inverter is used to convert DC to AC and to synchronize solar panels with the power supply system of the mechanical plant [11]. The maximum power of one inverter does not correspond to the power of the connected panels, consequently, it is necessary to calculate the number of inverters required for solar panels for each shop.

The Sofar 11KTL-X grid-tie inverter allows connecting up to 48 solar panels with a capacity of 250 W each [12]. For the production shops, where solar panels occupy almost the entire area of the roofs, the number of solar

Table 6. The calculation of NPV indicator (thousands rubles)

Period (year), T	Capital investment , *CI*	Cash inflows, *CIn*	Cash outflows, *CO*	Cash flows, *CF*	NPV
0	150 227,40				
1	-	20 909.75	6 009.09	14 900.66	-136 430.49
2	-	21 327.95	6 009.09	15 318.86	-123 297.04
3	-	21 754.51	6 009.09	15 745.42	-110 797.82
4	-	22 189.60	6 009.09	16 180.51	-98 904.66
5	-	22 633.39	6 009.09	16 624.30	-87 590.44
6	-	23 086.06	6 009.09	17 076.97	-76 829.06
7	-	23 547.78	6 009.09	17 538.69	-66 595.40
8	-	24 018.73	6 009.09	18 009.64	-56 865.35
9	-	24 499.11	6 009.09	18 490.02	-47 615.74
10	-	24 989.09	6 009.09	18 980.00	-38 824.33
11	-	25 488.87	6 009.09	19 479.78	-30 469.78
12	-	25 998.65	6 009.09	19 989.56	-22 531.65
13	-	26 518.62	6 009.09	20 509.53	-14 990.34
14	-	27 049.00	6 009.09	21 039.91	-7 827.07
15	-	27 589.98	6 009.09	21 580.89	-1 023.88
16	-	28 141.77	6 009.09	22 132.68	5 436.44

panels connected to one inverter is 48. For the rest of the shops, where the panels cover only part of the roof area, for even load distribution we calculated the number of the panels to be connected to one inverter (Table 5).

Knowing the inverter input power and voltage, we calculate the current for the system of solar panels. According to the calculated current, we choose a cable produced by HELUKABEL Company. This is Solar flex PV1-F NTS with a cross section of 10 mm^2 and an ampacity of 40 A [13]. The length of the cable running from the solar panels to the inverter is estimated at 30 meters. The total cable length is calculated by multiplying the number of inverters by the length of the cable from the panels to the inverter. The results of the above calculations are given in Table 5.

VII. Calculation of economic effectiveness of solar systems

Previously, we selected all the necessary equipment for mounting solar panels. In addition to the solar panels, we chose all the necessary auxiliary equipment. Below, Table 5 presents input and calculated data on the cost of this equipment. The cost of mounting is assumed to be 15% of the equipment cost [14]. Thus, the total capital cost of the entire system will be equal to 250379 thousand rubles. According to the calculations made earlier (Table 4), solar panels produce energy equal to 7085.65 MWh per year.

This is 27% of the total plant electricity consumption. This amount of energy is saved owing to dispersed renewable generation system (in other words, the power consumed by the plant from the grid is reduced by this amount).

Considering the fact that the electricity price for industrial enterprises with a power consumption above 10 MW in the Irkutsk region is equal to 2951.22 rubles/MWh, including value added tax (as of August 2018) [15], the cost of electricity saved will be 20911.31 thousand rubles/year.

Preliminary estimates show rather low economic effectiveness of the solar systems. This limits severely investor's activity in financing such projects. However, it should be borne in mind that the price of solar panels has decreased by almost 90% over the past ten years [16] and such dynamics of falling prices will continue. It is predicted that by 2030 the price of solar panels will fall by an average of 40% [17]. Not only the cost of solar panels, but also the cost of inverters and other equipment will be reduced [18].

Apart from the reduction in the equipment cost, another important point is a prospect of an increase in electricity price. Thus, according to the data presented in [15], the cost of electricity for industrial enterprises with power consumption above 10 MW in the Irkutsk region has increased by almost 20% (excluding inflation) over the past ten years, and the annual increase in electricity prices has been about 2%. There is no reason to believe that this trend will not continue in the future. Thus, we calculate the effectiveness of solar panels with a 40% reduction in the cost of equipment, and an increase in the price of electricity by 2 % per year. This will allow us to estimate the potential for the growth of the cost-effectiveness of solar panels.

For the analysis of the effectiveness of this project, we calculate such an indicator as Net Present Value (NPV) according to the formula:

$$NPV = \sum_{t=1}^{n} \frac{CF_t}{\left(1+r\right)^t} - CI \quad (3)$$

$$CF = CIn - CO \quad (4)$$

CF_t - cash flow in time t;

CI - capital investment;

r - discount rate (it is taken to be 8%);

CI_n - cash inflows;

CO - cash outflows.

CI_n is the cost of electricity from the centralized grid substituted by solar panels. CO is the maintenance cost of the panels. CI is the cost of the panels themselves and their installation. The results of calculations according to the above formulas are presented in the Table 6.

NPV was calculated taking into account the reduction in capital costs for equipment and the rise in electricity prices noted above. It reached a positive value in 16 years after the implementation of the project, which is much more cost-effective than the implementation under current conditions.

The achievement of more favorable conditions for such integration is real in the coming decades, as the dynamics of rising electricity prices from traditional energy sources and the reduction in the cost of solar panels themselves, due to the emergence of new technologies, contribute to this.

VIII. Conclusion

The paper is concerned with the possibility of using renewable energy sources to partially replace the electric power received by a mechanical plant from a centralized grid. For this purpose, we considered the possibility of using solar panels and wind turbines. The assessment of the climatic conditions shows that the use of wind turbines is not reasonable due to the low annual average wind speeds, consequently, their installation is not considered. At the same time, with the increased solar activity in the studied region, the use of solar panels for power supply to the plant is relevant. The specific feature of the shop buildings design enables a sufficient number of solar panels to be mounted on the roofs, which will make it possible to cover a significant part of the shop load during the daytime.

The total number of solar panels and the amount of energy generated by them were calculated. To exclude the possibility of feeding surplus electricity back to the grid, the number of solar panels on the roofs of non-production buildings was reduced.

The expected growth in the price of electricity and further steady decline in the cost of equipment for solar systems will significantly increase their economic attractiveness. Moreover, it will stimulate the integration of solar panels into the power supply systems of consumers in Russia.

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International Energy Cooperation in Northeast Asia: Problems of Development

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***Abstract* — The aim of this paper is to confirm the viability and present a methodological approach to the research into the multilateral international energy cooperation in Northeast Asia (NEA). It seems to be important for the methodology to be validated after ten years since the first version of this approach has been applied. The scope of the study includes the gradual formation of interstate energy markets in the region, active adoption of innovative energy technologies, as well as the further expansion of renewable and nuclear energy in the NEA countries. The aim of this study is to update the methodology by means of analysis of the multilateral international energy cooperation activity in Northeast Asia. The main objective of the study is to analyze the mechanisms of multilateral international energy cooperation, given the institutional changes that have occurred in the energy sectors of the NEA countries since the early 2010s.**

***Index Terms* — North-East Asian countries, development of international energy cooperation, energy infrastructure, energy policy.**

I. Introduction

The region of Northeast Asia (NEA), both for now and for the long time ahead, is of particular importance to Russia as the world's largest energy exporter. International energy initiatives (IEI) play an important role in the development of energy cooperation in the Northeast Asian region. This is a tool that allows states and representatives of the energy business to deepen multilateral inter-state relations, coordinate the modernization and construction of energy infrastructure. The study of experience of IEI implementation is also relevant for the assessment of priority trends in the development of energy sector in the NEA countries. The traditional bilateral format of energy cooperation is still the main one, and will remain so in the near future. However, multilateral energy cooperation has already proved its effectiveness and has good long-term prospects. Based on the findings of the international project "Understanding International Energy Initiatives" implemented by the international team headed by Sergey Popov at the APEC Energy Research Centre (APERC) in 2006-2008, two analytical reports were published. The purpose of these reports was to develop and introduce a methodology for integrated assessment of the IEI implementation in the Asia-Pacific region [1, 2].

The first report includes the definition, classification and summary of the main IEI involving three or more APEC economies. The result of this work was the classification of goals and methods, as well as an analysis of the relationship of international energy cooperation actors throughout the IEI lifecycle. A brief overview of this report is presented in [3]. The purpose of the second report was to assess the effectiveness of the IEI institute and to identify the promising areas for the multilateral cooperation in the energy sectors on the basis of the recommendations made in the first report [2].

The insights obtained by APERC in 2008 were applied to Northeast Asian countries, which is a subject of the research at issue. The list of initiatives under consideration has been changed compared to the APERC second report (Table 1). The initiative of the International Forum "Generation IV" was removed from the initial list due to the lack of reliable information about its activities over the past 10 years. There is a need to update the previous evaluation of the selected IEI, due to a number of changes that have occurred since the beginning of the so-called "shale revolution" in the United States (2007) and the financial crisis of 2008. The main ones are: a) strengthening of integration trends

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in the power and gas industry; b) significant changes in the structure of national and international energy markets in the NEA region in accordance to the energy transition paradigm.

II. Development of a methodology for the analysis of international energy initiatives

Within the framework of the updated analysis, changes in the composition of the IEI participants were considered; goals, methods and mechanisms of cooperation were confirmed or updated, and the results of the IEI activities achieved (or not achieved) as of 2018 were presented. Thus, the analysis was aimed at learning lessons from the real experience of international energy initiatives in three key areas [3, 4]:

- The role of the IEI participants (including the preservation or change of their weights) in achieving the goals of international energy initiatives;
- The importance of determining the uniqueness and relevance of the IEI mission;
- Requirements that contribute to the effective practical implementation of IEI.

The selected IEI are considered in terms of the extent to which the external factors influence the initiatives themselves, and in terms of the reverse impact of the international energy initiatives on their framework. The two-way relationship includes, for example, government institutions, technical and financial regulatory mechanisms, economic incentives, environmental issues, etc. It should be clarified that the international energy initiative evolves from its very inception, so the mutability is its inherited feature.

In order to confirm the applicability of the methodology developed in the abovementioned APEC publications, the activity of the selected IEI since 2009 has been analyzed, and their stakeholders' commitment to the original goals of cooperation has been analyzed.

The refinement of the research methodology suggests the use of quantitative indicators to assess the viability of the international energy initiatives. The indicators of a quantitative assessment are determined by the objectives of a specific initiative, and refer to the type of criteria that help to characterize the intensity of initiative's development.

1. Length of a constructed pipeline (for TAGP aimed at building the regional gas supply system);
2. Frequency of working conferences and periodicity of research reports (for NAGPF, designed to prepare governments and businesses of NEA countries for the establishment of a regional gas system; for INPRO, conducting similar work on a global scale with regard to nuclear technologies);
3. The number and status of participants (involved in the development of legal institutions within the framework of the Energy Charter Treaty).

However, the quantitative assessment cannot be considered as an indicator of the initiative's effectiveness or ineffectiveness. It is a good auxiliary tool that works together with all the rest evaluation mechanisms. It is worth noting that a comprehensive quantitative assessment of the IEI is beyond the scope of this study. The circumstances and objectives of the initiatives lifecycle are so varied that the assessment in terms of success/failure does not make it possible to grasp the full value of the lessons learned from the IEI experience analysis.

It is more important to understand the interaction of IEI mechanisms and external factors, which are formed not only from economic, technological, social and environmental prerequisites, but also stem from the general geopolitical situation in the given region. Below is a brief analysis of the four initiatives that was conducted in accordance with the updated methodological approach.

III. Trans-ASEAN gas pipeline (TAGP)

The mission of this initiative is to enhance energy security by natural gas supplies through international pipeline network in the ASEAN region. It is supposed that the integration of the existing national gas supply systems and bilateral international gas pipelines into a single united regional gas transportation network will create the environment for international gas trading [2].

Table I List of IEI selected for analysis of their effectiveness.

Abbreviation	Name	Method of realizing	Northeast Asian countries	Dates
TAGP	The project of gas pipelines system construction in ASEAN countries	Building of energy infrastructure	None, China in prospect	1988 – present
NAGPF	North-East Asian Gas and Pipeline Forum	Joint scientific research on the efficiency of energy infrastructure (mainly the gas transportation) development	Russia, China, Japan, Republic of Korea, Mongolia	1995 – present
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles	Development and promotion of the methodology for assessing the effectiveness of innovative nuclear energy technologies	Russia, China, Japan, Republic of Korea	2000 – present
ECT	Energy Charter Treaty Organization	Creation of the international legal system for unification of business rules in the energy sector	Mongolia, Japan	1990 – present

Sources [1, 2]

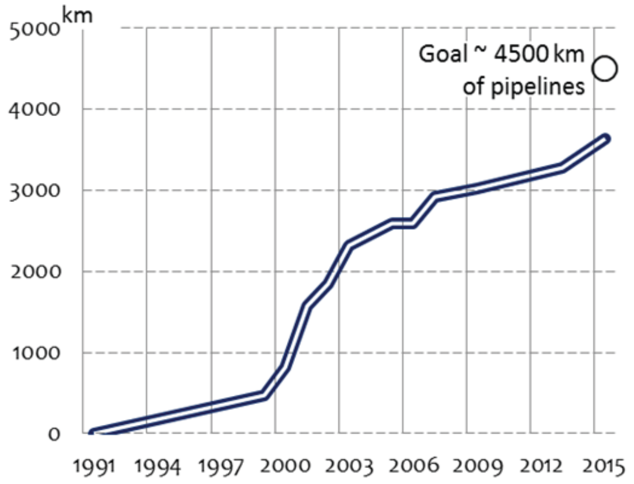

Fig. 1. Total length of the pipelines built under the TAGP project.

Provided the mission is accomplished, the importing countries will get an opportunity to lower the dependence on crude oil imports from Persian Gulf as well as to minimize CO_2 emissions by switching to gas. The exporters, in their turn, can open new markets and become more competitive with the suppliers from outside the ASEAN region.

The TAGP project was born in ASCOPE (The ASEAN Council of Petroleum) under the aegis of all the 10 ASEAN countries at the end of the 1980s. The national oil companies or the authorities in charge of petroleum issues represent ASEAN member countries in ASCOPE. The IEI's annual budget is about $7 billion; the main investors are national oil and gas companies, which are usually monopolies in the domestic markets. The role of private energy business is limited to the participation in forums and workshops [5].

Natural gas can be transported through pipelines or by railway, road and sea in the form of LNG (liquefied natural gas). When the TAGP project started, LNG was less competitive than pipeline gas. However, technology-driven reductions in LNG production and transportation costs led to the significant changes in the project. Today 4 LNG regasification facilities are in operation, 25 regasification facilities are planned to be built in the region.

Great progress has been achieved for the three decades of the IEI's life. The first 5 km Singapore – Malaysia pipeline was built in 1991. By the April of 2015, 13 pipelines with the total length of 3.6 thousand km from the planned 4.5 thousand km have already been established. The further integration of the bilateral pipeline connections into a single gas transportation network requires a coordinated policy from the participants to develop uniform technological standards, legal regimes and pricing mechanisms [5]. The dominance of the national monopolies in the domestic markets and limited third-party access to the infrastructure discourages private investments and makes the project financing dependable on the interests of several large players.

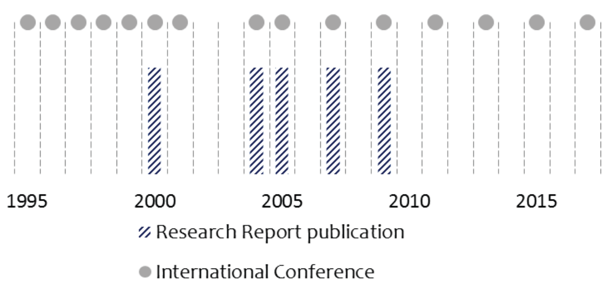

Fig. 2. Indicators of NAGPF activity in 1995-2017.

The IEI can be considered as successful. The main reason for this is the existence of the sufficient interest from ASEAN countries in establishing a regional gas market. Although the length of the pipelines does not provide a comprehensive judgment on the level of IEI's success, it demonstrates that the IEI still exists, and it is evolving. The analysis of the TAGP initiative shows that such factors as institutional frameworks, the level of domestic markets development and geopolitical environment should be taken into account. Further development of TAGP largely depends on the rates and the results of the gas market reforms aimed at increasing competition and liberalizing the markets in many ASEAN economies.

IV. Northeast Asian Natural Gas & Pipeline Forum (NAGPF)

After the USSR dissolution, the geopolitical environment was changed, and the interest of Japan, Korea and China in the import of Russian and the other former USSR countries' gas started to rise again. The establishment of a gas pipeline network in Northeastern Asia, which will connect large production centers with consumers, will support economic and social development and enhance energy security. NAGPF was created as a platform to discuss the plans and promote the establishment of gas transportation system in the Northeast Asian region.

NAGPF mechanisms include organizing the annual International Conferences, conducting collaborative R&D in order to facilitate discussions on barriers and problems facing the international natural gas pipeline development in the Northeast Asian region. This approach provides policy recommendations on natural gas development agreed by the member countries to international organizations and governments [2].

Since 1995, NAGPF has conducted regular conferences devoted to the gas supply and gas infrastructure development in the NEA region. The organizers are NAGPF "ordinary" and "sustaining" members. Ordinary members include the Asia Gas & Pipeline Cooperation Research Centre of China (AGPRCC), Mineral Resources and Petroleum Authority of Mongolia (MRPAM), Korea Pan-Asian Natural Gas & Pipeline Association (KPGA), Asian Pipeline Research Society of Japan (APRSJ), and the Asian Pipeline Research Society of the Russian Federation (ROSASIAGAS). Sustaining membership is freely open to any private organization [6]. NAGPF is

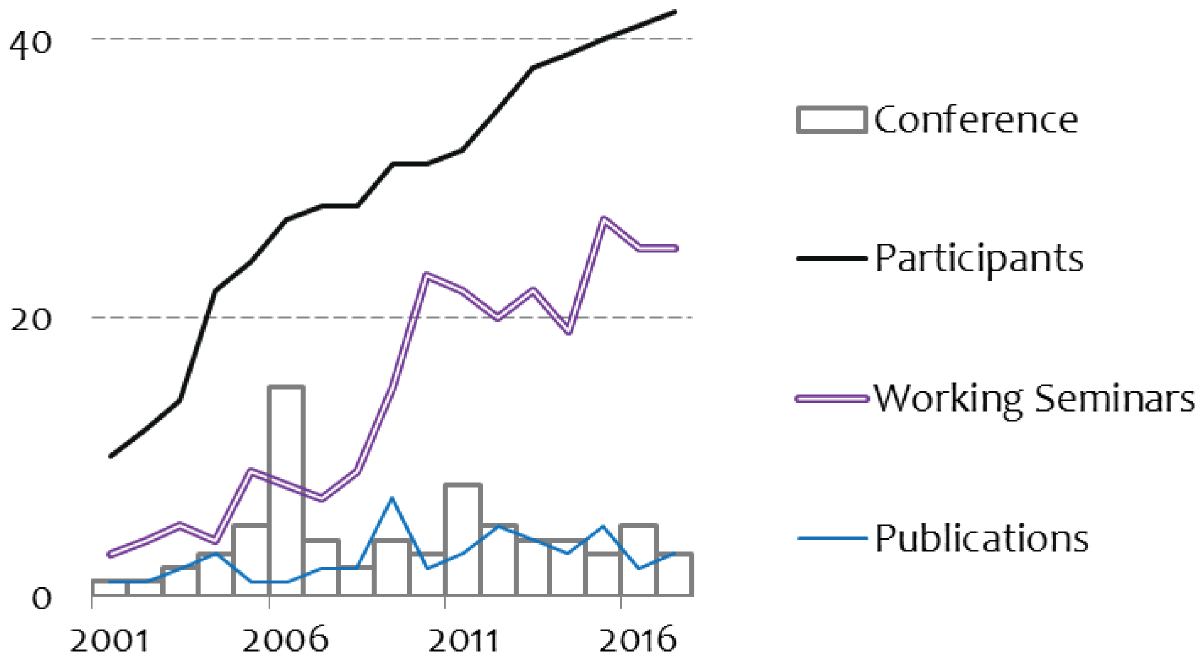

Fig. 3. INPRO activity indicators in 2001-2017

financed by membership fees; sponsors are attracted to organize conferences.

R&D projects conducted by NAGPF allow business to evaluate the opportunities of the NEA gas market development. Nevertheless, the dominance of state-owned companies in the domestic markets (Japan is an exception) and the lack of the institutes of international trade when applied to the continuous and coherent energy transportation systems (which are pipelines and power transmission lines) restrict private investments. During the period of 1995-2018, sixteen International Conferences were organized, five R&D projects were conducted. The latest R&D project was finished in 2009 [7].

Now NAGPF initiative is going through a difficult period characterized by unfavorable political and economic environment. The economic factors include high risks of capital-intensive projects in the absence of developed mechanisms for multilateral investment cooperation. The political factors include the lack of trust among the countries due to historical contradictions and different vision of integration processes in the NEA region. Because of insufficient organizational and financial support from the NEA countries, NAGF initiative could not go beyond the borders of research and expert community. Nevertheless, it is still an important tool for discussing the directions of gas market development in the Northeast Asian region.

Comprehensive studies on the priority directions of gas infrastructure development in the NEA region have been carried out under NAGPF initiative since the beginning of its foundation. The implementation of the proposed projects of gas infrastructure development is beyond the NAGPF format, as no real technical, financial, social and political implementation mechanisms were established within NAGPF mandate. The construction of gas infrastructure is under the competence of governments and businesses.

V. International project on innovative nuclear reactors and fuel cycles (INPRO)

The project was launched in 2000 by the decision of the General Conference of the International Atomic Energy Agency (IAEA) after Russia's proposal at the UN General Assembly session to develop international cooperation for the large-scale use of nuclear energy. The basis for the creation of INPRO was the interest of many countries in the nuclear energy development, and the main tool of this initiative is the creation of a single platform for the comprehensive assessment of the widespread use of innovative technologies in the field of nuclear reactors and nuclear fuel cycles [2].

INPRO develops regional and global scenarios of the nuclear energy development, evaluates the prospects for innovative technologies and regulatory institutions in the nuclear industry, and assists the interested states in a comprehensive assessment of the development of nuclear energy using INPRO methodology.

Today 41 countries, including Russia, China, Japan and the Republic of Korea from the NEA region, participate in the INPRO initiative. In 2001-2006, a methodology for evaluating innovative nuclear power systems was developed. Since 2006, this methodology has been implemented at three levels: national, regional, and global [8]. This initiative is well organized and structured, which eliminates duplication of functions between different departments of the parent organization and significantly

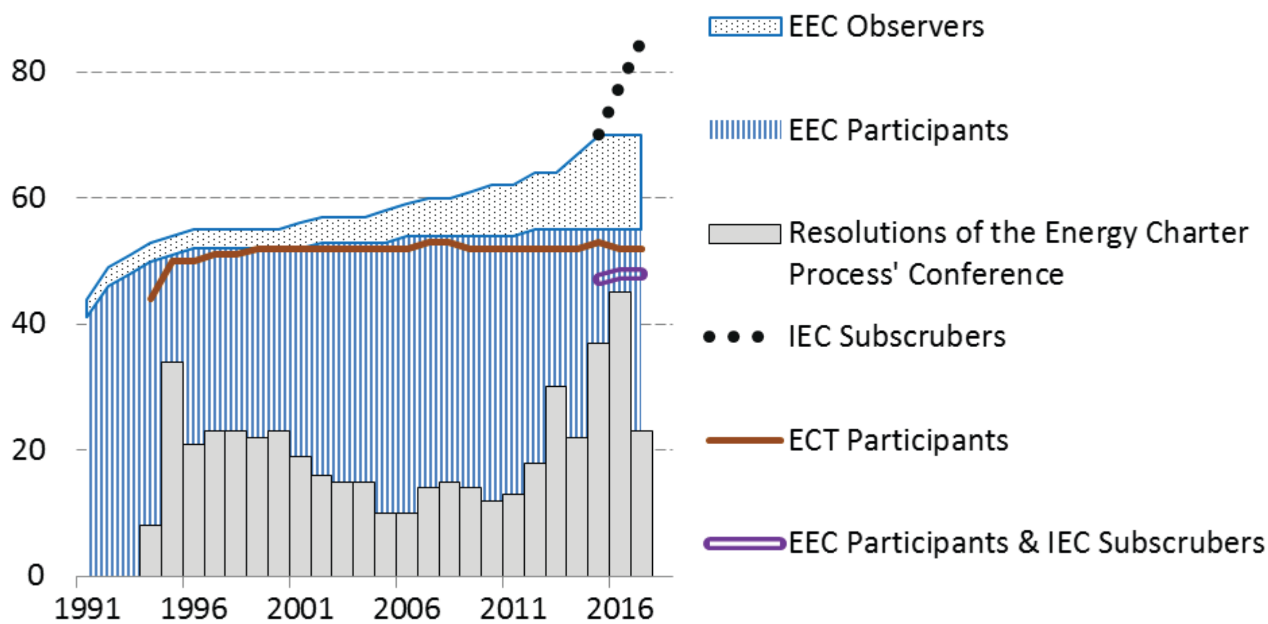

Fig. 4. Change in the number of participants in the Energy Charter Process

reduces the uncertainty of decision-making. The activities of INPRO are regulated by the Supervisory Board, which includes representatives of the participating countries. The INPRO is financed by the member countries and in part by IAEA [9].

The work of the initiative under the auspices of the IAEA is an important organizational factor. Despite a number of the existing political contradictions, there is a clear understanding among the participants of the initiative that it will be difficult to keep the leading positions in the field of peaceful nuclear energy without joint efforts for the sake of technology development.

The international project is an example of a successful IEI in nuclear energy. The results of the research on innovative nuclear reactors and fuel cycles are publicly available. The most productive period of INPRO's work was in 2002-2012 (Fig. 3). This period is characterized by a fast increase in the number of this IEI's participants, and by the large number of organized seminars and conferences. At the moment, the potential for further development of INPRO is not exhausted, but the presence of some economic and political contradictions between its main participants can significantly reduce the level of involvement of new member countries in the future.

VI. The energy charter treaty process (ECT process)

The Energy Charter Treaty (ECT) was signed in December 1994 on the basis of the idea "that multilateral rules can provide a more balanced and efficient framework for international cooperation than bilateral agreements alone or non-legislative instruments". It was a remarkable multilateral effort to improve energy security by means of binding regulatory framework for resolving disputes around two basic international energy issues: investments and international (including transit) overland energy deliveries by using a specialized technological infrastructure. These particular issues are beyond the scope of the World Trade Organization.

There are few mechanisms for the implementation of the Energy Charter Treaty objectives: a) monitoring of the ECT implementation and readiness to consider proposals for new tools development under the ECT parties' control (the so-called Energy Charter Process); b) the keeping and enhancing of the ECT's legislative platform; c) providing institutions for settling disputes at all communication strata of the Energy Charter Process' participants [10].

There are several strata to participate in the ECT: a signatory party, an observer, a full ECT member (Contracting Party). Among the Northeast Asian countries, only Mongolia and Japan are full ECT members, while China and the Republic of Korea are observers to the Energy Charter process [11]. The Russian Federation, being the ECT Signatory, unilaterally changed its institutional status in August 2009 and became an observer. In April 2018 Russia formally withdrew its signature under the Energy Charter Treaty, losing the right to vote for further development of this unique multilateral instrument to protect and stimulate energy investments [12].

In 2015, participants in the Energy Charter Process adopted a new Declaration – the International Energy Charter (IEC). The IEC lists important global energy regulation issues for multilateral cooperation [13]:

- The growing weight of developing countries for global energy security;
- Interrelations between energy security, economic

development and environmental protection;

- The role of energy trade for sustainable human development;
- The need to diversify energy sources and routes of energy delivery to its consumers;
- The process of energy markets' regional integration.

Full membership in the ECT allows one to take advantage of binding guarantees of access to international energy infrastructure, to investment and innovative technologies. Despite the widespread interest in the ECT, major actors at the energy stage prefer not to commit themselves. It is worth noting that eight of the top ten world's energy producers, as well as eight of the top ten energy consumers, are not among the participants of the ECT process. These are China, USA, Russia, Republic of Korea, Brazil, Saudi Arabia, India, Canada, and Iran [11; 13]. Most of these energy powers have a developed maritime transport infrastructure, and are not interested in the overland energy transit issues.

The obstacles are quite opposite in the Northeast Asian region, where both Mongolia and Japan are extremely interested in the ECT as a binding mechanism to reduce investment risks in energy sector and to level playground for the energy transit from landlocked Mongolia. Meanwhile, China relies on its economic, financial and geographical position to deal with investment and transit issues on a bilateral basis, without being bound by multilateral obligations. At the same time, the largest regional "island" importers of energy resources (Japan, the Republic of Korea, and Taiwan) need established legal regulation for energy transit infrastructure in order to get direct access to the Eurasia's energy resources [14].

VII. Results of the study

International energy initiatives provide a wide field for discussion in terms of their influence on national economies. As the economic ties between Northeast Asian countries improve, a strong interest in energy cooperation will gradually shift from endless conversations to particular practical implementation.

Thus, it is worthwhile to place an emphasis on several implications derived from the study:

1. All countries within the NEA region are interested in both the results and the very process of international cooperation, bearing in mind their own energy security;
2. The political factor is of high importance to each IEI considered. Despite significant slowdown, TAGP continues to build interstate gas pipelines with the ASEAN Member States support. The NAGPF example demonstrates both the importance and ambivalence of the international policy factor for bilateral and multilateral relations. The steady growth in the number of the IEI participants, such as INPRO and ECT, illustrates the importance of government support to the multilateral energy cooperation's progress.
3. The high practical value of proper management and adequate resources for IEI implementation is confirmed by the TAGP, INPRO, and the Energy Charter Treaty initiatives. The first has benefits from the ASEAN's umbrella exploitation, the second is under the auspices of the IAEA, and the last one is an important international organisation. For each of the initiatives a particular mechanism for regular revision of its mission, goals, and implementation procedures is incorporated within its organisational structure.

International energy initiatives discussed in the paper cannot be unambiguously evaluated as successful or unsuccessful, even after complete cessation of the initiative's activities and the elimination of its organisational structure. Initiatives can go through cyclical developments, alternating stages of activity and stagnation depending on the socio-political and financial-economic framework.

The paper recommends evaluating the development of IEI in NEA countries through overarching interaction within national governments, private energy businesses and R&D organizations. Today IEI create an international language in the Northeast Asian region, which will facilitate launching large-scale interstate energy infrastructure projects, introducing experience gained in negotiations, and increasing mutual trust.

VIII. Conclusion

Revision and refinement of the methodology for the assessment of the International Energy Initiatives was the main objective of this paper. The original methodology, briefly presented in the first part of the paper, identifies several factors that affect the international energy initiatives' progress. It was reaffirmed that the International Energy Initiatives are developed and implemented only if there is a strong common motivation among the participating countries. Furthermore, it is proposed to widen this methodology by using some quantitative indicators. Amid political and economic contradictions plaguing Northeast Asian countries, the analysis reasserts the existence of effective multilateral international energy cooperation in the region.

