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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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Methodological Framework for Planning The Development of Mongolia’s Electric Power Systems and Energy Industry

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***Abstract* — To successfully establish Mongolia's Unified Electric Power System (UEPS) and ensure its future participation in the global electricity market, it is crucial to create a scientifically supported methodology for the expansion planning and control of the country's electric power systems. The approach can and should be developed relying on the concepts provided for in the Mongolian Energy Development Policy Documents, with focus on the challenges of increase in the reliability, the growth of domestic electricity consumption, and the features of the external market. Modeling options and scenarios for the expansion planning of the UEPS of Mongolia are designed by means of systems analysis methods. This paper explores the research methodology utilized and presents a concise summary of its findings.**

***Index Terms* — unified power system, hierarchical level, expansion prospects, unified system model, system control, performance indicators.**

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I. Introduction

In light of the strategy and policy of Mongolia’s electricity industry development, the stages of its historical development in accordance with the stages of socio-economic development of the country can be divided into two-time intervals: the first covers the period before 1990 and the second covers the period after 1990.

The former time interval coincides with the period of building socialism in the country, i.e., the years when the country was governed in line with the principles of a centrally planned economy. During this period, various sectors of the national economy began to develop intensively throughout the country according to the state five-year planning regulation of national economic development with the aid of Comecon member countries, including the direct assistance of the USSR. This time span saw Mongolia’s transformation from a country with the economy based only on nomadic animal husbandry to a country with a developed multi-sectoral economy based on agriculture; processing and mining industries; construction; energy, transport, and communications infrastructures [1]. Consumption of electricity went beyond its usage predominantly for lighting purposes and came to be largely used in industry, agriculture, and other sectors of the economy. Statistical data indicate that in 1989, for example, electricity generation reached 3,568.3 million kWh and made it possible to cover 95.8% of demand for electricity by domestic sources. An important indicator of scientific and technological advances is the availability of electric power to the workforce in the national economy, which by that time was 19.2 thousand kWh/person, and electricity consumption per capita, which was 1,767.5 kWh/person and came close to the world average of electricity consumption at that time [2].

With the change in Mongolia's concept of development in the 1990s, when the country started transitioning to a market economy, there have been major changes in the electricity sector. Although there was some slowdown in the pace of the electric power industry development at the beginning of this period, the electricity sector gathered the necessary pace at the beginning of the 21st century owing to the introduction of new equipment and technology that complied with international standards. Over the past 20 years, electricity output has doubled, reaching 6,900.1 million kWh in 2019. However, 20% of the country's demand for electricity was still covered by electricity imports [3-5]. According to current data, electricity consumption per capita reaches 2,163.1 kWh/person, whereas the world average is 3,507.1 kWh/person. These data confirm the obvious growth of the domestic electric power industry.

Today's power industry is facing pressing issues, which include an increase in domestic consumption of electric power by boosting the availability of electric power to the workforce for the development of the processing industries, the creation of the unified electric power system (UEPS) of the country covering its entire area, the integration of the regional electric power industry, and the participation in the interstate electric power interconnection of North-East Asian (NEA) countries. These tasks need to be accomplished not only at the level of political and international relations. The optimal solutions require the development of a scientific and theoretical rationale and methodology reflecting the specific problems and unique features of the Mongolian context.

Mongolia has huge resources of renewable (solar, wind) and non-renewable (coal, oil shale) energy sources. However, due to the enormous territory, small population, and poor development of energy-intensive and continuous production, there are some specific features of electricity generation and supply to the population, and energy security.

Therefore, the specific methodologies applied in developed countries cannot be directly transferred or used for developing and defining the concept of the expansion of electric power systems in Mongolia. The unique features of the electric power system of Mongolia are generally due to such factors as low energy consumption in the country; no time zone differentiation, hence the impossibility of managing regional electric load curves; over 80% of electricity is produced by coal-fired combined heat and power plants (CHPPs); difficulties in controlling the

Fig. 1. Electric power systems of Mongolia and their electric ties with neighboring countries

operating states in the system due to heat and electricity co-generation and subsequent delivery to municipalities and industrial enterprises; and the lack of opportunities in this regard to incorporate large capacities of renewable energy sources (RES). In addition, energy policies of neighboring countries that lead the world in energy production and consumption generate the need to take them into account. At the very least, these factors constantly affect the development of Mongolia's energy policy as well.

Currently, Mongolia is connected with Russia and China via several power lines of different voltage levels, and these lines are designed for electricity imports alone (Fig. 1).

There is an opinion that one can meet all of their electricity needs through the self-generation. However, the above-mentioned specific features do not allow the creation of an independent power system with sufficient generating capacity, because, firstly, creating these capacities, given their necessary reserves, requires enormous unreasonable capital outlays, and secondly, keeping them partially or completely available also incurs massive operating costs. In [5], we investigate current operation of Mongolian electric power systems without regard to electricity imports. The findings indicate that, for example, the available power required for the Central electric power system alone necessitates 418 MW of new generating capacity to be commissioned in the areas of Erdenet and Sainshand towns. Meanwhile, the electric tie line with the Russian Federation not only provides the required available power but also serves as a power reserve and frequency regulator for the electric power system. Therefore, the choice of the best power supply option for the country should be approached in a way that would take into account the actual plausibility and reliability of power supply, and strengthen energy security and country's position in foreign markets. With the above factors in mind, in what follows, this paper presents the results of the research into the scenario of stand-alone expansion of the Mongolian energy system in the future without external interstate electric ties.

At different periods of electric power industry development, the goal was often put forward to create an independent power supply system by building several large power sources based on the country's energy resources, thus reducing electricity imports and subsequently switching from importing electricity to exporting it.

In fact, it is impossible to increase the level of energy security and reliability of the country's power supply without both appropriately limiting imported electricity and creating new generating capacities [6]. Therefore, it becomes crucial to develop a science-backed vision and to outline on its basis the most appropriate future lines of development for the electric power industry of the country, bearing in mind the above factors and the development of national fuel and energy resources [7].

The structure of the subsequent presentation of the material in this paper is as follows. Section 2 covers the main tenets of the methodology for the expansion planning of electric power systems in Mongolia. Section 3 presents the methods and findings of studies on the development of the electric power industry in Mongolia and an analysis of the findings obtained. The influencing factors are identified for different levels of the electric power system hierarchy. The mathematical modeling of the structure of the UEPS of Mongolia is carried out and the optimal option of backbone lines is selected. The formation of regional EPSs is substantiated and their performance indicators are analyzed. Section 4 discusses the directions and problems of smartization of Mongolia’s electric power systems. The conclusion contains key takeaways from the research findings.

II. RESEARCH METHODOLOGY

The study aims to develop a model of Mongolian electric power system, which would reflect the above-mentioned influencing factors and which would make it possible to determine a rational technological structure and directions for the creation of the Unified electric power system with its unique characteristics to capture the specific features of the country's economic development. To accomplish the goals and objectives of the study, we have developed a methodology characterized by four alternative scenarios of energy system expansion: Scenario 1 - an independent closed/isolated system (i.e., without external tie lines), which meets all its electricity needs and is independent of imports at any time (I); Scenario 2 - a half-closed system that ensures energy consumption under emergency conditions by relying on imports (II); Scenario 3 - a powerful open system, which operates on the basis of sufficient development of its primary energy sources and exports electricity to foreign markets (Fig. 2)(III); and Scenario 4 - the actual, even optimal unified electric power

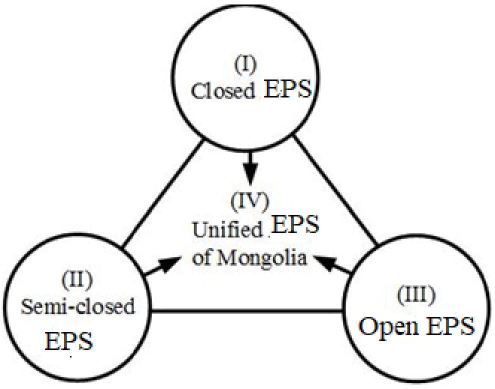

Fig. 2. Model for selecting an optimal scenario for EPS

system, which matches the specific features and scale of socio-economic development and the development of productive forces of the country, and operates in import-export modes as needed and possible (IV).

It is worth noting that at present, the commissioning of new generating capacities in Mongolia lags far behind the growing demand for electricity. Moreover, the problem is exacerbated by the significant aging of the main equipment at existing power sources. Incidentally, it can be pointed out that studies conducted to determine the energy security performance of Mongolia's power system show that with respect to some indicators it borders on a possible onset of a pre-crisis situation [6]. Moreover, the introduction of new wind and solar energy sources of relatively large capacity (50-100 MW) complicates the operating conditions of power plants. In order to enhance the reliability and operational efficiency of the country's power system and effectively implement the government's energy policy, it is imperative to develop well-founded and practical solutions and a robust model for the growth of the power sector. These solutions and model must align with the specific demands and conditions of the electricity market of Mongolia as well as the North-East Asia region [7].

The development of Scenario 4 involved the first three scenarios taken as indicators of limiting conditions. An attempt was also made to develop and apply a comprehensive analysis with an emphasis on a systems approach based on systems analysis. Based on the above methodology, the future acceptable state of the power system of Mongolia, corresponding to Scenario 4, can be defined as shown in Figure 2.

The EPS state corresponding to this scenario will not be a static point, as it will vary freely within the triangle depending on situational and temporal changes in the influential factors. From a research and methodological perspective, the entire power system can have four hierarchical levels of expansion, namely, Level 1: the currently existing EPSs; Level 2: Mongolia’s UEPS; Level 3: a system operating in parallel with electric power systems of neighboring countries; Level 4: Mongolia’s UEPS as part of the cross-border power interconnection being the "supergrid" of the North-East Asia countries.

Hence, there is a need to use methods of systems research with a hierarchical multilevel representation of power systems and the energy sector of Mongolia in general [8]. This study also aims to identify the indicators of energy

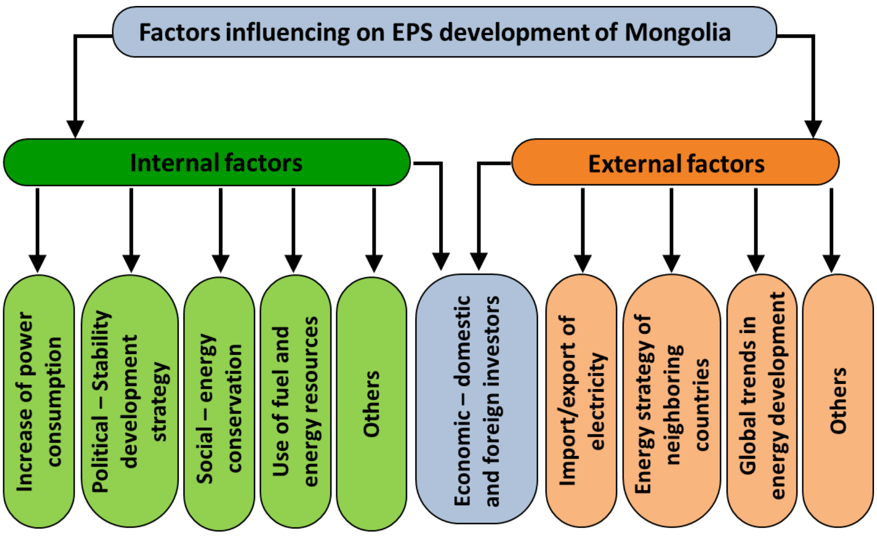

Fig. 3. Classification of factors influencing the development policy of Mongolia’s electric power systems

development based on the analysis of influencing factors for each hierarchical level. One of the reasons that makes this objective more complicated and difficult to achieve is the uncertainty and inaccuracy of data on the influencing factors. When processing mathematically uncertain data, we had to search for a possible way to determine the numerical values of indicators of power industry development.

III. Research and analysis of findings

3.1. Factor analysis

The factors that affect the development of the energy sector and expansion of electric power systems of Mongolia can generally be divided into external and internal with respect to their origin.

The systems analysis of the factors shown in Figure 3 indicates that they can be classified into the following levels of hierarchy (Figure 4). This classification makes it possible to properly assess their impact and identify the prospects of energy development for Mongolia.

The Table marks the factors that have an influence at a specific level of the hierarchy with (+) symbol, and the factors that have no influence, i.e., have no value, with (-) symbol.

Mongolia, with its small population and vast territory, can have multiple competitive options (within the triangle in Figure 2) in the electricity sector. To choose the most feasible option among them, one should develop a mathematical model, which could calculate the optimal ratio of factors at each level of the hierarchy.

The main directions are:

a. The success of the energy business, which is characterized by relatively long payback periods, depends largely on a sustainable and prioritized state policy on electric power industry [9] with long-term and stable support from the government. In this regard, budgetary funding is needed to build power plants that ensure stability in the electric power system. In addition, the financial policy of the state with respect to regional energy sources of private sector investment is also required (indicators 3, 5 of Table 1).

b. Active participation in the energy integration of Northeast Asian regions, connection to the cross-border grid through power lines transmitting high power to the electric power systems of neighboring countries, establishment of a rational ratio between electricity imports and exports, and delivery of energy security (indicators 6, 7, 8, 9 of Table 1).

Table 2 shows the conditions reflecting the effect of the factors on each level of the hierarchy and the corresponding criteria.

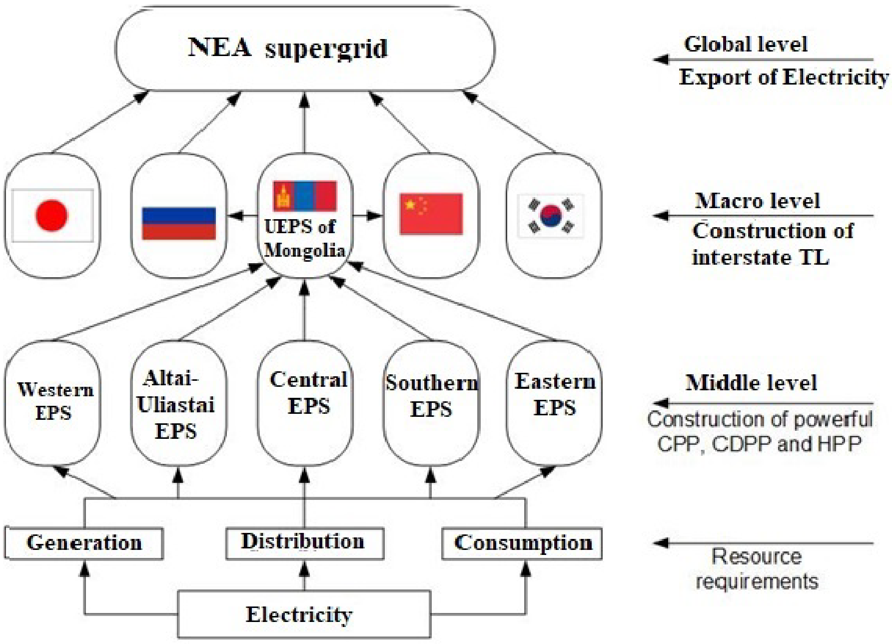

Fig. 4. Hierarchical diagram of energy development in Mongolia

Table 1. The matrix of factors to be considered at different levels of the EPS hierarchy

No.	Indicators of factors	Hierarchical level			
		I	II	III	IV
1	Growth - electricity consumption	+	+	-	-
2	Social indicator - energy conservation	+	+	-	-
3	Policy - stability of development policy	+	+	+	+
4	Fuel consumption - resources of energy sources	+	+	+	+
5	Economy - investment	+	+	+	+
6	Electricity imports	+	+	+	+
7	Electricity exports	-	+	+	+
8	Power industry strategies of neighboring countries	-	+	+	+
9	Global trends in the development of the power industry	+	+	+	-

Table 2. Interrelation of factors, hierarchical levels, and criteria

No	Factors	Hierarchical levels			
		I	II	III	IV
1	Growth: electricity consumption	Reliability of networks	Transmission of electric power over overhead lines	-	-
2	Social indicator: energy saving	Energy saving	Adoption of energy-saving technologies	-	-
3	Policy: stability of development policy	Unified development policy	Long-term development policy	Energy policy of neighboring countries	Policies of the NEA region
4	Fuel consumption: primary energy resources	Fuel and energy resources of a particular region	Location of sources	Balance of exports and imports	Resources of RES
5	Economy: investment	Recovery of capital outlays in a short run	Interests of domestic and foreign investors	Investment support	Economic feasibility
6	Electricity imports	Reduction in energy imports	Creation of an optimal ratio of exports to imports	Reduction in imports	Reduction in imports
7	Electricity exports	-		Increase in exports	Becoming an exporting country
8	Energy strategy of neighboring countries	-	Strategy of unified electric power system expansion	International / cross-border overhead power lines	
9	Global trends in energy development	Creation of distributed sources	Adoption of digital technologies	Infrastructure of digital technologies	Intelligent electric power system

3.2. Mathematical modeling of the structure of Mongolia's unified electric power system and selection of an optimal option for backbone lines

The proposed methodology utilizes a multi-nodal integrated structural diagram to determine the structure of the UEPS. This diagram effectively incorporates regional electric power systems and enables a comprehensive analysis. The calculation relies on the Soyuz model developed at the Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences (ESI SB RAS). The model has a modular structure and includes modules of power balances, balances of zones of daily load curves, flows through cross-nodal lines, as well as the modules describing the operation and expansion of various types of generating equipment [10].

The papers [7], [11], [12] present a detailed analysis of the structural diagram for calculation of the UEPS of Mongolia with 9 nodes (Fig. 5), which include the production and consumption of electricity of the corresponding economic and industrial areas, and the results of modeling energy and power flows along the

Fig. 5. Provisional calculation diagram of the electric power industry of Mongolia

backbone lines with imports factored out. The nodes include distribution networks for consumers (Level I of the hierarchy), and they are not explicitly captured in the calculation diagram. Possible surplus power and electrical energy that can be supplied to the external network or exported are marked in the diagram with corresponding values for specific nodes.