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System Inertia As A Barrier To The Acceleration Of The Energy Sector Development

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***Abstract* – This study is focused on the qualitative assessment of the barriers that hinder the acceleration of energy systems development. System inertia is one of the above barriers and as such, it is of tantamount importance. It is brought about by high capital intensity and material intensity of the electric power industry and the fuel industry as well as by the close direct and indirect production links they maintain with the machine industry, the iron and steel industry, and other industries that serve as their suppliers. We propose a system of performance indicators to characterize the property of inertia and the techniques for their estimation. The study reveals a nonlinear dependence of inertia on the acceleration rates of energy development. Furthermore, we elucidate the impact of imports from the industries related to the energy sector on its system inertia.**

***Index Terms* – energy sector, forecasting, inertia, indicators**

I. Introduction

High capital intensity and the inertia inherent in the energy sector industries urge us to pay due attention to their capacity to ensure the accelerated development of the Russian economy, the growth of energy consumption, and a significant increase in exports of energy resources. A possible bottleneck can manifest itself as a lack of time or that of materials, funding, and labor necessary for new capacity additions not in the energy sector itself but in its supporting industries.

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The higher is the hierarchical level, the more complex grow the systems representative thereof and the more significant is their inherent inertia. Hence the more challenging it becomes to overcome the barriers that appear when accelerating the development rates and when the structure of such systems has to undergo changes.

The list of barriers depends on a specific problem and a given hierarchical level. To this end, it makes sense to distinguish between constraints and barriers that are exogenous and endogenous to a given hierarchical level (see Table 1).

Of all endogenous constraints, temporal barriers conditioned by the development inertia of energy systems are among the most significant ones.

Published research [1-6] on inertia and flexibility of energy systems saw its heyday in the USSR back in the 1980s. A similar line of research was pursued at the International Institute of Applied Systems Analysis (IIASA), Austria [7-8]. In recent years, there has been a strongly felt need to deepen and reconsider the notion of the inertia of energy systems and the importance of temporal barriers under new conditions of the development of the national energy sector and economy.

II. System inertia

Inertia is an inherent property of large developing systems. To be deemed well-grounded no projection can ignore this property. The importance of investigations into potential quantitative manifestations of inertia under changing conditions of the energy development is reflected in the works by academician Lev A. Melentiev. He defined inertia as an ability of systems to resist development understood as external and internal stimuli that target to change the previously projected pathway (development) [9], and he treated inertia as bundled with the property of flexibility as constraining the latter. By flexibility, he meant the ability of a system to change its strategy at a required rate to ensure normal development and operation under potential disturbances.

Economic inertia can arguably be characterized by the

Table 1. Energy development constraints specific to various hierarchical levels.

Hierarchical level	Internal constraints	External constraints
1. Companies, enterprises	Available production capacity (assets, technologies, labor, reserves). Financial resources. Performance of projects and their investment risks. The time required for construction and modernization.	Demand for the company's products, market prices, export and import opportunities, competition, infrastructural constraints, directives.
2. Systems of individual industries	The scale and the required time for the potential development of resource fields and new capacity additions. Available capital investments. Availability and throughput capacity of major transportation links. Constraints on the development of individual companies (as applied to new capacity additions by regions).	Volumes and patterns of demand for products of a given industry, potential for its exports, market prices, directives, assignments, and regulations.
3. Regional energy sectors	Proven resources of fuel and energy resources, required time and volumes of new capacity additions in the electric power industry and the fuel industry within the region.	Demand for fuel and energy, prices. Cross-regional energy links. Environmental and social requirements
4. The national energy sector	Production volumes and development times of major centers of fuel production, the potential for new capacity additions in the electric power industry and the fuel industry.	Demand for energy commodities, boundaries on potential exports and imports of the energy products, prices on international and domestic energy markets, indicators of national security and energy security, limits on CO_2 emissions.

efforts required to change a development trajectory (growth rates, structure, composition) of a given economic system. When applied to energy systems such efforts manifest themselves as the following indicators:

1) total (direct and indirect) capital expenditures or total costs of labor and other resources in the national economy spent on production and consumption of an additional unit (in million tce) of a given energy resource factoring in the costs of development of related industries, as well as the production and social infrastructure;

2) time required to implement all such capital expenditures and all supporting measures (inclusive of design and survey work, provision of necessary facilities on site, etc.);

3) maximum incremental increase in the production of a given energy resource that can be achieved in n years per every billion rubles of additional capital expenditures.

The latter indicator is compound in nature and is derived from the former two ones. Quantitative assessment of all of the above indicators and their presentation in the form of functional dependencies enables us to compare and rank various centers of fuel production and alternative

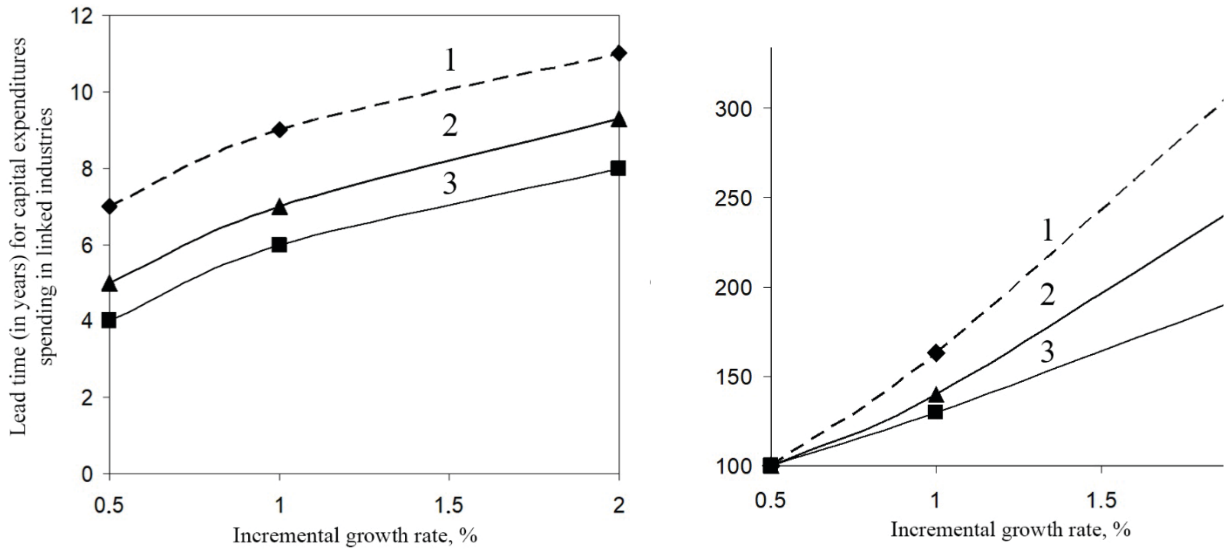

Figure 1. The general pattern of the effect an increase in incremental growth rates for the production of energy commodities has on an increase in time and capital expenditures required for the adequate development of related industries. 1 – electricity, 2 – gas, 3 – coal.
Note: exclusive additional imports of equipment and materials. Source: calculated by the authors [10].

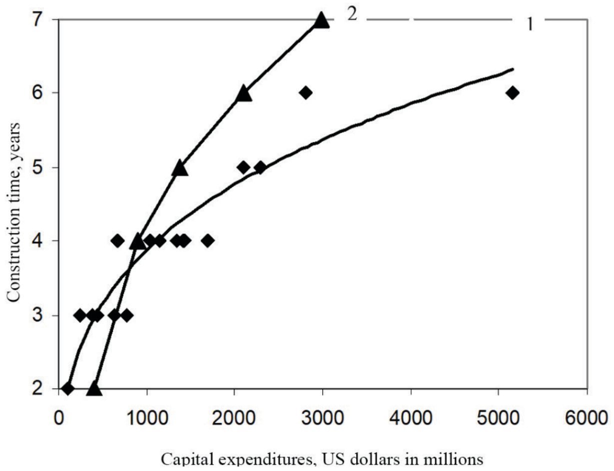

Fig. 2. The effect power plants construction costs have on the time it takes to put them into operation. 1 - in the USA, 2 - in Russia

Sources: Calculated by the authors based on [11] and [12].

energy sources based on their inertia levels.

Two complementary indicators can be applied to characterize relative inertia of the development of entire industries. These are 1) minimum time required to increase incremental growth rates of the products produced by the industry by 1 percentage point or its share in the gross output of the industry by 1 percent; 2) additional expenditures on the part of the resources of the national economy that are required to achieve this.

If one is to consider capital expenditures as a key factor that leads to changes in the structure and development rates, then total capital intensity can be understood by analogy with physics as the body weight, which characterizes the inertia of the system. The higher is the value of this indicator, the higher is the inertia.

The intrinsic inertia of the energy sector and its subsystems is made up of the inertia of new centers of fuel production and newly built energy facilities and technologies the development of which defines its prospective structure.

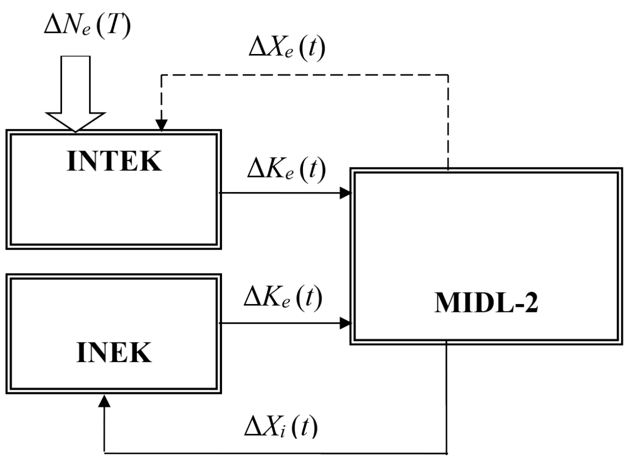

Fig. 3 The information flow diagram of the IMPAKT-2 model.

Obviously, inertia indicators for the development of new centers of hydrocarbon production, in addition to the features specific to a given energy production, are also influenced by region-specific features such as natural and climatic conditions, the level of development of the area, its distance from potential suppliers and consumers, the capacity of the construction base, labor balance of the district, etc. The less favorable are the regional conditions, the higher are the required direct and coupled capital expenditures for the implementation of a program.

Of all the external conditions that influence the inertia level of the energy sector, a key role is played by the level of development of related industries and the time required to produce equipment and materials to boost production, conversion, and transportation of energy resources. The implementation of large-scale projects in the electric power industry and the development of new centers of fuel production may require outpacing new capacity additions in energy-related machine industry, the iron and steel industry, the construction industry, and other industries and production units that support the energy sector. The higher is the growth rate of the energy sector industries, the higher, in general, is the number of production facilities involved in backing it and the more important is the role of remote adjacent links. Our calculations prove that additional (indirect) capital expenditures in such production facilities and their lead time grow in a non-linear way as the energy sector development accelerates (see Figure 1).

The non-linear growth of the time required for construction as directly related to the increase in required capital expenditures is furthermore proved by Figure 2 based on Russian and American data on capital expenditures (in 2009 prices) and time limits for construction of power plants of various types.

The energy sector development inertia is related to the inertia of the entire economy. The higher is its ability to make maneuvers with financial and labor resources, to change the structure of its industries and promptly respond to changing situation and state of international markets, the easier it is to ensure required changes within the energy sector and its related industries. On the other hand, the energy industry enhances the flexibility of the economy by lowering its inertia.

2. Methods and findings of the research into the temporal barriers and inertia of energy systems

The input-output IMPAKT model was developed as early as back in 1975 to enable the study of the inertia property. The model formalized the process of retrograde unfolding (i.e. from the future back to the present) of links of various levels from a given energy facility to production facilities that ensure its development. A shortcoming of this model was that it failed to account for expected economic conditions. To a certain extent, this issue is addressed by the IMPAKT-2 system of models developed at the Melentiev Energy Systems Institute, SB RAS (see

Figure 3). Its software implementation is made up of three modules: INTEK, INEK, and MIDL-2

MIDL-2 is an updated version of MIDL, a well-established dynamic optimization macroeconomic model [13] of the input-output type. The new version of this model takes into account the annual dynamics of economic development unlike the earlier version that was limited to the temporal resolution of five-year periods within the 30-year long timeframe. The model describes mutual production links between 29 branches of the national economy and between production and non-production industries via the consumption of goods and services, as well as investment links and export-import links.

INTEK is a model employed for the assessment of required dynamics of direct capital expenditures for the construction of new energy facilities (inclusive of the required infrastructure) that are part of a given development option. To this end, the model allows for standardized time limits for construction and the distribution of equipment costs and mechanical completion costs over the span of all years starting from land-use planning and development to commissioning and start-up of the facility. The model allows aggregating certain variables and presents them in a way that suits their use in a macroeconomic model.

The INEK model determines the dynamics of capital expenditures for related industries and production facilities. Requirements for their development rates are determined upon obtaining a corresponding solution from the MIDL-2 model.

IMPAKT-2 modeled calculations are performed as per the following iterative procedure under the assumption that the reference case of the development of the economy and the energy sector is pre-defined [10]:

1. MIDL-2 is calibrated so as to match the reference case.
2. The INTEK model then calculates the dynamics of new capital expenditures based on a pre-defined case of new capacity additions in the energy sector or one of its subsystems. The respective additional demand for equipment and construction and installation work are then fed into MIDL-2 together with data on the required increase in the energy sector production volumes in year T.
3. The solution provided by MIDL-2 and its comparative analysis against the reference case makes it possible to determine the rate of required additional development of related industries (first-level linking), as well as the corresponding increase in demand for energy commodities.
4. These data ($\Delta X_i\ (t)$) are fed into the INEK model that calculates additional capital expenditures required in related industries.
5. In the case of a significant increase in the fuel and energy demand in related industries, INEK is used to detail the capital expenditures required by the energy sector.
6. The results of calculations in stages 4 and 5 are then transferred to MIDL-2 in order to detail the dynamics of the additional development required of the economy relative to the reference case and to identify more remote linking levels.

By varying the product imports of various industries in MIDL-2, one can assess their impact on the inertia level (i.e. the required look-ahead development of related industries and its scale).

The following IMPAKT-2 model calculation results for a simplified case study provide an overview of potential impacts on the scale and time limits of required additional development of various branches of the economy, on the increase in the electric energy production and equipment imports. The scenario of the development of Russian economy and energy industry in which electric energy

Table 2. The effect of 60% imports of equipment on lowering the demand for products of related industries and coupled capital expenditures.

Industries	Decrease, %	
	gross output	capital expenditures
Machine industry	79	75
Construction industry	7	3
Oil and refinery industry	21	15
Gas industry	9	10
Coal industry	8	1
Iron and steel industry	54	50
Chemical industry	49	43
Construction materials industry	11	3
Transportation industry	29	20
Other industries	25	20
Total	**34**	**17**

production reaches the 1.5 trillion kWh by 2030 was used as the reference case. As its alternatives, we also studied the growth of electric energy production by additional 5 and 15 percent in 2026 to 2030.

Our calculations suggest that total capital expenditures of related industries, given no equipment and materials imports, can exceed direct investments in the electric power industry by 1.2 times under additional growth rates of the electric energy production by further 5%, and by 1.35 times under the growth rates of 15%. The share of the gas industry and other fuel industries in the overall composition of additional capital expenditures for related industries, the transportation industry, and the telecommunications is 15-22%, the construction industry accounts for 12-19%, the machine industry is 2-6%, the iron and steel industry is 2-3%, while the rest of the industries make up 11-12% altogether.

It is essential that a significant share of capital expenditures, the required increase in the demand for industrial products and services take place in the years prior to the surge in electricity production. Based on our calculations, the increase in the demand for industrial products, construction and installation work, the transportation and tertiary services manifests itself 5 to 10 years prior the required 5 percent increase in the electricity production and by 10 to 15 years and more in the case when such incremental growth increases up to 15 percent.

Imports of required equipment contribute to a notable decrease in the level of inertia by eliminating remote linking levels. This is illustrated by the data in Table 2 that reflect the results of calculations for the case of the incremental increase in the electricity production by 15 percent subject to the constraint that makes 60% of additional demand for the machine industry products (relative to the reference case) satisfied by imports in the time period from 2020 to 2030. The calculations suggest that the additional demand for the products of all related industries decreases by 34 percent. Here, most drastic (by 50 percent and more) is the decrease in the required production of ferrous and non-ferrous metals and chemical products. Freight turnover and demand for petroleum products fall by 21-29 percent (exclusive of gas pipelines). Required production output by the machine industry decreases over the entire period more than the volumes of additional imports of energy equipment due to the decrease in the demand for related capital expenditures. In this case, the lead time at the beginning of the investment process decreases as follows: by 8 to 12 years in the machine industry, by 5 to 10 years in the iron and steel industry, and up to 5 years in other related industries

III. Conclusion

It follows from the above that the inertia inherent in the energy sector development can be properly assessed only when viewed together with the entire economy, whereas an analysis of the inertia inherent in the development of individual centers of fuel production requires due consideration of its role in the national energy sector.

The present study outlines an approach to quantitative assessment that targets such inertia indicators as the timing and the scale of the required look-ahead development of the industries related to the energy sector alongside the corresponding capital expenditures. The method can prove instrumental in elaborating available approaches to a comparative ranking of the energy sector development options as based on the feasibility criterion [14]. Evaluation of risk in individual capital investment projects should serve as a vital part in the process of arriving at such a comprehensive criterion. This analysis on a par with addressing the issue of energy systems inertia is an integral component of assessing quantitatively the robustness of available options under changing conditions [15].

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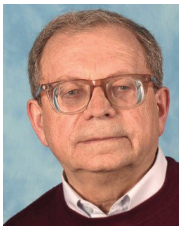

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Optimization Of Hydraulic Conditions Of Radial District Heating Systems With Pumping Stations

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Abstract – **The paper focuses on the problem of multi-criteria optimization of hydraulic conditions of district heating systems on the basis of the following objective functions: minimum costs of maintaining the operating conditions, the minimum time for adjustment measures, a decrease in the overall pressure level in a network to minimize unproductive expenses and risks of emergency situations. Specific features of the considered problem are a radial configuration of networks, availability of pumping stations and one heat source. The operating conditions optimization problem is mathematically formalized using controls such as a change in the number of operating pumps, impeller speed, impeller diameter at pumping stations and flow throttling. A modification of the problem-solving method is based on a combination of the methods of dynamic programming and reduction of series and parallel connections of the calculation scheme branches. The final algorithm comprises procedures for creation, stepwise increase, rejection and aggregation of possible phase variable trajectories in the first (forward pass) stage that terminates with the determination of the optimal solution for the single branch with subsequent restoration of components of this solution in the second (backward pass) stage of the algorithm for the initial scheme. The case study illustrating the application of the proposed method to a real district heating system with four pumping stations demonstrates the optimality of the obtained solution by several criteria concurrently and high computational efficiency compared to the methods for a general case of multi-loop networks with unknown flow distribution.**

Index terms: multi-criteria optimization, ndistrict heating system.

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I. Introduction

The problem of an increase in the energy efficiency of district heating systems (DHSs) is topical in Russia and abroad [1]–[4]. The natural processes of equipment ageing and wear, the change in load level and structure, organizational division of technologically related DHSs, their untimely reconstruction and adjustment, and other reasons, all lead to off-design conditions of DHSs, high losses of heat carrier and thermal energy, increase in energy consumption for pumping, emergency rates and violations of technological requirements and uninterruptable heat supply to consumers. The optimal operating conditions of DHSs can contribute to significant energy saving.

The problems of operation optimization arise in different stages of decision making on the DHS control: 1) during reconstruction – to assess the effects of old equipment replacement and new equipment installation (pumps with impeller speed control, automatic regulators and others); 2) during preparation for the next heating season in the process of DHS operation (operation planning) – to adjust and regulate heat networks in view of the changes in the DHS structure and parameters; 3) during real-time control – to plan the loading of basic equipment for the coming day. This paper is devoted to optimization problems of steady-state hydraulic conditions of DHSs that arise in the first and second stages.

In practice, the problems of DHS operating condition planning are solved by the multivariate flow distribution calculations to analyze the consequences of possible measures [5]. In this case, such measures are chosen by an expert performing calculations and the solution quality depends on both the expert's experience and skills and the DHS scale and complexity. As a result, such an approach does not guarantee optimal operating conditions and sometimes even feasible operating conditions. Automation of these problems-solving process is difficult because of some factors, such as their high dimensionality (reaching many hundreds of thousands of variables), nonlinearity, discreteness of part of variables, availability of several optimality criteria, etc. For these reasons, there are currently no methods and software for DHS operation optimization that would be appropriate for wide application. Therefore, the development and application of independent methods, algorithms, and programs are relevant for the calculation of DHS optimal conditions.

Recently, the optimization problems of DHS operating conditions have been much discussed in scientific publications, which indicates the increasing relevance and at the same time, complexity and versatility of such problems. A large number of studies ([6], [7] and others) are limited to the local small DHSs. The techniques proposed for large DHSs are 1) the aggregation of DHS schemes ([8], [9] and others), which do not allow considering the whole set of initial conditions and constraints; 2) the approximation of relationships between the objective function value and the state variables (chosen as the basis) [10], [11] in case of difficulties in adequately considering discreteness of the optimized equipment configuration; 3) the application of the off-the-shelf software to solve optimization and simulation problems by the general-purpose mathematical methods, which do not take into consideration the DHS features, and require considerable computational effort. In [12], [13], for example, the model of a physical network is constructed in the Simulink/Matlab environment and its state is calculated by the off-the-shelf CPLEX solver, while its optimization is performed by the ReMIND software; 4) the application of the semi-heuristic, but easily-implementable genetic and evolutionary algorithms, which, however, involve even more computational effort. In [14], for example, the pumping expenses are minimized by the nested iteration cycle. In the internal cycle, the feasible condition is iteratively calculated by the SIMPLE-algorithm. In the external cycle, the parameters that influence the condition are changed using the genetic algorithm. Optimization of the DHS conditions often involves partial criteria. For example, in [15] the total fuel consumption is minimized at a specified heat carrier flow rate in the pumps. In [10], [11] the optimal control problem of pumping stations (PSs) is solved using the criterion of minimum consumed electricity under specified heat carrier temperatures. At the same time, there are practically no works devoted to the multi-criteria statements of the optimization problems or the multi-criteria problem is solved by the formal weighting of diverse criteria [16].

In addition, the dynamic programming (DP) method is applied effectively enough and widely to solve the optimization problems of expansion and reconstruction of the tree-structured DHSs (when the flow distribution is known). This method is potentially applicable to the optimization of operating conditions ([17], [18] and others) as well. For a general case of the multi-loop networks with the unknown flow distribution, S.V. Sumarokov suggested a method based on the iteration process with the alternate application of the methods of flow distribution calculation and DP [19], [20]. A modification of this method [21], which also involves the iterative process of solution search but has no rigorous substantiation was proposed for multi-loop pipeline systems with the specified flow distribution.

There are also modifications of the DP algorithms for optimization of radial DHSs. These modifications are based on separate optimization of the supply and return pipelines of a heat network [18]. The radial DHSs have a tree topology in a single-line representation but their calculation schemes are multi-loop ones because each consumer forms an independent loop of heat carrier circulation. Applicability of such decomposition to the optimization of operating conditions was studied in [22]. The study indicated that solving the problem "by parts" did not yield either an optimal or even a feasible solution for the whole DHS.

This paper presents the results of the evolution of the DP method modification suggested by the authors earlier for optimization of hydraulic conditions of distribution heat networks [22] in order to allow for active components (pumping stations) and several optimality criteria. The proposed DP modification is applied to hydraulically related DHSs of a radial structure with one heat source (HS) which are studied as a whole (without decomposition). The temperature curves at a heat source are assumed to be specified, the heat losses are eliminated, and their residual value may be neglected. In this case, the requirements of heat energy supply to consumers are reduced to the necessity of maintaining an appropriate heat carrier flow rate, and the problem is reduced to hydraulic conditions optimization. Fixing the flow rates in the radial DHSs specifies the unique flow distribution in the network, and therefore the subject of DP method study and evolution is the hydraulic condition optimization in the network with the specified flow distribution and the multi-loop topology of a special type. Provided there are pumping stations in DHS, they are taken into account through consideration of the case typical of a DHS when the similar centrifugal pumps are installed at the pumping station and connected in parallel.

The proposed DP method with loop reduction [22], [23] has some advantages: 1) linear increase in the computational effort depending on the problem dimension, which allows optimization of large DHSs; 2) verifiability of the existence of at least one feasible solution; 3) possible optimization on the basis of several criteria simultaneously; 4) guaranteed optimality of the obtained solution; 5) high computational efficiency (without the iteration process) compared to the methods for a general case of multi-loop networks with the unknown flow distribution [24]; 6) potential adaptability to consideration of pumping stations while retaining all these properties.

II. Problem statement

The substantive objective of optimizing the hydraulic conditions of DHS is to find controls that ensure the implementation of a condition that satisfies the feasibility and optimality requirements in accordance with a given system of criteria.

The feasibility requirements are reduced to the necessity of meeting consumer loads and observing conditions of equipment operation. The energy saving requirements may be reduced to the uniform economic criterion – the variable component of operating costs. The other (technological) criteria are intended to minimize labor input of adjustment measures, decrease heat carrier leakages and risks of emergency situations. Optimization on the basis of technical criteria may be reduced to the minimization of pressure control points and minimization of the overall pressure level in the network. The considered controls are aimed at a possible change in the performance of DHS components (pumping stations, pipeline sections, and consumers) and include a change in the number of operating pumps, the impeller speed, the impeller diameter, and flow throttling. For the pipelines and the sections modeling consumers, the controls are performed mainly by throttling (by the regulator, the balancing valve or other devices).

III. Models of the controlled DHS components

Denote sets of the indices of branches of the DHS calculation scheme that model pipelines, pumping stations, and consumers by IPL, IPS, IC, respectively. Then $I_{PL} \cup I_{PS} \cup I_C = I$ is the set of indices of all branches, $|I| = n$, n is the number of the scheme branches.

A generalized hydraulic characteristic of the branch can be represented by [24]

$$h_i(x_i, z_i, \gamma_i, \kappa_i) = z_i s_i x_i |x_i| / \kappa_i^2 - \gamma_i^2 H_i, \ i \in I \qquad (1)$$

Here: i is the branch index; h_i is the pressure drop; x_i is the heat carrier flow rate; s_i is the hydraulic resistance of the pumping station; H_i is the pressure rise caused by pumps at the pumping station; γ_i is the relative impeller speed (or its diameter); k_i is the number of operating (from installed) pumps at the pumping station; z_i is the hydraulic resistance index because of throttling ($z_i \geq 1$). Thus, z_i, γ_i are the continuous controls, and k_i are the discrete controls.

In (1) any type of unavailable or impermissible control can be taken into consideration by assigning the constant to its value. For example, for $i \in I_{PL} \cup I_C$: $H_i = 0$, $k_i = 1$. For the illegal throttling $z_i = 1$, $i \in I$. If the speed control is impossible, then $\gamma_i = 1$, $i \in I_{PS}$. The variant $k_i = 0$, $i \in I_{PS}$ in (1) is modeled by the values $k_i = 1$, $H_i = 0$, and s_i is the bypass line resistance with possible throttle installation when z_i is variable.

Model of controlled hydraulic condition. Based on the indicated features of the radial network topology (the tree topology in a single line representation, the multi-loop calculation scheme, symmetric connection schemes of components for heat carrier supply and return which are connected through the source and consumers) (Fig. 1), and the requirement to meet the specified flow rates at consumers, we have fixed distribution of flows in the network (x_i, $i \in I$). Then expression (1) can be substituted by $\tilde{\omega}_i(z_i, \gamma_i, \kappa_i) = z_i s_i x_i |x_i| / \kappa_i^2 - \gamma_i^2 H_i, \ i \in I$, and the model of the controlled hydraulic condition of DHS which is applied in [24] for the general case of unknown flow distribution will have the form

$$\begin{pmatrix} A^{\mathrm{T}} P - y \\ y - \tilde{\omega}(z, \gamma, \kappa) \end{pmatrix} = 0 \qquad (2)$$

where: A is the $m \times n$-dimensional incidence matrix of the DHS calculation scheme;
m is the number of nodes in the calculation scheme; Q, P are the m-dimensional vectors of nodal flow rates and pressures; y is the n-dimensional vector of pressure drops in branches; $\omega(z, \gamma, k)$ is the n-dimensional vector function with the components $\tilde{\omega}_i(z_i, \gamma_i, \kappa_i)$, $i = \overline{1, n}$.

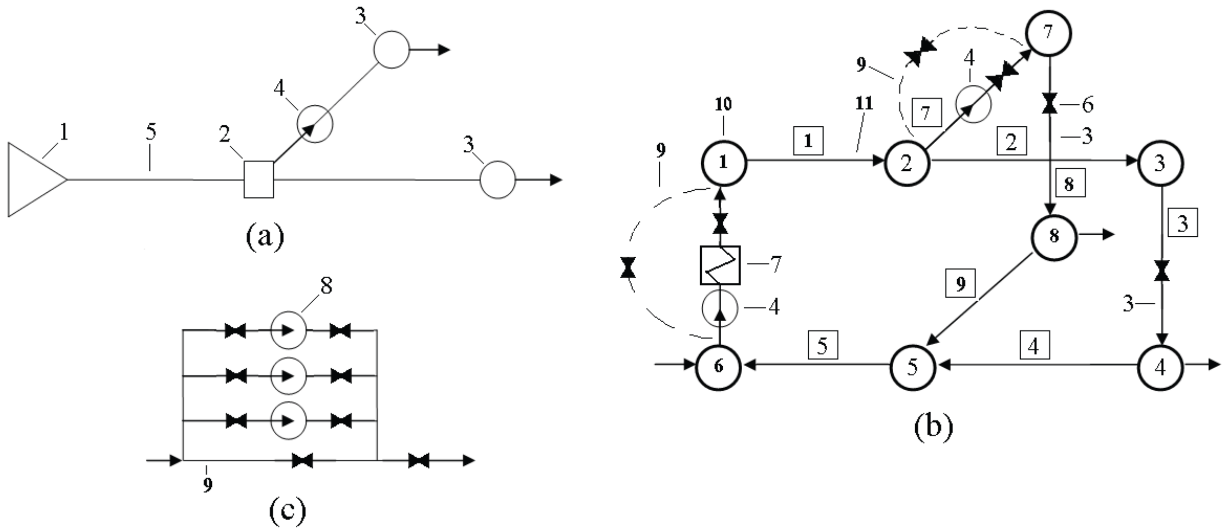

Fig. 1. Example of a single-line technological (a) and double-line calculation (b) DHS schemes and a block diagram of pumping station (c). 1 – heat source, 2 – heat chamber, 3 – consumer, 4 – pumping station, 5 – pipeline, 6 – control point z_i, 7 – heaters, 8 – pump, 9 – bypass line, 10 – number of node j (the figures in circles), 11 –number of branch i (the figures in squares).

Let us call part of the hydraulic condition parameters that depend on the environment boundary conditions. When the heat source is a boiler plant, it can be treated as an ordinary pumping station with the given pressure at the makeup node (at the inlet). Optimization of the cogeneration plant operation is an independent subproblem [26], and consideration of its operation at known connected load is reduced to assigning two pressures (at the inlet and outlet).

The feasibility requirements are: $\underline{P}_j \le P_j \le \overline{P}_j,\ j=\overline{1,m}$, $\underline{y}_i \le y_i \le \overline{y}_i,\ i=\overline{1,n}$, where the bottom and top lines indicate the given boundaries for the feasible value of the same parameter. The requirement of the effective range of feasible capacities should also be observed for pumping stations. Let $\underline{\chi}_i, \overline{\chi}_i$ be the boundaries of the effective range of flow rates for one typical pump on the i-th branch with a pumping station, then we have the inequality $\kappa_i\gamma_i\underline{\chi}_i \le x_i \le \kappa_i\gamma_i\overline{\chi}_i$ or $x_i/\overline{\chi}_i \le \kappa_i\gamma_i \le x_i/\underline{\chi}_i \quad i\in I_{PS}$. Besides, it is necessary to comply with the feasibility requirements of the controls: $1\le z_i \le \overline{z}_i$, $\underline{\gamma}_i \le \gamma_i \le \overline{\gamma}_i$, $k_i \in \{0,1,2,...K_i\}$, $i \in I$. Introduce the vector of the Boolean variables δ, whose components $\delta_i \in \{0,1\}$ indicate the absence or presence of a throttle on the i-th branch. The inequality $1\le z_i \le \overline{z}_i$, in this case, may be expressed as $1\le z_i \le 1+\left(\overline{z}_i-1\right)\delta_i$ On the whole, the system of inequality constraints has the form

$$\begin{aligned} &\underline{P}_j \le P_j \le \overline{P}_j,\ \underline{y}_i \le y_i \le \overline{y}_i, \\ &1\le z_i \le 1+\left(\overline{z}_i-1\right)\delta_i,\ \underline{\gamma}_i \le \gamma_i \le \overline{\gamma}_i, \\ &\kappa_i \in \{0,1,2...\mathrm{K}_i\},\ x_i/\overline{\chi}_i \le \kappa_i\gamma_i \le x_i/\underline{\chi}_i,\ i\in I \end{aligned} \tag{3}$$

Objective functions. The variable component of costs of maintaining the operating conditions consists of electricity costs (to pump heat carrier) and fuel costs (to heat water). In the considered case of DHS with one heat source, its heat load is fixed (equal to a total load of connected consumers), the fuel costs do not depend on the heat network operation and can be optimized within the local problem at the level of the heat source scheme. The electric power consumed by the pumping station is set by the function $N_i\left(\gamma_i,\kappa_i\right)=\beta_{0,i}\kappa_i\gamma_i^3+\beta_{1,i}\gamma_i^2x_i+\beta_{2,i}\gamma_i x_i^2/\kappa_i,\ \ i\in I_{PS}$ [24]. Here $\beta_0, \beta_1, \beta_2$ are the coefficients of the square polynomial that approximates the power consumption characteristic by one pump. The economic objective function has the form $F_C\left(\gamma,\kappa\right)=\sum_{i\in I_{PS}} c_i^{EP} N_i\left(\gamma_i,\kappa_i\right)$, where c_i^{EP} is the electricity rate for the i-th pumping station, γ, k are the real and integer vectors with the elements γ_i, k_i, $i \in I_{PS}$. Correspondingly, the "technological" objective functions [25] are the number of control points – $F_z\left(\delta\right)=\sum \delta_i$; the average pressure in the network – $F_P\left(P\right)=\sum_{j\in J} P_j/m$, where J is the set of indices of all nodes.

IV. Mathematical problem statement.

The known are: the calculation scheme topology (matrix A); the fixed pressure at least at one node (P_j^*); the coefficients of hydraulic and capacity characteristics ($\beta_{0,i}$, $\beta_{1,i}$, $\beta_{2,i}$, $i \in I_{PS}$, S_i, H_i, $i \in I$); the acceptable limits of change in continuous parameters of conditions and controls; the sets of possible values of the integer parameters ($\{0,1,2,...K_i\}$, $i \in I_{PS}$); and the electricity cost ($c_i^{EP}, i \in I_{PS}$).

By solving the following optimization problem with $F=(F_C,F_Z,F_P)^T \min F$ subject to (2), (3), (4) it is necessary to determine the throttling sites (δ) and value (z), the number of operating pumps (κ) and the values of their speed (γ), as well as the operating parameters (P and y).

The great number of criteria can be taken into consideration based on the lexicographic ordering of objective functions by the importance that corresponds to the sequence of their listing in (4). The solution to (4) in this case conforms to the solution to the minimization problem of $F_P(P)$ subject to (2), (3), $F_C(\gamma,\kappa)=F_C^*$, $F_Z(\delta)=F_Z^*$ where F_Z^* – is the optimum objective function value in the minimization problem of $F_Z(\delta)$ subject to (2), (3), $F_C(\gamma,\kappa)=F_C^*$, and F_C^* – is the optimum objective function value in the minimization problem of $F_C(\gamma,\kappa)$ subject to (2), (3).

V. Problem-solving method

Basic concepts. In terms of the DP theory, the pressure (P_j) can be determined as a phase variable concentrated at the calculation scheme nodes, and the pressure drop (y_i) – as the main parameter of the elementary trajectory section of this variable along one branch, the remaining unknowns (z,γ,κ) – as controls of this trajectory. DP involves 1) the possibility of representing the process of solution search as a multistep process; 2) the independence of decision making at each step of the stepwise increase in the phase variable trajectory of its prehistory; 3) additivity of the objective function that serves to verify its value for any section of this trajectory. A multistep process of the stepwise increase in the phase variable trajectories can be implemented by bypassing the scheme branches through the nodes connecting them. The only simple path connects any two nodes in the tree networks. In the considered case with available loops, the things are quite different, and the main problem is to reject trajectories that do not satisfy the second Kirchhoff law. The second condition is observed owing to the fixed flow distribution since the phase variable trajectory at each step depends only on the parameters of the function $\tilde{\omega}_i\left(z_i,\gamma_i,\kappa_i\right)$ at this step. All of the above objective functions are additive.

The main idea of the proposed modification of the DPLR (DP with loops reduction) method consists in a combination of the methods of DP and reduction of the series-parallel connections of the calculation scheme branches. The main DP procedures include creation, stepwise increase, and rejection of possible phase variable trajectories in the forward pass that terminates when the optimal solution is obtained, with subsequent restoration of the solution components in the backward pass of the algorithm. The reduction techniques are based on two simple relations $y_E = \sum_{i \in R_1} y_i$ and $y_E = y_i, i \in R_2$ for the pressure drop in the equivalent branch (y_E) that substitutes the set R_1 of branches connected in series or the set R_2 of branches connected in parallel. The last relation follows from the second Kirchhoff law for the simplest loop of two branches.

Trajectories of the phase variable are created in the space of its discrete values. The feasible pressure range at each node is divided into $W_j = (\overline{P}_j - \underline{P}_j)/\varepsilon_P$ cells, where is the specified cell size. Therefore, W_j possible discrete pressure values $P_j(w_j)$, $w_j = \overline{1, W_j}$ correspond to each node. Denote the starting and end nodes of the i-th branch by $f_i \in J$ and $l_i \in J$, respectively. By varying the feasible controls on this branch for each $P_{fi}(w_{fi})$, $w_{fi} = \overline{1, W_{fi}}$ at the node f_i, we generate various trajectory sections such that $y_i^k = \tilde{\omega}_i(z_i^k, \gamma_i^k, \kappa_i^k)$, $\underline{y}_i \le y_i^k \le \overline{y}_i$ and $P_{li}(w_{li}) = P_{fi}(w_{fi}) - y_i^k \in [\underline{P}_{li}, \overline{P}_{li}]$, where $P_{li}(w_{li})$ is rounded to the value corresponding to the nearest cell center at node l_i, and the unique combination of w_{li}, w_{fi} corresponds to each k. Thus, the cells (possibly, not all) are filled at node l_i, and on each branch there emerges a set of feasible local trajectories of the phase variable with pressure drops, which form the set $Y_i = \bigcup \{ y_i^k \}$, where k is the index of the element of this set. Each trajectory section on the -th branch can be associated with the increase F_i^k in the value of the vector objective function F with the components: $(F_C)_i^k = c_i^{EP} N_i(\gamma_i^k, \kappa_i^k)$; $(F_z)_i^k = \delta_i$, where $\delta_i^k = 0$ at $z_i^k = 1$ and $\delta_i^k = 1$ at $z_i^k > 1$; $(F_P)_i^k = P_{li}^k$, where P_{li}^k is the pressure at the end node for y_i^k. In the case of a pumping station, there can be a non-unique combination of controls (and correspondingly, of the values $(F_C)_i^k$ and $(F_z)_i^k$) that implement y_i^k. At the same time, for the $i \in I_{PL} \cup I_C$ control $z_i \in [1, \overline{z}_i]$ uniquely corresponds to the specific y_i. Therefore, $y_i^k i \in I_{PS}$ should be generated using the local procedure for selection of the optimal combination of controls.

VI. Local optimization of a pumping station

Local optimization of a pumping station is aimed at determining the controls $z_i^k, \gamma_i^k, \kappa_i^k$ optimal by the criterion F_i, which implement the given y_i^k, $i \in I_{PS}$.

For pumping stations, without speed control, the problem is reduced to the enumeration of the options $\kappa_i = 1, 2, ..., K_i$, and for each option $z_i \in [1, \overline{z}_i]$ is determined and F_i^κ is calculated (subject to the condition $x_i / \overline{\chi}_i \le \kappa_i \le x_i / \underline{\chi}_i$) based on the relation $y_i^k = \tilde{\omega}_i(z_i, \gamma_i^k, \kappa_i)$ (where $\gamma_i^k = 1$).

For the case of speed control (presuming that it consumes less power than throttling), the problem is also solved by enumeration of the options $\kappa_i = 1, 2, ..., K_i$, and for each: 1) the solution existence with respect to γ_i which is reduced to verifying the condition $\underline{\gamma}_i^\kappa \le \overline{\gamma}_i^\kappa$, where $\underline{\gamma}_i^\kappa = \max\left[\underline{\gamma}_i, x_i / \left(\overline{\chi}_i \kappa_i \right) \right]$, $\overline{\gamma}_i^\kappa = \min\left[\overline{\gamma}_i, x_i / \left(\underline{\chi}_i \kappa_i \right) \right]$, is tested; 2) the solution γ_i^* to the equation $y_i^k = \tilde{\omega}_i(z_i^*, \gamma_i, \kappa_i)$ where $z_i^* = 1$, is found; 3) if $\underline{\gamma}_i^\kappa \le \gamma_i^* \le \overline{\gamma}_i^\kappa$, the solution z_i^*, γ_i^* is found; if $\gamma_i^* < \underline{\gamma}_i^\kappa$, then assuming that $\gamma_i^* = \underline{\gamma}_i^\kappa$, z_i^* is defined as the solution to the equation $y_i^k = \tilde{\omega}_i(z_i, \gamma_i^*, \kappa_i)$., Otherwise, the solution z_i^*, γ_i^* does not exist, because the increase in throttling causes the increase in y_i, and that of speed control – to its decrease; 4) if the solution is found, F_i^κ is calculated.

Whether or not there is an speed control: 1) the option $\kappa_i = 0$, which is reduced to identifying $z_i \in [1, \overline{z}_i]$ to implement y_i^k, is additionally tested (just as for $i \in I_{PL} \cup I_C$. If the feasible solution z_i^* exists, then F_i^κ is determined; 2) if there are no feasible solutions among the considered variants, then the k-th trajectory section is rejected; if there are several of them, the solution $z_i^k, \gamma_i^k, \kappa_i^k$ that corresponds to $F_i^k = \min_\kappa F_i^\kappa$ is chosen.

VII. Extension and aggregation of trajectories

Consider two series-connected branches that have common node $l_{i1} = f_{i2}$ and no other branches are incident to this node $l_{i1} = f_{i2}$. Let the set $Y_{i1} = \bigcup \{ y_{i1}^k \}$ be formed for branch $i1$, therefore the cells for the pressures $P_{fi2}(w_{fi2})$ are filled. Then the set $Y_{i2} = \bigcup \{ y_{i2}^k \}$ is generated from these cells, and, as a result, the trajectories $P_{fi1}(w_{fi1}) - P_{li1}(w_{li1}) - P_{li2}(w_{li2}) = y_{i1}^{k1} + y_{i2}^{k2}$, where $P_{li1}(w_{li1}) = P_{fi2}(w_{fi2})$, are built.

For the equivalent branch $i3$(substituting $i1$ and $i2$) such a trajectory is aggregated by the rules: $y_{i3}^{k3} = y_{i1}^{k1} + y_{i2}^{k2}$, $(F_C)_{i3}^{k3} = (F_C)_{i1}^{k1} + (F_C)_{i2}^{k2}$, $(F_z)_{i3}^{k3} = (F_z)_{i1}^{k1} + (F_z)_{i2}^{k2}$, $(F_P)_{i3}^k = (F_P)_{i1}^{k1} + P_{li2}^{k2}$. If in the process of such aggregation there occur the trajectories with the coinciding end pressures ($w_{fi3} = w_{fi1} = w_{li2} = w_{li3}$), the resulting trajectory ($k3$) is given the best value of increase in the vector criterion F_{i3}^{k3}. Eventually, the set $Y_{i3} = \bigcup \{ y_{i3}^{k3} \}$ is formed.

Let there be two branches ($i1$, $i2$) connected in parallel, such that $f_{i1} = f_{i2}$, $l_{i1} = l_{i2}$, and for one of them (for example, $i1$) the set Y_{i1} is generated. The coincidence of the end pressures ($w_{fi1} = w_{fi2}$ and $w_{li1} = w_{li2}$) for each pair

y_{i1}^{k1}, y_{i2}^{k2} means that they satisfy the second Kirchhoff law. Therefore, for branch $i2$, it remains to verify feasibility of such trajectories that $y_{i2}^{k2} = y_{i1}^{k1} \in Y_{i1}$. The feasible pairs of trajectories that correspond to y_{i1}^{k1}, y_{i2}^{k2} are aggregated into the trajectory of the equivalent branch $i3$ (substituting $i1$ and $i2$) by the rules: $y_{i3}^{k3} = y_{i1}^{k1} = y_{i2}^{k2}$, $(F_C)_{i3}^{k3} = (F_C)_{i1}^{k1} + (F_C)_{i2}^{k2}$, $(F_z)_{i3}^{k3} = (F_z)_{i1}^{k1} + (F_z)_{i2}^{k2}$, $(F_P)_{i3}^{k} = (F_P)_{i1}^{k1} = (F_P)_{i2}^{k2}$. The remaining trajectories are not considered. The set $Y_{i3} = \bigcup \{ y_{i3}^{k3} \}$ is formed as a result of such processing

VIII. The computation scheme of DPLR, in general terms, includes the following basic stages.

1. Select the next fragment of the series-connected branches. If there are no such fragments, then go to stage 3. In the initial scheme of the radial DHS such fragments are always available. At least, any dead end with a consumer forms a series connection of three branches in the calculation scheme (for the supply line, the consumer, and the return line, see Fig.1).
2. Replace this fragment with one branch using the considered procedures of generation, extension, rejection and reduction of the phase variable trajectories for series connections of the branches. If in the generation process $Y_i = \varnothing$ even for one initial branch, then go to stage 6. If the current DHS scheme contains only one branch, then go to stage 5.
3. Select the next fragment containing the branches connected in parallel. As a rule, at least one of such branches equivalents series connections processed in the previous stage. Therefore, replace this fragment with one branch using the considered aggregation techniques of the trajectories of parallel connections. If in the aggregation process $Y_i = \varnothing$ at least for one branch, then go to stage 6.
4. If the current DHS scheme contains more than one branch, then go to stage1.
5. The trajectory of the optimal value of F_i^k for the only remaining branch corresponds to the aggregated problem solution. The backward pass of the algorithm is used to restore the optimal phase variable trajectory and the values of all controls in the initial scheme. This suggests that the correspondence between each equivalent branch and the substituted fragment and the correspondence between each section of the equivalent branch trajectory and the initial sections it aggregates are stored in the previous stages of the algorithm. End.
6. There is no feasible problem solution.

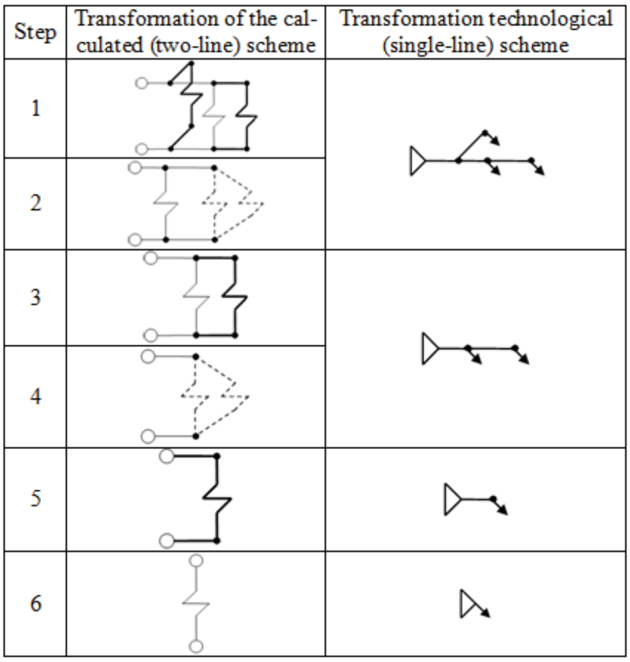

Fig. 2. An example of reducing a calculated scheme of a heating system to one branch by reducing series and parallel connections of branches. In the calculated scheme: bold lines – series connections of branches, dotted lines - parallel connections.

This algorithm is intended for the radial DHS with at least one heat source and one consumer that are connected by the branches for the supply and return lines. The reduction process of the radial DHS scheme to one branch is illustrated in Fig. 2. The Figure shows that there are series connections in the initial scheme, and their equivalenting (reduction) results in the formation of parallel connections, which in turn leads to the formation of new series connections and so on until the calculation scheme is reduced to one branch connecting the nodes at the heat source inlet and outlet.

IX. Numerical example

The proposed method was tested by a set of computational experiments. Their results are illustrated by the example of DHS in the town of Baikalsk, which is presented in an aggregated form in Fig. 3. PS-1 is installed on the supply pipeline, and the remaining PSs – on the return pipeline. Table 1 describes the characteristics of the installed pumps. All pumps are supplied with electricity at the same cost, therefore $F_C(\gamma, \kappa) = \sum_{i \in I_{PS}} N_i(\gamma_i, \kappa_i)$.

Reliability and computation efficiency of the proposed DPLR method were tested in comparison with the continuous branch and bound method (CBBM) [24] that was developed for a general case of the discrete-continuous optimization problem of hydraulic conditions in multi-loop DHSs with several heat sources, pumping stations, unfixed flow distribution but with one criterion (F_C). The calculation results by CBBM coincided with DPLR, however, in the last case, the computing time was less by an order of magnitude.

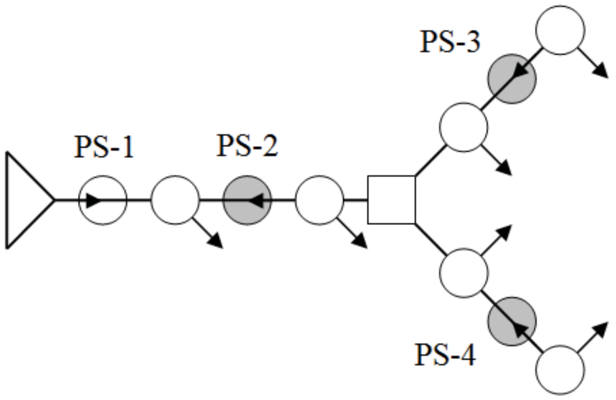

Fig. 3. Aggregated scheme of DHS in Baikalsk. Pumping stations on the return pipeline are highlighted in grey.

Besides, as was shown above, the computing time by DPLR did not depend on the number of criteria, whose lexicographic ordering is performed by elementary operations at each step of the DP process. Therefore, the multi-criteria problem is solved in a single algorithm run. Such problems are solved by the most common approach that involves sequential optimization based on multi-stage solving the optimization problems for each criterion by its importance with intermediate addition of constraint on the next criterion value calculated in the previous stage. Therefore, considering the great number of criteria by the standard methods in this case will additionally increase the computing time at least threefold, and the mixed nature of the problem (nonlinear, integer, Boolean programming) will increase it by several times more.

The flexibility of the proposed DPLR method (consideration of several criteria, availability of pumping stations and different control techniques) was tested for DHS in Fig. 3 for different combinations of calculation data: 1) different levels of consumer loads including "heavy" load (corresponding to the peak winter load of DHS) and "light" load (obtained from the previous one by the twofold load decrease); 2) impossibility ($\gamma_i = \text{const} = 1, i \in I_{PS}$) or possibility ($\gamma_i = \text{var}, i \in I_{PS}$) of pump speed control at the pumping stations.

Table 2 presents the results of optimization calculations in comparison with some feasible condition ("heavy feasible") that meets all constraints. The obtained solutions are seen to be more efficient for all criteria compared to this condition. Besides, the speed control considerably decreases the power consumed by pumping stations and the number of sites for throttling. The twofold load reduction in DHS ("light" load) leads to a more than threefold decrease in the power consumption, in particular owing to a decrease in the number of operating pumps and their complete disconnection at PS-3. A decline in the overall pressure level in DHS is notably lower than for an arbitrary feasible condition and it can be additionally decreased by the lower heat load.

X. Conclusions

1. For the first time, the problem of operating condition planning for the radial DHSs with pumping stations was formulated and studied as a mixed multi-criteria optimization problem with real, integer and Boolean variables. At present, there are no effective methods appropriate for extensive practical application.
2. The paper proposes a generalized option of the problem-solving method which is based on a combination of the methods of dynamic programming, reduction of series-parallel connections of branches in the calculation scheme and local optimization of pumping station operation.
3. The presented numerical example illustrates the computational efficiency of the proposed method and its versatility, which makes it possible to allow for one or several criteria, different types of controls and technological limitations, arbitrary number and allocation of pumping stations, establishment of solution existence, applicability to multilevel coordination of optimal conditions for heat networks and heat sources.

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Table 1. Characteristics of pumps at pumping stations.

PS	Number of pumps (K_i)	Pump brand	H	s	β_0	β_1	β_2
1	3	SE-800-100-11	120	0.0000375	119.4	0.238	-0.000091
2	5	1X 200-150-500	80	0.00004	40	0.16	0
3	3	TsN-400-105	120	0.000125	60	0.24	0
4	2	D 320-50	60	0.0001	30	0.09	0

Table 2. Results of optimization based on the number of operating pumps at pumping station.

Load	$\gamma_i, i \in I_{PS}$	PS-1	PS-2	PS-3	PS-4	F_C, kW	F_z, pcs.	F_P *m* of thr water column
Heavy feasible	1	3	4	3	1	1684	20	62
Heavy	1	3	4	2	0	1445	10	58
Heavy	Var	3	4	2	0	1396	7	58
Light	1	1	2	0	1	426	10	56
Light	Var	1	2	0	1	409	7	56

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Hydropower Development in Eastern Russia in the Context of Interstate Cooperation: Current State and Prospects

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***Abstract* — The paper describes the hydropower potential of Eastern Siberia and the Russian Far East. Currently, only 7.5% of the technical hydropower potential of Russia's East is used. Expansion of the hydropower sector in this region is a main goal of the national electric power development. Russia is also interested in the development of electric ties with Northeast Asian countries. The paper presents several potential projects for interstate electricity transmission to be implemented with the neighboring countries (China, Mongolia, Republic of Korea and Japan). Results of the international studies show evident advantages for interconnected countries. Continuation of a multilateral analysis and investigations of the hydropower development promotes the interstate power interconnection and cooperation.**

***Index Terms* — cross-border cooperation, Eastern Russia, hydropower potential, inter-state interconnection, investment attraction, potential utilization**

I. Introduction

Energy utilization has evolved over time from firewood to fossil fuels, and then to clean energy resources derived from hydropower, wind power, and solar power [1]. Fast industrialization caused rapid energy industry growth. At the same time, extensive utilization of fossil resources resulted in environmental pollution and climate change. Many of energy-scarce countries became dependent on resources and energy supply. Seeking a solution to energy scarcity and environmental problems most of the world's major nations followed the road of clean energy production. The world has abundant clean energy resources, far more than enough to meet global energy needs [1]. The massive development of hydropower, onshore wind energy, and solar power has become the world's dominant form of energy provision.

The efficiency of the power resources utilization and secure electricity supply increases with the large-scale interconnection of national electric power systems. The ultimate objective is the coordination of energy production and electricity exchange in line with progress in the political, economic and environmental fronts [1].

Hydropower is the most technologically and economically viable type of clean energy. Asia expects the development of large-scale hydropower potential in the future. Russia is among the top five countries in terms of hydropower reserves and developed capacities. World average water utilization is estimated at 41% of the global theoretical reserves [1]. Utilization rate in Russia is low and is estimated at 10.9 %. Development of the Russian hydropower potential, particularly in the Eastern part of the country, provides new prospects for interstate energy cooperation.

II. Hydropower potential and its current utilization

Russia has significant hydropower resources in different parts of the country.

The country has more than 3 million big and small rivers, and more than 2.8 million lakes. About 250 rivers are longer than 500 km, 58 of which are over 1,000 km long. Forty of these super long rivers are in Siberia and the Far East [2]. The major rivers in Siberia are the Ob River, the Yenisei River, and the Lena River. The Yenisei River is No. 1 in Russia because it provides the best water resources. In the Far East, the main river is the Amur River which is approximately 4,400 km long, flowing into the Pacific Ocean. Its upper and middle reaches are located along the Chinese-Russian border; while its lower reach

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Table 1 Hydropower Resources Of Rivers In Eastern Siberia And Russia's Far East.

Country, region	Total, 2013		Average electric energy output at operating HPPs, 2013, billion kWh	Use of energy potential, %
Potential	Billion kWh	%		
1. Theoretical (gross)				
- Russia, total	2396	100	1023,5	42,7
- Eastern Siberia	993	41,4		
- Far East	1009	42,1		
2. Technical				
- Russia, total	1670	100	174,74	10,46
- Eastern Siberia	757	45,3	94,72	12,5
- Far East	684	41	13,44	1,96
3. Economic				
- Russia, total	852	100	174,74	20,5
- East Siberia	396	46,5	94,72	23,9
- Far East	294	34,5	13,44	4,57

lies within the Russian territory.

The hydropower resources in Eastern Siberia and the Far East play and will play an important role in the implementation of Russia's energy policy. The gross hydropower potentials of the rivers in the Eastern Siberia and the Far East regions are respectively 993 and 1009 billion kWh /year, or 41.4 and 42.1% of the national hydropower potential (Table 1). Allocation of hydropower potential across the territory of the country is shown in Figure 1 [3].

Russia has 102 hydropower plants with the capacities of over 100 MW each, making it the world's fifth hydropower producer. The hydropower capacity installed in the country reached 49.7 GW in 2016 [4]. In terms of installed capacity, three of the world's top 10 hydropower plants are located in Russia.

Small hydropower plants with a capacity of less than 30 MW are an alternative to the fossil fuel which is used for electricity production in the remote regions in Russia. Replacement of traditional fuel plants in such regions by small hydropower plants will make it possible to increase the local energy security and to decrease fuel delivery costs.

Russia's hydropower generation represents 4.88 % of the world's electricity generated using this type of energy source. Within Eurasia, the electricity generation from hydropower plants represents 66.79 % of the total [4].

Hydropower generation in Russia was 174.7 TWh in 2013 and accounted for about 17% of the total electricity generated (1023,5 TWh). The amount of 174.7 TWh represented 20.5 % of the economic and only 10.46 % of the country's technical potential. The technical potential of

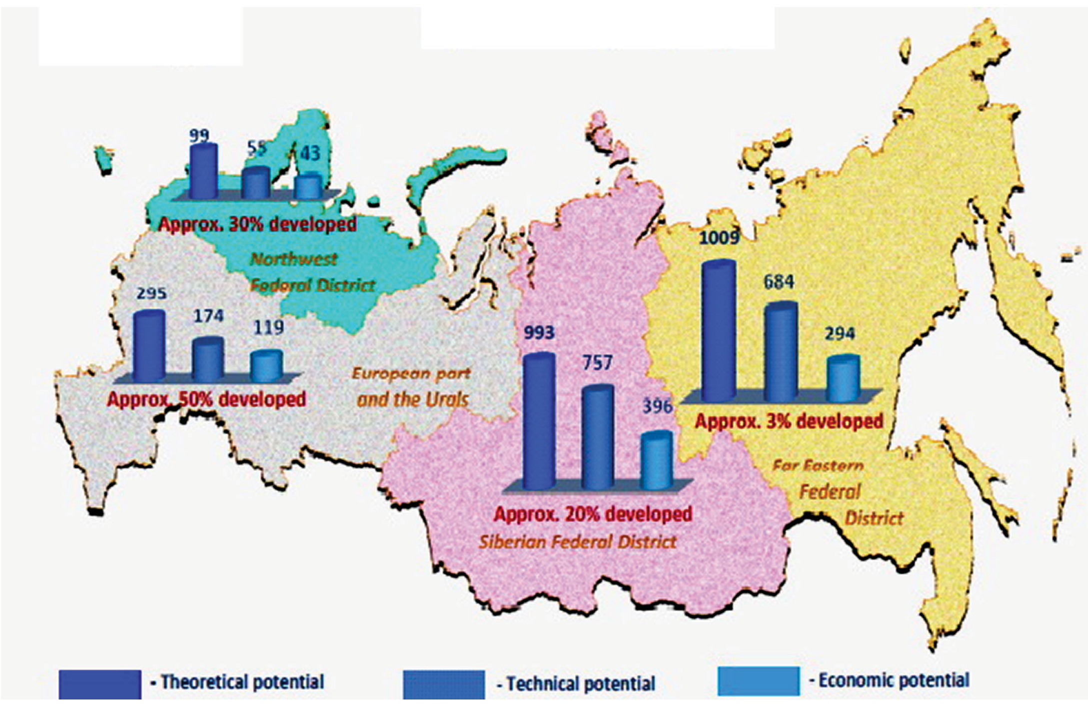

Fig 1. Allocation of hydropower potential in Russia.

the Eastern regions is used by less than 7.5 % .

Hydropower plants with the total installed capacity of 7 million kW are under construction and more than 12 million kW are planned for construction [2]. Technical conditions for the development of hydropower resources in the east of Russia, especially in Eastern Siberia, are more favorable than in the rest of the country.

III. Hydropower development in eastern russia: current state and prospects

Hydropower is the pillar of Eastern Russia's power industry. Growing utilization of hydropower provides [3]: high capacity flexibility, no fuel component in the production cost, renewable and environmentally clean power generation, the synergistic effect for the territory development due to new emerging energy-intensive enterprises.

Water use for electricity production in the Eastern territories of the country started in the 1950s. Several powerful hydroelectric plants have been built since then on the Yenisei, Angara, Zeya and Vilyui rivers. The power plants provided regional economy and industries with reliable energy supply. Aggregate installed capacity of those plants was around 23,5 GW [4].

Several new hydropower projects were designed in the 1960 -70s. However, for various reasons, not all of the plans developed 40-50 years ago turned out to be feasible under modern socio-economic conditions. In particular, in the new contexts, for economic, environmental and water management reasons, it was necessary to abandon the construction of previously designed powerful hydroelectric plants on the main channels of large rivers (the Yenisei, the Lena, and the Amur) in the east of the country. Thus, the prospected technical potential of the hydropower resources of Eastern Siberia and the Far East was noticeably reduced.