The mathematical modeling of the power flow in Mongolia's UEPS creates the need to exchange energy and power flows of the nodes of Level II of the hierarchy at the corresponding points with Levels I and III of the hierarchy. Designed for exports, the environmentally friendly thermal power plants built at large coal deposits will not only supply electricity to the foreign market but will also serve to increase the reliability of Mongolia's UEPS under emergency conditions, and to cover power shortages under peak loads of normal and off-design operating conditions of the system.

Therefore, further research was conducted based on the results of analysis of the previous option in terms of some unique features of the system, including such of them as excess power in some areas and shortage in other areas of the Central EPS, and with changes in the calculation diagram. For this purpose, 12 nodes were formed at Level II of the hierarchy on the basis of the former 9 nodes (Fig. 6). In doing so, the currently active overloaded nodes (e.g., 6 and 10) are not specified and are expressed indirectly. In order to effectively manage the system's peak load, a pumped-storage plant is located at node 3 in Ulaanbaatar. The formulas and expressions for the mathematical modeling are described in detail in [11].

As seen, this flow diagram somewhat differs from that in [7], i.e., the planned overhead line 1 (between nodes 8 and 9), overhead line 2 (between nodes 12 and 9), and overhead line 7 (between nodes 3 and 9) fail to meet the conditions imposed by the modeling process (i.e., they are not needed), and the optimization revealed the need to introduce new overhead lines to increase the transfer capability of existing overhead lines, and the number of their circuits. The calculation results also show that the overhead line that connects node 8 with other nodes and represents the electric connection of the Western EPS to other nodes of the electric power system is economically and technically unfeasible, unless large industrial enterprises, for example, powerful mining and other production, transport, and social sector facilities are put into operation.

In general, it is worth noting that the absence of electricity-intensive industries of the economy greatly affects the rational placement of generating capacity and the operating conditions of Mongolia's power systems. Therefore, a crucial requirement for establishing the UEPS in the country is a government commitment to a well-defined policy that focuses on developing and strategically locating domestic industrial and transportation infrastructure. This involves the creation of processing

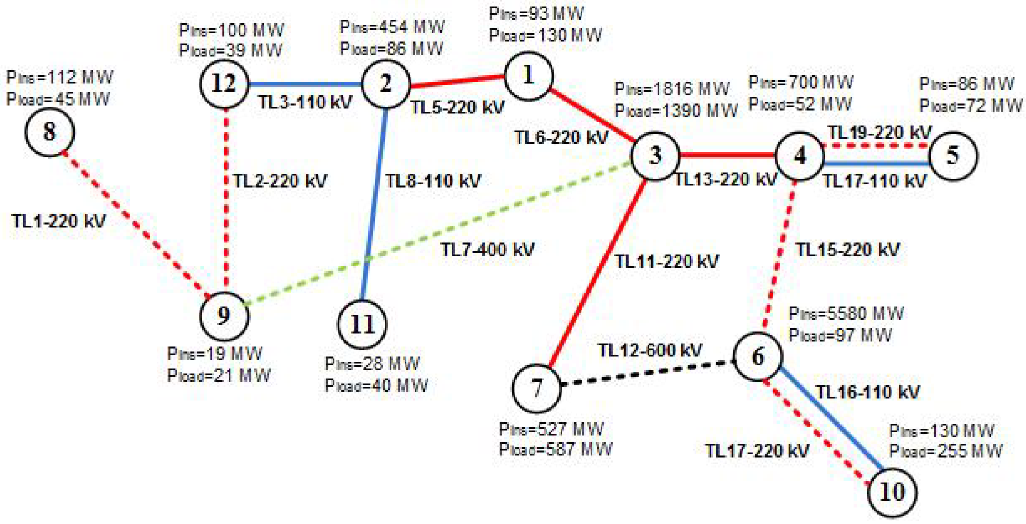

Fig. 6. The primary version of the structure of Level 2 of the UEPS hierarchy

1 - Darkhan, 2 - Erdenet, 3 - Ulaanbaatar, 4 - Baganur, 5 - Choibalsan, 6 - Choir, 7 - Tavantolgoi, 8 - Western, 9 - Altai, 10 - Sainshand, 11 - Bayanteeg, 12 - Khuvsgul (Mogoin Gol)

facilities for agricultural and mining resources, coal processing [13], as well as eco-friendly thermal power plants for the energy and agricultural sectors [14]. Additionally, the development of electrified railroads is an essential component of this effort [15].

3.3. A study on Mongolia's electric power industry development strategy without considering external cross-border electric tie lines

As previously mentioned, the possibility of developing Mongolia's electric power industry independently, without considering external cross-border electric tie lines is considered in this paper as one of the equally significant options, and in a way, as the reference case. Let us consider the main findings of scenario-based studies of this option using the SOYUZ optimization software [10]. The initial conditions for the studies were assumed to be identical to those used in section 3.2.

Given the geographical location of existing power facilities of the country and potential new energy capacities, the placement of existing consumers and the emergence of new ones in the future, an aggregate diagram of the backbone power grid of Mongolia was built for the

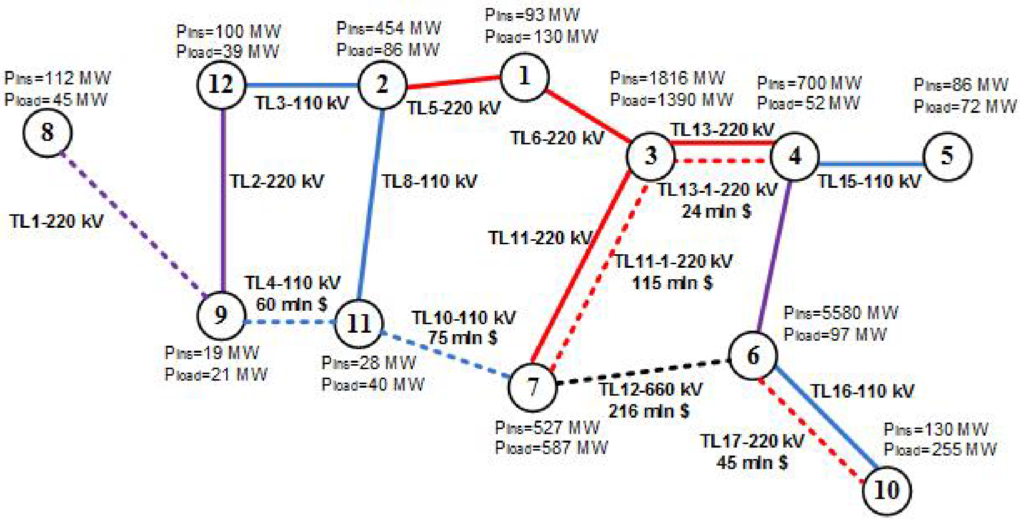

Fig. 7. Schematic diagram of the obtained solution (using the optimization model)

time horizon until 2030 (Fig. 6). Based on this diagram, a mathematical model of the expansion of Mongolia's electric power system was constructed, and the expansion scenarios for electric power systems (without external cross-border electric tie lines) were examined to analyze the internal needs and opportunities of the country in terms of development of the electric power industry and the expansion of electric power systems. The calculations considered one option of electricity consumption for 2030 corresponding to the directions of the State Energy Policy [9] and being twice the level of electricity consumption of the reporting year 2018 (Fig. 7). The main load nodes in these years are the same - Darkhan, Erdenet, and Ulaanbaatar. The share of these nodes in the total electricity consumption is about 90%.

Four scenarios of the Mongolian electric power system expansion to 2030 were calculated. The calculations optimized the expansion of condensing power plants (CPPs) and power plants running on renewable energy sources: wind power plants (WPPs) and solar power plants (SPPs). The HPP and CHPP capacities to be added were determined based on expert assessment according to the National Energy Strategy: Taishir HPP is under construction; the commissioning of Egiin HPP is due to the need for flexible capacity; CHPPs are tied to the thermal loads at the respective nodes.

The baseline scenario (No. 1) assumes the expansion of the main power grid to be fixed. The results of the calculation are presented in Table 3.

The baseline scenario suggests that covering the power and energy balances of Mongolia's electric power system requires about 1.5 million kW of capacity to be commissioned at power plants, including 200 MW at HPPs and 434 MW at CHPPs. According to this scenario, it is also necessary to add coal-fired capacities in Tavantolgoi (92 MW) and Baganuur (254 MW); wind capacity in Gobitek (460 MW) and Choir (55 MW); and SPPs with a total capacity of 38 MW. The installed capacity of Mongolia's power plants will increase by more than 1.5 times and will be 2.7 million kW by 2030. In this scenario, the electrical loads of all nodes are fully covered taking account of the daily and seasonal irregularity of their electricity consumption.

The main power flows go from the peripheral nodes of the electric power system to the central nodes - Ulaanbaatar, Darkhan, Erdenet, which account for 86% of total electricity consumption. The Choibolsan and Western nodes have weak links with the power system and are virtually self-sufficient.

The construction of the Egiin hydropower plant in Erdenet may lead to serious and as yet poorly studied consequences for the environmental situation in the Lake Baikal area. With this in mind, three more scenarios of the expansion of Mongolia's EPSs were considered (Scenarios

Table 3. Calculation results for generating capacities at nodes for baseline scenario

Indicators	Installed capacity, 2018						Capacity additions, 2018-2030						Installed capacity, 2030					
Nodes	HPP	CPP	CHPP	WPP	SPP	**Total**	HPP	CPP	CHPP	WPP	SPP	**Total**	HPP	CPP	CHPP	WPP	SPP	**Total**
Darkhan			48		10	**58**			35		3	**38**			83		13	**96**
Erdenet			65			**65**	120		47			**167**	120		112			**232**
Ulaanbaatar			881	50	10	**941**			202		10	**212**			1083	50	20	**1153**
Baganuur								254				**254**		254				**254**
Choibalsan			36			**36**			100			**100**			136			**136**
Choir										55	25	**80**				55	25	**80**
Tavantolgoi			24	50		**74**		92				**92**		92	24	50		**166**
Western	22					**22**	80		50			**130**	102		50			**152**
Gobitek										460		**460**				460		**460**
Total	**22**	**0**	**1054**	**100**	**20**	**1196**	**200**	**346**	**434**	**515**	**38**	**1533**	**222**	**346**	**1488**	**615**	**58**	**2729**

Table 4. Generating capacity additions in Mongolia's EPSs for different scenarios to 2030, MW

Nodes	Scenario 2						Scenario 3						Scenario 4					
	HPP	CPP	CHPP	WPP	SPP	Total	HPP	CPP	CHPP	WPP	SPP	Total	HPP	CPP	CHPP	WPP	SPP	Total
Darkhan			40		2	**42**			35		2	**37**			35		3	**38**
Erdenet		141	47			**188**		300	47			**347**			47			**47**
Ulaanbaatar			202		10	**212**			202		11	**213**			202		11	**213**
Baganuur		256				**256**		160				**160**		480				**480**
Choibalsan			100			**100**			100			**100**			100			**100**
Choir				55	16	**71**				55	28	**83**				55	27	**82**
Tavantolgoi		77				**77**						**0**						**0**
Western	80		50			**130**	80		50			**130**	80		50			**130**
Gobitek				466		**466**				425		**425**				440		**440**
Total	**80**	**474**	**439**	**521**	**28**	**1542**	**80**	**460**	**434**	**480**	**41**	**1495**	**80**	**480**	**434**	**495**	**41**	**1530**

2, 3, 4). The main findings of the study on these scenarios are shown in Table 4.

Given the above, in Scenario 2, the construction of the Egiin hydropower plant is not considered. In this case, the power and electric energy balances in the electric power system are not covered. The transfer capability of power transmission lines is insufficient to transmit electricity from new sources to the Central EPS of Mongolia, which leads to a power shortage of about 140 MW at the Erdenet node. The Choir - Baganuur - Ulaanbaatar line is loaded to the maximum and cannot be used to mitigate the shortage. Therefore, it is necessary to commission a new coal-fired power plant in Erdenet or at other nodes with the corresponding strengthening of cross-nodal connections.

Scenario 3 considers the commissioning of a 300 MW coal-fired power plant in Erdenet instead of the Egiin HPP without additional reinforcement of the power grid. This scenario will mitigate the power shortage in the power system and reduce the need for new capacity at the Baganuur and Tavantolgoi nodes by about 90 MW at each node.

Scenario 4 proposes an alternative to the coal-fired power plant in Erdenet. This alternative suggests enhancing the transfer capability of the line along the Gobitek - Choir - Baganuur - Ulaanbaatar - Erdenet route, in order to transmit electricity from new CPPs, WPPs, and SPPs to the nodes of Central EPS (see Table 4).

Thus, the studies on the expansion scenarios of Mongolia's EPSs to 2030, without external cross-border electric tie lines, attest to the need for significant expansion of generating capacity and the main power grid.

3.4. Principles of control of the Mongolian UEPS

The construction of an optimal model for the UEPS of Mongolia involved a calculation using the model (considering unified supervisory control) based on the determination of minimum costs. Violations of the UEPS operating conditions have serious socio-economic implications. On the one hand, the UEPS is subject to operational supervisory control that regulates power generation and active power flows between interconnected electric power systems. On the other hand, the UEPS determines the boundaries of individual electric power systems (interface points) in terms of the structure of electrical networks based on the location of generating capacities, on the geographical location of consumers and their economic performance, and based on the location of administrative units.

The power balance of the i-th EPS, which is part of the UEPS, is determined by the following equation:

$$S_{Ci} + S_{LdHi} + S_{Li} + S_{Oi} = 0\,, \qquad (1)$$

where: S_{Ci} - total power of all power plants of the i-th system; S_{Ldi} -total load of the i-th system; S_{Li} - total electricity transmission losses of the i-th system; S_{Oi}- generated and/or received power of the i-th system, which is transmitted through cross-system transmission lines (Fig. 8).

The energy balance for the UEPS is expressed by the following system of equations:

$$\left.\begin{aligned} S_{C1} + S_{Ld1} + S_{L1} + S_{O1} = 0; \\ S_{Ci} + S_{Ldi} + S_{Li} + S_{Oi} = 0; \\ S_{Cn} + S_{Ldn} + S_{Ln} + S_{On} = 0. \end{aligned}\right\} \quad (2)$$

The power balance of the UEPS (Fig. 9) is expressed by the equation of interrelation of the electric power systems included in it:

$$S_{01} + S_{02} + \dots + S_{0i} + \dots + S_{0n} = 0 \quad (3)$$

In order to control and regulate the output of the UEPS capacity, it is first of all necessary to determine the minimum value of the electricity generation costs within the system. One way to assess the performance of the UEPS is to describe it by the function of the basic production costs (C_{bas}) and determine its minimum value $(C_{bas})_{min}$ as the objective function that determines the performance of the system:

$$C_{bas} = \mathrm{g}\left(\sum_{i=1}^{n} S_{Capi}\right) = C_1 + C_2 \dots + C_i + \dots + C_n\,, \quad (4)$$

where: $g -$ constant cost factor; $\sum_{i=1}^{n} S_{Capi} -$ total capacity of the UEPS; C_i - components of current operating costs of the i-th power system (in practice, the fuel component of costs accounts for 60-70%).

Thus, in order to control the UEPS with the minimum economic fuel costs and the greatest economic effect, the optimized control of the UEPS can be expressed as follows:

$$\lim_{u_i} C_{bas} \to min\,, \quad (5)$$

where: u_i - control signal of the supervisory control center of the upper level.

The minimum value of expression (5) is determined subject to conditions (1) - (3). For this purpose, control of the UEPS subsystems should be carried out from a single Control center or it should be based on the principle of multi-stage (multi-level) control (Fig. 9). Meanwhile, each EPS, as a subsystem of the UEPS, should be controlled by its Control center.

Acceptable supervisory control, management, protection relays, and a modern integrated automation system will ensure reliable and stable operation of the UEPS. In this regard, the objective is set to establish an intelligent power system, where the application of digital technology for measuring, processing, and transmitting information is essential.

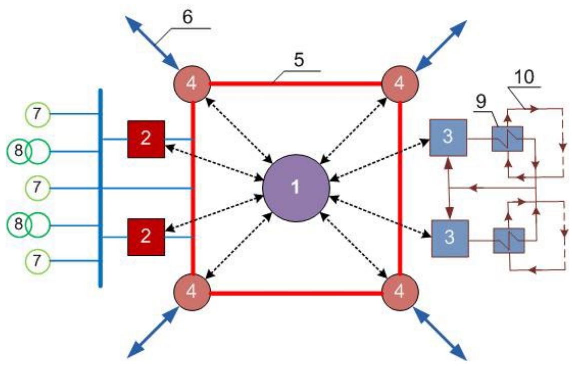

Fig. 8. Control diagram of the electric power system: *1 - central control room; 2 - electric power plants (CPP, HPP, SPP, etc.); 3 - combined heat and power plants (CHPPs); 4 - distribution substations; 5 - ring power lines; 6 - lines connecting adjacent systems; 7 - distribution networks; 8 - electricity consumers; 9 - heat consumers; 10 - heat network.*

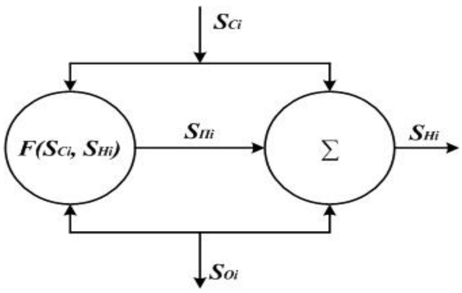

Fig. 9. Diagram of power balance in the electric power system

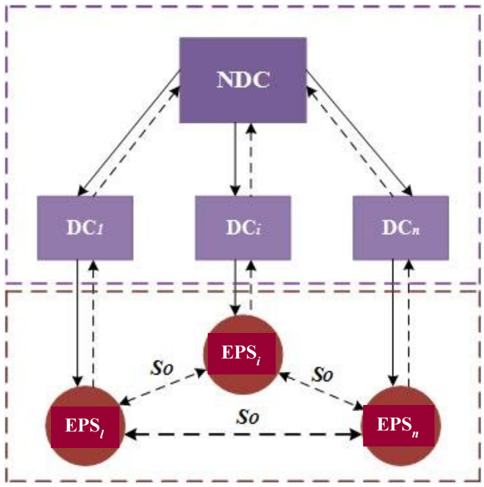

Fig. 10. Schematic diagram of the UEPS multistage control structure

In other words, the SCADA systems or automated process control systems based on digital technology, as well as information systems and automated information management systems such as WAMS, WAMPAC adapted to local conditions for operational supervisory control, are the basis for developing an intelligent UEPS (Fig.10). The prospects and problems of making Mongolia's EPSs intelligent are discussed in detail below in subsection 3.6.