The new contexts include changed schemes for attracting investments, revision of plans for the development of industrial production in the regions, the introduction of additional environmental and technological restrictions, new technologies in the construction industry and the emergence of new ways of generating electricity. The new contexts are reflected in the Energy Strategy of Russia for the period until 2030 developed by the Ministry of Energy of the Russian Federation. Individual sections of the Strategy indicate the targets for the use of the hydropower resources of Siberia and the Far East.

At the end of 2017, the total installed capacity of hydropower plants in the eastern regions of Russia was 28946.4 MW [4], including 25286.4 MW in Eastern Siberia, and 3660.0 MW in the Far East. In the coming years, the hydropower potential of the eastern territories will be increased due to the construction of Bureya hydropower plant (2000 MW) in the Far East, Svetlinskaya hydropower plant (360 MW) in Eastern Yakutia and Ust-Srednekanskaya (570 MW) hydropower plant in the Northeast. The Bureya and Svetlinskaya HPPs are in the final stages of construction. Location of the existing and new HPPs is shown in Figure 2 [6]. Difficulties in the development of hydropower potential are associated with extremely high capital intensity and long construction periods of hydropower plants. These are the main barriers to the development of hydropower generation under tough global competition, even in the countries with a large hydropower potential. The construction of a large hydropower plant costs billions of dollars (several thousand dollars per 1 kW of installed capacity) and lasts 5-8 years. Given the site selection, design and preparatory work, it may take 15-20 years to construct a hydropower plant.

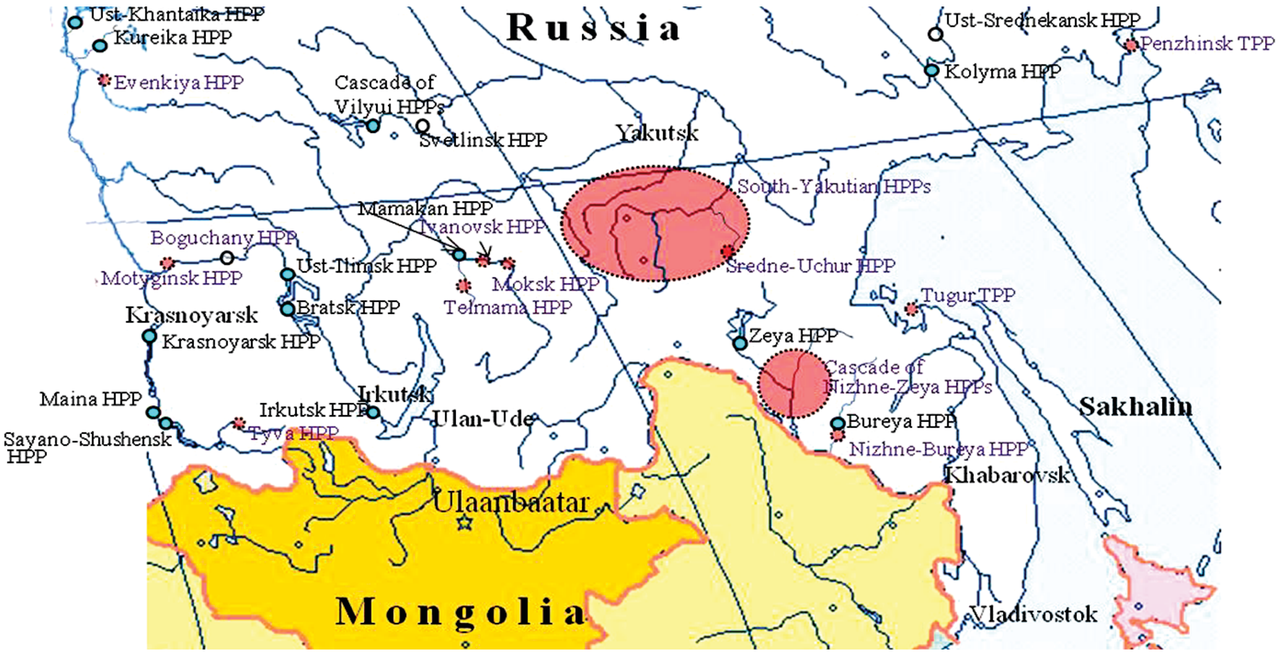

Fig. 2. A map of hydro and tidal resources development in Eastern Russia.

Further hydropower development in Eastern Russia depends essentially on how the economy of the eastern regions will grow and how the cross-border electric ties will be built.

Currently, there are no tidal power plants (TPPs) in Eastern Russia. Sites for construction of two TPPs are available in the Far East region, but the construction has not been started yet.

IV. Attraction of investment in the hydropower development

Russia encourages domestic and foreign investment in its power industry. The Russian power sector needs around $600-$800 billion until 2030, including $55-$125 billion for hydropower development [7], which has been complicated by the chronic lack of funding over the past 15 years. Currently, policymakers continuously try to find the right balance between investments and reasonable end-user power prices.

There are different forms of investment attraction from domestic financial sources, including financial funds of the power companies, emission of additional shares (stocks) and bonds, bank loans, budget funds, and leasing schemes. Practically all main Russian banks take part in financial support of the projects for construction of new power facilities and modernization of existing ones.

In spite of the existing international financial pressure, there is a favorable climate for investment in Russia's power industry. Since 2007-2008, Fortum (Finland) E.On (Germany), Enel (Italy) have become the main foreign investors. These companies own more than 25 GW or almost 10% of available generation capacity [2].

The Commission for Power Production Enterprises established in April 2008 mainly comprises Russia's domestic and foreign power enterprises, covering 40% of Russia's total installed capacity and over half of the independent power producers in Russia. Its members include Russian private stock companies IES Holding, EuroSibEnergo, SUEK, Nornikel, and Lukoil.

The Russian hydropower industry stagnated during the industry reforms in the 1990s but it has been reviving with the establishment of State-controlled RusHydro Holding in 2004. RusHydro currently includes 15 federal hydropower plants, including Sayano-Shushenskaya (6000 MW) and Zeiya (1330 MW), the first large hydropower plant in the Far East region. The goals of the Holding are to ensure reliable and safe operation of existing hydropower facilities, to complete projects in progress, and to design and build new plants. RusHydro is investing massively in upgrading its aging infrastructure.

Those initiatives are now beginning to bear fruit. The Holding has completed construction of 3 GW Boguchanskaya hydropower plant in Siberia, in collaboration with Russian aluminum producer RUSAL. Another project of the RusHydro Holding is Bureya (2 GW) hydropower plant located at the Amur River in the Far Eastern region. The plant has six 335 MW turbines and is designed to reduce regional fossil fuel consumption and local flooding on the Bureya and Amur rivers.

Several concluded contracts have paved the ways for various opportunities across the country, including the upgrade of EuroSibEnergo's existing assets and construction of new hydro plants, specifically in Siberia. New generation facilities will not only meet growing domestic demand but will also create additional capacity for electricity export to Northeast Asian countries.

New sources of finance and investment have appeared in the past few years. One of the sources is 'New Development Bank' founded by the BRICS countries including Brazil, Russia, India, China, and South Africa in July 2014. Several key countries have established the China-led Asian Infrastructure Investment Bank, which intends to include hydropower in its investment portfolio.

In the private sector, new financial sources such as the IFC's InfraVentures (IFC Global Infrastructure Project Development Fund) have emerged offering innovative solutions for hydropower development.

V. Cross-border and inter-state power cooperation

Eastern Russia possesses enormous unused hydro resources. Expansion of hydropower construction in

this part of the country is considered to be a main goal of the national electric power development. There are plans to construct HPPs not only to cover the increasing domestic demand but also to export electricity to the neighboring countries in Northeast Asia (NEA): China, Republic of Korea (RoK), Democratic People's Republic of Korea (DPRK), Mongolia and Japan. The electricity export will foster the development of interstate electric ties and the formation of NEA-wide interstate electric ties (ISETs). This will allow the connected countries to gain system benefits which will enhance the effectiveness of power plants and transmission system themselves.

Construction of hydropower plants plays an important role in the development of interstate power pool (ISPP) in many parts of the world. Changes in the political situation in NEA have made it possible to establish such kind of a grid in Northeast Asia. Interstate pools create the conditions for utilization of electricity generated by different types of power plants (fuel-burning, small hydro and tidal, renewable and others).

The development of hydropower and the development of interstate ties are mutually interrelated processes. On the one hand, both of them enlarge the utilization of renewable resources and enhance involvement of environmentally friendly generation. On the other hand, the development of ISETs and ISPPs makes it possible to increase the capacities of some HPPs. This increases their cost-effectiveness, decreases prices in the electricity markets and improves the reliability of electricity supply. The high load-following capability of HPPs with reservoirs allows decreasing the

Table 2. Potential interstate electric ties in northeast asia. [8]

The direction of interstate electric ties	Length, km	Voltage, kV	Transfer capability, GW	Power transmission, TWh per year
		Russia–China		
Bratsk–Ulaanbaatar–Beijing	2250	±600	5–6	18
DC system Ust'–Ilimsk–Khabarovsk	5000	±750	10.0	40
		Russia–Korean Peninsula		
Vladivostok–Pyongyang–Seoul	1150	±500	4.0	7
		Russia– Japan		
Sakhalin–Hokkaido–Honshu	1850/ 1400**	*±600*	4/3	24
		Asian Asian SuperGrid		
Gobitec– Mongolia, Russia, China, Korea, Japan	7300	±800	100*	200*

required generation capacities and fossil fuel consumption in interconnected electric power systems. Hydropower plants with regulated reservoirs have certain advantages as backup plants.

Seasonally variable annual load maximums in different national electric power systems (EPSs) ensure the difference in electricity consumption structure which is caused by the difference in climate and the level of socio-economic conditions in various countries. In the countries with the hot climate, this leads to a shift of the annual load maximum in the EPS from winter to summer. In NEA, such a situation is observed in Japan, RoK, and northern EPS of China.

In Eastern Russia, however, the winter load maximum exceeds essentially the summer one and this is expected to remain in the foreseeable future.

Due to the seasonal differences in the annual load maximums, the same generation capacities (including HPPs in different countries) can be employed to meet annual load maximums coming in different seasons. This will considerably reduce the demand for new generation capacities.

The efficient cross-border exchange requires the construction of reliable and productive transmission networks. There are several projects for the NEA interstate ties, Table 2, Figure 2. The projects are distinct in purposes of cooperation, electric energy sources on supplying (sending) end, directions, and technical performance of power transmission lines between cooperating countries.

The first project of Bratsk–Beijing interstate power transmission is focused on the organization of surplus electricity export from power plants in the electric power system of the East Siberia and its interconnection with the electric power system of North China to implement the integrated effects. The main goal of the project is to decrease the commissioning of new generating capacities in both electric power systems thanks to the non-coincident annual load peaks. According to the studies, the capacity effects amount to 9–11 GW and investment savings upon the project implementation are estimated at 6–7 billion USD.

A number of proposals for electric energy transmission from Siberia to China are largely oriented to the utilization of excessive seasonal hydropower output of the Angara–Yenisei cascade and Bureya HPP. The DC link Ust-Ilimsk HPP–Khabarovsk can become the backbone for this transmission in the future. It will transport over 70 TWh of environmentally clean and relatively cheap electric energy to provide Siberian and Far Eastern consumers with electricity and to export electricity to the East Asian countries.

The study findings indicate that electric tie between the EPS of the Russian East and the electric power system of the Republic of Korea, i.e., Vladivostok–Pyongyang–Seoul interstate electric ties, is the most effective. Compared with other potential projects (Table 2), this project is the most developed one. The estimated economic effect of the project will reach 14 billion USD in investments and nearly 2 billion USD in annual expenditures. Furthermore, the yearly economic benefit for Russia can reach 450 million USD. High efficiency of this project can be explained by the possible saving of generating capacities (8 GW) due to the variation in annual load peaks. However, the implementation of the project and safe ISET operation requires solving the political issues on the Korean Peninsula and the creation of conditions for strong economic and technical partnership between all counties participating in the project.

Nowadays, a pressing issue is electricity export from Russia to Japan. The idea of the project Sakhalin–Hokkaido–Honshu interstate transmission tie appeared in the 1990s. It was supposed to build two export-oriented TPPs in the Russian Far East in the first stage, and the Sakhalin–Sapporo–Tokyo DC transmission line - in the second stage. Supposed technical parameters of the line were: a voltage of ±400 kV, line length of 1600 km with two (50 and 40 km) underwater cable ducts.

As an alternative to this project, the project of an energy bridge between Russia and Japan was proposed later. It supposed the construction of a combined cycle power plant on Sakhalin Island with a capacity of 4 GW, cable DC transmission line with a length of 1800 km (1400 km of underwater cable) from Sakhalin to Honshu, and converting substations in Sakhalin, Hokkaido, and Honshu. The extension of this interstate transmission line to Khabarovsk could connect the EPS of the Russian East to the EPS of Japan. According to the studies, the expected potential power effect will make up 1.6 GW and investment savings will be 1 billion USD [9].

Now the initial project is revived, but with certain changes. It involves the construction of export-oriented power plants in Sakhalin (two coal-fired plants with a capacity of 1050–1200 MW and a combined cycle plant with a capacity of 800 MW), AC power transmission line in the territory of Sakhalin, and DC power transmission line through La Perouse Strait with a converter substation in the northern part of Hokkaido Island. This project is actively supported by the authorities of neighboring regions of Russia and Japan.

An alternative direction of electric tie lines between Russia and Japan is the construction of an interstate tie through China and countries of the Korean Peninsula. However, the implementation of this project is hindered by the problems in the Korean Peninsula.

Another possible area of interstate electric connections in NEA is electricity transportation from the Gobi energy complex. This project includes the creation of GobiTec complex with a total capacity of 100 GW based on wind and solar power plants (in equal proportion) and DC interstate links for electricity transmission to China, the Republic of Korea, Japan, and Russia. The creation of these links will lead to the formation of the Asian Super Grid.

It is clear that this is a long-term and very expensive project.

VI. Studies for the Northeast Asian interstate electricity interconnections

Since the early 1990s, there have been studies on the efficiency and prospects of the interstate transmission system construction, and formation of the interstate power pool in Northeast Asia [10–12]. Research institutes of Russia, Republic of Korea, the People's Republic of China, Japan, Mongolia, and other countries, as well as Asia Pacific Energy Research Centre (APERC) in Tokyo (Japan) take part in these studies. The studies are financed by state budgets of the Russian Federation and the Republic of Korea, as well as the World Bank, and Russian holding companies (Evrosibenergo, InterRAO EES, and RusHydro).

The prospects for international cooperation in the electric power industry are conditioned by different causes. These include the differences in available domestic natural energy resources and in the level of their use, different demand for energy resources, as well as the acuteness of environmental problems in the individual countries. This is why the country-specific interests in integration and cooperation have been thoroughly investigated.

The People’s Republic of China plays a leading role in the electric power industry in NEA. With regard to the electricity consumption growth rates and the degree of development of the power sector, China overtakes many countries and, in electric energy production, it has been a world leader since 2011.

The prevalence of coal in the structure of natural energy resources has determined the coal domination in the energy generation. Nowadays, the coal-fired thermal power plants (TPP) provide 80% of the total electric output in the country. A serious consequence of this situation is significant environmental pollution. In order to cope with this issue, China is planning to develop wind and solar energy complexes in the northern territories. This causes the necessity to transport capacities of these complexes to other areas and adjust the intermittent energy generation from wind and solar power plants.

The connection of China’s national electric network to the eastern regions of Russia and other countries may play a certain role in solving domestic energy problems.

The Russian Federation is also highly interested in the development of interstate electric ties with the NEA countries. Moreover, the export of electricity from Eastern Russia to neighboring countries is considered as a factor that could stimulate the acceleration of economy, transport infrastructure, utilization of natural resources in undeveloped territories, and the development of these territories in general.

Electricity export from Russian hydropower plants is usually effective when surplus electricity is sold from operating power plants that do not require investment in capacity expansion. However, in the presence of interstate electric ties, it would be possible to sell surplus electric energy from the newly commissioned HPPs.

Integrated effects in the case of the interconnection of electric power systems of Russia and other NEA countries will significantly increase the efficiency of the cross-border transmission. The greatest effect can be achieved by decreasing the demand for generating capacities due to different seasons and time of the annual peak loads.

The consequences of the Fukushima nuclear power plant accident in Japan in 2011 have seriously impacted on the development of interstate electric ties in NEA. This accident has fundamentally changed the situation in the Japanese electric power industry. Since 2012, several nuclear power plants have been shut down. The termination of this part of electricity production had to be compensated for by an additional load of thermal power plants and a significant growth of gas and oil import. Due to the lack of possibilities for a wide development of renewable energy in the short term the country's electric power industry faces dependence on imported energy resources and the negative environmental effects of the thermal electric production.

In this context, it could be possible to significantly improve the environmental situation with the development of interstate electrical connections with neighboring countries and with the import of environmentally clean electric energy from Russia and China.

The Republic of Korea (RoK) has a very high level of electric power industry development. The structure of generating capacities in RoK is analogous to that in Japan. Besides, it has the same problems with energy resources endowment, like Japan. The Republic of Korea shows interest in developing electrical connections with Russia at the state level [10]. Furthermore, as evidenced by the studies conducted by the Russian (ISEM) and Korean (KERI) Institutes, the interconnection of Russian East EPS and RoK's EPS is technically feasible and very effective, especially for the Korean part. However, the unstable political situation on the Korean Peninsula is a serious obstacle to it. This cause is also an obstacle to the cross-border power transmissions to Northeast China.

The role of Mongolia in the development of the interstate electrical connections in NEA is significant, despite the relatively weak development of its electric power industry. Joint studies with Russia in the field of electric power supply have been carried out for a long time. Nowadays, the Mongolian Power sector is actively developing its electrical connections with China. A transit power transmission line between Russia and China could run through its territory. In the case of the creation of the Asian Super Grid, this country can play a decisive role in the formation of an interstate power pool in northeast Asia.

Summarizing the results of the international studies, we can state that in the event that the electric power interconnection is established in NEA, the countries involved will gain evident advantages. The formation and development of a regional interstate interconnection consist of several stages, whose succession and duration will depend on various conditions. However, in the first stage, the crucial role belongs, not to economic and technical factors, but rather to the political situation and the readiness of the countries and their electric power systems to cooperate in the field of statutory regulation in order to support their power security.

Another avenue for the studies to be conducted is the development of procedures for the medium-term hydropower generation scheduling in the interconnected electric power systems considering the participation of hydropower plants in the internal electricity markets.

Electricity generation scheduling is essential in the power system operation and management. Traditional problem statements aimed at reducing the total production cost hardly correspond to the market environment. In a new commercial framework, generation companies tend to maximize their profit. The problem statement should take into account the strategic behavior of electricity producers, locational marginal prices and the consumer response to the price levels.

The hydrothermal power systems require consideration of the objective function and water balance constraints embracing the whole medium-term scheduling period. Conducted studies have considered specific features of the problem statement for a wholesale market environment. The proposed approach is based on a bi-level optimization technique [13, 14]. The problem formulation allows for possible distortions of economic and technical parameters of generating units. The proposed technique obtains equilibrium of the generation companies' interests and simulates the competitive behavior under oligopoly electricity market. The developed algorithm is based on the stochastic dynamic programming method [15]. The applicability of the proposed method and algorithm is demonstrated on the example of the Siberian electric power system.

VII. Conclusion

Eastern regions of Russia possess enormous hydropower resources. The technical hydro potential of Eastern Russia is used by less than 7.5%. Expansion of hydropower construction in this part of the country is considered to be a main goal of the national electric power development.

Russia is highly interested in developing interstate electrical connections with Northeast Asian countries. Moreover, the electricity export from Eastern Russia to neighboring countries is considered as a factor that could stimulate the growth of the economy, transport infrastructure, utilization of natural resources in undeveloped territories, and the development of these territories in general. However, the possibilities of interstate cooperation in the short term are limited due to formidable political and economic obstacles.

In the event of their electrical interconnection, the NEA countries neighboring Russia gain evident advantages. Should the existing obstacles be eliminated, the electric power systems to be connected should be poised to cooperate in the field of statutory regulation for the provision of their power security.

Conducted multilateral analysis and investigation of the hydropower development in Northeast Asia promotes the interstate power interconnections and cooperation.

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The World Is On The Cusp Of Global Energy Changes

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Abstract **— The paper describes the features of the world energy development at the turn of the twentieth and twenty-first centuries with a special focus on the main events, trends and factors of energy transformations in this period. A new energy landscape of the world and the most important challenges, processes and factors that shape this landscape have been analyzed. The inconsistency of a number of trends was especially noted, which, in the author's opinion, indicates an increase in the degree of uncertainty in the development of the world economy as a whole and the world energy in particular. Globalization, geopolitics, and the rapid development of science and technology make their contribution to this growth. The situation is aggravated by the emerging surplus of energy resources, which changes the very basis of the energy philosophy. The new driving forces of the observed and upcoming transformations are examined in detail, in particular the need to respond to the challenges facing humanity due to climate change, and the projected alterations in the energy balance caused by the effects of the 4th industrial revolution. The most important directions and tools for implementing a climate-oriented energy policy, including the formation of low-carbon or carbon-free energy sector of the future, the role of globalization in the future energy development, as well as trends and transformations of global energy markets, are explored. Consideration has been given to new approaches to the long-term forecasting of the global energy development, that are applied by leading international and national analytical centers, as well as to their assessments of trends in global consumption of energy, oil and other liquid fuels. The current energy situation in Russia is analyzed and conclusions are made about the need to change the priorities of the energy policy of the Russian Federation in the context of the global energy changes.**

Key words **— world energy, energy transformations, geopolitics, global climate change, energy markets, globalization, geopolitics, energy philosophy, energy surplus, low-carbon energy, long-term forecasting, Russia.**

I. Introduction

The world energy sector, being the most important part of the global economy, is evolving under the influence of various factors, most of which are interdependent and interrelated, which increases the degree of uncertainty of their cumulative effect. A special role in this process belongs to the basic, fundamental factors that have long-term influence. It is worthwhile to note some of them, first of all[5: Chapter 7, 6: Chapter 4]:

- The international division of labor, including the increasing complexity of economic relations between national economies and their growing interdependence, international specialization and cooperation of production, as well as the industrialization of developing countries;
- The internationalization and economic integration of economic life (production and capital), including the intensification of inter-country exchange (overflow) of labor, capital, technology, means of production, and information;
- The uneven economic development of individual countries and the cyclical development of the world economy;
- The technological progress and the latest technological

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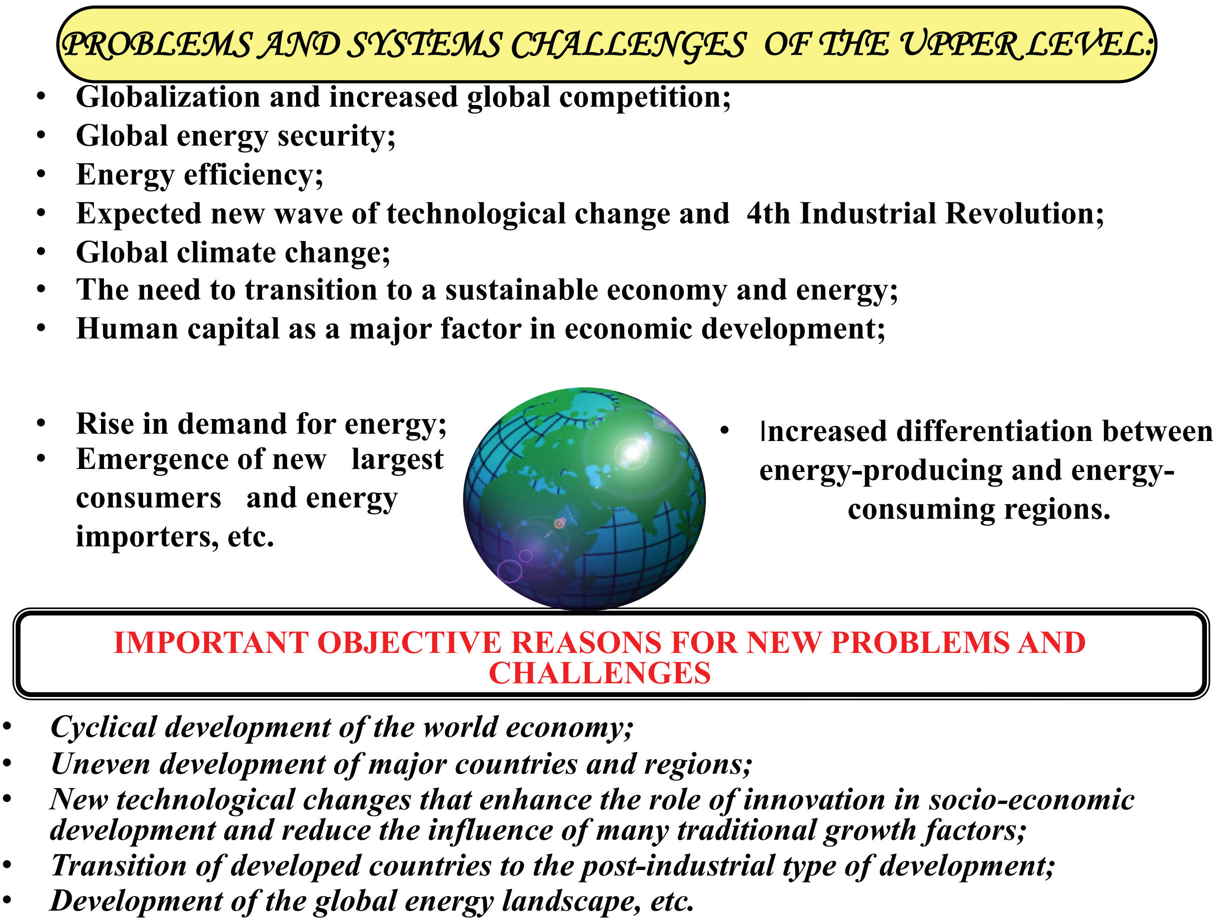


Fig.1. Challenges facing today's energy sector and their most important objective reasons.

advances, including the informatization of national and world economies and the full digitalization of production and domestic life;

- The trans-nationalization, i.e. the activities of transnational corporations and transnational banks;
- The strengthening of the role of international economic and financial organizations (IMF, World Bank, World Trade Organization, UNO, etc.) in the regulation of world economic processes;
- The increased participation (increased interference) of the state in the economy, etc.

These factors also include the need to jointly cope with the most important global issues . Such sector-specific fundamental factors of energy development as demand-supply, price, technical-technological, resource security, etc. are of no less significance for the energy sector.

A special feature of the modern stage in the development of the economic systems in most countries of the world is their high degree of internal instability against the background of developing processes of fluctuations in the external economic environment (variations in commodity prices, high volatility in the international financial market – leaps in interest rates and exchange rates, changes in the customs policy of foreign partners and others). In addition, these processes are also influenced by such factors as the discovery of new sources of energy resources, global warming, demographic processes, sharp increase in social inequality, social revolutions and armed conflicts.

In the new geopolitical realities that have developed in the world in recent years, the so-called geopolitical factors have begun to determine the vector of energy relations between countries in almost all areas. Under their influence, a new architecture of the world economy and international relations is formed, a return to the policy of balance of power begins, and numerous barriers arise in the way of international energy cooperation. At the same time, the immense importance of energy resources in world politics causes an aggravation of hidden and open confrontation between the leading powers for control over them and over energy markets.

II. A New Energy Landscape of the World

We have had to say and write repeatedly that growing changes occur in the global economy; that serious challenges face modern humanity, in particular in the energy sector, and it is necessary to answer the bell; that the world is on the verge of a global systems crisis, on the verge

Main trends shaping the future of global energy

- **Balancing between globalization and regionalization, the threat of energy shortage and the onset of the global energy surplus;**
- **Change in technological paradigm in the fuel and energy production and consumption;**
- **The end of the hydrocarbon era and the development of an innovative carbon-free energy sector, etc.**

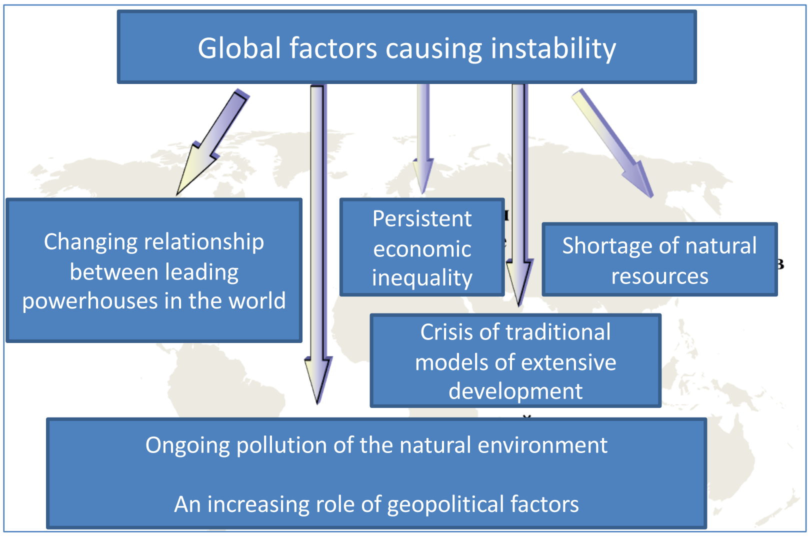


Fig.2. The world on the cusp of global energy changes.

of global changes and replacement of both technological and civilizational patterns (if one can say so, the world has reached "a breakpoint") [1,3,7-9, etc.].

Moreover, a unique matrix of these challenges (Fig. 1), as well as trends and factors generating the instability (Fig.2) was developed in a general form.

Numerous studies conducted by domestic and foreign experts in recent years [11-16, etc.] convincingly confirm and develop the following our conclusions made several years ago [1,4,17-19]:

- The world is currently on the verge of a systems crisis, covering the economy, energy and politics; on the verge of a change in the basic paradigms of its development and global energy changes, including international relations ; This was recently evidenced in the interview with the French political analyst Thierry de Montbrial. For 40 years, he has headed one of the leading world centers of international research – French Institute of International Relations [20]. In his interview, Mr. Montbrial notes that we are in transition when everything is too unstable, and instead of a new world order, there is a disorder, in which individual characteristic features become obvious.
- Modern energy sector has faced a number of serious challenges that are simultaneously geopolitical, resource, macroeconomic, environmental, technological and social (Fig. 1);
- Global changes, significant qualitative changes are beginning, unfolding and already occurring in the development of the global energy sector;
- A fundamentally new energy landscape of the world is beginning to take shape. Its most important features are the transformation of the United States from the leading consumer of hydrocarbons into their largest producer and a future significant exporter, and the evolution of China into the largest oil consumer.

At the same time, there also remain global factors generating instability, such as the changing relationship between the powerhouses of the world; persistent economic inequality; the shortage of natural resources in the background of their wasteful expenditure; the progressive pollution of the natural environment, especially with production waste; the crisis of traditional models of extensive development (Fig. 2).