3.5. Rationale for establishing regional electric power systems and analysis of their indicators

Regional electric power system is part of the regional energy sector, which in the traditional sense is characterized by the following indicators: sufficient fuel resources; generating capacity ensuring flexibility; ability to be governed by supervisory control in the optimal operating state of the UEPS; several cross-system tie lines allowing the exchange of power and energy flows with adjacent systems under emergency and off-design conditions.

In the context at issue, the adequate fuel resources of the regional power system mean the availability of coal enterprises that can fully meet the demand for fuel of all thermal power plants and other consumers of the considered region for a sufficiently long time, for example, for a year. At the same time, it is necessary to take into account the increasing output of electricity from renewable energy sources (WPP, SPP, and HPP). In this case, the research should factor in the share of the increase in renewable electricity generation, which was 20% in 2020 and will be 30% in 2030 [9]. Therefore, to take into account this circumstance in (6), we introduced the per-unit quantity β, which factors in the reduction in the amount of electricity produced at the TPP and, in principle, at other fuel sources. Thus, we can determine the annual electricity output at coal-fired thermal power plants using expression (6).

$$E_{el}^{CHPP} = E_{el}^{reg}(1-\beta) + E_{el}^{loss}, \qquad (6)$$

where: E_{el}^{reg} - annual electric load of consumers in the region, kWh/year; E_{el}^{loss} - electricity losses in the system networks, kWh/year;

The remaining types of the region's coal consumption (B_{fuel}^{ind}) are calculated on the basis of the regional annual coal balance:

$$B_{fuel}^{ind} = \sum_{j=1}^{J} B_{fuel,j}^{ind}. \qquad (7)$$

Then the annual coal consumption of the region is calculated as follows:

$$B_{fuel} = E_{el}^{CHPP} \cdot b_{c.e.}^{el} + B_{fuel}^{ind} + \Delta B_{fuel}^{loss}, \qquad (8)$$

where: E_{el}^{CHPP} - electricity production by thermal power plants in the region, kWh/year; $b_{c.e.}^{el}$ - specific coal consumption for electricity generation (as converted to tce), tce/kWh; $B_{fuel,j}^{ind}$ - coal consumption by other industries, tce/year; J - number of socio-economic industries included in the coal balance and in the unified energy balance; ΔB_{fuel}^{loss} - coal transportation losses, tce/year.

The annual coal production is determined as the sum of productions of all $(k = 1, \ldots, K)$ coal enterprises in the region:

$$B_{fuel} = \sum_{k=1}^{K} B_{mines,k}^{coal}. \qquad (9)$$

In this regard, the condition for the creation and operation of power system as part of the regional energy sector is the presence of sufficient reserves and the actual production of primary energy resources (coal), which can be written as follows:

$$B_{fuel,i} > K_{res} B_{fuel}\,. \qquad (10)$$

Here, the fuel reserve factor (K_{res}) takes into account the standardized reserves, which should be available at the TPP operating under the standard conditions, and the emergency reserves. The substitute fuels of the region can also be considered in (9).

One of the main indicators of the power system performance is the quantity of electricity losses E_{el}^{loss}, which is included in (6) and depends on the parameters of electricity transmission through transmission lines, for example, on the voltage level and the total length of the lines.

When analyzing the expansion of EPS at the level of the regional energy sector, the following parameters can be used as indicators of the fuel and energy supply:

The ratio ($\alpha_{ins.cap}$) of the total available capacity of power plants (P_{av}) to the maximum electric load capacity within the region (P_{max}).

$$\alpha_{ins.cap} = \frac{P_{av}}{P_{max}}\,. \qquad (11)$$

The ratio ($\alpha_{int.tl}$) of the sum of the power available and transmitted through the intersystem tie-line at the maximum load of consumers ($P_{int.tl}^{max}$) to the maximum load power of a given region (P_{max}):

$$\alpha_{int.tl} = \frac{P_{av}+P_{int.tl}^{max}}{P_{max}}. \quad (12)$$

3. The transfer capability of backbone high-voltage transmission lines (110 and 220 kV) of the intersystem tie-line:

$$P_{int.tl} = \sum_{i=1}^{N} P_{int.tl.i}\,, \quad (13)$$

where N is the number of intersystem tie-lines.

The possibility of supplying primary fuel and energy resources (FER) at the expense of local resources is expressed by the following formula:

$$\alpha_{fuel} = \frac{\sum R_{fuel,i}}{\sum B_{fuel,i}} 100\%\,, \quad (14)$$

where: $R_{fuel,i}$ and $B_{fuel,i}$ are production and consumption of the i-th primary fuel and energy resource respectively.

The calculation of reliability indices of the fuel and energy supply to the region's energy sector should factor in first of all the ability to provide fuel and energy resources under normal conditions and in the event of extreme conditions, i.e., under a steep increase in fuel demand due to unforeseen conditions, for example, due to cold weather not taken into account in the analysis of thermal loads, and others. The following three indices will be considered here: the share of fuel resources ($\alpha_{pr.fuel}$) prevailing in the total consumption of fuel and energy resources in the region; the share of the most powerful power plant in the electric power sources of the region ($\alpha_{large\ PP}$), the amount of backup fuel resources necessary to cover consumption in the event of an emergency, such as the ability to supply a 10% increase in fuel consumption ($\alpha_{b.fuel}$). They are expressed as follows:

$$\alpha_{fuel} = \frac{max(\sum B_{fuel,i})}{\sum B_{fuel,i}} 100\%\,; \quad (15)$$

$$\alpha_{large.PP} = \frac{P_{large.PP}}{P_{\Sigma ins.cap}} 100\%\,. \quad (16)$$

The indices of backup fuel resources under extreme conditions are determined as per the following formula:

$$\alpha_{b.fuel} = \frac{R_{fuel\ ext.}}{B_{ext.}} 100\%\,, \quad (17)$$

where $R_{fuel\ ext.}$ - the maximum possible primary fuel resources supply for the region's needs, mln tce; $B_{ext.}$- the maximum (with a 10% increase) region's fuel consumption under extreme conditions, mln tce.

Here R_{heat} is expressed by the following formula.

$$R_{heat} = \sum min\left(P_{heat,i}\,, P_{HN,i}\right), \quad (18)$$

where: $P_{heat.i}$ is the total power of the normal operating state of the i-th district heating source of the given region, Gcal/h; $P_{HN,i}$ is also heat delivered to consumers of the i-th heat network, Gcal/h.

Determination of R_{heat} is the subject of a separate

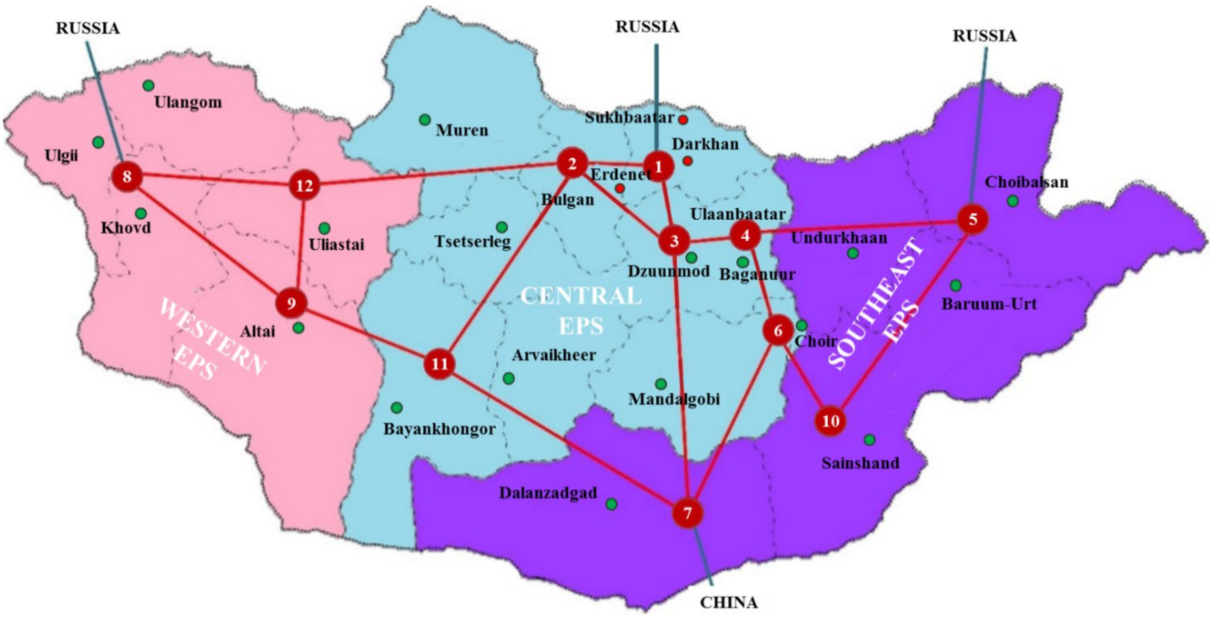

Fig. 11. Location and lines connecting electric power systems of Mongolia's regions (with 12 nodes of the model considered)

independent optimization study of the heat and power economy of the region. Here we took the value of this index as a given input value.

Initially, a study on the selection of a rational structure of the UEPS was conducted for the parameters (indicators) of currently operating five electric power systems of regional importance within the areas they serve in accordance with the medium-term development program of the electric power industry of Mongolia until 2030. The analysis has indicated that it is advisable to transform them into three power systems as shown in Fig. 11. Then the newly formed power systems meet the requirements for the fuel resources, capacity to ensure their flexibility, and controllability under the optimal operating conditions of the Unified EPS given the existing and proposed several intersystem lines, which ensure to an adequate extent the exchange of power and energy flows with neighboring systems under emergency conditions.

To calculate the indicators of annual coal consumption and reliability indices of fuel and energy supply on a regional scale, we used coal balance data for 2019 from the unified database of the National Statistical Committee. This database shows that in 2019, Mongolia extracted 55.9 million tons of coal and consumed 9.8 million tons, of which 7.7 million tons of coal were consumed by thermal power plants. The remaining 2.1 million tons of coal were consumed for the household needs of the population, mainly for heating. Transportation and storage losses amount to 661.4 thousand tons [3]. Table 5 shows the general characteristics of the three electric power systems.

When determining the indicators of fuel and energy supply, optimization using expression (10) (with 2019 as the baseline year) reveals that currently all three systems have $\alpha_{ins.cap} < 1$ (Table 6), which confirms the demand for new sources. In 2050, however, by the end of the period of the long-term policy document "Long-Term Vision - 2050" [16], the same indicator for the Western and Central EPSs is projected to be $\alpha_{ins.cap} > 3$. The sources of Southeastern EPS, however, prove inadequate by this time, although, the Southeastern EPS is supposed to have reliable connection to the Central EPS through five overhead transmission lines and, in this case, the system will operate properly. In addition, the reliability of the Central EPS sources will be ensured and the system will work for the external market, i.e., electricity exports will be provided.

Table 5. General characteristics of Mongolia's regional electric power systems (1)

No	Regional power systems	Territory area, km^2	Population, thousand	Electricity consumption, million kWh/year	Share of RES, %	Fuel consumption, thousand tons			Fuel losses, thousand tons
						TPP*	Others	Total	
1	Western EPS	415.2	408.9	858.69	55	0.97	0.27	1.24	83.5
2	Central EPS	583.1	2,473.2	5,193.72	20	5.88	1.60	7.48	505.1
3	Southeastern EPS	561.1	356.4	748.44	30	0.85	0.23	1.08	72.8
	Total	1,559.4	3,238.5	6,800.85		7.70	2.10	9.80	661.4

* This factors in a 100 MW coal-fired power plant to be commissioned in the western region.

Table 6. General characteristics of Mongolia's regional power systems (2)

No	Regional power systems	Installed capacity, $P_{ins\,cap}$[MW]		Maximum load, P_{max}[MW]		Power of the tie line**, P_{tl} [MW]		Indicators of fuel and energy resources supply			
								α_{ins}		α_{tl}	
		2019	2050	2019	2050	2019	2050	2019	2050	2019	2050
1	Western EPS	31.1	331	58	105	16	48.2	0.54	3.15	0.81	3.61
2	Central EPS	1,223	8,801	1,153	1,745	-	-	1.06	5.04	-	-
3	Southeastern EPS	243	743	208	884	23.4	395.7	1.17	0.84	1.28	1.29
	Total	1,497	9,875	1,419	2,734	39.4	443.9	1.05	3.61	1.08	3.77

** The 2019 value is determined by the maximum power transmitted through the existing transmission line in 2019, and the 2050 value is obtained by calculations (see [11]).

3.6. Problems of power supply to off-grid consumers in Mongolia

The above-discussed principles and directions for the development of the electric power industry and electric power systems of Mongolia concerned the expansion of large generation capacities, high and ultra-high voltage of backbone electrical network; and the establishment on this basis of the country's Unified electric power system, in particular, for Mongolia to participate in the creation of an interstate power grid of North-East Asia.

Meanwhile, in recent years, small-scale power generation in Mongolia has developed significantly. In 2019, there were 13 mini- and micro hydropower plants, 17 mini- and micro- solar power plants, 3 mini wind power plants, and 7 hybrid microgrids (photovoltaic panels and wind turbines with or without electricity storage). Mongolia successfully implemented an impressive national project "The 100,000 Solar Gers" program to electrify individual gers of nomads, which is of great social significance [17]. The program was funded by the Governments of Japan and China, and by the World Bank [18]. The program was launched in 2000 and continued until 2012. As a result, 70% of the nomads (about 500,000 inhabitants) were supplied with electricity. The total power of PV panels per ger is 3-4 kW. In addition, there are backup PV panels and electricity storage units. These microgrids run on direct current.

A typical set of electrical appliances in a ger now includes at least the following units: lighting, electric stove, refrigerator, electric heater, digital TV, and PC. In the not-too-distant future, there will be additional electrical loads, in particular, an automatic washing machine, and other domestic appliances. The total number of electrical loads in a ger, as follows from international experience [19], can be much more than ten.

This will increase the total electricity consumption and the total maximum load of the individual consumer, as well as the irregularity and uncertainty of their daily load curve. It is crucial that the random nature of the operation of some electrical loads (for example, the timing of switching on and off the washing machine), if their number goes up, will lead to an increase in the random component of the daily load curve of the consumer.

Many modern domestic appliances operate on a digital basis and therefore have higher requirements for power supply reliability and power quality. At the same time, the power generation by the photovoltaic panels is stochastic in nature, and these random fluctuations in power generation must be smoothed out by the electricity storage unit. The efficiency of the "PV panel - storage" system is ensured by the control system.

Important non-trivial tasks arise when considering a local mini system consisting of microgrids for a large family residing in several adjacent gers. Another unique, fundamentally new situation will occur when nomads have electric cars, which are already widely used in cities.

In general, the development of a comprehensive methodology, models, and methods is required to justify the expansion of such microgrids and small local systems consisting of several microgrids for power supply to isolated individual consumers and the control of their operation. It seems obvious to maintain the off-grid operation of the considered mini- and microgrids of individual consumers due to their remoteness from the centralized power supply areas.

3.7. Environmental issues of Mongolia's energy sector

In light of the current requirements of the 21st Century Sustainable Development Concept and the UN Paris Agreement on Climate Change, both on the scale of a single country and on a global scale there are requirements to reduce emissions of triatomic gases, which produce the so-called "greenhouse effect," from energy sources (TPPs, boiler-and-furnace systems) and transport vehicles. Today, the majority of power and heat sources in Mongolia run on coal and emit carbon gases which make up 15.7 million tons of CO2 equivalent (as estimated in [20]), 84.5 thousand tons of nitrogen oxides, and 107.3 thousand tons of sulfur dioxide (2020) [21]. Coal-fired sources generate more than 90% of electricity and all thermal energy. Other facilities that produce a large share of air pollutants are cars.

Direct greenhouse gas emissions from these sources can be reduced by taking the following measures: 1) substitute conventional technologies and means of coal combustion at energy sources for new technologies that significantly reduce the aforementioned gas emissions, of which the most harmful are nitrogen oxides and sulfur dioxide; 2) reduce the share of coal and other conventional fossil fuels by substituting them for renewable and other environmentally friendly energy resources (hydraulic, solar, wind and geothermal energy, hydrogen and fuels of advanced processing of natural feedstocks); 3) use all kinds of electric cars, underground railroads, and other advanced types of vehicles in cities.

The Mongolian government is currently taking a variety of measures to support new innovative technologies in the energy sector. Since 2007, under the Law on Renewable Energy, there have been incentivizing tariffs for RES-based electricity generation for power generating sources of electric power systems and the heat power economy [23].

The widespread adoption of the entirety of these measures for the energy sector can be referred to as the greening of energy sources. Here we consider aspects of greening in the field of electric and thermal power.

The policy document of energy development "The Long-Term Vision - 2050" [16] sets the goal to increase the share of renewable energy sources in the power generation sources to 20% in 2020, to 30% in 2030, and to 40% in 2050. In 2020, in the Mongolian energy sector, the capacity of SPPs, WPPs, and small HPPs combined reached 271.2 MW, which is 18.3%. We can say that the goal set at this stage is almost fulfilled. However, because of the operating conditions of electric power systems, which are due to the lack of large basic condensing and hydraulic capacities, and the nature of electrical load curves, the annual output from these environmentally friendly sources is around 9.1% of the total annual production [22]. The use of renewable energy, such as solar energy [24], on a large scale can also cover the demand for heat of individual consumers and maintain the operation of local power grids in remote areas.

To provide a methodological framework for the adoption of "green technology" in the energy sector, over the past more than 20 years, we have conducted a large amount of basic scientific research on the combustion of coal particles [25], experimental studies on the combustion of domestic coals in the fluidized bed and circulating fluidized bed. The studies were also carried out on vortex technology, which serves as a basis for the creation of large steam generators for export-oriented environmentally friendly TPPs in the electric power systems [26], [27]. These works have led to the development of boilers with fluidized bed technology and their implementation in several municipal heat sources. In recent years, circulating fluidized bed boilers of various unit capacities (7 to 116 MW) have been introduced at thermal power plants in Mongolia. In the future, it is planned to install such boilers of large capacity at CPPs to be built at coalmines. Therefore, detailed studies of the mechanical and thermal engineering properties of Mongolian coals are required to draw up design specifications for circulating fluidized bed (CFB) boilers. In addition, it is necessary to investigate the combustion of these coals in the CFB conditions, the yield of nitrogen oxides and sulfur dioxide, and ways to reduce the latter.

The comparative studies of the standards on coal specifications indicate that Mongolian lignite of grades X1, X2, and X3 correspond to coal grades B1, B2, and B3 respectively according to the standards set in the Russian Federation. Coal of grade X3 corresponds to ligB and ligA as per American rankings and to Chinese grades HM1 and HB2. Domestic coals X1, X2 correspond to American sublignites (subB and subC) and Chinese semi-hard CY grade coal. Mongolian coal of Ch12 grade corresponds to the Russian marking of long-flame coal D, American sublignite of sub and subA grades, and to Chinese semi-hard coal of CY grade. All coals of grades Ch11-Ch2 correspond to Russian coking coals, American bituminous coals, and Chinese hard coals of grades QM-FM [26]. Thus, individual coal grades in the standards of different countries overlap with each other and there are some differences in coal grading in different countries, which complicates the choice of design specifications of furnaces and heating surfaces and generates the need to conduct detailed experimental studies of domestic coals as applied to specific boilers produced abroad. This strand also underlies the methodological framework for the adoption of clean coal technology in the energy sector.

Ultimately, the gradual implementation of these new lines in the energy sector provides the greening of Mongolia's fuel and energy balance, which also includes energy and water use of watercourses of inland and transboundary rivers.

3.8. Prospects and challenges of the transition to intelligent electric power systems in Mongolia

In the context of current global trends, the Mongolian Ministry of Energy declared 2019 as the "Year of Smart Energy" and proposed the national program "Smart Energy System" developed to improve the reliability and efficiency of Mongolia's electric power system and its energy security.

To implement this program, it was planned to carry out a set of studies in the following areas:

Ensuring reliable and stable operation of electric power systems under various conditions.

Improving the economy and efficiency of the country's electric power industry as a whole.

Implementing intelligent systems, primarily in the distribution grids and at the level of electricity consumption.

Analysis of the package of studies proposed in the adopted program with respect to the three areas noted above raises the following overriding concerns:

a) Establishment of an intelligent electric power system (IEPS) is a systemic transformation of the electric power industry, which, according to the experience of other countries [[20] – [22], etc.], requires the development of conceptual principles and a rationale behind the IEPS creation priorities. Meanwhile, as a basis for the transition to intelligent electric power system of Mongolia, the program provides for the development of documentation for the IEPS infrastructure (standards, regulations, etc.). Without detracting from the importance of regulatory documents, we emphasize that they should be based on the vision of the IEPS creation [23].

b) Future mass use of wind and solar power generation plants will radically alter the properties of Mongolia's electric power system. This will reduce its controllability and flexibility and will cause the system instability in emergency operating states due to random fluctuations in the power output of the WPP and SPP and insufficient maneuverability of the TPP.

c) Issues of the transition to intelligent microgrids for power supply to the off-grid consumers are not touched at all. Despite the relatively small scale of this area, it has extremely important social significance. Furthermore, it is clear that the implemented 100,000 Solar Gers Program does not address all problems.

d) Implementation of the program aimed at intelligentization of Mongolia's power system requires training a new generation of professionals [24]. The program fails to reflect this extremely important task.

The transition to the intelligent power system is a complex integrated engineering, economic, scientific, and organizational task, which includes a large-scale revamping of the electric power equipment fleet on an innovative basis and the transition to a next generation of process control and market operations management systems at all levels of management. The process of changing the methods and tools for managing the expansion and operation of power systems in Mongolia involves research consisting of three important stages:

Improving automation that ensures greater responsiveness of technical devices and control systems not only during emergencies but also during normal transients with extensive use of emergency control devices to limit voltage and frequency decrease and increase, prevent loss of stability, etc.

Increasing informatization to enable a new level of observability and monitoring of the power system, controllability of operating states of facilities and the system as a whole, with extensive use of digital phasor measurements of state variables.

Adopting intelligent technologies at all levels of power system control to ensure not only "a response related to the actual state," but also "a prediction-driven response," based on probable changes in the operating parameters of individual facilities, systems, and consumers.

Thus, the transition to a new type of electric power industry should harmonize all directions of innovative modernization of power systems, naturally expand the boundaries of the usual production process and take it beyond the conventional extensive scenario of power system development, which is characterized by a simple quantitative increase in production capacity and its saturation with innovative technologies. At the same time, compared to centralized power system, intelligent microgrids possess a higher level of readiness for implementation when it comes to supplying power to the off-grid consumer. This is because they have newer equipment and are much less complex and smaller in scale.

The transition to an intelligent power system represents a significant step forward in the evolution of the electric power industry. This transformation brings about a change in functionality, altering existing properties and giving rise to new ones in various structural components as well as in the power system as a whole.

IV. Conclusion

1. There are currently five electric power systems of regional importance in Mongolia. They cannot fully meet the demand for electricity by their sources and do not comply with the classical definition of the power system in terms of structure and principles of monitoring and control.

2. Based on the study on the factors that influence the development of the electric power industry in Mongolia,

the paper identifies and details the conditions and actions to determine specific indicators for each level of the hierarchy of Mongolia's electric power industry development.

3. A mathematical model of establishing the UEPS of Mongolia was developed, numeric values of some quantitative indicators of fuel and energy supply to consumers were determined, and the findings of the analysis were summarized.

4. The developed model of Mongolia's UEPS meets the fuel resources and power requirements necessary for its maneuverability. It also ensures controllability in the optimal operating state of the UEPS and provides the capacity to regulate power flows from the adjacent systems through several cross-system tie lines. Under emergency conditions, the Mongolian UEPS is connected to Russia along three routes and to China along one route. This connection provides the basis for Level 4 of the UEPS hierarchy.

5. This study examined the existing regional electric power systems and energy consumption levels within the respective areas they serve. To meet the growing need for electricity and align with Mongolia's long-term economic development program, we will continue to research and implement measures to ensure a reliable power supply, optimize power transmission lines, and build new sources of electricity. The study suggests creating three large regional power systems having reliable cross-system tie lines, meeting the requirements of the UEPS, and fitting into the overall configuration of the country's energy sector.

6. The unique features of Mongolia stem from the presence of remote and isolated consumers, which prompted the implementation of the national program "100,000 Solar Gers." To effectively analyze the features and operational conditions of microgrids, as well as their potential for expansion, it is essential to develop a comprehensive methodology, robust models, and effective methods for solving specific challenges. This paper discusses some of them.

7. In order to establish an intelligent power system in Mongolia, it is crucial to develop a scientifically-supported framework for transitioning to a self-aware and self-healing system. This framework should include integrated control functions across all hierarchical levels, catering to both the overall Unified Energy Power System of the country and the microgrids of individual isolated consumers. The implementation of the Intelligent Power System is essential for the successful achievement of Mongolia's Energy Strategy targets, as it plays a crucial role in transforming the energy sector industries. The country's intelligent UPS should be aimed at the quantitative and qualitative economic growth of Mongolia. Innovative technological solutions should be implemented to harness intelligent microgrids, which will effectively address the social problems faced by the nomadic population in the country.

8. The studies conducted had the purpose of enhancing the environmental efficiency of power boilers by implementing new and innovative technologies for burning Mongolian coals. We have identified the key strategies for making conventional energy sources more environmentally friendly. Moreover, replacing conventional coal-fired sources with renewable energy sources on a large scale promotes a significant shift towards a greener energy sector.

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A Novel Technique for Technical and Non-Technical Power Loss Control and Monitoring in Power Distribution Systems as Based on the Data from the Automated System for Electricity Revenue Metering

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***Abstract* — Uncontrolled power losses caused by electricity thefts in power distribution systems (PDSs) have a detrimental impact on technical and economic performance of these systems. Modern automated systems for electricity revenue metering (ASERMs), which are nowadays widely used for automation and computerization of processes in PDSs, lack digital technologies for separate estimation and monitoring of technical and non-technical power losses. The paper proposes a novel technique and an algorithm for its implementation based on the data obtained from electricity meters that are part of the ASERM structure. In order to ensure the solvability of the identification problem, we introduce the concept of a virtual network model representing the desired state of the PDS in the absence of ETs. The model serves as the basis for deriving algebraic equations. Such equations allow identifying technical and non-technical power losses in three-phase networks. Our research findings aim at further improvement of modern ASERMs and enhancement of their performance and reliability.**

***Index Terms*— Power distribution system, power loss, detection and monitoring algorithm.**

I. Introduction

Automation of information processes in power distribution systems (PDSs) is currently carried out by introducing automated systems for electricity revenue metering (ASERMs) [1], which are part of the Smart Grid infrastructure [2]. As it is known, integrated software and hardware systems of ASERMs belong to the class of meter data management systems, the main function of which is revenue metering of electricity in PDSs. The analysis of the functional structure of existing ASERMs reveals that they fail to separately identify and perform real-time monitoring of technical and non-technical power losses in the network [3] and they do not carry out optimization [4–7], which compromises their efficiency and technical and economic performance of distribution utilities. This is partly due to the fact that proper and instrumental techniques have not

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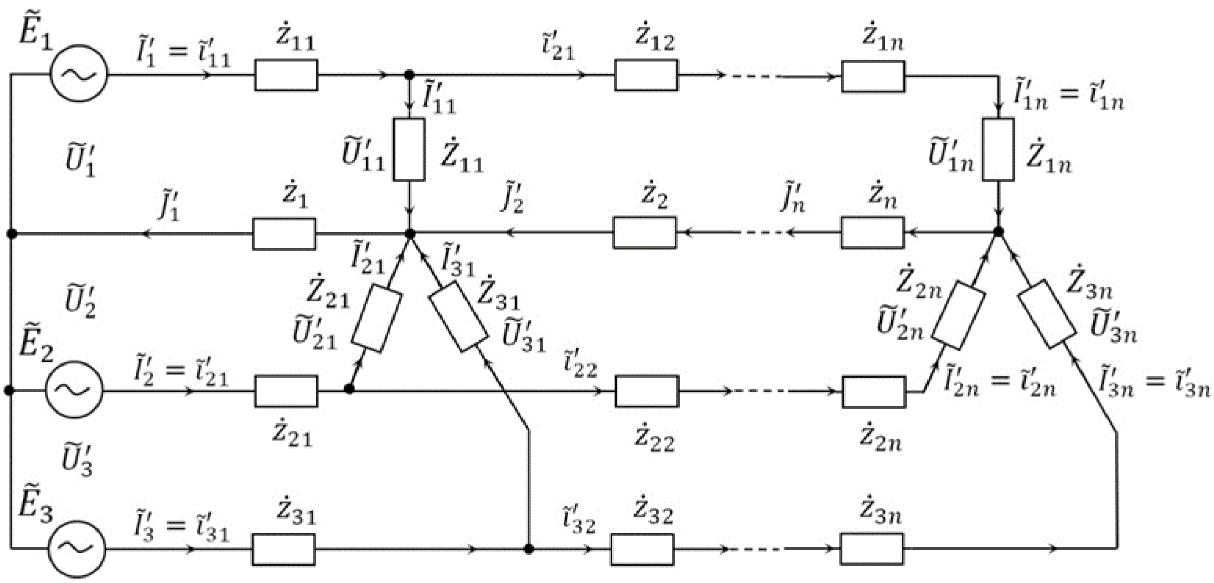


Fig. 1. Notional equivalent circuit of a three-phase network.

been sufficiently developed to solve the above problems to date. By proper techniques we understand those capable of factoring in electricity thefts (ETs) in the system [8–10] and unbalanced load flows in PDSs [11–14]. Another issue to be addressed is that most PDSs are large dynamic systems, which have a complex structure and operate under incomplete information about their states and parameters. The papers [15, 16] present several approaches to power loss detection in 0.4 kV distribution systems. This paper discusses algorithmic problems associated with elaboration of those approaches.

II. Problem Statement

The study centers on a four-wire 0.4 kV PDS, the simplified equivalent circuit of which is shown in Fig. 1. The notation used in the figure are: k, ν are index variables denoting the numbers of phases A, B, C ($k = \overline{1,3}$) and electrical circuits of the network, respectively ($\nu = \overline{1,n}$); $\tilde{E}_k$ is the instantaneous electromotive force of the power source for the k-th phase; $\tilde{I}'_{k\nu}$, $\tilde{U}'_{k\nu}$, $\dot{Z}_{k\nu}$ are instantaneous values of sine wave current, voltage, and impedance of the customer's load with the coordinate (k, ν), respectively; $\tilde{i}'_{k\nu}$, $\dot{z}_{k\nu}$ are instantaneous values of sine wave current and impedance of the ν-th inter-customer section of the k-th phase; $\tilde{J}'_\nu$, $\dot{z}_\nu$ are instantaneous values of current and impedance of the ν-th section of the neutral; $\tilde{I}'_k$, $\tilde{U}'_k$ are instantaneous values of current and voltage at the inputs of the corresponding phases.

The following conditions are assumed to be satisfied:

1. The power distribution system operates under unbalanced conditions.
2. There are electricity thefts (ETs) in the network.
3. The cross sections of the phase and neutral wires are the same, i.e., $\dot{z}_{k\nu} = \dot{z}_\nu$.
4. At a discrete moment of time $t = t_\xi$, the electricity meters of ASERM synchronously measure the effective values of currents I'_k, $I'_{k\nu}$ and voltages U'_k, $U'_{k\nu}$ at the phase inputs and at network loads, respectively. The power factors $c_k = \cos\varphi'_k$ and $c_{k\nu} = \cos\varphi'_{k\nu}$ between them are also measured. The obtained information is entered into the ASERM database and vectors of input phase currents $I' = [I'_1, I'_2, I'_3]$ are formed on their basis. The above data are used to determine the active P_k, $P_{k\nu}$ and reactive Q_k, $Q_{k\nu}$ powers consumed by phases and customers of the network, respectively, by relying on known equations.

At the time ($t = t_\xi$) of synchronized readings of electricity meters included in the ASERM, the distribution system may be in a default (normal, desired) (C^0) or disturbed (C') state. In the first case (state C^0), there are no uncontrolled power losses in the network. In the disturbed state (C') of the network, at least one of its phases has uncontrolled power losses. In this case, the following balance relations hold for powers:

$$\dot{S}_k(\xi) = \dot{S}_k^a(\xi) + \dot{S}_k^T(\xi) + \Delta\dot{S}_k(\xi),\ k = \overline{1,3}, \quad (1)$$

where $\dot{S}_k(\xi)$ is complex power consumed by the k-th phase at the time $t = t_\xi$; $\dot{S}_k^a(\xi)$ is total complex power consumed by customers of the k-th phase; $\dot{S}_k^T(\xi)$ is technical power losses in the k-th phase; $\Delta\dot{S}_k$ is uncontrolled power losses in the k-th phase of the network, caused by ETs in the PDS.

At the same time, powers $\dot{S}_k(\xi)$ and $\dot{S}_k^a(\xi)$ are known values, as existing ASERMs enable the calculation of their values from the data of active and reactive power obtained from the main electricity meter and customers' meters according to the known equations:

$$\dot{S}_k(\xi) = P_k(\xi) + jQ_k(\xi), \tag{2}$$

$$\dot{S}_k^a(\xi) = \sum_{\nu=1}^{n} \dot{S}_{k\nu},\ k = \overline{1,3}, \tag{3}$$

where $\dot{S}_{k\nu} = P_{k\nu} + jQ_{k\nu}$; $j = \sqrt{-1}$ is an imaginary number.

It is worth noting that traditional ASERMs do not detect separately technical power losses $\dot{S}_k^T(\xi)$ and non-technical power losses $\Delta\dot{S}_k(\xi)$. Existing ASERMs estimate only the sum total of power losses $\dot{S}_k^\Sigma(\xi)$ based on metering data, i.e.,

$$\dot{S}_k^\Sigma(\xi) = \dot{S}_k^T(\xi) + \Delta\dot{S}_\kappa(\xi) = \dot{S}_k(\xi) - \dot{S}_k^a(\xi), k = \overline{1,3}.$$

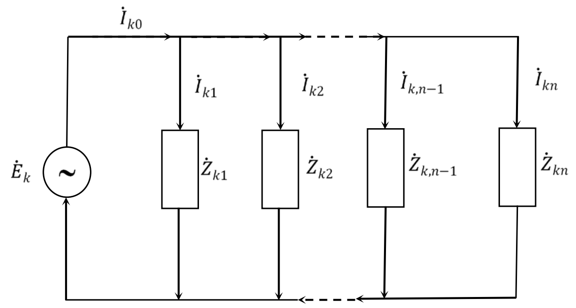
The objective is to detect non-technical $\Delta\dot{S}_k(\xi)$ and technical $\dot{S}_k^T(\xi)$ power losses in real time on the basis of metering data obtained from ASERM electricity meters.

Solving the above-stated detection problem includes the following main stages:

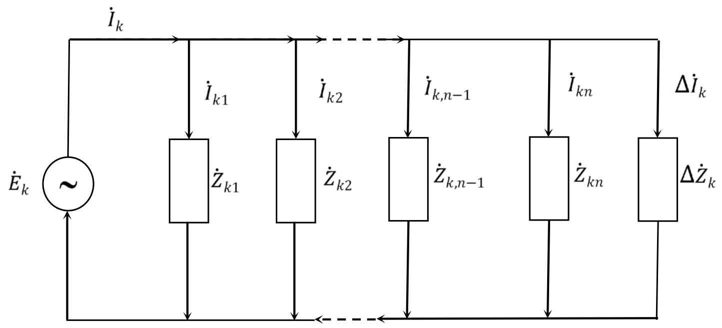
1. Build a virtual network (VN) model.
2. Identify the current state of the physical network.
3. Establish the overall procedure for power loss detection in the PDS.
4. Estimate the desired input phase currents of the virtual network.
5. Estimate currents of unauthorized consumers.
6. Design an algorithm for power loss detection in the network.