The energy landscape of the world however is not frozen. It is changing all the time both in time and in space. New trends, factors and driving forces of the observed and upcoming transformations are emerging and gaining

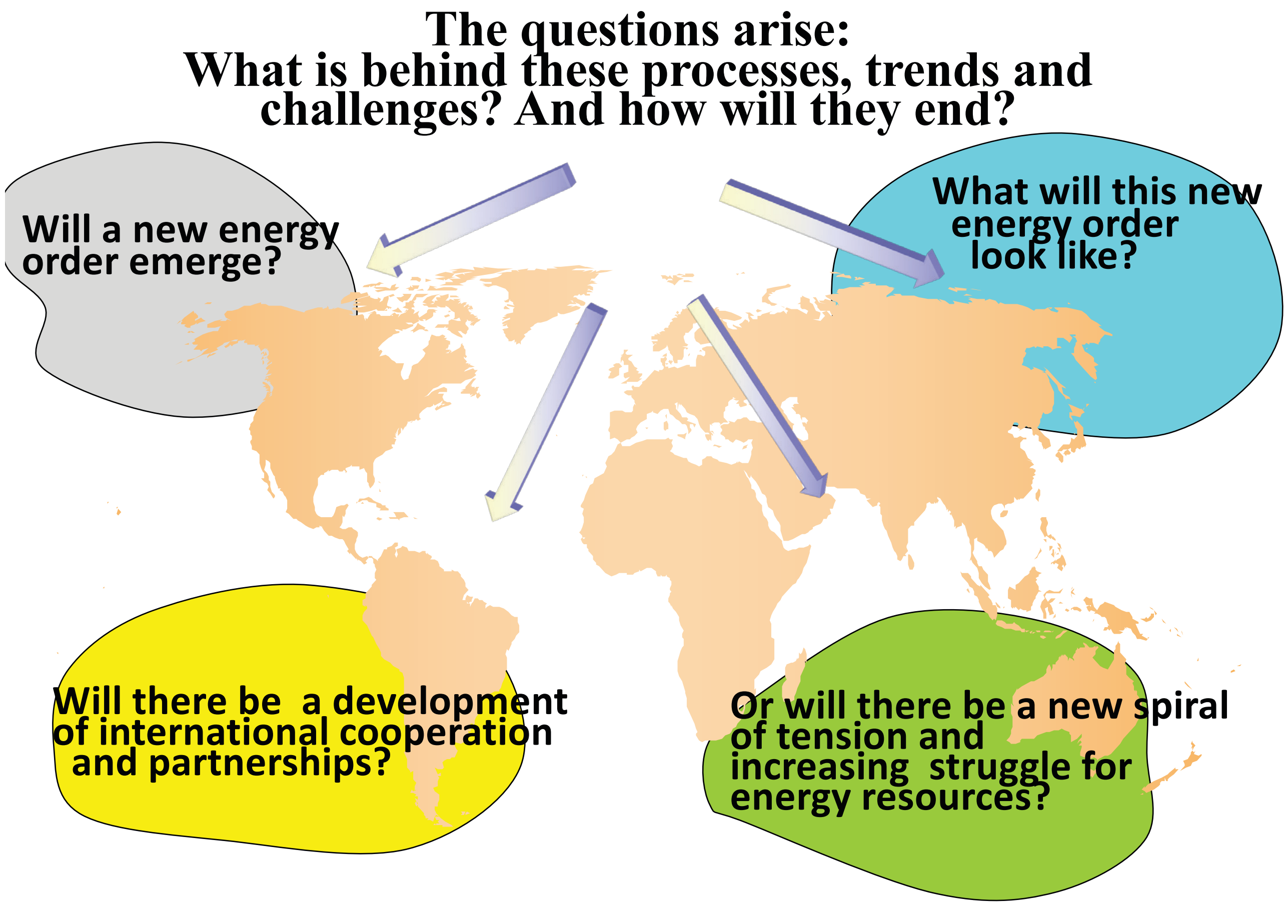


Fig.4. What will the world's energy landscape look like?

momentum. In recent years, the main ones have included the need to respond to the challenges facing humanity in connection with climate change, and the projected changes in the energy mix caused by the effects of the 4th industrial revolution.

Accordingly, the future of the global energy industry, as well as the future of the entire world economy, will be largely determined by such trends as:

- Balancing between globalization and regionalization, the threat of energy shortage and the onset of a global surplus of energy resources;
- Change in the technological structures both in the production of fuel and energy, and in their consumption;
- The end of the hydrocarbon era and the development of innovative carbon-free energy, etc. (Fig. 2).
- One of the most important factors determining a totally new energy landscape is a fundamental change in the energy sector due to the adoption of new technological solutions and radical technological advances in all areas, which primarily implies (Fig. 3):
- New technologies for oil and gas exploration and production (and hence the shale revolution in the United States, and the large-scale development of Canadian oil sands);
- Reduction in the cost of renewable energy production and protection of the environment. As a result, the need for fossil fuel is reduced;
- Growth of liquefied natural gas (LNG) production and volumes of its transportation. The natural gas market is becoming mobile and interregional;
- Improvement in the energy saving technologies, which refutes the forecasts of a constant growth of energy consumption, etc. Source: [21,22]

Factors determining a fundamentally new energy landscape:

- The USA turns from a leading consumer of hydrocarbons into their largest producer and, in the future, a significant exporter;
- China becomes the largest oil consumer;
- Fundamental changes occur in the energy sector due to the adoption of new technological solutions, radical technological advances in all areas:
  1. new technologies for oil and gas exploration and production (and hence the shale revolution in the United States, and the large-scale development of Canadian oil sands);

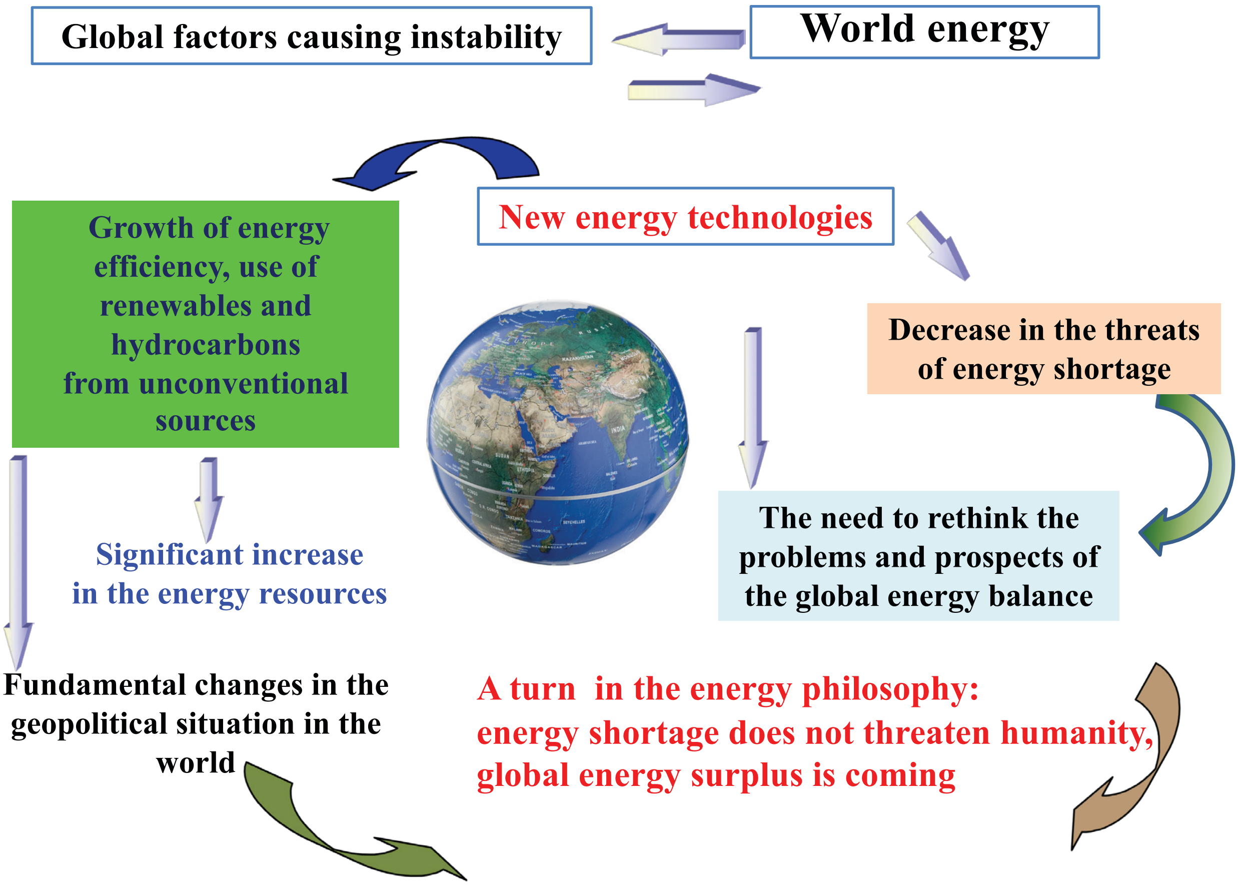


Fig.5. Some implications of global energy changes.

2. reduction in the cost of production of renewable energy sources and environmental concerns. As a result, the need for fossil fuels is reduced;
3. growth of LNG production and its transportation volumes. The natural gas market becomes mobile and interregional;
4. improvement in energy saving technologies, which refutes the forecasts of a constant growth of energy consumption, etc.

Source: [5,21]

In the coming decades, we expect the emergence of fundamentally new technologies, for example, the technologies that capture, utilize and store carbon dioxide (carbon, capture utilization and storage technology - CCUS), as well as the technologies that provide energy storage on an industrial scale (Energy storage technologies) [23,24].

Foreign economic risks, trends and factors will also have a great impact on the future world development [5: Chapter 7]:

- the exacerbation of a number of problems with which the existing international institutions cope so far unsatisfactorily. These include, first of all, the threat of aggravation of the global financial and economic crisis; persistent and even increasing imbalances and disproportions in the world trade, in the capital flow, in the restructuring of the world economy and the world financial system;
- The growing uncertainty of world development, caused, among other things, by the increased number of countries that determine the formation of world economic dynamics. New powerhouses have a growing impact on all world economic trends, change the configuration of world trade, monetary sphere, capital flows and labor resources;
- The increase in the rate of change of a number of key world economic trends, due to the intensification of innovation activities;
- Various economic sanctions, which are increasingly more often becoming a tool in world politics.

The emergence of these external economic risks, trends and factors introduces additional uncertainties into the already complex energy landscape of the world. Naturally, more and more questions arise: what is behind these processes, trends and challenges? Will there be development of international cooperation and partnership or strengthening of the struggle for energy? Will a new

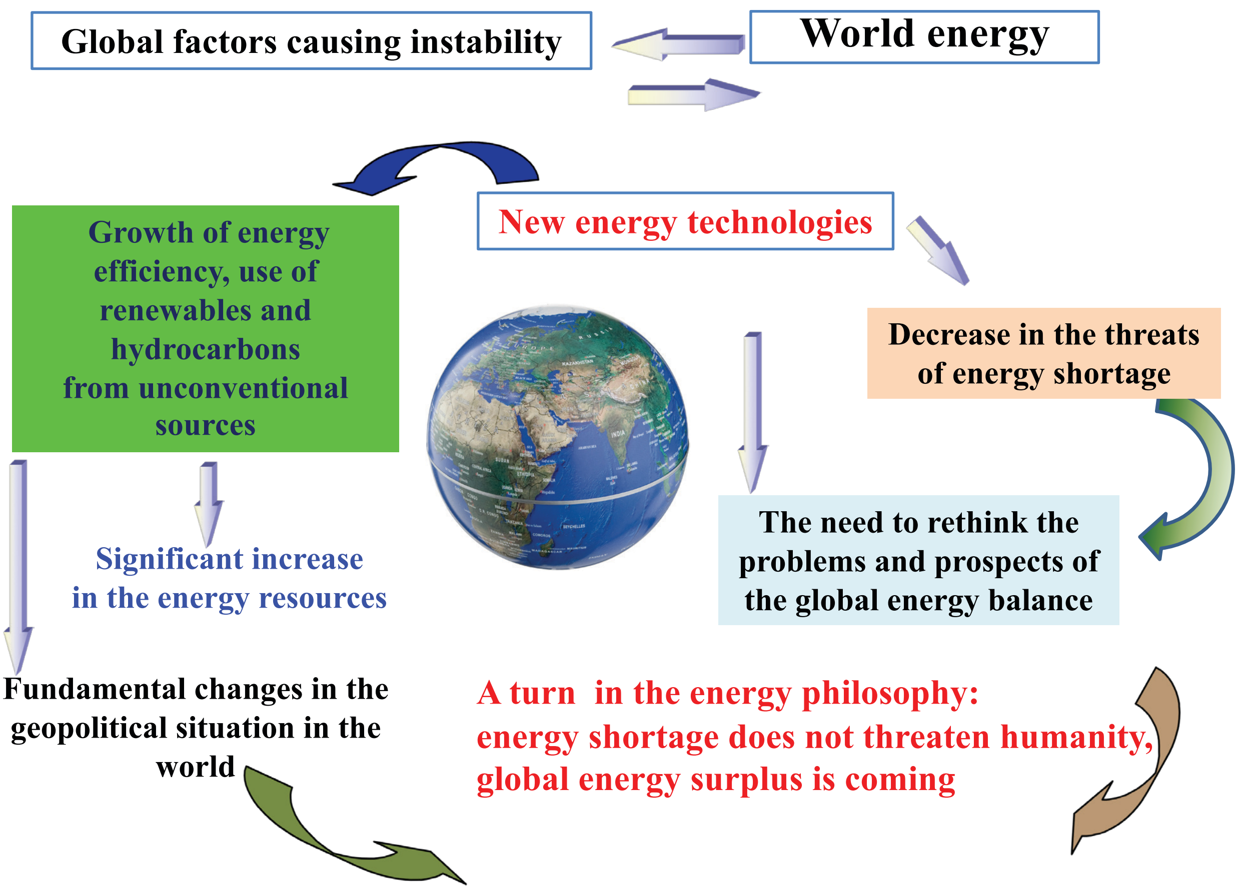


Fig.5. Some implications of global energy changes.

energy order be established? What will this new order be like? Will it draw a line under the struggle for energy resources or, on the contrary, will strengthen it, and move to a military dimension? (Fig. 4). It seems that only time will give answers to these questions.

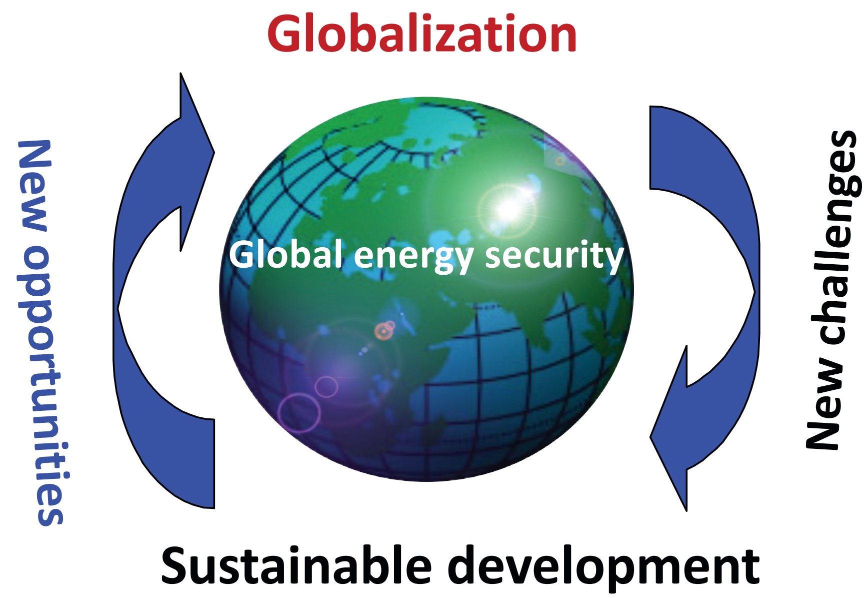
III. A New Energy Philosophy and Factors That Determine It

A peculiar result of the impact of the entire set of the above-considered factors and processes on the world energy sector was the change in the energy philosophy itself.

As is known, this philosophy has been long based on the problem of energy shortage, which was formulated (and substantiated based on that level of knowledge) in the middle of the last century by the Rome Club. Since then, mankind has evolved "under the sword of Damocles" of energy shortage, a possible lack of energy for its development. This threat determined not only the general economic and energy policies of the leading countries, but also practical measures by governments and businesses [5: Chapter 7]. At the same time, the oil peak theory (Hubbert peak theory), put forward by the American geophysicist King M. Hubbert in 1956, gained popularity among oil industry workers, according to which the world's maximum possible oil production will be achieved in the coming decades, followed by the decline of its production [26].

At the beginning of this century, the situation began to change. The development of science and technology has opened up the possibility of commercially efficient use on a large scale of not only renewable energy sources, but also practically unlimited amounts of unconventional hydrocarbon resources. Moreover, the fundamental science - the theory of polygenesis (a variety of ways of oil formation) and the biosphere theory of oil and gas formation - not only significantly expands the search for new hydrocarbon fields, but also suggests that hydrocarbons, including oil, are also a renewable energy source [27,28].

At the same time, as experts state, oil has already passed its peak as fuel. The 19th century was the century of coal, the 20th century was the century of oil, the 21st century (or rather, its first half) will be the century of diversification of energy resources (oil, gas, coal and renewable, including biomass, energy sources). In the 21st century, other energy carriers will increasingly compete with oil, and not only when used as a boiler and furnace fuel in the power industry where the oil positions are currently quite modest, but also as a motor fuel, where oil still dominates. In particular, the



“Sustainable energy development” = the establishment and operation of an energy system that meets the growing needs of socio-economic development of the world community on the basis of equitable, economically acceptable access to energy resources without irreparable damage to the environment and without infringement of the interests of future generations

Fig. 6. Sustainable energy development in the coordinates of globalization and energy security.

rapidly declining costs of electricity production based on renewable energy sources allow them to win one of their main consumers, the motor transport, from hydrocarbons through electricity.

The technological advances and accomplishments not only have demonstrated that the energy famine does not threaten the world, but also have given rise to the “Peak demand for oil” theory among oilmen and power engineers. These achievements also strongly push for the need to rethink not only the problems of and prospects for the global energy balance, but also the energy philosophy itself, and allowed us to formulate a hypothesis about the coming era of global energy surplus (Fig.5). Source: [25, 29]. The hypothesis about the coming global surplus of energy resources was put forward by the author in 2009-2010 in his speeches at the annual forums of the “Club of Nice – Energy and geopolitics” [7,8,17].

In addition, the possibility of efficient use of renewable energy and non-conventional hydrocarbons not only increases the total energy resources, but also radically changes the geopolitical situation in the world, in particular - the balance of power and the division of states into exporting and importing countries [5: Chapter 7].

The theory of “peak demand for oil” (the most appropriate amount of its consumption) is closely linked with the humanity’s awareness of how important and serious the problem of the so-called global climate change is. Experts have yet to thoroughly investigate this phenomenon, its causes and trends. Until now, scientists have not been able to say with 100% confidence what causes the current climate change. From their perspective, the causes of global warming include changes in solar activity and changes in the angle of the rotation axis of the Earth and its orbit, unknown interactions between the Sun and the planets of the Solar System, the ocean, volcanic activity, and human activity. It is highly likely that the current global warming is the result of many factors.

Nevertheless, the scientific understanding of the global warming causes has become more definite over time, and now experts believe that there is a 90% probability that most of the temperature change in the last century has been caused by an increase in the concentration of greenhouse gases due to human activity (i.e. due to man-made factor) [30].

Thus comes the conclusion that it is necessary to switch to low-carbon or carbon-free energy (and the economy). The climate agreement reached in Paris on December 12, 2015 during the 21st conference held under the United Nations Framework Convention on Climate Change (COP21) gave additional impetus to the discussion about the role of oil and gas and the global energy balance of the future.

Another reason for the increased attention to the issues of low-carbon or carbon-free energy of the future is the theory that the exhaustion of energy resources by 2030-2035 due to the last wave of rapid industrial growth and, accordingly, the energy consumption growth, may lead to stabilization of consumption of natural resources and the industrial economy as a whole. This means that in the long term, the demand for raw materials and traditional energy sources will grow slower, then stagnate, and then will completely decline [5,31]. In the next decade, in particular, the developed countries will switch to the formation of a new technological platform of economic systems based on the use of the latest advances in biotechnology, computer science and nanotechnology, which can significantly reduce their needs for primary energy resources . However, there are exactly opposite estimates of the future energy consumption. For example, experts from one of the new think tanks of the Republic of Korea, the Future Consensus Institute, believe that the 4th industrial revolution can become a serious challenge for energy security, because the process of innovations and development of technologies that meet its requirements are accompanied by extremely high energy consumption [22,23].

The natural basis for the increased attention to the problems of low-carbon or carbon-free energy of the future is the development of science and technology noted above, which has expanded the boundaries of our understanding of the capabilities of energy and energy supply of humanity, especially the capabilities of using renewable energy sources.

The transition to low-carbon and carbon-free energy will certainly not happen immediately, and for a long time carbon and non-carbon energy facilities will operate simultaneously. One of the possible scenarios for the start of such a transition to the low-carbon world is shown in the 2016 forecast by the BP Group [34]. During this transition period, the role of natural gas as the most environmentally acceptable type of hydrocarbon resources should increase. However, for natural gas to play this role, its prices should be at least no higher than the prices of alternative energy sources (given the costs throughout the whole chain from production to final consumption, including measures related to the use of environmentally friendly, "green" technologies).

Undoubtedly, during this transition period (at least in the period up to 2035–2040), oil will retain its role in shaping the global energy balance as one of the main energy resources. This however will take place, as already noted above, against the background of the expected systems crisis, which will cover the economy, energy, and politics, including international relations, in conditions of the high uncertainty in almost every component that makes up the overall energy picture of the future . The studies on the key uncertainties that can affect the development of global energy markets until 2040 are presented in the BP Energy Outlook 2019 published on 14.02.2019. According to BP, the greatest uncertainty in this period is related to a greater amount of energy necessary to provide further growth of global economy and welfare and to the need to rapidly transition to low-carbon future. These scenarios emphasize the dual problem facing the world [35].

The fundamental factors of development of the world economy and energy in recent decades have impacted on the emergence of such a unique phenomenon as the globalization of the world economy, which, in turn, has become one of the most important driving forces for further economic development [5: Chapter 7] . It is worth noting however that although the concept of "globalization" has been lately one of the most frequently encountered terms in the economic literature, in the economic theory there is still no an unambiguous view on this phenomenon defined by this term. Thus, there is no universal definition for the term "globalization". Moreover, according to Professor V.S.Pankov, head of the Chair of International economic relations of the Higher School of Economics, in the scientific and social-political literature devoted to the world economy issues, the term of globalization is used massively, chaotically and often in an ugly fashion.

The role of globalization in the future energy development is dual, since it exerts both direct and indirect influence on the development of world energy, encompassing not only energy markets and energy resources, but also such energy-related activities and forms as [1.8] :

- The globalization of energy technology and equipment markets based on international specialization and cooperation;
- The formation of a unified global system of energy information, knowledge and know-how based on the unification of national information systems and liberalization of access to national information resources on energy;
- The approximation and unification of national energy legislation, regulations, technical regulations, etc., including those related to environmental protection during energy activities;
- The establishment of international energy organizations and associations and the strengthening of their role.

Globalization brings new challenges to humanity and at the same time provides it with new opportunities to solve the most complex problems. The former engender increased competition for the right of access to energy resources, increasing threats to global energy security and global economic chaos. The latter lead to the concentration of the world's intellectual and financial resources, the creation of new technologies for the production and use of energy resources, awareness of the need to care about the environment and to fundamentally change the global financial sphere; promote the development of international energy cooperation and reduce the threats to global energy security and of global economic chaos.

The factors associated with globalization, according to specialists from IMEMO RAS and the Atlantic Council (USA) [37], will also affect the growth of price uncertainty in world energy markets. These are:

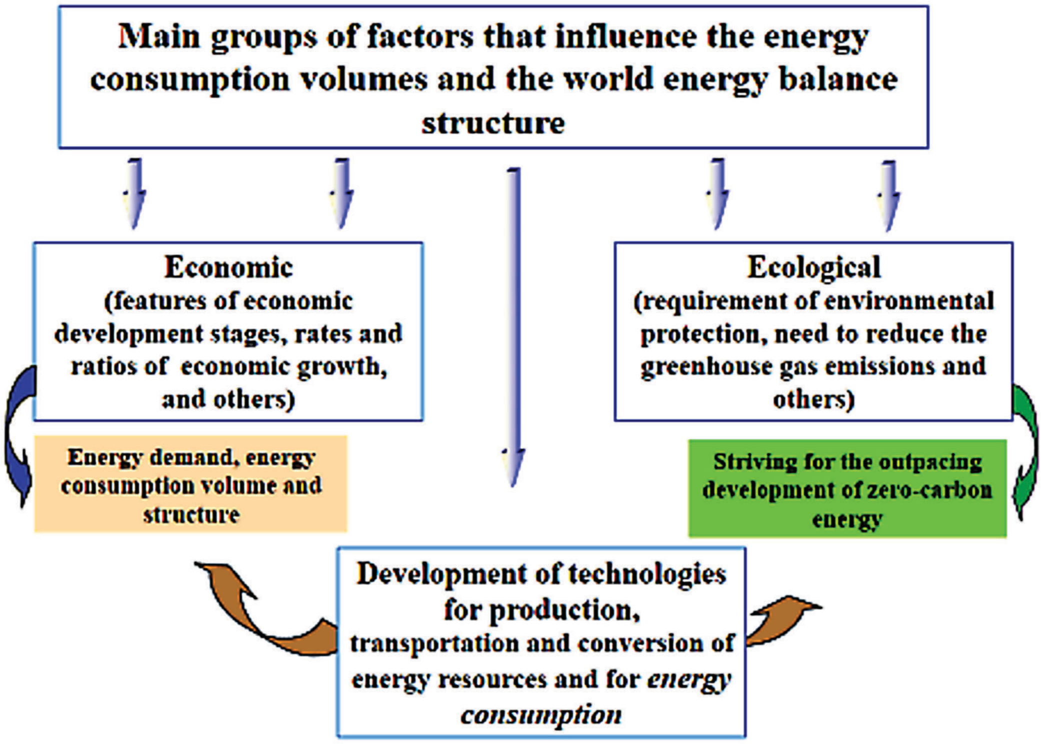


Fig. 7. Some basic energy-economy relationships.

- The transition to a multi-level, polycentric regulatory system capable to keep and stabilize a large-scale global financial system developing much faster than the real economy;
- The development of free trade zones, common markets and currency unions;
- The diversification of technologies and sources of energy, as well as increased energy efficiency in the developing world.

At the same time, globalization activates a number of other, primarily economic factors, such as: economic growth rates, ownership structure, models and instruments for raising capital, accumulation rates, investment, debt burden, relations between public and private finances, internal and external sources for funding the economic growth, macroprudential supervision and reduction of systemic risks, etc. The effect of globalization on the energy development prospects is presented in more detail, for example in [5: Chapter 7]. However, currently, the impact of globalization on the world energy development (as well as on the global economy) can be estimated only on a qualitative level. As was justly pointed out by the authors of the paper "War and peace of the 21st century. The international stability and balance of a new type" prepared in the framework of the international discussion club "Valdai", everybody understands that the fundamental changes are coming but nobody can comprehend them or at least draw the outlines of the future" [38].

In the light of globalization, energy security, understood, above all, as a reliable and uninterrupted supply of consumers with fuel and energy in the required amounts, required quality and at economically acceptable prices, has acquired a new, global dimension and has become one of the most relevant components of the global security considered in the context of sustainable development of the economy and humanity as a whole. The issues of sustainable development deserve special consideration. Therefore, here we will only note that the term "sustainable development" appeared in the UNO documents in the middle of the 1980s, and its widespread use started after the United National Conference on Environment and Development held in Rio de Janeiro in 1992.

Thus, the concept of "sustainable energy development" has appeared (Fig. 6) .Source: [29]. In Russia, the concept of "sustainable energy development" was introduced at the turn of the 20th and 21st centuries owing to the work of a large group of specialists under the leadership of the President of the International Fuel and Energy Association on the public-state program "Put Russian energy industry on the road to sustainable development through joint efforts of the government and civil society"[39]. Somewhat later, this concept was supplemented and developed by specialists from the Melentiev Energy Systems Institute SB RAS and the Institute of Energy Strategy, that by sustainable energy development began to understand "the establishment and operation of an energy system capable to provide the growing needs of the socio-economic development of the world community on the basis of equitable, economically acceptable access to energy resources without irreparable damage to the environment and without infringement of rights of future generations" [40]. In later studies, the improvement of this concept continued. Thus, according to [4], the concept of "sustainable energy development" means an approach to energy development, which consists in prioritizing the efficient, safe and balanced development of an energy industry over constant quantitative growth in order to achieve a balance of requirements for further economic progress, improvement of the quality of life of people, respect for the interests of present and future generations, the preservation and effective use of the capabilities of the natural environment and energy potential.

Energy security is simultaneously the most important part of the entire energy policy and the national security of the leading states, and one of the main systems challenges faced by the modern energy sector. Thus, energy security acts as a technical, an economic, a political and a philosophical category. The energy security system is designed to ensure the reliability of energy supply in the common interests of the world economy, in the interests of all countries, both energy consumers and producers. Hence the understanding that this system should be transparent, based on international law and responsible policy regarding supply and demand.

Along with this, the dangerous trend of politicizing energy markets is gaining momentum in order to use them as a tool of geopolitics. World energy markets are constantly under strong influence of non-economic factors, which increases the conflict potential and the distrust of market participants to each other, makes them look for alternative, often very expensive solutions to problems. Attractive in theory, the principle of diversification of energy sources and routes of supply, which underlies many energy strategies, in real life provokes increased geopolitical rivalry between countries. In energy diplomacy, it becomes a practice to single out entire regions of critical importance in terms of international energy security.

Of paramount importance for neutralizing the threats to energy security are the technological progress, innovative technologies and technical solutions. These are, first of all, the involvement of heavy, shale and matrix oil; coal bed methane; shale gas and gas hydrates; synthetic liquid fuels; and renewable energy sources in the fuel and energy balance. These are long-distance energy transportation (including via a cryogenic cable) and sea transportation of natural gas in a hydrated (solid) state. Such lines of the technological progress, providing promising energy supply to humanity are at the same time the most important factors directly affecting the global energy security.

In the last decade, the technologies associated with the development of new and unconventional energy sources have made it possible to efficiently use local energy resources, minimizing the transportation component in their price, and refuse from long-distance (and therefore expensive) energy resources. The development and emergence of new technologies will occur constantly. However, new technologies are developing in cycles, according to their laws and regularities, which makes it difficult to predict the results of this process.

The globalization of scientific and production relations and the transfer of knowledge and technology enabled many oil and gas importing countries to have at their disposal technologies for extraction of unconventional hydrocarbons, renewable energy technologies and to commence their own developments in these areas, focused on energy self-sufficiency and energy security [41: 375].

IV. New approaches to long-term forecasting of energy future

Long-term forecasting of the world energy development is an important component part of its operation. However, the considered factors that determine the world economy future, challenges facing humanity, risks and trends considerably hinder this process. In the recent decades, hundreds of national and international teams and tens of thousands of experts in various countries — both exporters of energy resources and their consumers – have been engaged in such long-term forecasting. The events of recent date have increased the degree of uncertainty of future energy development (Fig. 7) and shaped the demand for new approaches to forecasting our common energy future. Globalization, geopolitics and onrush of the science and technologies all contribute to the uncertainty increase. The situation is aggravated by the emerging surplus of energy resources.

This uncertainty encourages the leading international and national analytical centers to build a set of different scenarios covering, in essence, practically all possible options of situation development. At the same time, it allows them to claim that their forecasts, in general, are neither forecasts nor predictions of what can happen. This is merely a study of the pathways for potential development of the world, provided certain conditions are met, and the activities that can lead to such development of events. This is just the basis for speculations about the global energy future [43].

As a result, the estimates and trends of the global demand for energy and consumption of oil and other types of liquid fuel in the long-term forecasts of the world energy development that have been made by these centers recently are very often exactly opposite.

For example, in the basic scenario of the latest forecast by IEA (World Energy Outlook – WEO-2018) — Scenarios of the new policy — growth of the world demand for energy resources, including oil, slows downs, but does not reach its maximum until 2040 [43].

In 2040, the demand for oil, without liquid biofuel, equals 106.3 million bbl/d, which is by 11.5 million bbl more than in 2017. If liquid biofuel is considered, the oil demand increases to 110.9 million bbl/d, or 27.6% of the global energy consumption equal to 17 715 million toe. On the contrary, in the Scenario of sustainable development new for IEA, which provides an integrated strategy for implementation of the key energy-related items of the UN agenda in the area of sustainable development, including the energy access, the air quality and the climatic goals, the maximum oil demand (97 million bbl/d) is reached by 2020 (the maximum total energy consumption by 2030 is 13 820 million toe). By 2040, the world oil consumption in this Scenario decreases to 69.9 million bbl/d (including liquid biofuel – to 77.2 million bbl/d or to 23% of the world primary energy consumption). In the Scenario of the current policies which is based on maintaining the status quo, the current state policy of the leading world countries, the global demand for oil and other liquid fuel types in 2040 is 124.1 million bbl/d or 29% of the world energy consumption equal to 19 328 million toe [43].

The continuing rapid growth of the world oil consumption in the period up to 2040 is forecasted by the US Energy Information Administration as well. In its latest IEO-2018, by 2040 the global oil demand will be about 229 quadrillion BTU (above 131 million bbl/d or 31% of the total world energy consumption) [44].

The estimates of the Secretariat of OPEC (World Oil Outlook 2018) are close to the estimates of the basic Scenario, the latest forecast by IEA. They also believe that in the future the growth rates of the world oil demand will slow and in 2040 they will make up 111.7 million bbl/d or 27.8% of the world primary energy consumption [45].

The forecast of BP Energy Outlook 2019 published on February 15, 2019 [35] considers a set of scenarios: the basic scenario (Evolving Transition Scenario) and the alternative scenarios (Rapid Transition, More energy, Less carbon, Less globalization, Single-use plastics ban, Greater reforms and others). Accordingly, depending on the scenario, the oil demand in this forecast is estimated for 2040 to be from 80 million bbl/d (23% of the global energy consumption) in the Fast Transition Scenario up to 108 million bbl/d (27.2%) in the basic Evolving transition scenario, and up to 130 million bbl/d in the More energy scenario.

Possibility of higher transition rates to low-and zero-carbon energy is analyzed in some prognostic studies by the analytical centers focusing on sustainable development, unconditional fulfillment of targets of the Paris agreement on climate and renewable energy sources.

For example, the prognostic study “Energy Transition Outlook 2018. A global and regional forecast to 2050” presented by the company DNV GL on September 10, 2018 in London notes that the progress in the area of energy efficiency and usage of renewable energy sources (RES) allows anticipating great changes in both the volumes of global primary energy demand and its structure [46]. In particular, the total primary energy consumption will reach its peak (15 809 million toe) in 2032, and its final consumption – in 2035 (11 224 million toe). By 2050, these volumes will decrease to 13 994 and 10 746 million toe, respectively. In addition, the peak oil demand (4 033 million toe or 91.2 million bbl/d) will be reached as early as 2023, then oil consumption will start to decline and make up in 2050 only 2 052 million toe (46.4 million bbl/d). Hence, the oil share in the global consumption of primary energy resources will equal only 15%. In 2050, the share of oil, coal and natural gas will be only half the energy consumed by humanity.

However, even such changes, as acknowledged by the authors of this study, will be insufficient to achieve the targets of the Paris agreement: a combination of higher energy efficiency, more extensive use of RES and more extensive use of carbon capture and storage technologies will be required.

Even more considerable decline in oil consumption is justified in the studies by the International Renewable Energy Agency (IRENA). For example, in the study “Perspectives for the Energy Transition: Investment needs for a low-carbon energy system (IEA and IRENA, 2017)” in the scenario aimed at achievement of the targets of the Paris climate agreement (66% 2°C Scenario), the RES share in the global energy consumption in 2050 is estimated at 47%, and the total volume of fossil fuel use will be only half the 2014 level. Despite the greatest reduction in coal consumption, the oil demand will also decrease almost by 60%, to 760 million toe (to 40 million bbl/d). This scenario can be implemented, as is noted by its authors, “by the unprecedented buildout of all low-carbon technologies in all countries” [47].

IRENA sets even more ambitious targets in the work published in 2018 “Global Energy Transformation: A roadmap to 2050. IRENA 2018”: to increase the RES share in the total consumption of primary energy resources by 2050 to 66% (including their share in electricity generation – to 85%) with parallel decrease of energy consumption to the level lower than that in 2015. Hence, the oil consumption volumes also decrease (approximately to 24 million bbl/d) [48].

Thus, the scatter in estimates of future oil demand in the world, as well as energy consumption as a whole, is quite wide. Based on different scenarios, in the considered prognostic studies for 2040-2050 it varies from 24 to 131 million bbl/d, and from 13.1 to 22.3 billion toe, respectively.

Nevertheless, despite the uncertainty of quantitative estimates of future energy resources production and consumption in the world, the considered forecasts allow identifying some patterns in the future world energy development. The most important of them are:

- A considerable increase in the energy efficiency and development of advanced energy consumption technologies that slow down the growing demand for energy carriers. The developed countries will switch to the development of a new technological platform of economic systems which is based on employment of cutting-edge achievements in the sphere of biotechnologies, computer science and nanotechnologies, which can substantially decrease their demands for primary energy resources.

- Improvement in the competitiveness of renewable energy sources, an increase in their use in absolute terms and in the structure of the total energy consumption.
- Outpacing development of electric power industry. Development of distributed (decentralized) generation and energy storages, smartization of energy sector and energy consumption as a whole ("smart well", "smart home", "smart city", etc.).
- Technological evolution of thermal power industry with a steady increase in its efficiency and environmental compatibility.
- Maintenance of the achieved proportion (or even its slight growth) of nuclear energy (about 6-7%) in the world production of primary energy resourcesв.
- Stricter energy policy on the climate change and its consequences, stimulation of developing the environmentally clean and environmental protection technologies.
- Improvement and transformation of functioning and regulation of the world energy markets, including the change in contract terms and evolution of exchange market regulation that strengthens the consumer positions; the change in the internal mechanisms that determine price formation in the world energy markets.
- Increase in the international competition in the world energy markets, first of all – in the European gas market, appearance of new energy exporters.

V. On the priorities of russia's energy policy in the context of global energy changes

The energy sector is the most important component part of the economy of the contemporary Russia as it is based on abundant natural resources and intellectual potential of our people and makes a great contribution to the national security and socio-economic development of the country.

Russia has abundant resources that can satisfy the country's needs and provide a rational fuel export at least until the middle of the 21th century. Russia also occupies leading positions in the world energy, especially in the oil and gas sector. Correspondingly, as we stated almost five years ago, despite the fact that the country possesses a huge energy (including hydrocarbon) potential and is of paramount importance for providing the global energy security, Russia must be ready for the considered qualitative changes in the global energy system, the world is going to face, as long as all the indicated and not indicated challenges will directly influence future socio-economic development of the country, prospects for its energy sector, especially its oil/gas industry [49].

Awareness of this fact is particularly important because the Russian energy sector faces a complex set of internal problems, such as [50]:

- Low competitiveness and a resource-export model of the Russian economic development;
- Low rates of economic growth that considerably slow the growth of the internal demand for fuel and energy, and weaken the investment activity in the energy sector;
- Technological gap between some segments of the Russian energy sector and the advanced level of their development with excessive dependence on the import of some types of equipment, materials and services;
- Low modernization rates of infrastructure and production assets, high dependence on the external economic situation;
- Limited capabilities for attraction of accessible long-term financial resources.

Correspondingly, the Russian energy sector requires not only re-equipment and upgrade, but rather fundamental technological reconstruction aimed at increasing the flexibility and growth of the economic efficiency in the long-term future.

The recent events have shown that Russia's economy, with all its openness and integration into the world around, must be self-sufficient and rely, first of all, on own resources, own and adapted technologies. The energy sector possesses a significant potential for creating the demand for domestic knowledge-intensive and innovative products. However, the innovation-oriented development pathway of Russia's energy sector has been shaped highly weakly yet.

Moreover, as noted in [49], the performed analysis has showed that at present different subindustries of the oil/gas industry experience, though to a different extent, shortage of both up-to-date technologies and really breakthrough innovative strategies for the long-term development. Therefore, the future of the Russian oil/gas industry, the competitiveness of its products in the world market will largely depend on the extent to which the domestic science and the Russian companies will succeed in design of new, especially breakthrough, revolutionary technologies along the whole "chain" from exploration to consumption of hydrocarbons. Primarily this concerns the technologies of effective development of hydrocarbon resources in the arctic shelf and resources of unconventional oil and gas sources, totally new technologies for long-distance transportation of natural gas, advanced conversion of hydrocarbons.

We should be fully aware that Russia and its oil/gas industry are not threatened by the "shale revolution" itself, but rather by the lack of technologies, reluctance to see the need to design advanced technologies, and the lag that can decrease competitiveness of the Russian economy and increase its vulnerability in the context of the escalating geopolitical rivalry. Therefore, both the "shale revolution" and the imposed sanctions should become an additional incentive for extension of import substitution, positive shifts towards local production of equipment for the energy sector, restoration of the innovation process and refusal to follow the resource-import model of the Russian economy development in favor of the shift to the resource-innovative socially-oriented economic development. For details on the necessity and possibility for the Russian economy transition to the resource-innovative pathway of development see [2,3].

The oil/gas industry of Russia still possesses the world richest mineral resources, developed infrastructure, skilled engineers, considerable innovation potential, and, what is equally important, is characterized by the scaled, quick and effective return on financial assets. At the same time, the oil/gas industry faces a situation dangerous for the national economy. The threat is caused by the rapid depletion of the "active" reserves of readily recoverable oil. By 2022, the production of this oil is expected to decrease by 45-50 million t. The share of hard-to-recover oil reserves is growing, the productive capacity of oil reservoirs is decreasing, the oil and gas resources at a depth of up to 3000 m have been depleted to a great extent, development of the gigantic fields with the unique oil and gas reserves, whose exploitation started in the 1960-70s, is terminated [51].

Let us repeat once again, since over the last years this situation has practically not changed, design of domestic technologies and adaptation of foreign ones should be recognized as the highest priority of the Russian energy policy pertaining to the oil/gas industry development in the emerging conditions. This mainly concerns the technologies that ensure considerable decrease in production costs in the whole "chain": oil/gas production, processing, transportation and distribution. In the external markets without cheap hydrocarbons, Russia will loose its competitive advantages as an oil/gas exporter. In the internal market, under the natural-climatic and geographical conditions of the country's economy, without cheap hydrocarbons (in particular, without cheap gas – a source of energy and feedstock for gas chemistry) Russia's competitiveness prospects are slim. The loss of competitiveness, in turn, can give rise to a prolonged economic recession and a large-scale political crisis in Russia [52].

VI. Conclusions

The studies presented in the paper allow the following conclusions to be drawn (or the conclusions of our previous research to be confirmed).

1. At the turn of the 20th and 21st centuries the human civilization faced a set of new, interrelated and interdependent problems and challenges that concern not only the entire economic activity of humanity, including the energy sphere, but its social and political aspects. Under highly uncertain conditions of their impact, a new energy landscape, whose outlines at present are rather blurred, is emerging. The objective of our further studies is to assess the extent of this uncertainty, identify critical important processes, factors, challenges and limitations that influence the prospective development of the Russian energy sector in the context of the global economy and energy.
2. A specific resulting effect of the totality of the considered factors and processes on the world energy sector was the change in the energy philosophy itself that was long based on the energy shortage problem. The technological progress and advances gained at the beginning of the current century have shown that the energy shortage does not threaten the planet, and have made it possible to generate a hypothesis on the coming era of the global energy resources surplus. Correspondingly, the time, when availability of natural resources enabled their owner to dictate their terms, has gone, and even if there is a hope for its return, it will not happen soon. Therefore, the people making decisions affecting the interests and lives of millions of people should not only understand this, but also act on the basis of this understanding.
3. Changes in the world energy situation are taking place virtually continuously. However, the critical impact on the situation is made by the changes that have long-term effects and fundamentally alter our vision of the energy sector in the coming decades. This is, above all, the problem of global climate change and the related need to transition to low- or zero-carbon energy, the necessity of its sustainable development, and a new interpretation of the energy security problem. This is the world economy globalization, whose role in the future energy development is dual, since it influences the world energy development directly and indirectly including both the energy markets and energy resources, and the scope of directions and forms of energy-related activities. This is, at last, the technological factor that is the core driver of the forthcoming changes in the world energy balance and its structure.
4. Specific features of the future global economy and the structure of the prospective world energy balance will depend on the accessibility and efficiency of the technologies for production of conventional and unconventional oil/gas resources, utilization of renewable energy sources, growth of energy efficiency, formation of the innovative economy on the basis of the low-energy, nano-, bio-, information, cognitive and other similar technologies. And the world energy landscape in the mid-21st century, and surely, the future of the main energy resources exporters, including Russia, will depend on the technologies, which will enter the market faster – new technologies for production of new energy resources, technologies aimed at effective transportation of conventional energy resources over long distances or technologies aimed at a considerable increase in the

energy efficiency.

5. The timely understanding of the role of one fuel and energy type or another in forming the future global energy balance requires a thorough analysis of capabilities of each energy source - in terms of available resources (volumes), and the economic (primarily, cost) indicators, and the environmental compatibility.
6. There are a lot of opinions, forecasts and studies concerning the development pathways of the global energy sector and its most important components. By virtue of the high degree of uncertainty of practically each of these components of the future energy picture, none of them can be neglected. The way out for Russia and the companies planning to actively participate in the international energy markets is to steadily monitor all new trends and forecasts, sift them, in in order to understand what underlies these forecasts. Furthermore, they should pursue their flexible policy remembering the necessity of comprehensive reduction in costs of their export projects.
7. Future of the Russian oil/gas industry, competitiveness of its products in the world market will largely depend on the extent to which the domestic science and the Russian companies will succeed in designing new, especially breakthrough, revolutionary technologies in the whole "chain" from hydrocarbons exploration to consumption.
8. To solve the indicated problems and provide transition of the Russian economy to the resource-innovative development it is necessary to create effective conditions for attraction of financial resources to implement the innovation projects. This can be achieved through the tax exemptions and soft loans by inclusion of the innovation expenses in the production cost with the multiplying factor, creation of beneficial conditions for both concentration of financial resources in the target science-and-technology areas and projects, and for design and development of integrated technologies. These measures are even more necessary in the situation, when the key problem of the current national science and technology system is its chronic underfunding.

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Prevention Of Outages In Power Systems With Distributed Generation Plants

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***Abstract*— The paper is concerned with the study aimed at the development of methods for emergency control in power systems with distributed generation plants. The control actions enabling the state parameters to meet stability constraints were generated by changing the vector of controlled parameters along a preset path corresponding to the shortest distance from a point of the initial state to a limiting hypersurface. In this case, limit loads equations of the power system were used. The quality of dynamic processes during control actions was ensured by harmonized tuning of the automatic voltage regulator (AVR) and automatic speed regulator (ASR) of distributed synchronous generators. Computer-aided modeling was used to demonstrate that the post-emergency operating conditions meeting stability constraints can be calculated using limit load equations while using the starting algorithm that enables the values of operating parameters to reach the nearest boundary of the feasibility (stability) region. Modeling of the power system in MATLAB environment demonstrates that the fuzzy algorithms used to control AVR and ASR settings considerably enhance the quality of transient processes of voltage, frequency, and power when the power of distributed generators in post-emergency conditions is reduced.**

***Index Terms* — power supply systems, distributed generation plants, emergency control, harmonized setting, automatic voltage regulator, automatic speed regulator.**

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I. Introduction

The use of intelligent electric power systems (EPS) with active-adaptive networks implies the active use of distributed generation (DG) plants located in the immediate vicinity of power consumers. The following facilities can be referred to as the DG plants:

- unconventional renewable energy sources: solar panels, wind generating plants, fuel cells, and others;
- small- and medium-capacity cogeneration plants (small thermal power plants based on gas turbine and combined cycle gas turbine technologies), as well as mini- and micro-hydro power plants.

Active use of DG technologies in EPS requires new algorithms and systems for control in normal, emergency and post-emergency conditions [1 – 4] to provide the required stability and quality of the dynamic transition.

A main function of emergency control (EC) systems is to ensure static non-oscillatory stability of post-emergency conditions (PEC) of EPS. In this case, the control actions are generated to provide the PEC parameters meeting the feasibility (stability) constraints along a certain trajectory $D\mathbf{Y}$ in the space of controlled parameters $\mathbf{Y}$ [5 – 7]. Normally, the trajectory $D\mathbf{Y}$ is assumed to be linear and can be determined either by setting based on the preliminary calculations; or based on the condition of the shortest distance to a limiting hypersurface or according to the minimum damage caused by disconnecting power sources and consumers.

The use of DG plants makes the calculation of operating conditions meeting stability constraints relevant to the distribution networks and power supply systems. This is of special importance in electric power systems equipped with DG plants based on unconventional renewable energy sources. Such plants, as mini hydropower plants and offshore windmill farms, can be located at a distance from the load centers, which ‘narrows' the static non-oscillatory stability areas.

When set optimally, the automatic regulators of distributed generators can ensure the necessary oscillatory stability margin and quality dynamic transition in emergency and post-emergency conditions. Optimal adaptive control of DG plants in different conditions can be achieved by using advanced intelligent technologies [8 – 18].

The paper describes a DG emergency control system which, in contrast to the approaches described in [2, 5, 7], is based on determination of the post-emergency conditions that meet the stability constraints with the limit load equations and a fuzzy control system for tuning the controllers of the DG plants in emergency and post-emergency conditions that provide a qualitative dynamic transition. This makes it possible to maintain the steady-state and dynamic stability of power supply systems with distributed generators.

II. Problem statement

The emergency control is illustrated in Fig. 1, where the stability region is cut by the coordinate plane of generator active powers P_i, P_j. In this Figure, it is assumed that the stability and transmitted power limits coincide [7]. Curve 1 corresponds to the boundary of the stability region for the complete network diagram, Curve 2 corresponds to a similar boundary when one of the main transmission lines is disconnected, and curve 3 corresponds to the condition $\Im$ = const, where $\Im$ is the required value of the stability margin of the post-emergency conditions.

The aim of the emergency control application is to reach one of the points: $\mathbf{Y}_Z^{(1)}, \mathbf{Y}_Z^{(2)}, \mathbf{Y}_Z^{(3)}$

$$\mathbf{Y}_Z^{(1)} = \mathbf{Y}_0 + D\mathbf{Y}^{(1)} = \mathbf{Y}_0 + t_1\boldsymbol{\Delta}\mathbf{Y}^{(1)},$$

$$\mathbf{Y}_Z^{(2)} = \mathbf{Y}_0 + D\mathbf{Y}^{(2)} = \mathbf{Y}_0 + t_2\boldsymbol{\Delta}\mathbf{Y}^{(2)},$$

$$\mathbf{Y}_Z^{(3)} = \mathbf{Y}_0 + D\mathbf{Y}^{(3)} = \mathbf{Y}_0 + t_3\boldsymbol{\Delta}\mathbf{Y}^{(3)},$$ where $D\mathbf{Y}^{(k)},\ k = 1..3$ – the trajectories of the condition change in space **Y**; $\boldsymbol{\Delta}\mathbf{Y}^{(k)},\ k = 1..3$ – directions of the condition change; $t_k,\ k = 1..3$ – scalar parameters that determine the amount of generator power reduction in the relevant direction; index k = 1 corresponds to the direction set a priori, index k = 2 corresponds to power reduction in the direction of the normal to the limiting hypersurface, while k = 3 – corresponds to power reduction ensuring minimal possible damage caused by disconnection of power sources and consumers [5 – 7].

Power should be reduced in the chosen direction $\boldsymbol{\Delta}\mathbf{Y}^{(k)}$ with an acceptable quality of the dynamic processes, which can be achieved through the use of automatic voltage regulator (AVR) and automatic speed regulator (ASR) in the synchronous generators of DG plants. The relatively small power of DG plants and the small constant value of DG plants rotor inertia require that the mutual influence of AVR and ASR be taken into account when tuning them. It should also be noted, that the optimal control requires the adjustment of AVR and ASR settings when the operating conditions change greatly in of both DG and power supply systems.

Below are the results of the studies aimed at the

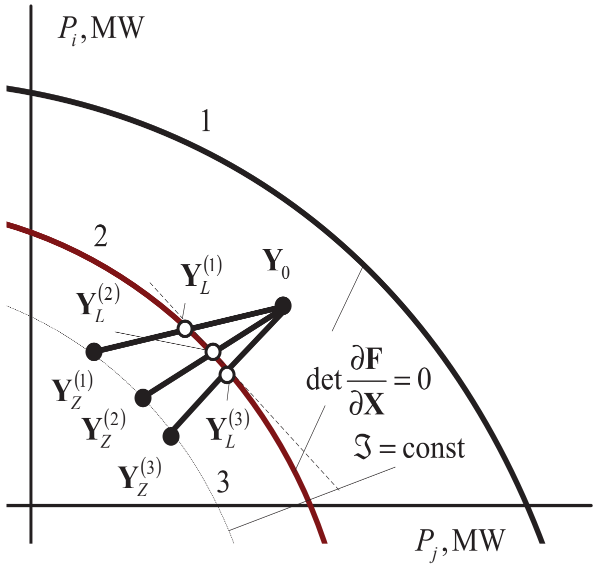


Fig. 1. Determination of post-emergency conditions meeting. stability constraints: $\frac{\partial \boldsymbol{F}}{\partial \boldsymbol{X}}$ ***– matrix of Jacobi for steady-state equations (SSE);*** $\Im$ ***– stability margin***

development of methods for determining the post-emergency operating conditions that meet the stability constraints and for ensuring a quality dynamic transition when generator power is reduced.

III. Methods for determining post-emergency operating conditions meeting stability constraints

The emergency control system of distributed generation plants is intended to ensure stable operation of generators in electric power system in post-emergency conditions, in which case the parameters of the conditions meeting the stability constraints can be determined by different methods, for instance, a method based on limit loads equations (LLE) [7, 19, 20] whose derivation is described below.

The equilibrium position of the autonomous system of differential equations $\frac{dx_i}{dt} = w_i(x_1, x_2, ..., x_n)\ \ i = \overline{1...n}$, (1) is asymptotically stable according to Lyapunov, if the linearized system (initial approximation system) is stable too:

$$\frac{dx_i}{dt} = \sum_{k=1}^{n} \left(\frac{\partial w_i}{\partial x_k} \right)_{|x_k = x_{k0}} \Delta x_k,\ i = \overline{1...n} \qquad (2)$$

where $\Delta x_k = x_k - x_{k0}$; x_{k0} – equilibrium point coordinates

satisfying the equations

$$w_i(x_{10}, x_{20}, ..., x_{n0}) = 0\ ;\ i = \overline{1...n}.$$

The linearization procedure is performed based on the expansion of functions $w_i(x_1, x_2, ..., x_n), i = \overline{1...n}$ in Taylor's series

$$w_i(x_1, x_2, \ldots, x_n) = w_i(x_{10}, x_{20}, \ldots, x_{n0}) + \sum_{k=1}^{n} \left(\frac{\partial w_i}{\partial x_k} \right)_{|\mathbf{X}=\mathbf{X}_0} \Delta x_k +$$

$$+ \frac{1}{2!} \sum_{k=1}^{n} \sum_{j=1}^{n} \left(\frac{\partial^2 w_i}{\partial x_k \partial x_j} \right) \Delta x_k \Delta x_j + \ldots$$

and rejection of nonlinear terms.

Solutions to equations (2) are stable if real parts of all roots of the standard equation are negative

$$D(p) = \det \left(\frac{\partial \mathbf{W}}{\partial \mathbf{X}} - p\mathbf{E} \right) = 0 \quad (3)$$

where $\frac{\partial \mathbf{W}}{\partial \mathbf{X}}$ the Jacobian matrix of $\mathbf{W}(\mathbf{X})$ calculated at the equilibrium point

$$\frac{\partial \mathbf{W}}{\partial \mathbf{X}} = \begin{bmatrix} \frac{\partial w_1}{\partial x_1} & \ldots & \frac{\partial w_1}{\partial x_n} \\ \ldots & \ldots & \ldots \\ \frac{\partial w_n}{\partial x_1} & \ldots & \frac{\partial w_n}{\partial x_n} \end{bmatrix}$$

$\mathbf{E} = diag1$ – an identity matrix of order n. Equilibrium will be unstable if equation (2) has at least one root with a positive real part. If there are no such roots but there are just imaginary ones, then the system of initial approximation cannot be used to judge about stability. In this case, an additional study is required.

With regard to steady states of EPS, the stability according to Lyapunov, which is called steady-state stability, is subdivided according to the nature of disturbance into non-oscillatory (aperiodic) and oscillatory stability. The first type of instability is associated with the appearance of positive real roots, while the second type – with the emergence of complex roots with a positive real part. Practical methods for determining the non-oscillatory and oscillatory stability differ from one another. Below, we analyze only the methods and criteria that are used to determine the non-oscillatory instability.

In order for the standard equation (3) that can be represented in the following expanded form with regard to p symbol

$$D(p) = p^n + a_{n-1} p^{n-1} + \ldots + a_0 = 0 \quad (4)$$

not to have real positive roots p_k, it is necessary and sufficient that all coefficients (4) be higher than zero. However, if stability limit is determined in the process of load increase with respect to initial steady state, there is no need to follow the signs of all coefficients, because the constant term α_0 of the characteristic polynomial will be the first to change the sign for negative.

Indeed, it follows from (3) and (4) that

$$a_0 = (-1)^n \det \frac{\partial \mathbf{W}}{\partial \mathbf{X}} \quad (5)$$

and $\alpha_0 = 0$ when $p_k = 0$.

Therefore, with changes in the real root value from negative to positive, the change in the sign of α_0 is inevitable. The sign control of the constant term of a characteristic polynomial is the basis for the main methods used to determine stability –limited conditions.

The electrical power system steady states are defined by non-linear equations of the type

$$\mathbf{F}(\mathbf{X}, \mathbf{Y}) = \mathbf{0} \quad (6)$$

where $\mathbf{F} = [f_1 f_2 \ldots f_n]^T$ – n-dimensional vector function, satisfying the balance equations of power or currents at network nodes; $\mathbf{Y} = [y_1 y_2 \ldots y_m]^T$ – the set vector of regulated parameters (independent variables); $\mathbf{X} = [x_1 x_2 \ldots x_n]^T$ – required vector of non-regulated parameters (dependent variables).

Active and reactive powers of generators and loads, as well as voltage magnitudes observed at some network nodes, are usually used as controlled parameters. Dependent variables are real and imaginary components or magnitudes and phases of nodal voltages. EPS frequency value can also be part of **X** dependable variables vector.

The EPS loads corresponding to the points of parameter space $\mathbf{Z} = \mathbf{X} \cup \mathbf{Y}$, at which equations (1) and condition

$$a_0 = (-1)^n \det \frac{\partial \mathbf{W}}{\partial \mathbf{X}} = 0 \quad (7)$$

are satisfied can be considered to be steady-state non-oscillatory stability-limited conditions, where **W** – n-dimensional vector function, corresponding to right-hand sides of differential equations

$$\frac{d\mathbf{X}}{dt} = \mathbf{W}(\mathbf{X}, \mathbf{Y}) \quad (8)$$

that describe transient processes in EPS for small-scale disturbances; a0 – the constant term of the characteristic polynomial $\det \left(p\mathbf{E} - \frac{\partial \mathbf{W}}{\partial \mathbf{X}} \right) = 0$

The expression for a_0 can be obtained without generation of differential equations, but immediately from steady-state equations (SSE).

$$\mathbf{W}(\mathbf{X}, \mathbf{Y}) = \mathbf{0} \quad (9)$$

written considering characteristics of the electrical system components for small-scale disturbances.

Points satisfying condition (5) form discriminant hypersurface L_W in space **Y** (Fig. 2).

The conditions can be considered to be limited by the existence (transmitted power) when they correspond to the parameter space points $\mathbf{Z} = \mathbf{X} \cup \mathbf{Y}$, at which steady-state equations (6) and the condition

$$\det \frac{\partial \mathbf{F}}{\partial \mathbf{X}} = 0 \quad (10)$$

are satisfied, where $\frac{\partial \mathbf{F}}{\partial \mathbf{X}}$ – the Jacobian matrix for the steady-state equation (6).

Points satisfying condition (10) form the discriminant hypersurface L_F in space **Y** (Fig. 2).

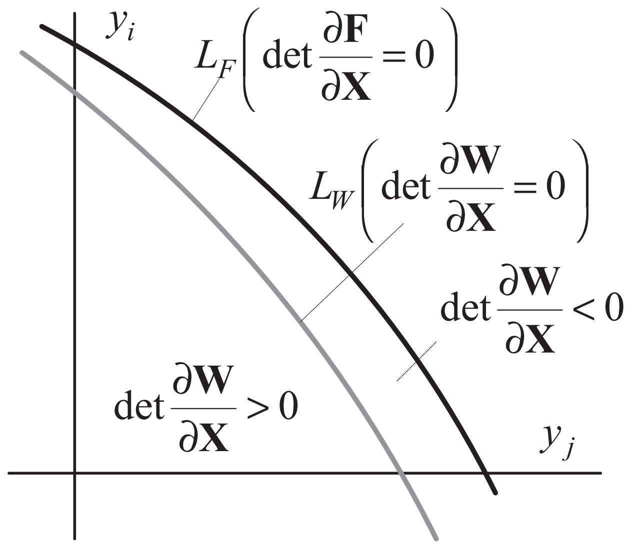


***Fig. 2. Regions of stability and existence of conditions in space of parameters* Y.**

In a general case, matrices of Jacobi $\frac{\partial \mathbf{F}}{\partial \mathbf{X}}$ that are used to determine steady-state parameters, and matrices $\frac{\partial \mathbf{W}}{\partial \mathbf{X}}$ that are used for stability analysis can fail to coincide for the following reasons:

1. Steady-state equations (6) can be written for various assumptions and in various forms, which, in the general case, do not coincide with those made to write differential equations (8).
2. Based on the assumption that astatic control of voltage U_G at generator buses is performed by changing the settings of automatic voltage regulators, the magnitude of U_G for calculations of operating conditions is normally assumed to be given. If such a control is performed by dispatcher discretely, then the supposition on voltage stability at generator buses, which is quite admissible for the calculation of operating conditions, will be unsatisfactory for the determination of stability. In this case, it would be more correct to assume generator electromotive force to be constant with some reactance determined depending on type and values of AVR amplification factors or to fully take into account the mathematical formulation of the excitation control law. In the case of sufficiently high AVR amplification factors, both methods of generator modeling lead to the same results.
3. When the substations that power the consumer have transformers with on-load voltage regulation, the load power can be considered constant in the calculations of operating conditions. Contrastingly, in an analysis of stability, the load power should be assumed to be changeable as per static characteristics, because the said control is of discrete nature and does not work in the case of small-scale disturbances.