III. Building a Virtual Network Model

It is worth noting that the investigated detection problem is the one where the input data and conditions for solving it are not fully specified, i.e., the problem should be solved under insufficient information about the state of the physical network. This uncertainty is due to the lack of data



a)



b)

Fig. 2. Virtual network diagrams.

on unauthorized consumers, such as their coordinates and load parameters. In order to solve the detection problem under these conditions, we will introduce the concept of the virtual network (VN) model, which describes the desired state of the physical PDS under certain conditions. To this end, it is reasonable to introduce two types of virtual networks (Fig. 2):

1. Virtual network of the first type (VN_1) has no uncontrolled power losses $\Delta\dot{S}_k$ and zero end-to-end impedances $\dot{z}_{k\nu}$ (Fig. 2a):

$$\Delta\dot{S}_\kappa = 0,\ k = \overline{1,3},\quad \dot{z}_\nu = 0,\ \nu = \overline{1,n}. \tag{4}$$

2. Virtual network of the second type (VN_2) is the one with ETs, i.e., the following conditions are met (Fig. 2b):

$$\Delta\dot{S}_k \neq 0,\ k = \overline{1,3}, \tag{5}$$

and relations (4) hold. Here $\dot{E}_k$ is complex electromotive force of the network power source; $\dot{I}_{k\nu}$, $\dot{Z}_{k\nu}$ are complex current and load impedance of the virtual customer having the coordinate (k, ν); $\dot{I}_{k0}$, $\dot{I}_k$ are complex currents at the inputs of the k-th phase of VN_1 and VN_2, respectively; $\Delta\dot{I}_k$, $\Delta\dot{Z}_k$ are complex current and load impedance of the unauthorized consumer connected to the corresponding phase of the PDS. Next, without loss of generality of the problem and for the sake of brevity, let us consider the k-th phase of a virtual network to which n customers are connected.

Input phase currents $\dot{I}_{k0}$ of VN_1 indicate the default operation of the considered real-life distribution system with no uncontrolled currents $\Delta\dot{I}_k$. Therefore, in what follows, we will call them the desired phase currents. A comparative analysis of the structures of the original PDS (Fig. 1) and virtual networks (Fig. 2) subject to conditions (4) and (5) shows that the following relations hold for the complex currents $\dot{I}_k$, $\dot{I}_{k0}$ and $\Delta\dot{I}_k$:

$$\dot{I}_{k0} = \sum_{\nu=1}^{n} \dot{I}'_{k\nu},\ k = \overline{1,3}, \tag{6}$$

$$\dot{I}_k = \dot{I}_{k0} + \Delta\dot{I}_k,\ k = \overline{1,3}, \tag{7}$$

where $\dot{I}_k = \dot{I}'_k$.

The values of currents $\dot{I}_{k\nu}$ and voltages $\dot{U}_{k\nu}$, describing the states of virtual networks, differ from their corresponding values indicating the state of the original physical PDS (Fig. 1), i.e., $\dot{I}_{k\nu} \neq \dot{I}'_{k\nu}$, $\dot{U}_{k\nu} \neq \dot{U}'_{k\nu}$. In this case, the values of load impedances $\dot{Z}_{k\nu}$ of customers of physical and virtual networks have the same values. In what follows, the above-mentioned network variables will be expressed in a complex form as follows [17]:

$$\dot{I}_{k\nu} = I_{k\nu}\, e^{j(\beta_k + \alpha_{k\nu})}, \tag{8}$$

$$\dot{Z}_{k\nu} = Z_{k\nu}\, e^{j\varphi_{k\nu}},\ k = \overline{1,3},\ \nu = \overline{1,n},$$

where $I_{k\nu}$, $Z_{k\nu}$ are magnitudes of corresponding complex quantities; $\varphi_{k\nu}$ is the argument of impedance $\dot{Z}_{k\nu}$; $\alpha_{k\nu}$ is deviation of phase shifts from their baseline values β_k determined using the equation $\beta_k = \dfrac{2(k-1)\pi}{3}$.

Impedances $\dot{Z}_{k\nu}$ of network customers' loads are known values, which are calculated on the basis of readings (data) of customers' electricity meters by the following equations:

$$Z_{k\nu} = \frac{U'_{k\nu}}{I'_{k\nu}},\ \varphi_{k\nu} = \arccos\left(c_{k\nu}\right). \tag{9}$$

Corresponding admittances $\dot{Y}_{k\nu}$ of network customers' loads are:

$$\dot{Y}_{k\nu} = \frac{1}{\dot{Z}_{k\nu}} = Y_{k\nu} e^{-j\varphi_{k\nu}},\ k = \overline{1,3},\ \nu = \overline{1,n}, \tag{10}$$

where $Y_{k\nu} = \dfrac{1}{Z_{k\nu}}$. At the same time, the powers $\dot{S}_{k\nu}$ consumed by the network customers and included in expressions (3) are determined by the equations:

$$\dot{S}_{k\nu} = \left(I'_{k\nu}\right)^2 \dot{Z}_{k\nu},\ k = \overline{1,3},\ \nu = \overline{1,n}. \tag{11}$$

IV. Identification of the Current State of the Physical Network

Given the conditions of the stated problem, the current values of phase currents $I'_k = I'_k(t_0)$ at the input of the real-life physical distribution system (Fig. 1) at the time $t = t_0$ are measured by the main three-phase meter. These data are stored in the ASERM database in the form of the vector $I' = [I'_1, I'_2, I'_3]$. The complex currents of unauthorized consumers $\Delta\dot{I}_k$ are written in the form:

$$\Delta\dot{I}_k = \Delta I_k\, e^{j(\beta_k + \Delta\alpha_k)},\ k = \overline{1,3}, \tag{12}$$

where ΔI_k, $\Delta\alpha_k$ are magnitudes and phases of complex currents $\Delta\dot{I}_k$, respectively. Next, we will estimate the effective values of ΔI_k.

Our analysis shows that it is reasonable to use the following conditions to identify the current state of the PDS:

$$\Delta I_k \leq \Delta I,\ k = \overline{1,3}, \tag{13}$$

where ΔI is the maximum permissible error of current measurement in the ASERM.

Obviously, if at least one of the relations (13) does not hold, there are ETs in the network, whereas their validity means that the PDS operates normally. Thus, relations (13) can be used as a criterion for identification of the current state of the PDS.

V. A General Procedure for Power Loss Detection

Consideration is given to the virtual network diagrams shown in Fig. 2. We use $\dot{S}'_k$ to denote the powers consumed by the loads of the k-th phase of VN_2. The analysis shows that the following balance relations exist between powers $\dot{S}'_k$, $\dot{S}^a_k$ and $\Delta\dot{S}_k$:

$$\dot{S}^a_k + \Delta\dot{S}_k = \dot{S}'_k, \; k = \overline{1,3}, \tag{14}$$

where the total power $\dot{S}^a_k$ consumed by the loads of the k-th phase is determined by equation (3). Each of these components, when conditions (4) and (5) are satisfied, is determined by the following functional relations:

$$\dot{S}^a_k = I^2_{k0}\dot{Z}_{k0},$$
$$\dot{S}'_k = I^2_k\dot{Z}_k, \tag{15}$$
$$\Delta\dot{S}_k = \Delta I^2_k\Delta\dot{Z}_k, \; k = \overline{1,3},$$

where $\dot{Z}_{k0}$, $\dot{Z}_k$ are the impedances of the virtual phases shown in Fig. 2a and Fig. 2b, respectively; $\Delta\dot{Z}_k$ is the impedance of load of the unauthorized consumer connected to the k-th phase. Estimates of the unknown quantities included in relations (15) will be determined further on.

The corresponding admittances are determined using the following equations:

$$\dot{Y}_{k0} = \sum_{\nu=1}^{n}\dot{Y}_{k\nu},$$
$$\dot{Y}_k = \dot{Y}_{k0} + \Delta\dot{Y}_k, \tag{16}$$
$$\dot{Y}_{k\nu} = \frac{1}{\dot{Z}_{k\nu}}, \quad \Delta\dot{Y}_k = \frac{1}{\Delta\dot{Z}_k}.$$

Now, given (15) and (16), relations (14) can be written in the form:

$$I^2_{k0}\dot{Z}_{k0} + \frac{\Delta I^2_k}{\Delta\dot{Y}_k} = \frac{I^2_k}{\dot{Y}_{k0} + \Delta\dot{Y}_k}, \; k = \overline{1,3}.$$

After simple transformations, given (15), they are equivalent to the following equalities:

$$\dot{S}^a_k\left(\dot{Y}_{k0} + \Delta\dot{Y}_k\right)\Delta\dot{Y}_k + \Delta I^2_k\left(\dot{Y}_{k0} + \Delta\dot{Y}_k\right) = I^2_k\Delta\dot{Y}_k, k = \overline{1,3},$$

By transforming these relations, we can derive quadratic equations with respect to unknown admittances $\Delta\dot{Y}_k$ of loads of unauthorized consumers:

$$a_k\left(\Delta\dot{Y}_k\right)^2 + b_k\Delta\dot{Y}_k + c_k = 0, \; k = \overline{1,3}, \tag{17}$$

where the coefficients a_k, b_k, c_k are determined by the equations:

$$a_k = \dot{S}^a_k,$$
$$b_k = \dot{S}^a_k\dot{Y}^0_k + \Delta I^2_k - I^2_k,$$
$$c_k = \Delta I^2_k\dot{Y}^0_k.$$

To solve the quadratic equations (17), we can use the well-known Vieta's formula:

$$\Delta\dot{Y}_k = \frac{-b_k \pm \sqrt{b^2_k - 4a_kc_k}}{2a_k}, \; k = \overline{1,3}. \tag{18}$$

Given (15), the coefficients b_k and the products of a_k and c_k are real values, i.e.,

$$b_k = I^2_{k0} + \Delta I^2_k - I^2_k,$$
$$a_kc_k = I^2_{k0}\Delta I^2_k, \; k = \overline{1,3},$$

which simplifies the process of solving equations (17).

As a result, the required load impedances $\Delta\dot{Z}_k$ of unauthorized consumers are calculated as follows:

$$\Delta\dot{Z}_k = \frac{1}{\Delta\dot{Y}_k}, \; k = \overline{1,3}. \tag{19}$$

Then the required values of power losses $\Delta\dot{S}_k$, caused by electricity thefts in the phases of the physical network, given (8), are calculated by the equations:

$$\Delta\dot{S}_k = \frac{\Delta I^2_k}{\Delta\dot{Y}_k}, \; k = \overline{1,3}, \tag{20}$$

where the effective values of currents of unauthorized consumers ΔI_k will be determined below.

Now, based on the balance relations (1), we determine the values of technical power losses $\dot{S}^T_k$ in the phases of the physical network:

$$\dot{S}^T_k(\xi) = \dot{S}_k(\xi) - \dot{S}^a_k(\xi) - \Delta\dot{S}_k, \; k = \overline{1,3}, \tag{21}$$

where $\dot{S}_k(\xi)$ is the complex power consumed by the k-th phase of the physical network at the time $t = t_\xi$, which is calculated from the data of the main three-phase electricity meter by equations (2).

Let us assume that data from ASERM meters are collected at discrete moments of time $t = t_\xi$, $t = t_{\xi+1}$, $t = t_{\xi+2}$, …, $t = t_{\xi+m}$. Then the above computational procedure based on these data enables automated real-time control and monitoring of power losses in PDSs.

VI. Estimation of Desired Input Phase Currents of the Virtual Network

To calculate the effective values of the desired input phase currents I_{k0} in VN_1, the first relations of system (15) are written in the form:

$$\dot{S}_k^a = \frac{I_{k0}^2}{\dot{Y}_{k0}}, \; k = \overline{1,3}. \quad (22)$$

Next, the complex quantities $\dot{S}_k^a$ and $\dot{Y}_{k0}$ are expressed in their exponential form:

$$\dot{S}_k^a = S_k^a e^{j\varphi_k^a}, \quad (23)$$

$$\dot{Y}_{k0} = Y_{k0} e^{-j\varphi_k^a}, \; k = \overline{1,3},$$

where S_k^a, Y_{k0}, φ_k^a are the magnitudes and phases of the complex quantities $\dot{S}_k^a$ and $\dot{Y}_{k0}$, respectively.

Relations (22), given (23), have the form:

$$S_k^a e^{j\varphi_k^a} = \frac{I_{k0}^2}{Y_{k0}} e^{j\varphi_k^a}, \; k = \overline{1,3}. \quad (24)$$

Based on equalities (24), we obtain the required numerical values of the desired input phase currents I_{k0} of the virtual network, since S_k^a and Y_{k0} are known quantities:

$$I_{k0} = \sqrt{S_k^a Y_k^a} = \sqrt{\frac{S_k^a}{Z_k^a}}, \; k = \overline{1,3}. \quad (25)$$

VII. Estimation of Currents of Unauthorized Consumers

To estimate the currents of unauthorized consumers, relations (7) are used to write the expressions for complex currents $\Delta\dot{I}_k$ of unauthorized consumers:

$$\Delta\dot{I}_k = \dot{I}_k - \dot{I}_{k0}, \; k = \overline{1,3}. \quad (26)$$

Provisionally, these currents will be expressed in an exponential form:

$$\dot{I}_k = I_k e^{j(\beta_k + \alpha_k)},$$

$$\dot{I}_{k0} = I_{k0} e^{j\left(\beta_k + \alpha_k^0\right)},$$

where I_k, I_{k0}, α_k, α_k^0 are the effective values and phase shifts of the corresponding complex currents.

The following expressions can be written for the squares of the effective values of the unknown currents ΔI_k of unauthorized consumers:

$$\Delta I_k^2 = \left(\dot{I}_k - \dot{I}_{k0}\right)\left(\dot{I}_k - \dot{I}_{k0}\right)^* = \left(\dot{I}_k - \dot{I}_{k0}\right)\left(\dot{I}_k^* - \dot{I}_{k0}^*\right) =$$
$$= \dot{I}_k \dot{I}_k^* + \dot{I}_{k0}\dot{I}_{k0}^* - \left(\dot{I}_k \dot{I}_{k0}^* + \dot{I}_{k0}\dot{I}_k^*\right), \quad k = \overline{1,3}.$$

The components of these expressions are determined by the equations:

$$\dot{I}_k \dot{I}_k^* = I_k^2, \; \dot{I}_{k0}\dot{I}_{k0}^* = I_{k0}^2,$$

$$\dot{I}_k \dot{I}_{k0}^* + \dot{I}_k^* \dot{I}_{k0} = I_k I_{k0}\left(e^{j\left(\alpha_k - \alpha_k^0\right)} + e^{-j\left(\alpha_k - \alpha_k^0\right)}\right) =$$
$$= 2 I_k I_{k0} \cos\left(\alpha_k - \alpha_k^0\right).$$

Hence, we obtain expressions for the squares of the sought currents ΔI_k^2:

$$\Delta I_k^2 = I_k^2 + I_{k0}^2 - 2 I_k I_{k0} \cos\left(\alpha_k - \alpha_k^0\right), \quad k = \overline{1,3}.$$

Similarly, given (12), we obtain expressions for the squares of the currents I_k^2 and I_{k0}^2:

$$I_k^2 = I_{k0}^2 + \Delta I_k^2 + 2 I_{k0}\Delta I_k \cos\left(\alpha_k^0 - \Delta\alpha_k\right),$$

$$I_{k0}^2 = I_k^2 + \Delta I_k^2 - 2 I_k \Delta I_k \cos\left(\alpha_k - \Delta\alpha_k\right), \; k = \overline{1,3}.$$

Next, we introduce the following phase shift differences:

$$\eta_k = \alpha_k^0 - \Delta\alpha_k, \quad \lambda_k = \alpha_k - \Delta\alpha_k,$$
$$\theta_k = \lambda_k - \eta_k, \quad k = \overline{1,3}.$$

where $\alpha_k - \alpha_k^0 = \lambda_k - \eta_k$.

Based on the expressions obtained for the squares of the currents ΔI_k^2, I_k^2, and I_{k0}^2, we can write the following equations:

$$\begin{aligned} &\Delta I_k^2 - I_k^2 - I_{k0}^2 + 2 I_k I_{k0} \cos\theta_k = 0, \\ &I_k^2 - I_{k0}^2 - \Delta I_k^2 - 2\Delta I_k I_{k0} \cos\eta_k = 0, \\ &I_{k0}^2 - I_k^2 - \Delta I_k^2 + 2\Delta I_k I_k \cos\lambda_k = 0. \end{aligned} \quad (27)$$

The entire set of relations (27) is a system of algebraic equations, which includes three equations with three unknown quantities ΔI_k, η_k and λ_k. The analysis of relations (27) indicates that the sought currents ΔI_k are determined by solving the following equations:

$$\Delta I_k^4 + e_k \Delta I_k^2 + r_k^2 +$$
$$+ q_k \sqrt{\Delta I_k^8 + m_k \Delta I_k^6 + d_k \Delta I_k^4 + s_k \Delta I_k^2 + r_k^4} = 0, \quad (28)$$
$$k = \overline{1,3}.$$

where their coefficients are known quantities determined by the equations:

$$e_k = -2 f_k, \; f_k = I_k^2 + I_{k0}^2,$$
$$r_k = I_k^2 - I_{k0}^2, \; m_k = -4 f_k,$$
$$d_k = 16 I_k^2 I_{k0}^2 + 6 r_k^2, s_k = -4 f_k r_k^2.$$

The sign function q_k is selected as follows:

$$q_k = \begin{cases} +1, \text{ if } \operatorname{sign}\left(\Delta I_k^4 + e_k \Delta I_k^2 + r_k^2\right) < 0, \\ -1, \text{ if } \operatorname{sign}\left(\Delta I_k^4 + e_k \Delta I_k^2 + r_k^2\right) > 0. \end{cases}$$

Solving the algebraic equation (28) for a given k is not particularly difficult if numerical methods are used [18–20], since its approximate solution ΔI_{k0} can be obtained on the basis of relation (26), i.e., $\Delta I_{k0} = I_k - I_{k0}$.

VIII. General Algorithm for Power Loss Detection in the Network

Based on the obtained results, we can formulate the following high-level algorithm for power loss detection and monitoring in distribution systems.

1. Poll cyclically the main three-phase electricity meter and customers' electricity meters of ASERM at a discrete instant of time $t = t_\xi$.
2. Enter the received information into the ASERM database and build vectors $I' = [I'_1, I'_2, I'_3]$.
3. Calculate impedances $\dot{Z}_{k\nu}$ and admittances $\dot{Y}_{k\nu}$, as well as complex powers $\dot{S}_{k\nu}$ consumed by the network customers, using equations (9)–(11), respectively.
4. Estimate total powers $\dot{S}_k^a$ and impedances $\dot{Z}_k^a$ using equations (3) and (24), respectively.
5. Determine desired input phase currents I_{k0}, $k = \overline{1,3}$, using equations (25).
6. Find the values of uncontrolled currents ΔI_k, $k = \overline{1,3}$, by solving the algebraic equations (28).
7. Check the current state of the PDS by checking conditions (13).
8. When conditions (13) are satisfied, there are no ETs in the network. Go to Step 1. Otherwise, go to Step 9.
9. Calculate admittances $\Delta\dot{Y}_k$ by solving equations (17).
10. Estimate non-technical $\Delta\dot{S}_k$ and technical $\dot{S}_k^T$ ($k = \overline{1,3}$) power losses in the PDS using equations (20) and (21), respectively, at time $t = t_\xi$.
11. Go to step 1 and repeat the computational procedure for successive instants of time $t = t_{\xi+m}$, where $m = 1, 2, 3, \ldots$

IX. Conclusion

The operating practices of modern automated systems for electricity revenue metering, which are used to control and measure electric power in 0.4 kV power distribution systems, demonstrate a noticeable lack of digital technologies. That means that they are unable to provide real-time detection and monitoring of power losses with separate detection and estimation of technical and non-technical losses. This paper introduces a novel approach to address this issue, utilizing a virtual model of the power distribution system. The virtual model describes the desired state of the power distribution system in the absence of external random factors, which, in particular, include electricity thefts. This model utilizes metering data received via communication links from electricity meters installed in the transformer substation and at network customers. The systems of algebraic equations are obtained to describe functional relations between variables and parameters of the virtual model of a three-phase network. We proposed the techniques to solve these equations and a generalized algorithm to detect and monitor technical and non-technical power losses in power distribution systems. The findings of this research will be used to advance the development of algorithmic and specialized software for the subsystem of real-time power loss monitoring in PDSs as part of the ASERM.

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Impact of Integrated Renewable Energy Sources with Variable Power Output in Terms of Constrained Voltage Stability Limit

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***Abstract* — The paper is concerned with the development of a methodology for estimating the amount of balancing power in a system with a high penetration of renewable energy sources. To this end, it is crucial to analyze the influence of growing installed capacity of wind farms on the value of the balancing power of the energy system and random characteristics of its variability for various numbers of wind farms operating in the system. The possibilities of balancing power distribution are considered for characteristic critical load conditions of the system. The operating conditions of a real-world power system are simulated using wind speed measurement data obtained for the geographical locations of wind farms. The simulation is performed on a PC using developed programs for various combinations of these farms. The research involves constructing the relationships for the balancing power, determining the conditions for its reduction and the conditions for its limitation in terms of voltage stability in the balancing part of the system.**

***Index Terms* — power system, variable renewable energy sources, balancing power, load flow in the electrical network, voltage stability.**

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I. Introduction

The increasing share of renewable generation has significantly changed the approaches to the technological implementation of balancing power in the modern energy system. As a result, along with traditional sources that have a preset specific character of power generation, modern energy systems have renewable sources operating in parallel. A substantial proportion of the renewable sources are wind turbines and solar PV electrical systems with variable (randomly indefinite) output. A balancing source (BS) to be chosen under these conditions should with a high probability provide the absolute range of variability of power generation (MW), as well as the average value of the rate of power generation increase (MW/min).

In addition, it is also crucial that a balancing source is chosen so as to ensure the system stability for each range of variability of balancing source generating capacity.
The production of electrical energy by renewable sources depends on weather conditions and load [1–3].

Continuous spatio-temporal balancing of the magnitude of deviations between supply and demand in the power system enables a stable and reliable power supply. However, it is not possible based only on measurements of random processes of power generation from wind and solar sources to accurately build a model of the magnitude of their variability [4].

The rise in the number of renewable energy sources connected directly to the buses of the load node of the electrical network in the power system makes the consumption prediction highly uncertain [5]. Electrical energy storage devices (battery systems) are used when there is insufficient power generation to cover the load of the node to which they are connected [6].

The random and intermittent nature of power generation from wind farms and solar power plants (SPPs) requires selecting a source to balance (compensate for) the random share of power generation from them. In most cases, one or two of the existing traditional power plants are selected as balancing sources, which allocate part of their total generated power to compensate for the surplus or shortage of power output from the wind farm and solar power plants integrated in the system.

The choice of the value of the preset power for the balancing plant enables optimal load distribution between the plants in various periods of the daily load curve, control of the power flow in the electrical network of the power system, and effective utilization of the power output from wind farms and solar power plants.

Preliminary results of the research demonstrate that for the energy system of Azerbaijan, the gas turbine stations Shirvan and Sumgait, which are connected to 110 kV distribution networks, can be considered as balancing ones. These stations are also connected to the system's supply network through 220 kV lines. It was established that the probability of line overload in distribution networks due to fluctuations in the power generation from wind and solar power plants is small, which leads to a slight reduction in their generation.

Power systems with a high share of integrated renewable energy sources [7–11] present a challenge for dispatchers due to the intermittency of their power output and limited predictability. At some point, the operator may be forced to reduce wind and solar generation relative to current generation. This amount of reduction in the output from wind and solar energy conversion can be considered as an opportunity to cut down the total generation in the system. Thus, limitations arise when transmitting power through the supply network or when balancing power in the distribution network between incoming and consumed power [7, 8, 12]. Therefore, it is necessary to boost the flexibility of the power system in order to increase variable renewable generation while compensating for the intermittent power generation from renewable sources [8, 13, 14]. Some conventional power plants are unable to quickly adapt the control of their output in the system due to technical or economic limitations [4].

Operating restrictions are related to the load increase rate, start-up duration, and the magnitude of the minimum load [8, 13, 14].

According to the above restrictions and purposes of operational control, power plants can be classified into those not participating in the control process, those used in certain situations, and those completely involved in control to provide power flow in the system [15, 16].

The power generation from wind and solar power plants is intermittent and probabilistic, which does not allow system dispatchers to involve these plants in operational control of the power system. Power plants that do not participate in the operational control of the energy system usually include nuclear power plants and thermal power plants, i.e., those meeting the basic part of the total demand of the power system. Power plants with traditional technology (gas turbine, hydroelectric power plants) and all other renewable sources (except for wind and solar) are involved in the power flow control in the system.

The steady-state voltage stability of the power system, which can be compromised primarily due to overloading of backbone power lines or insufficient means of the active and reactive power flow control in the electrical networks of existing traditional power systems, faces new problems caused by the large-scale integration of variable renewable generation. This paper proposes a method for assessing the steady-state voltage stability in a system with a large portion of power generation from wind and solar plants. This study examines the influence of the number of operating wind farms and solar power plants on the operation of the balancing source in order to determine the amount of power to be generated by it to maintain voltage stability. An analytical criterion is derived to ensure voltage stability on the buses connecting wind farms and solar power plants to the system for their various power outputs and their shares of participation in the total demand at current time points. A methodology for optimal system planning is proposed to minimize power generation from a balancing station by optimally distributing active and reactive power generation between renewable sources.

II. Modeling the Estimation of the Balancing Power Reserve in a Power System with Renewable Energy Sources

Integration of RES into the energy system enhances the uncertainty of the generated power and, together with the effect of load uncertainty, makes it impossible to strictly deterministically describe the amount of balancing power. In general, the amount of balancing power can be determined from the following equality:

$$0 = P^{t_i}_{conv.s.} + P^{t_i}_{RES} - P^{t_i}_{load} - \Delta P^{t_i} + P^{t_i}_{b.p.}, \quad (1)$$

where $P^{t_i}_{conv.s.}$, $P^{t_i}_{RES}$ are power of conventional and renewable sources in the interval of the daily load curve; $P^{t_i}_{load}$ is load power in the balancing part of the power system in interval t_i; ΔP^{t_i} is electrical network losses; $P^{t_i}_{b.p.}$ is the value of balancing power.

In equation (1), $P_{conv.s.}$, P_{RES}, P_{load} are specified based on the measurements obtained during a long period of system operation. Balancing power and network losses ΔP, $P_{b.p.}$ are desired parameters.

To solve equation (1) with stochastic set input parameters $P_{conv.s.}$, P_{RES}, P_{load}, the latter are specified by limits of their range of variation in the form of inequality equations, for example

$$P_{\min,RES} \le P_{RES} \le P_{\max,RES}, \quad (2)$$

$P_{\min,RES}$, $P_{\max,RES}$ are set at the stage of preliminary analysis of stochastic variables P_{RES}.

Thus, the estimation of balancing power $P^{i}_{b.p.}$ in each interval [0, t_i] is reduced to solving a stochastic system of equations (1) subject to

$$P^{t_i}_{\min,RES} \le P^{t_i}_{RES} \le P^{t_i}_{\max,RES}.$$

III. Studies on the Influence of Renewable Energy Sources on the Power Balance in the Azerenergy System

Due to the unpredictable nature of renewable energy sources (RES) generation, the probabilistic approach is used to determine the power reserve needed to balance supply and demand. The use of stochastic approach to choose balancing power is associated with a probabilistic analysis of observational data on wind speeds and solar radiation over a long observation period. This approach is also important to obtain a robust estimate of the characteristics of their distribution and to design a predictive model of power generation from wind plants in the geographical area under study, and other parameters. At the same time, it is also crucial to have data on the nature of the stochastic variability of the system load.

Determining the balancing power for steady-state post-emergency conditions (after failures of generators and power lines) will require an analysis of stability limits for the system under these operating conditions. The value of the balance during periods of critical conditions, in contrast to the existing deterministic approach, must be probabilistically estimated considering the uncertainty of the expected emergency conditions. This paper proposes a method for statistically assessing the limit of steady-state voltage stability for N-1 and N-2 states of the system.

The paper presents the results of the power balance calculation in the national energy system of Azerbaijan with various combinations of RES-based power plants for normal and post-emergency steady-state conditions and various states during emergency shutdowns of system components. Given that the basic part (80% of the installed capacity) of the power plants consists of thermal power plants, which are expected to be used to place the capacity reserve to cover the imbalance caused by renewable energy sources, the placement of the capacity reserve and the determination of strategies to manage power flow in the network are significant factors.

In 2025, Azerenergy plans to put into operation three wind farms in the system: 240 MW Khyzi wind farm (conventionally named Baku wind farm), 220 MW Janub wind farm (Lankoran), and 240 MW Shimal wind farm (Maraza).

Assessment of balancing power and analysis of power flow in the Azerenergy system for the case of commissioning the above variable renewable energy sources involved modeling and computer tests for the following options:

- the Baku wind farm is connected to the system;
- the Maraza wind farm is connected to the system;
- the Lankoran wind farm is connected to the system;
- the Baku wind farm + Lankoran wind farm are connected to the system;
- the Baku wind farm + the Maraza wind farm are connected to the system;
- the Baku wind farm + Lankoran wind farm + Maraza wind farm are connected to the system.

Figure 1 shows the balancing and synchronous parts of the Azerenergy system. In the synchronous part, the

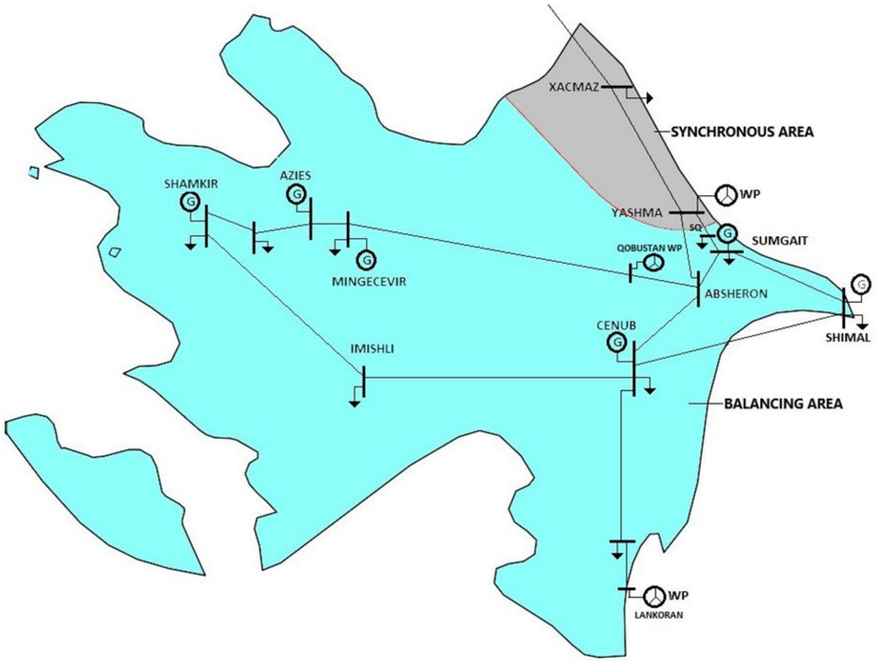


Fig. 1. Balancing and synchronous areas.

Azerenergy system is connected to the Russian unified power system by a 330 kV power transmission line Khachmaz–Darbend. This line is used to eliminate active power imbalance and to control frequency.

Figures 2a, 2b show the probability distribution function of the wind farm power prediction error for various values of the power output. When solving the problem of integrating renewable energy sources and estimating the capacity reserve at the nodes to which they are connected, it is crucial to correctly determine errors in their power output prediction as the errors affect the determination of the balancing power. As seen from Fig. 2, there is a gradual decrease in the magnitude of the error in different options for connecting wind farms, which reduces the error in determining the balancing power.

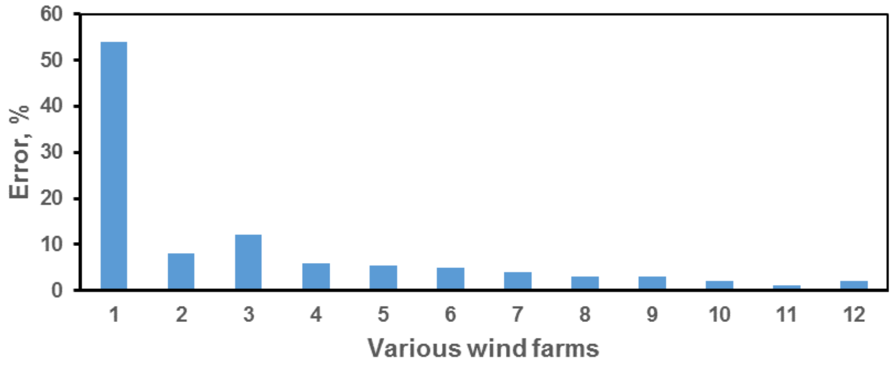
Figure 3a indicates a reserve for balancing power in the energy system of Azerbaijan for each case of the wind farm location, including the Baku wind farm, Lankoran wind farm, and Maraza wind farm. Figures 4–6 show the change in wind speed in the areas of Baku, Maraza, and Lankoran.

Figure 7 shows the average seasonal wind speeds for individual areas in which wind farms are installed. As seen from the figure, placement of wind farms in these areas is feasible and their integration into the system needs appropriate power flow studies in terms of power system stability.

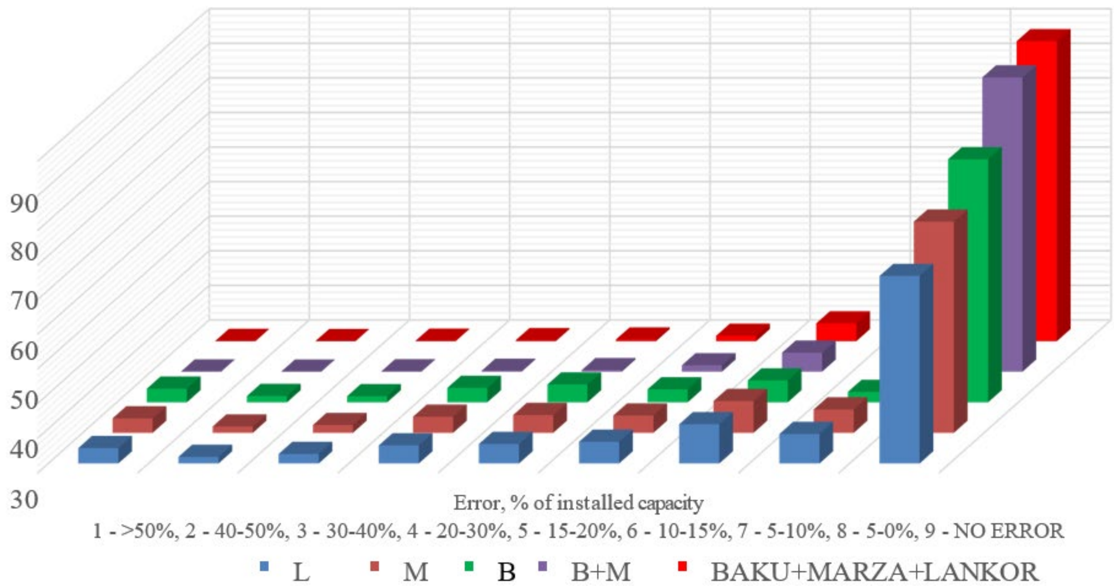
IV. Impact of Renewable Energy Sources on Steady-State Stability When Balancing Power

The need to analyze the impact of RES on steady-state stability of Azerbaijan's energy system when providing the operational control of the selected value of the balancing power reserve is caused by the large proportion of power generated from wind farms (up to 20% of the installed capacity of conventional power plants). Long-term observations of climatic conditions show that in some areas of Azerbaijan, the electrical energy produced by wind turbines in some periods of time can have a large amplitude due to the characteristic features of the dynamics of the energy potential of wind speeds. This study employs the method of sequential increase in the load at each stage of the balancing power reserve implementation to assess the limit of voltage stability in the balancing part of the power system (Fig. 1) [6].