An analysis carried out in [7] shows that despite the development of a number of effective algorithms, the problem of express calculation of operating conditions that are limiting in terms of their static stability and transmitted power remains relevant. The technique for determining the limiting conditions, which does not require multi-step computational procedures, which is applicable whether or not the transmitted power and stability limits coincide, and which allows avoiding the difficulties in solving ill-conditioned systems, can be implemented on the basis of the LLE and their generalizations [7, 19, 20].

This technique is based on the replacement of condition (5) with an equivalent ratio which can be represented in two ways:

$$\mathbf{VS}=\frac{\partial \mathbf{W}}{\partial \mathbf{X}}\mathbf{S}=\mathbf{0} \tag{11}$$

$$\mathbf{VR}=\left(\frac{\partial \mathbf{W}}{\partial \mathbf{X}}\right)^T\mathbf{R}=\mathbf{0} \tag{12}$$

where **VS**, **VR** – n-dimensional vector functions; $\mathbf{S}=[s_1 \;\; s_2 \;\; \ldots \;\; s_n]^T$; $\mathbf{R}=[r_1 \;\; r_2 \;\; \ldots \;\; r_n]^T$ – respectively, eigenvectors of matrices $\frac{\partial \mathbf{W}}{\partial \mathbf{X}},\left(\frac{\partial \mathbf{W}}{\partial \mathbf{X}}\right)^T$ that satisfy zero eigenvalues.

Since (11) and (12) define the eigenvectors to the accuracy of constant factor, one of their components can be assumed to be arbitrary, different from zero. For example, $r_n=s_n=1$. Another way for the extension of definition for equations (11) and (12) is to set a length, for example, unit length for vectors R and S, that is, to supplement these systems with the equations: $U(\mathbf{S})=\mathbf{S}^T\mathbf{S}-1=0$ or $U(\mathbf{R})=\mathbf{R}^T\mathbf{R}-1=0$

The Jacobian matrices elements are the functions of dependable parameters X. Consequently, unlike (7), conditions (11) and (12) allow an analytical description of hypersurface LW of limiting conditions.

Determination of static stability-limited conditions is reduced to simultaneously solving the sets of equations which can be represented in two ways

$$\left.\begin{aligned}&\mathbf{F}[\mathbf{X},\mathbf{Y}(T)]=\mathbf{0};\\&\mathbf{VS}[\mathbf{X},\mathbf{S},\mathbf{Y}(T)]=\frac{\partial \mathbf{W}}{\partial \mathbf{X}}\mathbf{S}=\mathbf{0};\\&U(\mathbf{S})=\mathbf{S}^T\mathbf{S}-1=0.\end{aligned}\right\} \tag{13}$$

or

$$\left.\begin{aligned}&\mathbf{F}[\mathbf{X},\mathbf{Y}(t)]=\mathbf{0},\\&\mathbf{VR}[\mathbf{X},\mathbf{R},\mathbf{Y}(t)]=\left(\frac{\partial \mathbf{W}}{\partial \mathbf{X}}\right)^T\mathbf{R}=\mathbf{0},\\&U(\mathbf{R})=\mathbf{R}^T\mathbf{R}-1=0,\end{aligned}\right\} \tag{14}$$

where **F** – ℓ-dimensional vector function satisfying steady-state equations; **X** – ℓ-dimensional vector of uncontrolled parameters; $\mathbf{Y}$ – m-dimensional vector of controlled parameters; $\mathbf{Y}(t)=\mathbf{Y}_0+t\Delta\mathbf{Y}$; $\mathbf{Y}_0$ – the value of vector of controlled parameters in the initial (pre-emergence) conditions; $\mathbf{R}$ – eigenvector of matrix $\left(\frac{\partial \mathbf{W}}{\partial \mathbf{X}}\right)^T$ satisfying zero eigenvalue. In the case where the limits of stability and transmitted power coincide, matrix $\frac{\partial \mathbf{F}}{\partial \mathbf{X}}$ is used instead of matrix $\frac{\partial \mathbf{W}}{\partial \mathbf{X}}$.

Systems (13) and (14) are equivalent, however, in equations (14), eigenvector $\mathbf{R}$, which coincides with the direction of normal to hypersurface $L_{W,}$ is used. This makes it possible to generalize the limit load equations for the case of their search in the most dangerous (critical) direction of load increase that corresponds to the shortest distance in the metrics of normalized independent variables from the point of the considered conditions to the limit hypersurface, and thus to obtain an objective estimate for the static non-oscillatory stability margin. For this reason, below, the equations of limit loads are considered in the form of (14). Multiple calculation experiments [7] show that equations (14) can be used to calculate the operating conditions of an electric power system to reach the boundary of the stability region: the point $\mathbf{Y}_L^{(1)}$ (Fig. 1). To achieve the required stability margin, power should be additionally reduced in the direction of $\Delta\mathbf{Y}^{(1)}$ (point $\mathbf{Y}_Z^{(1)}$) or in the direction of vector R, Fig. 3.

It is worth noting that the two-stage procedure refers only to the algorithm of determining the point $\mathbf{Y}_Z^{(\mathbf{R})}$, whereas dynamic transition is performed directly from point $\mathbf{Y}_0$ to point $\mathbf{Y}_Z^{(\mathbf{R})}$, .

The post-emergency conditions meeting the stability constraints can be calculated with respect to the shortest path by modifying the limit load equations, which is indented to search for the limit load in the critical direction of load increase [7, 20]. Provided the limits of stability and transmitted power coincide, this problem can be formulated as follows:

Find

$$\Im_{min}=\min\left(\mathrm{D}\mathbf{Y}^{\mathrm{T}}\mathbf{M}^2\mathrm{D}\mathbf{Y}\right)^{\frac{1}{2}} \tag{15}$$

subject to

$$\mathbf{F}(\mathbf{X},\mathbf{Y}_0+D\mathbf{Y})=\mathbf{0} \tag{16}$$

where $\mathbf{Y}_0$ – vector of controlled parameters in the initial (pre-emergence) conditions; $D\mathbf{Y}=[dy_1\ dy_2\ ...\ dy_n]^T$ – incremental vector of variables $\mathbf{Y}_0$ which ensure that the operating conditions attain the hypersurface L_F; $\mathbf{M}=\mathrm{diag}\boldsymbol{\mu}_i,\boldsymbol{\mu}_i$ – scaling factors.

To solve the formulated problem (assuming that the limits of stability and the transmitted power coincide), the Lagrange function is written as follows

$$L(\mathbf{X},\mathbf{Y}_0+D\mathbf{Y},\boldsymbol{\Lambda})=\left(D\mathbf{Y}^{\mathrm{T}}\mathbf{M}^2D\mathbf{Y}\right)^{\frac{1}{2}}+\mathbf{F}^T(\mathbf{X},\mathbf{Y}_0+D\mathbf{Y})\boldsymbol{\Lambda}$$

where $\boldsymbol{\Lambda}$ – the undetermined multiplier vector.

The L minimum corresponds to the conditions

$$\begin{aligned}
&\frac{\partial L}{\partial D\mathbf{Y}}=\mathbf{M}^2D\mathbf{Y}\left(D\mathbf{Y}^{\mathrm{T}}\mathbf{M}^2D\mathbf{Y}\right)^{-\frac{1}{2}}+\left(\frac{\partial \mathbf{F}}{\partial D\mathbf{Y}}\right)^T\boldsymbol{\Lambda}=\mathbf{0}\\
&\frac{\partial L}{\partial \mathbf{X}}=\left(\frac{\partial \mathbf{F}}{\partial \mathbf{X}}\right)^T\boldsymbol{\Lambda}=\mathbf{0};\\
&\frac{\partial L}{\partial \boldsymbol{\Lambda}}=\mathbf{F}(\mathbf{X},\mathbf{Y}_0+D\mathbf{Y})=\mathbf{0}.
\end{aligned} \tag{17}$$

The first equation of the system corresponds to the shortest distance $\Im_{min}$ from the point $\mathbf{Y}_0$ to hypersurface L_F in metrics set by $\mathbf{M}$ matrix. The second equation of the system ensures that the operating conditions correspond to the hypersurface $\Im_{min}$ for non-zero $\boldsymbol{\Lambda}$. The third equation of the system corresponds to the balanced operating conditions.

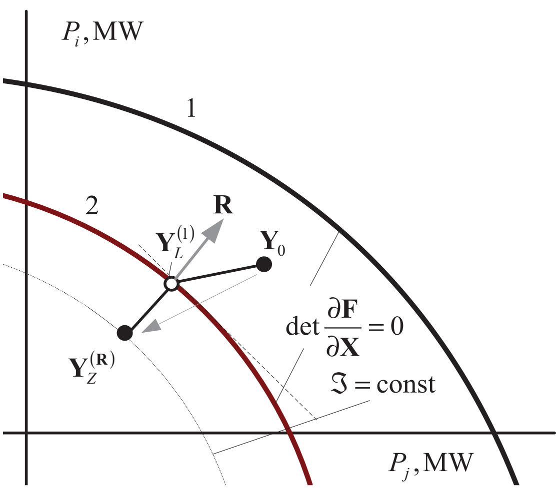


***Fig. 3. Additional power reduction in the direction of vector* R.**

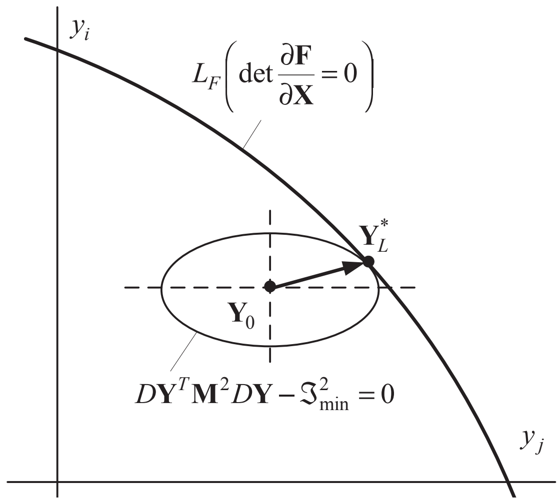


Fig. 4. Geometrical interpretation of search for a critical direction of load increase.

Geometrically, the solution to system (17) is the contact point of hypersurface L_F and ellipsoid with the center at point $\mathbf{Y}_0$ (Fig. 4), defined by the equation:

Geometrically, the solution to system (17) is the contact point of hypersurface and ellipsoid with the center at point (Fig. 4), defined by the equation: $D\mathbf{Y}^T\mathbf{M}^2 D\mathbf{Y} - \Im^2_{\min} = 0$

Equations (17) can be represented as follows:

$$\frac{\partial L}{\partial D\mathbf{Y}} = \mathbf{M}^2 D\mathbf{Y} + \left(\frac{\partial \mathbf{F}}{\partial D\mathbf{Y}}\right)^T \mathbf{\Lambda}\left(D\mathbf{Y}^T\mathbf{M}^2 D\mathbf{Y}\right)^{\frac{1}{2}} = \mathbf{0}$$

$$\frac{\partial L}{\partial \mathbf{X}} = \left(\frac{\partial \mathbf{F}}{\partial \mathbf{X}}\right)^T \mathbf{\Lambda} = \mathbf{0}$$

$$\frac{\partial L}{\partial D\mathbf{Y}} = \mathbf{F}\left(\mathbf{X}, \mathbf{Y}_0 + D\mathbf{Y}\right) = \mathbf{0}$$

Vector $\mathbf{\Lambda}$ is determined with the accuracy of the multiplier, consequently the variables can be replaced

$$\mathbf{R} = \Im_{\min}\mathbf{\Lambda} = \mathbf{\Lambda}\left(D\mathbf{Y}^T\mathbf{M}^2 D\mathbf{Y}\right)^{\frac{1}{2}}$$

then

$$\frac{\partial L}{\partial D\mathbf{Y}} = \mathbf{M}^2 D\mathbf{Y} + \left(\frac{\partial \mathbf{F}}{\partial D\mathbf{Y}}\right)^T \mathbf{R} = \mathbf{0}$$

$$\frac{\partial L}{\partial \mathbf{X}} = \left(\frac{\partial \mathbf{F}}{\partial \mathbf{X}}\right)^T \mathbf{R} = \mathbf{0}$$

$$\frac{\partial L}{\partial D\mathbf{Y}} = \mathbf{F}\left(\mathbf{X}, \mathbf{Y}_0 + D\mathbf{Y}\right) = \mathbf{0}$$

After determining from the first equation

$$D\mathbf{Y} = -\mathbf{M}^{-2}\left(\frac{\partial \mathbf{F}}{\partial D\mathbf{Y}}\right)^T \mathbf{R}$$

and after substituting it in the third equation, we can obtain a system representing the modification of the limit load equation which makes it possible to calculate the post-emergency conditions meeting the stability constraints based on the shortest path:

$$\left.\begin{aligned} &\mathbf{F}\left(\mathbf{X}, \mathbf{Y}_0 - \mathbf{M}^{-2}\left(\frac{\partial \mathbf{F}}{\partial D\mathbf{Y}}\right)^T \mathbf{R}\right) = \mathbf{0}; \\ &\mathbf{VR}(\mathbf{X}, \mathbf{R}) = \left(\frac{\partial \mathbf{F}}{\partial \mathbf{X}}\right)^T \mathbf{R} = \mathbf{0}. \end{aligned}\right\} \quad (18)$$

If vector components $D\mathbf{Y}$ belong to the first group of equations (18) linearly, then $\left(\frac{\partial \mathbf{F}}{\partial D\mathbf{Y}}\right)^T = \mathbf{E}$

This takes place when steady-state equations written in a Cartesian coordinate system can be represented as:

$$f_{2i\text{-}1}(\mathbf{X}, \mathbf{Y}) = P_{i0} + dP_i - P_{ci}\left(U_1' U_1'' \ldots U_p' U_p''\right) = 0;$$

$$f_{2i}(\mathbf{X}, \mathbf{Y}) = Q_{i0} + dQ_i - Q_{ci}\left(U_1' U_1'' \ldots U_p' U_p''\right) = 0,$$

where $P_{i0,}$ Q_{i0} – power injections in the initial conditions; U_i', U_i' – real and imaginary components of nodal voltage; dP_i, dQ_i – vector components $D\mathbf{Y}$; p – the number of network nodes except for the slack node. With an implicit $\mathbf{X}$ dependence of $\mathbf{Y}$, the $\left(\frac{\partial \mathbf{F}}{\partial D\mathbf{Y}}\right)^T$ matrix is block-diagonal and its elements are determined by the formulas given in [7].

When Newton's method is used to solve equations (18), the following system of linear equations is solved at each iteration:

$$\begin{bmatrix} \frac{\partial \mathbf{F}}{\partial \mathbf{X}} & \frac{\partial \mathbf{F}}{\partial \mathbf{R}} \\ \frac{\partial \mathbf{VR}}{\partial \mathbf{X}} & \frac{\partial \mathbf{VR}}{\partial \mathbf{R}} \end{bmatrix} \begin{bmatrix} \Delta\mathbf{X} \\ \Delta\mathbf{R} \end{bmatrix} = -\begin{bmatrix} \mathbf{F} \\ \mathbf{VR} \end{bmatrix}$$

where $\frac{\partial \mathbf{F}}{\partial \mathbf{R}} = \mathbf{M}^{-2}\left(\frac{\partial \mathbf{F}}{\partial D\mathbf{Y}}\right)^T$; . $\frac{\partial \mathbf{VR}}{\partial \mathbf{R}} = \left(\frac{\partial \mathbf{F}}{\partial \mathbf{X}}\right)^T$

Modeling shows that based on equations (18), the electric power system operating conditions can be calculated to meet the boundary stability constraint using the shortest path: the point $\mathbf{Y}_L^{(2)}$ (Fig. 1). To achieve the required margin, power should be additionally reduced.

In some cases of using equations 14 or 18, however, the ‘remote boundary’ of the stability region can be achieved [21], i.e. the point $\mathbf{Y}_L^{(db)}$ in Fig. 5. In this case, the obtained solution differs in the inversion of power injection signs, and cannot be used in practice.

An effective method to cope with the ‘remote boundary’ problem can be implemented based on starting algorithms, which employ special methods of solving the steady-state equations [19, 22].

The starting algorithm, in particular, can be based on V.A. Matveev method whose iterative formula has the form

$$\mathbf{X}^{(k+1)} = \mathbf{X}^{(k)} - \lambda^{(k)}\left[\frac{\partial \mathbf{F}}{\partial \mathbf{X}}\left(\mathbf{X}^{(k)}\right)\right]^{-1} \mathbf{F}\left(\mathbf{X}^{(k)}\right) \quad (19)$$

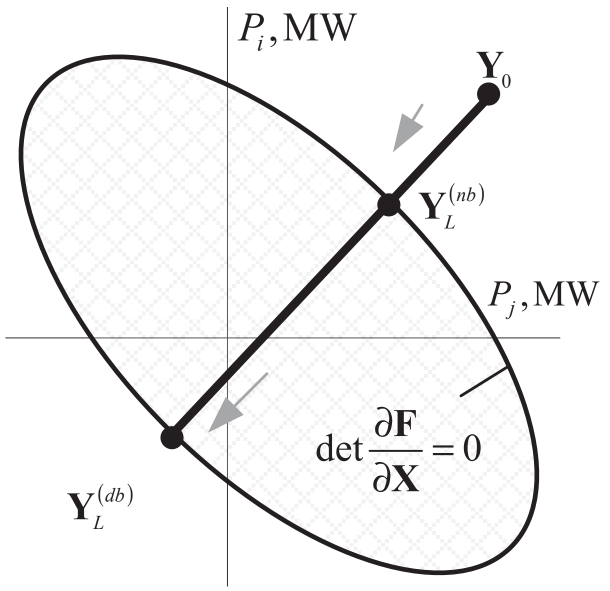


Fig. 5. To the problem of the ‘remote boundary’ of the stability region.

where $\lambda^{(k)}$ – an adjusting factor, determined by the expression

$$\lambda^k = \begin{cases} \frac{1}{B_k}, if\ B_k > 1 \\ 1, if\ B_k \le 1 \end{cases}$$

$$B_k = \frac{1}{2\max\left|\mathbf{F}\left(\mathbf{X}^{(k)}\right)\right|}\max\left|\sum_{(i)}\sum_{(j)}\frac{\partial^2 f_i\left(\mathbf{X}^{(k)}\right)}{\partial x_i \partial x_j}\Delta x_j^{(k)}\Delta x_i^{(k)}\right|$$

The second multiplier for B_k is the maximum absolute value of the vector component obtained by multiplying the matrix of the second derivatives of vector-function **F(X)** by the elements of correction vector $\mathbf{\Delta X}$ that are determined at the *k*-th iteration. The iterative procedure (19) ensures the convergence of the computational process for any existing conditions, while when nonexistent conditions are calculated, the calculation process "hangs" at the point of the limiting hypersurface, where the Jacobian of the system of steady-state equations equals zero.

Another starting algorithm can be implemented based on the computational methods [19], which additionally take into account the higher-order terms of the Taylor series expansion of the vector-function $\mathbf{X} = \mathbf{\Phi}(\mathbf{Y})$ inverse to **F(X)**.

Based on the expansion, X is represented as

$$\mathbf{X} = \mathbf{X}_0 + \Delta\mathbf{X}_1(\Delta\mathbf{F}) + \Delta\mathbf{X}_2\left(\Delta\mathbf{F}^2\right) + \ldots + \Delta\mathbf{X}_k\left(\Delta\mathbf{F}^k\right) + \ldots$$

where $\Delta\mathbf{X}_k\left(\Delta\mathbf{F}^r\right)$ – correction vectors, depending on products of vector components

$$\Delta\mathbf{F} = \mathbf{F}(\mathbf{X}) - \mathbf{F}(\mathbf{X}_0) \quad (20)$$

with the sum of powers equal to r. Besides, at the point of solution , it is necessary to assume $\Delta\mathbf{F} = -\mathbf{F}(\mathbf{X}_0)$.

Corrections $\Delta\mathbf{X}_p$ are calculated using the recurrent expressions:

$$\mathbf{\Delta X}_1^{(k)} = -\left[\frac{\partial\mathbf{F}}{\partial\mathbf{X}}\left(\mathbf{X}^{(k)}\right)\right]^{-1}\mathbf{F}\left(\mathbf{X}^{(k)}\right)$$

$$\mathbf{\Delta X}_2^{(k)} = \left[\frac{\partial\mathbf{F}}{\partial\mathbf{X}}\left(\mathbf{X}^{(k)}\right)\right]^{-1}\mathbf{B}_2^{(k)}$$

$$\mathbf{\Delta X}_3^{(k)} = \left[\frac{d\mathbf{F}}{d\mathbf{X}}\left(\mathbf{X}^{(k)}\right)\right]^{-1}\mathbf{B}_3^{(k)}$$

where k – iteration number; $\Delta\mathbf{X}_r^{(k)}$ – vector of r-th corrections; r = 1...3.

Components of vectors

$$\mathbf{B}_r^{(k)} = \left[b_{r1}^{(k)} \quad b_{r2}^{(k)} \quad \ldots \quad b_{ri}^{(k)} \quad \ldots \quad b_{rn}^{(k)}\right]^T,$$

which are parts of expressions for the second and third corrections, are calculated using the formula

$$b_{2i}^{(k)} = \left[\Delta\mathbf{X}_1^{(k)}\right]^T \mathbf{\Gamma}_i^{(k)}\Delta\mathbf{X}_1^{(k)};\ b_{3i}^{(k)} = \left[\Delta\mathbf{X}_1^{(k)}\right]^T \mathbf{\Gamma}_i^{(k)}\Delta\mathbf{X}_2^{(k)},$$

where $\mathbf{\Gamma}_i^{(k)}$ – Hessian matrix of the function $f_i(\mathbf{X})$, calculated at the point $\mathbf{X}^{(k)}$.

The first correction coincides with the one determined by Newton's method and corresponds to the linear approximation of **X** from **ΔF**. The second and subsequent corrections correspond to the approximation of **X** with polynomials of a higher degree, hence the acceleration of the iteration process when the number of considered corrections increases.

In the presented form, the method under consideration, due to the poor convergence of the series

$$\mathbf{X}^{(k)} = \mathbf{X}_0 + \sum_r \Delta\mathbf{X}_r$$

with the initial approximations chosen 'far' from the solution, gives a less reliable calculation of 'heavy' loads than Newton's method. An increase in the reliability of the method is associated with the improvement in the convergence of the indicated series, and to this end, the correction factors are introduced as follows. Instead of search for the point of the solution $\mathbf{X}_p$, where $\mathbf{F}(\mathbf{X}_p) = \mathbf{0}$, we determine an intermediate point $\mathbf{X}^*$ with the value of the function of residuals

$$\mathbf{F}\left(\mathbf{X}^*\right) = (1-\alpha)\mathbf{F}(\mathbf{X}_0),\ \alpha < 1$$

Substitution

$$\Delta\mathbf{F} = \mathbf{F}\left(\mathbf{X}^*\right) - \mathbf{F}(\mathbf{X}_0) = -\alpha\mathbf{F}(\mathbf{X}_0)$$

in (20) indicates that the introduction of adjusting factors changes the corrections by α^r times, where r – the correction number.

Thus, $\mathbf{X}^* = \mathbf{X}_0 + \sum_r \alpha^r \Delta\mathbf{X}_r$.

Enumeration of α can always provide convergence of the series, and when the intermediate point $\mathbf{X}^*$ is found, one can start searching for a solution $\mathbf{X}_p$ or the next intermediate point, if the series converges unsatisfactorily. As a result, we will either obtain a solution or the search process will 'hang' at some limit point $\mathbf{X}_L$, if there is no solution. The latter manifests itself in that the coefficients α, ensuring the convergence of the intermediate series, start tending to zero, while the sequence of intermediate points tend to point $\mathbf{X}_L$, where the Jacobian of steady-state equation vanishes.

Reliable convergence of the series is ensured when α is chosen by the condition

$$\alpha = \sqrt{\beta\frac{\left\|\Delta\mathbf{X}_1^{(k)}\right\|}{\left\|\Delta\mathbf{X}_p^{(k)}\right\|}}$$

where $0<\beta<1$ – the coefficient ensuring a set speed of the series convergence;

$$\left\|\Delta\mathbf{X}_1^{(k)}\right\|=\left\{\sum_{i=1}^{n}\left[\Delta\mathbf{X}_{1i}^{(k)}\right]^2\right\}^{\frac{1}{2}}\ ;\ \left\|\Delta\mathbf{X}_p^{(k)}\right\|=\left\{\sum_{i=1}^{n}\left[\Delta\mathbf{X}_{pi}^{(k)}\right]^2\right\}^{\frac{1}{2}}$$

– norms of the vectors of the first and higher-order corrections.

The next approximation of the vector of dependable variables is calculated as follows:

$$\mathbf{X}^{(k)}=\mathbf{X}^{(k)}+\sum_{r=1}^{p}\frac{1}{r!}\alpha^r\Delta\mathbf{X}_r^{(k)}.$$

A large group of starting algorithms can be implemented using the steady-state equation solving methods based on the minimization of residual vector norm [22]. Computational experiments indicate that when the starting algorithms are used, high accuracy is not required, it is sufficient to obtain approximated values lying in a wide neighborhood of the desired solution.

The use of X parameters calculated using the starting algorithms as initial approximations when solving equations 14 or 18, ensures reliable convergence to the required points $\mathbf{Y}_L^{(nb)}$, lying on the 'near' boundaries of the stability region (Fig. 5).

In [7], the authors propose the equations which can be used to determine the limit conditions satisfying extreme values of functionals that depend on controlled and non-controlled operating parameters. These equations can be used to implement a technique of selecting optimal control actions of emergency control equipment that will provide the minimal damage caused by generator tripping and load shedding to perform the emergency control actions. It is also possible to take into account the damage due to variations in voltage at the nodal points of the network and frequency in the electric power system. A distinctive feature of the proposed technique of choosing optimal control actions is the absence of multi-step optimization procedures and numerical differentiation. The search for the optimal solution is carried out by solving a system of equations with quadratic nonlinearity using Newton's method.

IV. Dynamic transition in the case of reduction in generator power

A qualitative dynamic transition during the reduction in power of synchronous generators can be performed based on the optimal tuning of AVR and ASR [9, 12]. In this case, the coordinated tuning of AVR and ASR becomes particularly important, which is associated with the relatively low power of distributed generators and low inertia constant of their rotors. The principle of harmonized tuning implies the determination of optimal tuning factors for AVR and ASR which ensure minimal voltage and frequency deviations from the set values, as well as high damping properties during electrical transient processes, which is confirmed by the studies performed on simulation models of EPS with DG plants [9, 12, 13, 18].

The AVR and ASR settings are harmonized in two steps [9]: identification of 'turbine-generator' model based on the experimental data using wavelet transform; search for optimal setting of regulators using genetic algorithm [9–12] and determination of the oscillatory stability margin.

For identification, a model of the closed-loop system of the DG plant control is built using the experimental data. To this end, apriori information is used to determine numeric values of complex transfer factors of the DG plant transfer function matrix, as a relation of spectrums of relevant output and input signals of the closed-loop 'turbine-generator' system (Fig.6).

The characteristic polynomial of the considered system is determined using the following expression:

$$D^M(j\omega)=\det\left[\mathbf{E}+\mathbf{W}_G(j\omega)\cdot\mathbf{W}_R(j\omega)\right] \quad (21)$$

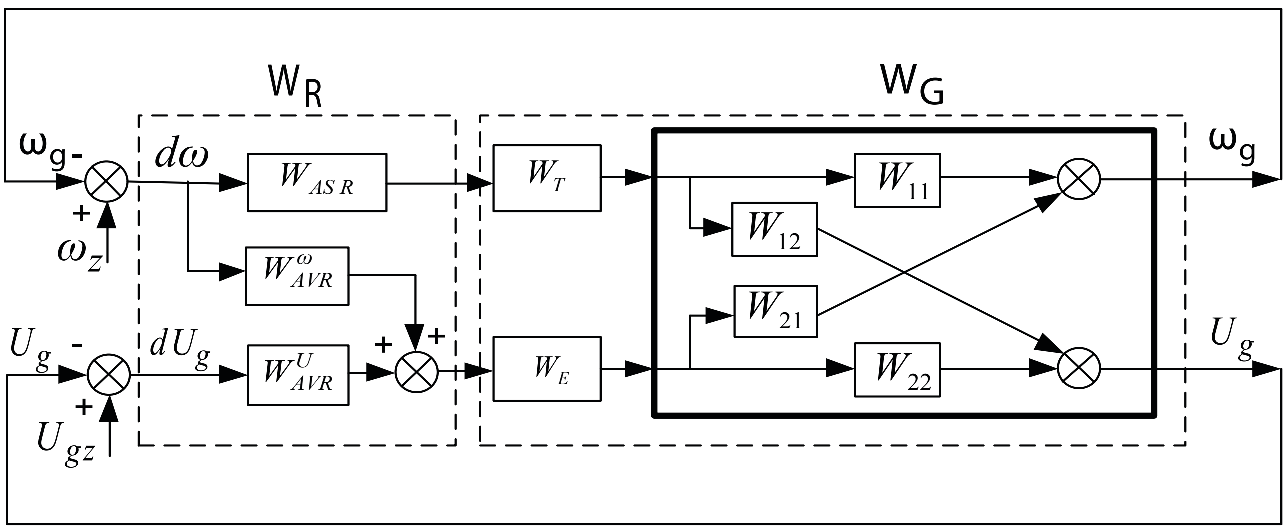


Fig. 6. The 'turbine-generator' system structural diagram: W_T ***– complex turbine gear ratio;*** W_E ***– complex exciter gear ratio.***

where $\mathbf{W}_G(j\omega)$ – matrix transfer function of the controlled object ('turbine-generator' system), which is determined experimentally; $\mathbf{W}_R(j\omega)$ – regulator matrix transfer function that takes into account relationship between AVR and ASR, and includes the required tuning coefficients:

$$\mathbf{W}_R(j\omega)=\begin{bmatrix} W_{ASR}(j\omega) & W_{AVR}^{\omega}(j\omega) \\ 0 & W_{AVR}^{U}(j\omega) \end{bmatrix};$$ $W_{ASR}(j\omega)$ – ASR complex transfer factor; $W_{AVR}^{\omega}(j\omega)$ – complex transfer factor for frequency-tuned AVR channel; $W_{AVR}^{\omega}(j\omega)$ – complex transfer factor for AVR voltage-tuned channel.