Figure 8 shows the *U–P* relationship curves for power transmission along a 220 kV power transmission line during the hours of evening peak load. The total output from all wind farms is about 340 MW, which is about 10% of the total demand of the system. As was established earlier [3], when three wind farms (Baku, Maraza, and Lankoran) operated together, the total reserve was about 25% of the installed capacity of the wind farms (≈ 80–85 MW).



(a)



(b)

Fig. 2. Distribution of wind farm power prediction error probability for various levels of power output.

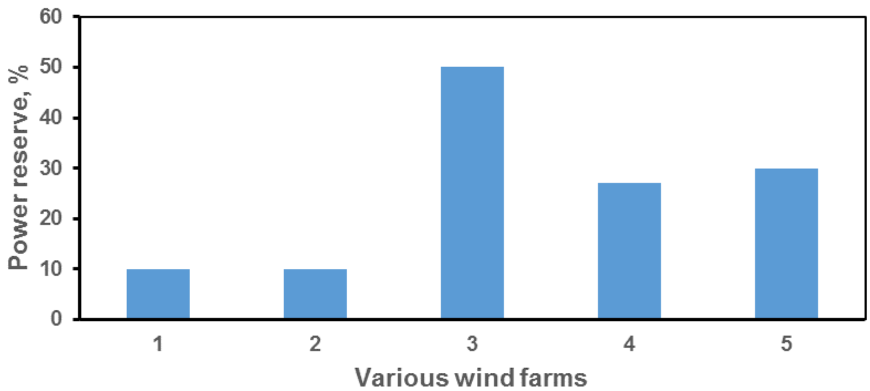


Fig. 3. Reserve for balancing power in the energy system of Azerbaijan for each location of wind farms (Baku, Maraza, Lankoran) and their combinations; 1 – Lankoran; 2 – Maraza; 3 – Baku; 4 – Baku+Maraza; 5 – Baku+Maraza+Lankoran.

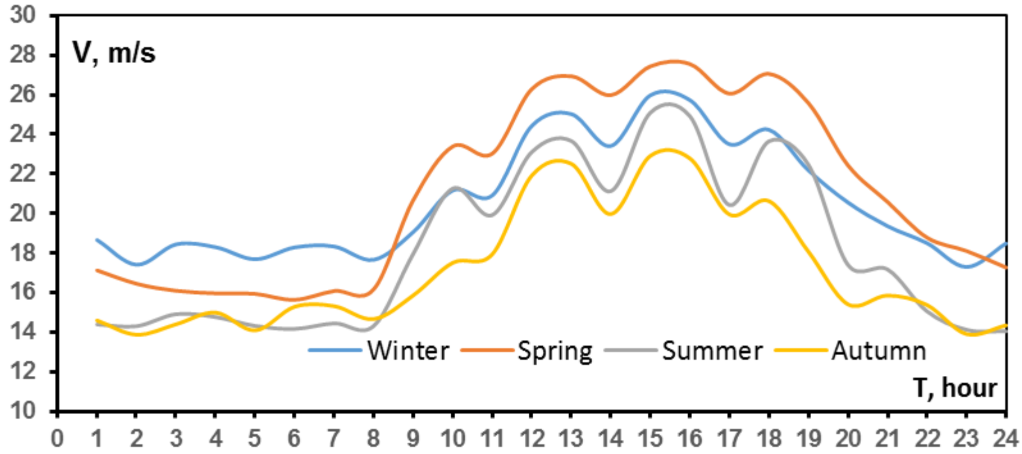


Fig. 4. Hourly changes in wind speed in the area of the Baku wind farm.

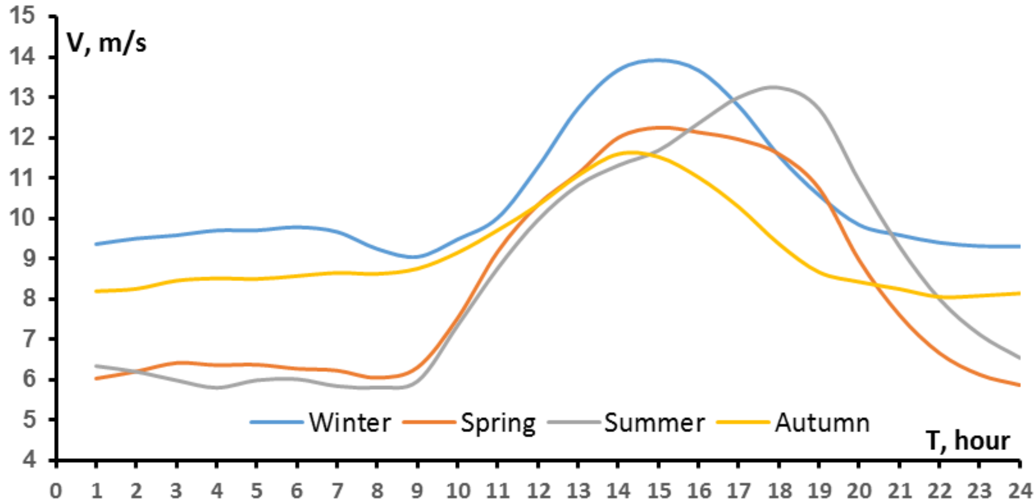


Fig. 5. Hourly changes in wind speed in the area of the Maraza wind farm.

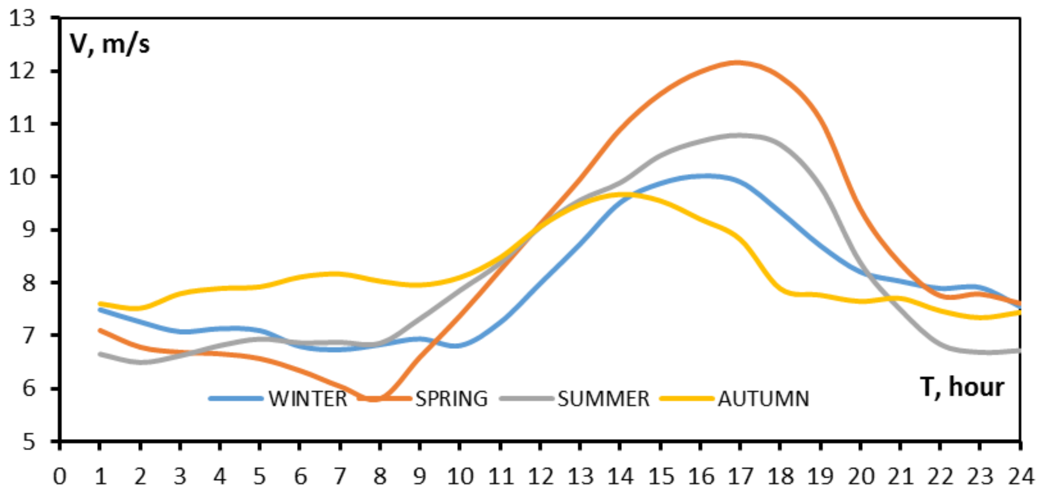
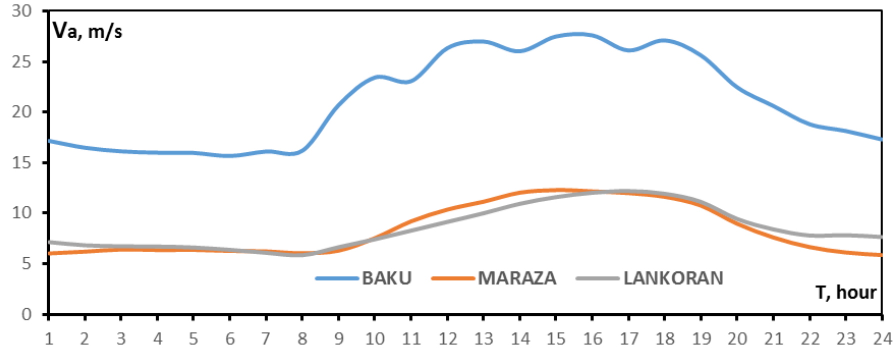
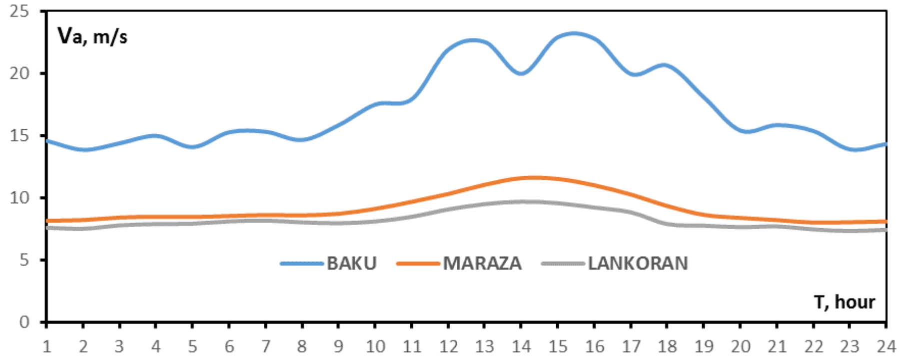


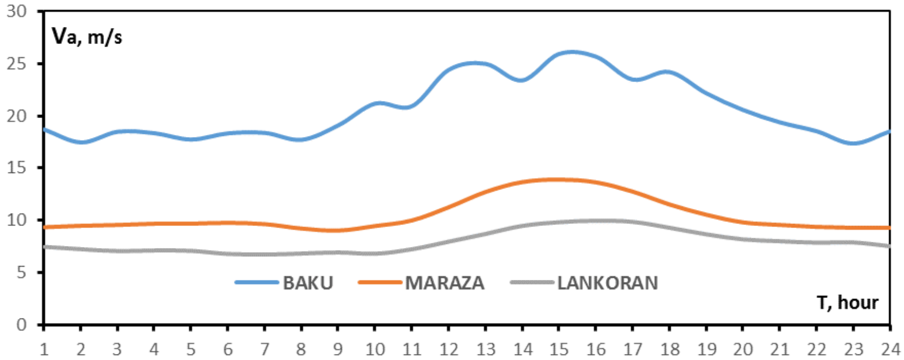
Fig. 6. Hourly changes in wind speed in the area of the Lankoran wind farm.



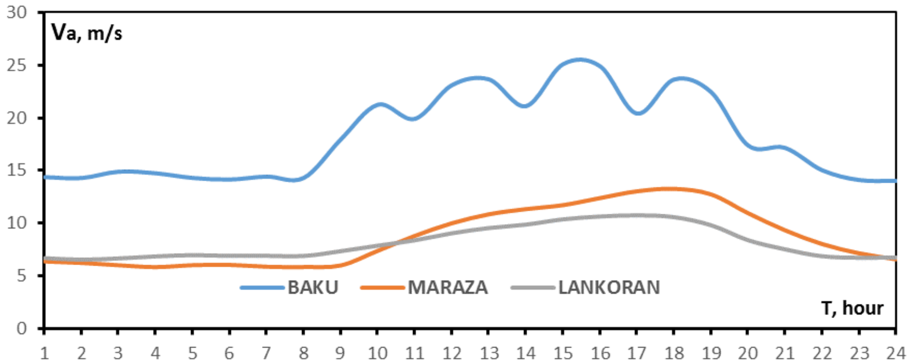
(a)



(b)



(c)



(d)

Fig. 7. Average seasonal wind speeds for selected areas: a – average wind speed in spring; b – average wind speed in autumn; c – average wind speed in winter; d – average wind speed in summer.

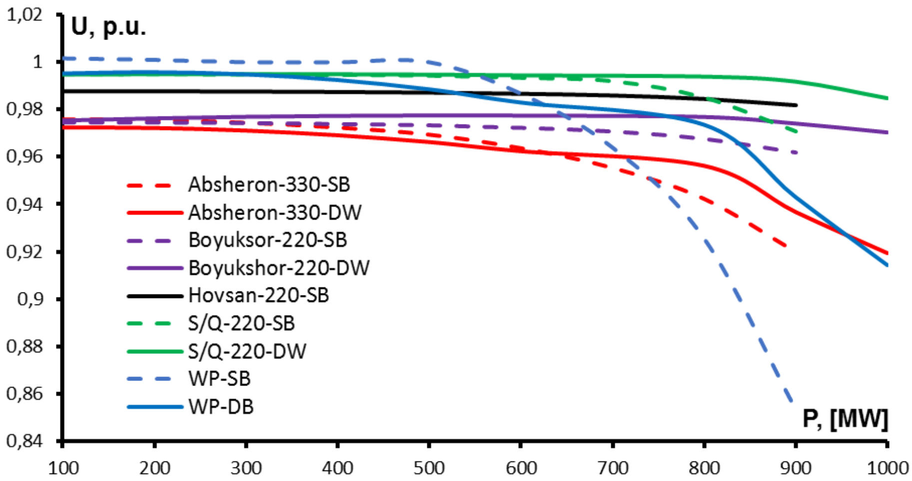


Fig. 8. The U–P relationship curves for power transmission along 220-330 kV power lines during evening peak load hours.

It is important to emphasize that if the total output from wind farms is reduced by 30–40%, i.e., by more than 85 MW, the power reserve will keep the voltage of the controlled power transmission line within the permissible critical values. Voltage collapse is possible only for one backbone line – the S/Q-220-SB line. To eliminate this risk of voltage instability, appropriate technical measures must be taken.

In addition, (Fig. 8), when the total integrated wind power is 700 MW (240+240+220 MW), voltage stability on power lines is maintained even for the S/Q-220-SB line (which is in a relatively heavy-load state) and voltage values higher than 0.97 U_{nom} are ensured. Therefore, at the first stage of integration of large powerful wind farms, the voltage stability condition is satisfied at all nodes of the power system.

V. Conclusion

1. The growing integration of renewable energy sources heightens the need for power reserve to cover the imbalance between power supply and demand. The stochastic variability of wind energy sources requires considering the influence of several factors when choosing the value of power reserve to compensate for the imbalance. These are the errors in the prediction of power generation from wind farms and solar power plants and the errors in the calculation model of balancing reserves, which affect the limit value of the reserve for balancing the deviation between total generation and consumption.

2. The paper proposes an approach to estimating the reserve for balancing active power in a system with a dominant share of renewable energy sources in a 30-minute interval of stochastic changes in power generated from wind turbines, stochastic load changes, and random emergency failures of conventional generators and power lines of the supply network. The proposed approach factors in the dynamics of changes in balancing power depending on the error in prediction of the discrepancy between the power generated by RES and power consumed.

3. The computational and experimental studies in a real-world power system have revealed the opportunity to significantly reduce the need for power reserve by increasing the number of wind farms connected to the backbone network at its different nodes. The effects of wind farms of identical power at different points of the power system diagram can be different and the amount of balancing power required depending on these effects can vary significantly.

Acknowledgements

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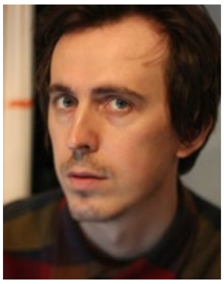

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Ensuring Reliability and Sustainable Development of the Central Asian Power System in the Context of Growing Energy Consumption

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***Abstract* — A set of necessary conditions for sustainable development of the Central Asian Power System (CAPS) is considered with an emphasis on economic, environmental, and social aspects against the backdrop of widespread integration of renewable energy sources (RES). Such conditions are provided for by the decisions of the governments of the countries in the region in the context of growing energy consumption. The efficiency of utilizing renewables in Central Asia is assessed. The findings highlight primary scientific and engineering issues related to the large-scale use of renewables in the power system and ways to address them. The use of energy storage facilities in power systems of the Central Asian countries, as well as the joint implementation of renewables and energy storage systems in the CAPS are discussed.**

***Index Terms* — power system, reliability, system accident, renewable energy, energy storage.**

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I. Introduction

In today's world, sustainable development of the Central Asian Power System (CAPS) requires a comprehensive approach. Such an approach should include several key conditions to balance energy demand and economic, environmental, and social aspects.

At the same time, there is more to power systems than the necessity to efficiently utilize available energy resources when energy consumption grows. Strengthening energy security, reducing reliance on limited natural resources or suppliers, and lowering greenhouse gas emissions from electricity generation require addressing a wide range of issues. These include diversification of energy sources, adoption of renewables, utilization and advancement of energy storage technologies as well as the use and development of methods for bolstering energy efficiency, increasing energy conservation, and managing load.

The energy profile of Central Asian countries for 2019 is given in Table 1 [1].

Table 1 shows that a significant percentage of electricity in some of CA countries is generated by thermal power plants running on fossil fuels.

To give an example, CO_2 emissions in Kazakhstan in 2021 amounted to 0.56% of the total emissions in the world and the country ranked 31st in the world with respect to this metric [2]. This is primarily due to the fact that coal-fired generation in the country is the dominant technology of electricity and heat generation. Its share is about 70%. In 2021, coal accounted for more than half of the country's domestic consumption of primary energy resources, according to the Kazakhstan Electricity and Capacity

TABLE 1. Concise Energy Profile of Central Asian Countries for 2019

Country	Kazakhstan	Kyrgyzstan	Tajikistan	Turkmenistan	Uzbekistan
Installed net capacity of power plants, MW	23 965	3 869	6 451	5 201	15 948
TPPs running on fossil fuels, %	83.8	19.0	11.1	100	88.0
Gross electricity generation, mln kWh	106 879	15 100	20 676	22 534	63 021
Electricity generation by TPPs, %	89.2	8.3	7.3	100	89.7

Market Operator. Moreover, most of the coal burned at TPPs comes from the Ekibastuz coal basin and is characterized by high ash yield (over 40%), which makes its beneficiation unprofitable. However, the low cost of such coal makes electricity cheap, thus ensuring the competitiveness of Kazakhstan's economy. This is facilitated by the energy infrastructure that has been developing in the country for decades.