Experimental determination of DG plant matrix transfer function allows taking into account the influence of other DG plants and relation with EPS in possible steady-state conditions of the power supply system.

An approach is proposed to obtain accurate complex transfer factors of the DG plant. In this approach, the testing effect occurs on the basis of the regulator noise [9] detected using the wavelet transform. The technique of regulator noise detection with wavelet transform includes the following steps:

1. Select a basic wavelet and decomposition level N; perform wavelet decomposition of signal $f(t)$ to level N;
2. Set a threshold for each level and process the detail coefficients;
3. Reconstruct wavelet by using initial approximating factors of level N and modified detail coefficients of levels 1... N;

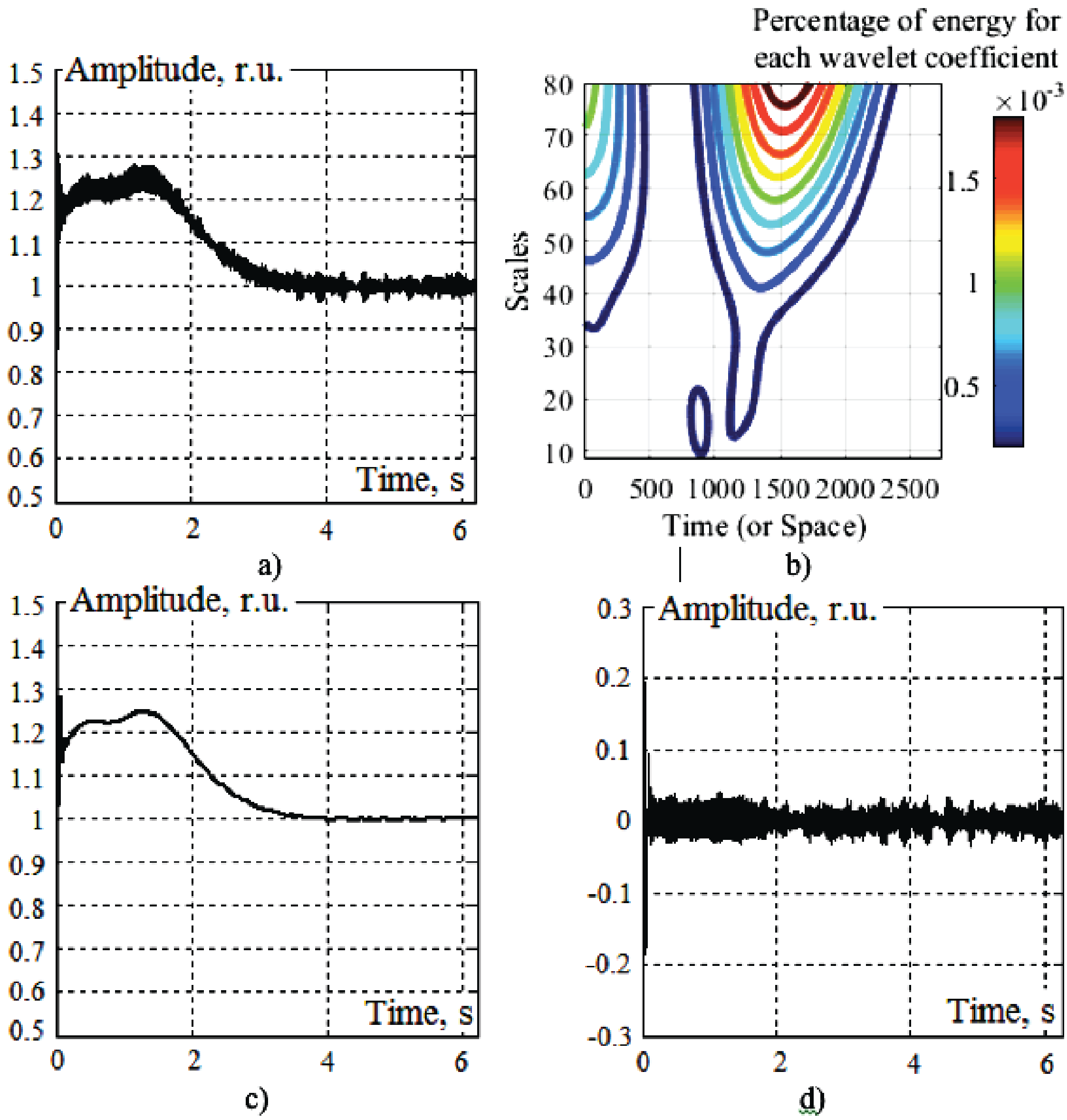


Fig. 7. Regulator noise detection using wavelet transform technology: a) initial regulator signal with noise; b) scaling-gram of the initial regulator signal with noise; c) the detected useful signal; d) regulator noise.

4. Detect signal noise used for identification: $f_v(t) = f(t) - f_w(t)$, where $f_w(t)$ – useful signal component obtained with the wavelet transform; $f_v(t)$ – noise.

Figure 7 shows the effectiveness of wavelet transform technology for detection of regulator noise when used for identification: initial regulator signal containing noise; scalinggram of the initial noisy regulator signal, whose uneven lines are indicative of the noise presence; the detected useful signal and regulator noise. Daubechies [23] wavelet was used as a basic one.

The AVR and ASR settings of DG plant generator are optimized using the genetic algorithm (GA) with the following quadratic criterion [9]:

$$J = \int_0^{\Omega} e^2(j\omega)d\omega \to \min \tag{22}$$

where $e(j\omega) = D^D(j\omega) - D^M(j\omega)$ – mismatch between the desired set of values $D^D(j\omega)$ and model set $D^M(j\omega)$ of characteristic polynomials; ω – actual frequency value from a range [0; Ω] determined by the system 'bandwidth'. Newton's or Butterworth polynomials can be used as desired polynomials.

Optimization criterion (22) has a large number of local extrema, consequently, it is advisable to use the genetic algorithm to search for a global minimum in the presented task. This algorithm represents an optimum search technique based on the mechanisms of natural selection and inheritance. The main idea of GA was first proposed by J. Holland in 1975 [24]. This idea was further developed in the works by his followers: Goldberg and de Jong [25, 26].

Because the mismatch value $e(j\omega) = \mathrm{Re}(\omega) + j\mathrm{Im}(\omega)$ is a complex one, it is difficult to minimize functional (22). Therefore, it is advisable to use linear convolution:

$$J = \frac{1}{2}J_{\mathrm{Re}} + \frac{1}{2}J_{\mathrm{Im}} \to \min \tag{23}$$

where J_{Re}, J_{Im} – criteria satisfying the proximity of hodographs in the regions of real and imaginary values. These criteria are formed as follows:

$$J_{\mathrm{Re}} = \int_0^{\Omega} \left(\mathrm{Re}D^D(\omega) - \mathrm{Re}D^M(\omega) \right)^2 d\omega \tag{24}$$

$$J_{\mathrm{Im}} = \int_0^{\Omega} \left(\mathrm{Im}D^D(\omega) - \mathrm{Im}D^M(\omega) \right)^2 d\omega \tag{25}$$

Characteristic hodograph of system (21) with determined AVR and ASR tuning coefficients allows judging on stability and other dynamic properties in a limited frequency range. In particular, the stability of distributed generators can be estimated with respect to the rate of change in the phase of characteristic hodograph (21) using the curve analysis method [27] proposed by Bushuev V.V.:

$$V(\omega) = \left[\frac{d\varphi_D(\omega)}{d\omega} \right]^{-1} \tag{26}$$

where $\varphi_D(\omega)$ – phase-frequency characteristic determined by the system frequency hodograph.

When frequency ω_P reflects the equivalent frequency of system self-oscillations, characteristic (26) determines the real part of some equivalent root, which can be used to assess the extent to which the system is stable.

The method of harmonized AVR and ASR tuning allows determining the optimal tuning coefficients of regulators for different operating conditions of the power system and forming a basis of rules for the fuzzy control system. To this end, the use of an auto-tuning unit with the modules of operating condition identification and harmonized tuning of regulators is proposed. Figure 8 shows a block diagram of the proposed fuzzy control system.

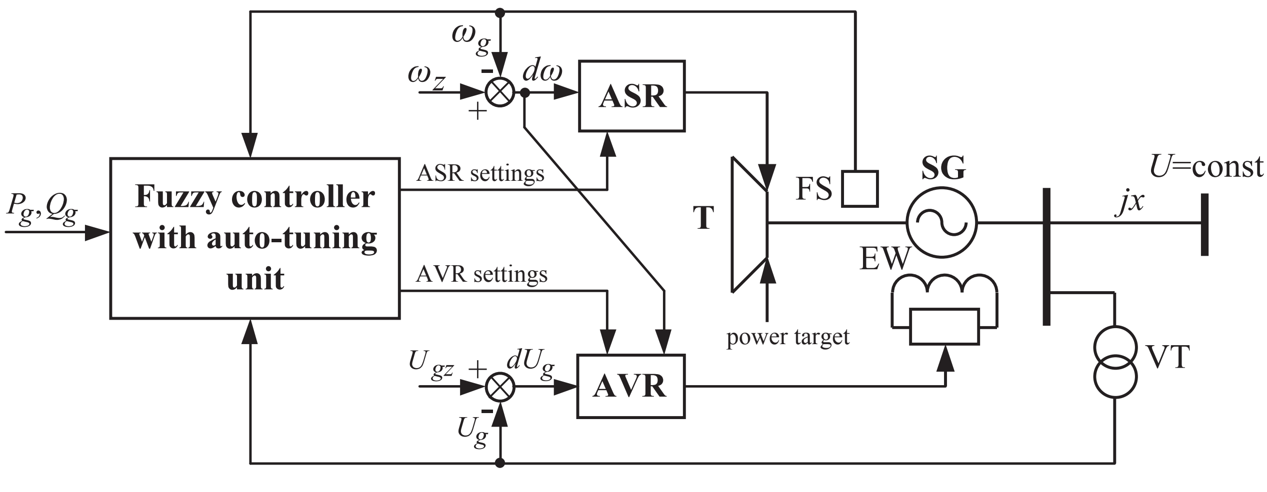


Fig. 8. Structural scheme of the fuzzy control system of AVR and ASR of the DG plant: FS - frequency sensor; EW - excitation winding; SG - synchronous generator; T - turbine; VT - voltage transformer.

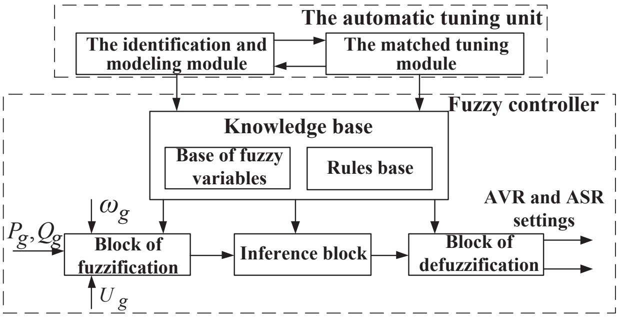


Fig. 9. The block diagram of the fuzzy control system with self-tuning unit.

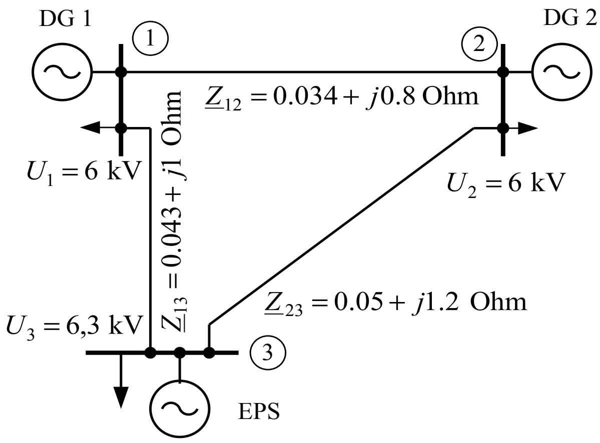


Fig. 10. Diagram of the considered power system.

The input parameters of the fuzzy control system are the actual values of voltage U_g, rotor speed ω_g, and powers P_g,Q_g of DG plant. The fuzzy control system determines AVR and ASR tuning coefficients that are optimal for a current condition. This system with a self-tuning unit is a system of fuzzy logic inference with modules of identification and harmonized tuning of AVR and ASR (Fig.9) [12, 13]. The self-tuning unit consists of an identification and modeling module and a module of harmonized tuning which allow it to form a knowledge base for the fuzzy control system of AVR and ASR settings in different operating conditions of the DG plant.

V. The modeling results

Modeling was carried out for the power system shown in Fig. 10. In the power system in question, there are two mini hydropower plants with a capacity of 24 MW each, operating for the industrial lumped load (timber processing facilities) connected at nodes 1 and 2. The facilities operate in one shift, and in the evening peak hours in the EPS, each generator supplies 15 MW to the receiving system (node 3). The network is implemented via flexible symmetrical electrical pathways [28]. Tripping of line 1-3 was considered as an emergency condition.

The post-emergency conditions meeting the stability constraints using the set and shortest paths that are calculated with equations (14) and (18) are shown in Fig.11. The initial loading condition of the DG plant generators is represented by a point with coordinates $\mathbf{Y}^0 = [20 \quad 20]^T$; the calculation of the operating conditions meeting the stability constraints using the set path is represented by point $\mathbf{Y}_{L1} = [12{,}9 \quad 20]^T$, and with the shortest path – $\mathbf{Y}_{L2} = [16{,}56 \quad 16{,}45]^T$; additional reduction in generator power that ensures the necessary stability margin corresponds to the points $\mathbf{Y}_{Z1} = [10{,}8 \quad 17{,}85]^T$; $\mathbf{Y}_{Z2} = [10{,}8 \quad 17{,}85]^T$ (Fig. 11).

The multiple computer-aided experiments indicate that

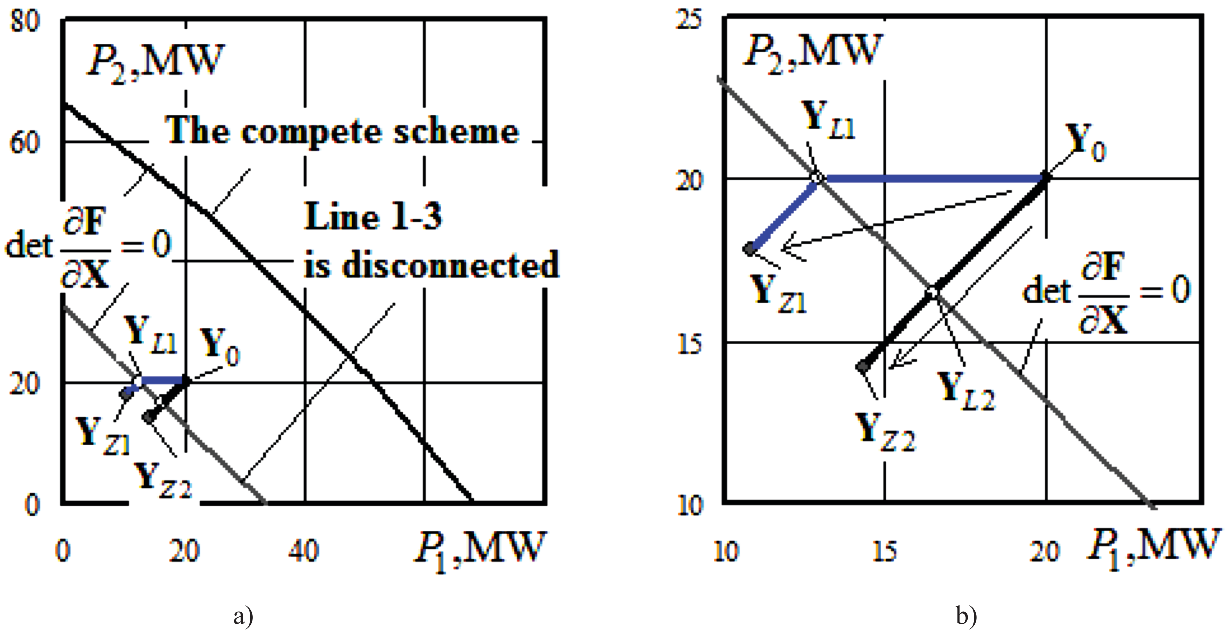


Fig. 11 Calculation of operating conditions meeting the stability constraints, using limit load equations.

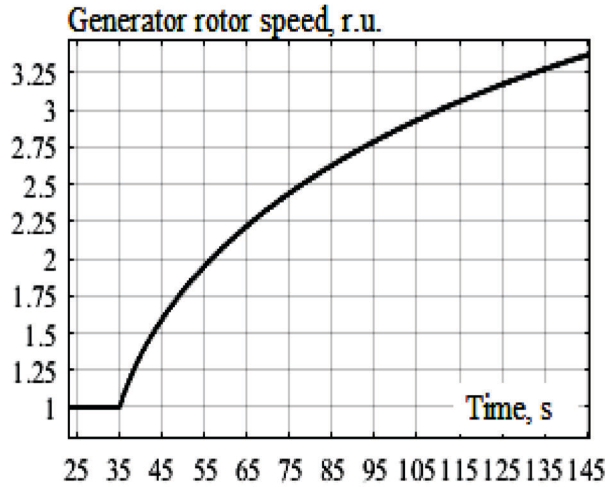


Fig. 12 Oscillogram of generator rotor speed of the DG plant 1, without AVR and ASR when line 1-3 is disconnected

the use of the limit load equations and starting algorithm based on minimization of functional residuals makes it possible to calculate the required boundary value of the stability region.

Additionally, the MATLAB-based modeling was carried out given the models of AVR and ASR defined with the following complex transfer factors:

$$W_{\mathrm{ASR}}(j\omega)=\left(k_p+\frac{k_i}{0{,}1j\omega}+\frac{k_d\,j\omega}{j\omega+1}\right)\cdot\frac{1}{0{,}01j\omega+1}$$

$$W_{\mathrm{AVR}}^{\omega}(j\omega)=\frac{1+0{,}5j\omega}{0{,}5j\omega}\left[\frac{2\,k_{0\omega}j\omega}{(2j\omega+1)(0{,}02j\omega+1)}+\frac{0{,}05\,k_{1\omega}j\omega}{0{,}05j\omega+1}\right]$$

$$W_{\mathrm{AVR}}^{\mathrm{U}}(j\omega)=\frac{1+0{,}5j\omega}{0{,}5j\omega}\cdot\left(k_{0u}-\frac{0{,}02\,k_{1u}j\omega}{0{,}06j\omega+1}\right)$$

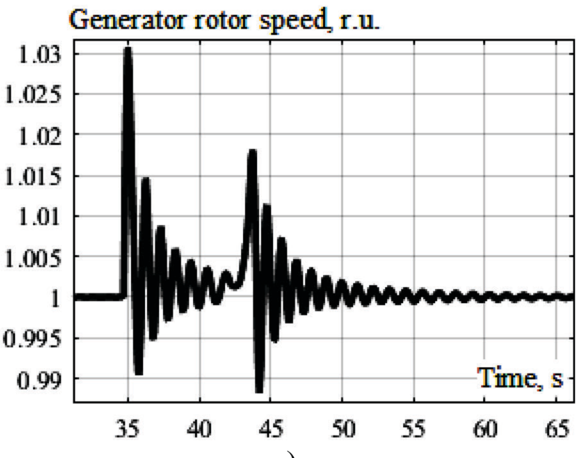
where k_p, k_i, k_d – ASR tuning coefficients; k_{0u}, k_{1u}, $k_{0\omega}$, and $k_{1\omega}$ – tuning coefficients for AVR adjusting channels.

A detailed description of the used model of regulators is given in [9, 12, 13]. The method of harmonized tuning was used to determine the parameters of the regulators for three loads of the generators (minimum load, average load, and maximum load). These parameters were then used to build a rule base for the fuzzy control system.

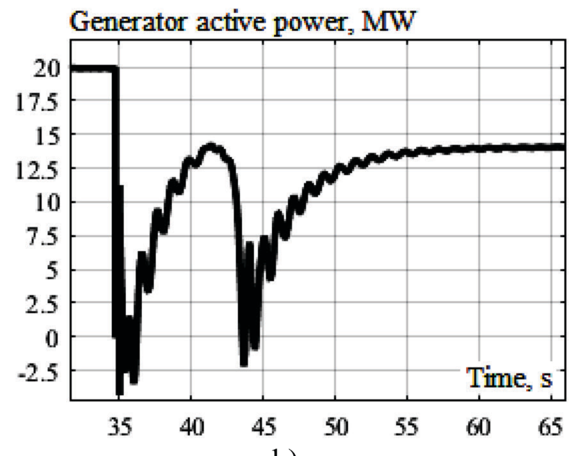
The modeling results show that without AVR and ASR, disconnection of one line causes instability of generators. The corresponding oscillogram of generator rotor speed for DG plant 1 is shown in Fig. 12. This is due to the relatively low power of the generators and the low constant inertia of their rotors, which require fast and coordinated control.

Modeling involved the calculation of the DG plants operating conditions meeting the stability constraints for the case of a short circuit on line 1-3, which occurs in electric power system, and its disconnection by relay protection in 0.3 s. When DG plants operate without regulators, disconnection of one line causes stability loss in the system. To ensure stability in the post-emergency conditions, it is necessary to reduce the power of the DG plant generators. In this case, the correctness of DG plants AVR and ASR settings influences greatly the quality of the system dynamic transition. As an example, oscillograms of generator speed and active power of DG plant 1 are given. They indicate a negative effect of non-harmonized settings of regulators on the quality of the transient process (Fig. 13).

Harmonized settings of AVR and ASR and their change in different operating conditions of generators considerably improve the quality indices of transient processes. The corresponding oscillograms of voltage, frequency, and power of the DG plants for the case of short circuit and tripping of line 1-3 are shown in Figs. 14 and 15. The main advantage of the change in the AVR and ASR settings in different operating conditions is a decrease in oscillation, overshoot and time of the transient process for voltage, frequency, and power of the DG plant, which ensures a qualitative dynamic transition when generator power is reduced in the post-emergency conditions.

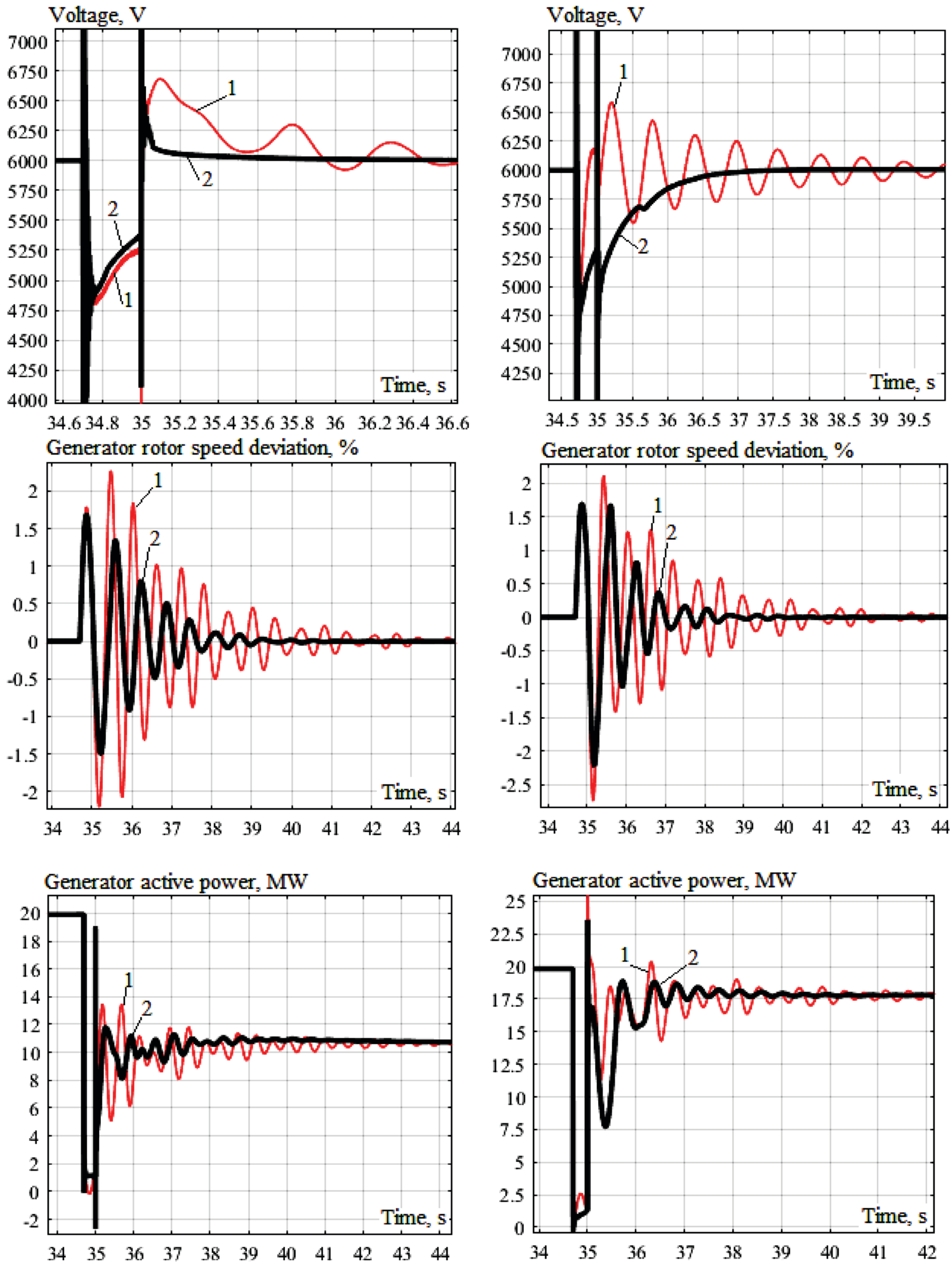


a)



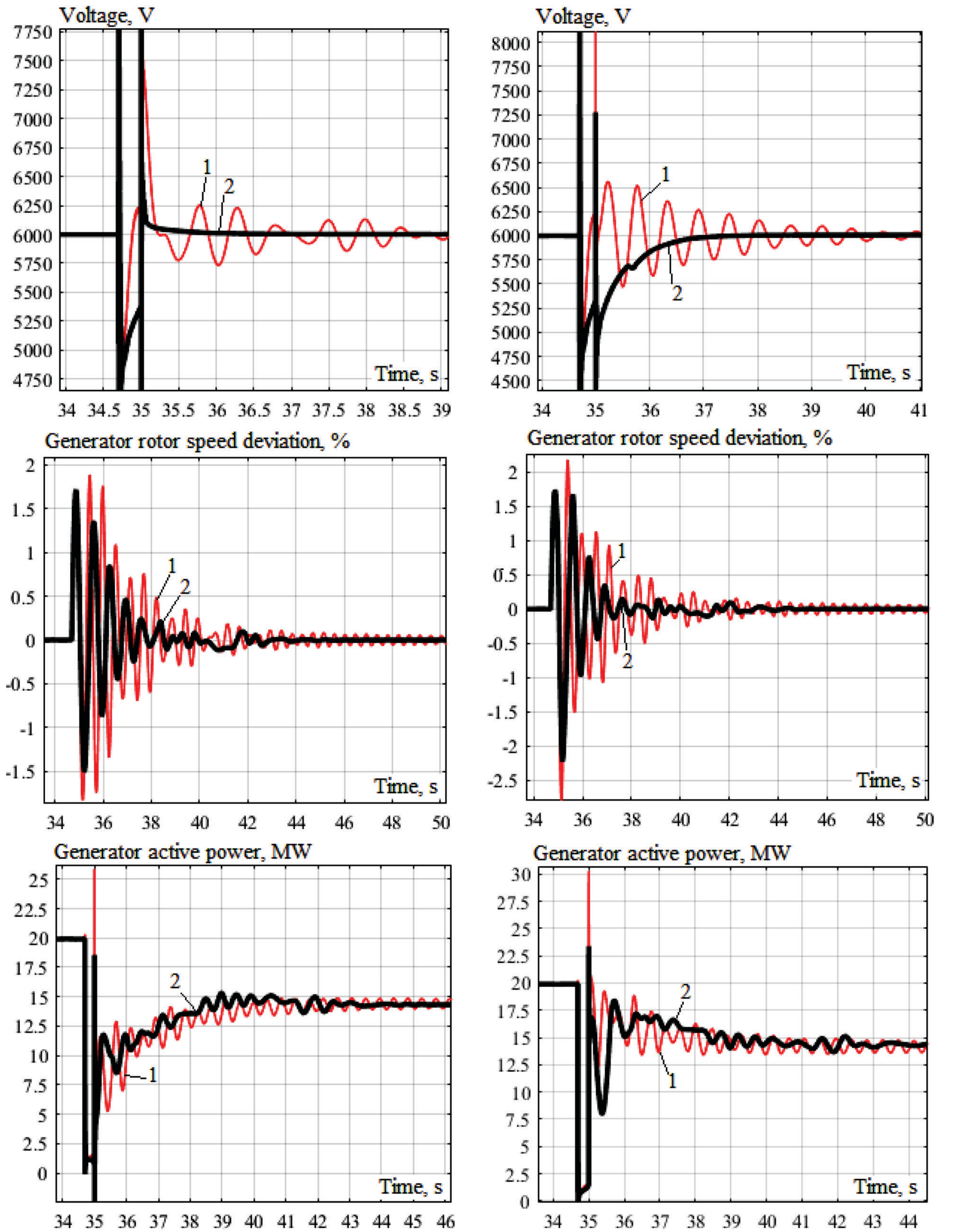
b)

Fig. 13. Oscillograms of generator rotor speed (a) and active power (b) of DG plant 1 for non-harmonized AVR and ASR settings (the operating conditions meeting stability constraints are calculated using the shortest path).



a) for DG plant 1 b) for DG plant 2

Fig. 14. Oscillograms for voltage, frequency, and power of DG plants in the case of tripping line 1-3 (the operating conditions meeting the stability constraints are calculated using the set path): 1 – without changes in the AVR and ASR tuning coefficients; 2 – using a fuzzy controller that changes the AVR and ASR settings.



a) for DG plant 1 b) for DG plant 2

Fig. 15. Oscillograms for voltage, generator rotor speed deviation and power of DG plants in the case of tripping line 1-3 (the operating conditions meeting the stability constraints are calculated by the shortest path): 1 – without changes in the AVR and ASR tuning coefficients; 2 – using a fuzzy controller that changes the AVR and ASR settings.

VI. Conclusion

The paper presents the methods for calculating the operating conditions meeting the stability constraints based on the limit load equations that can be used in the emergency control to be performed by distributed generation plants. A fuzzy control system is proposed to control the parameters of the DG plant regulators. The knowledge base of this system allows the formation of a self-tuning unit based on the application of AVR and ASR harmonized tuning technique using wavelet transform and genetic algorithm.

Based on the performed calculations and computer modeling, the following conclusions can be drawn:

1. The post-emergency conditions meeting the stability constraints can be effectively calculated using the limit load equations with the aid of a starting algorithm that enables the operating condition to reach the near boundary of the stability region.
2. Harmonized tuning of generator regulators provides a good quality of dynamic transition along the set path when DG plants generator power is reduced in post-emergency operating conditions.
3. Application of fuzzy algorithms to control AVR and ASR settings considerably enhances the quality of voltage, frequency and power transient processes when the power of DG plant generators is reduced in the post-emergency conditions.

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