At the same time, main and auxiliary equipment of TPPs in Kazakhstan is highly worn out. On average, wear and tear have reached 66% in the country, and in the case of TPPs located in some large cities, they even exceed the critical level of 80% [3]. By 2035, Kazakhstan plans to ensure new capacity additions of 17.5 GW in total [4].

In Uzbekistan, the share of CO_2 emissions in 2021 was 0.56% of total emissions in the world and the country ranked 42nd in the world with respect to this metric [1]. The energy sector is the leader in greenhouse gas emissions in the country, accounting for 80% of total emissions. A significant part of TPP units commissioned in Uzbekistan in the middle of the last century have reached the end of their useful fleet lives, are energy inefficient and do not meet energy efficiency requirements. By 2030, Uzbekistan plans to commission 15.6 GW of new and modernized generation capacity and decommission 6.4 GW of obsolete generation capacity at TPPs [5].

At the same time, Central Asia has recently experienced increasingly more acute power shortages. For example, Kazakhstan has faced major power shortages in the past two years, especially during peak load hours. In 2022, power shortages were recorded for a period of 8 months. According to the projection of the Ministry of Energy of the Republic of Kazakhstan for 2023–2029, the amount of electricity used in the country will increase by an average of 3% annually, but the projection assumes that the balance of production and consumption in the electricity sector for the next seven years will be negative. Last winter, Kyrgyzstan started to switch off electricity to reduce its consumption. The electricity shortage was caused by the lack of necessary generation capacity in the country. Furthermore, this year, the country may also face a significant electricity shortage of as much as 1.9 billion kWh. The current situation is similar in Uzbekistan. Power outages lasting for hours are quite frequent there due to the energy shortage in the country. During winter peak load, there is a recurring electricity shortage of approximately 18–20 million kWh.

According to the projections of the International Energy Agency (IEA) for 2023–2025, demand for electricity in Uzbekistan is expected to grow by 3% annually, while the annual growth rate in Kazakhstan will be 1.7% [6]. Projections until 2030 show that the annual growth of electricity consumption in Uzbekistan will be about 6–7% [5]. The increase in electricity consumption requires accelerated construction and commissioning of new generation capacity and expansion of power grids in the region. Given that different countries in the region are planning a large-scale use of renewables, it is imperative to make a preliminary assessment of the efficiency of the energy resources used.

The EROEI (Energy Return on Energy Invested) is a well-known criterion used to assess the efficiency of energy production. The EROEI is defined as the ratio of energy output from a particular resource to the energy used to produce that resource:

$$\text{EROEI} = E_{out} / E_{in},$$

where E_{out} – energy output, E_{in} – energy input.

This metric is methodologically inadequate in many respects. Its value may vary depending on the technology used and the location of the power plant. Nevertheless, it is instrumental in comparing energy alternatives over time. If the EROEI value is greater than one, the energy source is a net producer of energy; if it is less than one, it is a net energy sink. The higher the EROEI, the more useful the energy source is, as it provides more energy per unit than others. It is assumed that the energy return on investment must be at least 5:1 for stable operation of the energy sector.

Renewables (solar and wind power plants) have long been considered to have a lower EROEI than conventional plants. For example, the paper [7] explicitly states that nuclear, hydroelectric, coal-fired, and gas-fired power plants are orders of magnitude more efficient than photovoltaic and wind power plants. Furthermore, the study [8] claims that, in the case of Russia, alternative energy in the form of solar and wind power has completely compromised itself and this is no longer in doubt. Russia is known to be a major producer of oil and gas, has significant hydro resources and therefore conventional power plants are often powered by these natural and fossil resources. However, on the one hand, not all CA countries have such resources, and, on the other hand, RES potential in CA is also country-specific.

Our analysis indicates that for conventional power plants in CA, such as thermal power plants fired by fossil fuels (coal, oil, gas), the EROEI value is of about 10:1 to 30:1. This means that every unit of energy consumed to produce and process fossil fuels yields 10 to 30 units of energy in the form of electricity. It is known that the EROEI of the main fossil fuels (oil and gas) decreases over time, which will entail a decline in the EROEI of fossil fuel-fired thermal power plants [9].

The EROEI values of renewable energy sources such as solar power plants (SPP) and wind farms (WF) may vary depending on some factors, including technology, climatic conditions, placement, and production methods. However, they increase every year due to advancements in solar and wind technology [9]. Reduction in material consumption per unit of output (consumption of feedstock, whose production causes the largest energy costs associated with solar power) is the main driver behind the EROEI growth. Furthermore, the increase in the energy efficiency of photovoltaic cell production and longer lifetime of photovoltaic cells also contribute to this.

Common EROEI values for solar power plants, which are favored in many regions of CA, range from about 10:1 to 30:1. Although more precise values may vary depending on the type of solar technology (photovoltaic or solar power towers) and their location. For example, the EROEI of silicon solar installations with an estimated lifetime of 25 years, which are located in Switzerland with the number of sunny days much smaller than in Central Asia, is 9–10. Consequently, the energy payback period is 2.5–2.8 years [10]. The EROEI values of wind farms typically range from 15:1 to 40:1, although they can also vary depending on turbine size, wind speed, and other factors.

Our analysis shows that in the case of CA it is economically feasible to use SPPs and WFs along with conventional energy sources. Therefore, expansion planning in all CA countries, which are part of the CAPS, suggests both the construction of new conventional power plants (a nuclear power plant (NPP) and a pumped storage power plant in Uzbekistan, a planned NPP in Kazakhstan, and a major hydropower plant (HPP) in Kyrgyzstan) and a widespread integration of RES.

II. Expansion of the Integrated Power System of Central Asia with Renewable Energy Sources

The development of RES in Central Asia comes with many advantages and can be very feasible. The main reasons behind that include the following:

Resource potential. CA has a huge potential for RES development, making it ideal for intensive and efficient utilization of these energy sources.

Solar power. The region has vast areas with high solar activity and long sunshine duration. Therefore, SPPs can prove a viable option for clean power generation.

Wind power. CA is also characterized by strong winds, especially in its mountainous areas, where wind farms can be installed to generate electricity.

Hydropower. The region has significant potential for hydropower development. It is expedient to build large HPPs on the Amu Darya and Syr Darya rivers. Small and medium-sized hydropower plants can be in demand to serve local energy needs.

Energy independence. The development of natural resources will strengthen the energy independence of the countries in the region by reducing their reliance on energy imports. It will also contribute to diversification of energy production and the economy, and lead to a reduction in the use of oil, gas, and other conventional energy sources.

Ecological resilience. The development of renewables in CA will help to cut down greenhouse gas emissions, limit negative environmental impacts, and counteract climate change.

Economic benefits. Energy generation from renewables

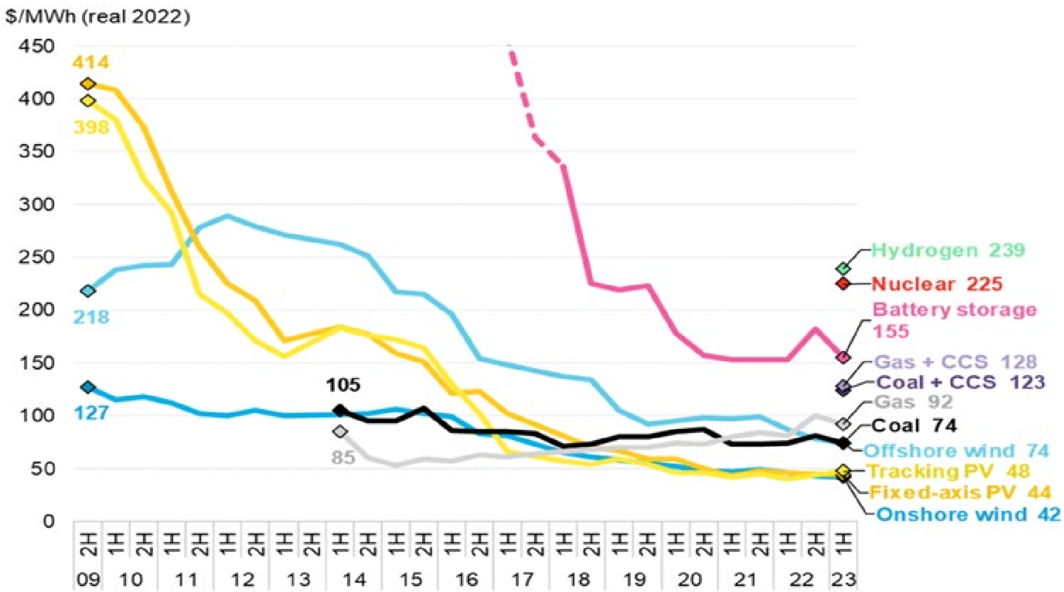

Fig. 1. Global benchmarks for levelized cost of electricity.

can outperform conventional energy sources in economic terms, which is especially important if the resource potential of the region is factored in.

It is crucial to emphasize here that BloombergNEF (BNEF), the global leader in strategic business and financial information, published a new report in 2023 [11] containing global benchmarks for the levelized cost of electricity (LCOE) for a variety of power generation technologies (Fig. 1).

The report notes that in the last six months, onshore wind farms and photovoltaic power plants have been the cheapest new electricity generation technologies in the countries that account for 82% of the world's total electricity production. Moreover, in 2022, the costs of both wind power and energy storage projects based on various types of storage, decreased compared to the levels of 2009 when BNEF began collecting data on these projects. The decrease was due to market developments.

For example, the global average LCOE for onshore wind power plant is $42 per MWh, for PV power plant – $44–48 per MWh (depending on the availability of trackers in the projects), for gas-fired power plants – $92 per MWh, and for coal-fired power plants – $74 per MWh. If, on the other hand, the cost of carbon capture and storage (CCS) is added to the cost of gas and coal-fired electricity generation technologies, their LCOE increases to $128 and $123, respectively.

An effective strategy for RES utilization in individual countries of the region has not yet been developed. However, the construction of RES-based power plants requires significant investment outlays. Therefore, the development of renewables in CA requires not only a legislative framework but also the development of mechanisms for their financing.

It is crucial to emphasize that the development of domestic grid infrastructure, as well as the strengthening of interconnectors both between countries within CA itself and with Russia will largely contribute to large-scale integration of renewables into the CAPS and increase the reliability of electricity supply.

Europe’s energy transition to zero-carbon electricity by 2050, as stipulated in the Paris Agreement, involves more than the widespread construction of large numbers of solar panels and wind turbines. It also entails a comprehensive transformation of infrastructure. Cross-border interconnectors play a special part in this process and have a significant impact on its cost-effectiveness. Therefore, it is advisable for CA to follow the same path to create a more flexible system that can balance geographical differences in wind and solar generation and minimize fluctuations in power generated by RES. This path will enable the CA countries to capitalize on the optimal placement of renewable energy sources and their potential, improve their generation efficiency, and reduce the costs of implementing decarbonization policies.

In addition, increased interconnection between countries in the region can incentivize investors by bolstering their confidence in their ability to sell their output in both domestic and foreign markets, which will also encourage RES deployment in the region.

Solar power plants and wind farms are known to be intermittent and depend on weather conditions, which adversely affects the power system operating conditions. Furthermore, accidents in the power system, e.g. external short-circuits, can lead to a decrease in the voltage on the busbars in the locations of RES placement. If SPPs and WFs are not equipped with energy storage units that can maintain the voltage, the inverters that are part of RES are "flipped back" and the RES are disconnected from the grid by protective relays.

The accident will lead to a decrease in the available power of the system, equivalent to the disconnected capacity of SPPs and WFs

$$P^c_{avail\ emerg} = P^c_{initial} - (\sum P_{SPP} + \sum P_{WF}).$$

In this case, if there is insufficient operational ("hot, spinning") capacity reserve intended to compensate for the imbalance between power production P^c_{avail} and consumption P_{load} caused by failures or emergency shutdowns, the power system will have a power shortage equal to

$$\Delta P^c_{shortage} = P_{load} - P^c_{avail\ emerg}.$$

The resulting shortage of available power P^c_{avail} will lead to a decline in the frequency in the power system relative to the nominal value f_{nom} = 50 Hz

$$f^c_{emerg} = f_{nom}\,(1 - \Delta P^c_{shortage} / P_{load}).$$

If the automatic under-frequency load shedding scheme or operational actions fail to prevent the frequency decrease in the power system and it goes below some critical value $f^c_{critical} \approx$ 46.5–47 Hz,

$$f^c_{emerg} < f^c_{critical}\,,$$

the low-inertia gas turbine units (GTU) and gas generator sets will be disconnected from the grid, which will create an additional power shortage in the power system and may lead to a cascading development of a system accident.

The effect of the share of power generated from SPPs and WFs in the presence of GTU and gas generator sets in the CAPS is discussed in [12]. The study demonstrates that in the absence of energy storage units in the power system, the probability of disruption of the normal operation of the power system and the damage caused by the shortage of generating capacity increase.

The above-discussed issues related to power regulation will become even more relevant when the first stage of a nuclear power plant with two 1 200 MW units designed for baseload operation in Uzbekistan is constructed. In addition, the increased demand for natural gas and fuel oil in the country predetermines the need to diversify the supply of primary energy resources and to perform a feasibility study on the construction of the second stage of the NPP with similar units.

It is worth noting that for solar and wind power, the installed capacity utilization factor (ICUF) can be relatively low due to the variability and intermittency of RES operation depending on natural conditions. Therefore, the ICUF for solar and wind power falls typically between 20% and 40% or is even less, depending on the specific operating conditions and the technology used. The value of ICUF varies across the world from 15 to 25%, on average.

In contrast, conventional power plants such as coal-fired, gas-fired, or nuclear power plants can have a higher ICUF because they typically operate continuously throughout the day serving both constant and variable load. The ICUF for these conventional power plants can be around 70–90% or more, depending on their operating conditions. Therefore, in order to eliminate the above disadvantages of RES and increase their efficiency, it is advisable to equip RES with energy accumulation and storage systems.

Renewables are becoming increasingly more important in Central Asia due to the significant solar and wind power potential there. Therefore, energy storage systems can not only enable the widespread integration of renewables in the CAPS but also improve the technical and economic performance of the power system. For this reason, it is crucial to install various energy storage units in the power system along with the construction of new power plants and the integration of renewables.

Storage units will make it possible to store excess energy and use it more efficiently during periods of absence or insufficiency of sunlight and wind during the day, compensate for the intermittent operation of RES, and ensure reliable energy supply. Furthermore, the use of energy storage systems in the CAPS can prove very feasible for the entire power system and make it technically and economically advantageous.

Storage units together with their power control system can improve the reliability of the power system, shave peak loads, and balance fluctuations in power generation and consumption. Energy storage units capable of long-term energy storage will increase the energy security of CA countries, given that some countries continue to encounter challenges with their electricity supply especially when demand is at its peak.

Energy accumulation and storage can reduce electricity costs by enabling the use of more efficient tariff schemes, e.g., energy can be stored during periods of low demand and used during periods of peak demand when electricity prices are higher.

At the same time, the use of energy storage systems (ESS) can reduce the cost of building additional power plants to serve peak demand and the cost incurred by overloaded transmission lines. Instead, surplus energy can be stored during periods of low loads and used during periods of peak demand, thus optimizing the use of available resources and delaying the construction of new transmission lines.

ESS can also influence the distribution of energy in the CAPS between different countries, which may have different energy demand at different times. This will also contribute to better economic efficiency of electricity supply. Energy storage allows efficient distribution of energy between countries according to their needs and reduction in power loss during long-distance transmission.

ESS will also be instrumental in improving environmental sustainability in CA. The use of ESS along with large-scale deployment of RES can help cut down the use of fossil fuels, limit negative impacts on the climate and the environment by lowering greenhouse gas emissions.

Common international practices favor lithium-ion batteries, which have a high rate of degradation – up to 5% per year, and a relatively short life span.

The recent years have seen a rapid advancement in liquid air energy and cryogenic energy storage technologies [13]. Such energy storage systems (especially high-capacity and high-power installations whose economic performance is way superior to that of lithium-ion batteries) are capable of recovering only 50% of stored energy. However, they will be in high demand not only for peak shaving but also for long-term energy storage and improvement of the power supply reliability.

When it comes to deciding on the adoption of ESSs in the CAPS, it is crucial to consider a multitude of factors. These are regional cooperation potential, level of infrastructure development, social and environmental aspects, costs of energy storage systems, technical feasibility of different systems and complexity of their implementation.

In this context, each of the countries should perform dedicated studies to determine the permissible penetration of RES in the mix of generation capacity deemed safe with respect to stable operation of the power system of this country as part of the CAPS. The counties should also select the necessary types of storage from a range of the most promising currently available types of storage units, decide on their placement, and calculate the necessary power and capacity of energy storage units.

III. Conclusion

The primary focus of published research is typically limited to the installation of storage units solely at RES-based plants. However, it is also important to install energy storage units at existing conventional power plants to improve their operation and energy efficiency. Moreover, it is crucial to place them in distribution networks and at the consumer’s end, which will also improve technical and economic performance and contribute to more reliable operation of the power system as a whole.

At the same time, an important factor in maintaining the reliability of the power system is the introduction of demand response practices, which implies actions on the part of load-controlled consumers to reduce their electricity consumption. The introduction of such consumers will help mitigate and overcome emergencies in the power system, such as a sharp increase in electricity consumption during weather changes or emergency shutdowns of individual units.

Integrating the load-controlled consumers within the acceptable power consumption limit during peak load hours and removing them from operation in the event of power shortages, as well as introducing automatic load and frequency control systems and stability margin monitoring systems are also priority solutions for the power system.

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The Role of Nuclear Energy in Enhancing Energy Security of the Republic of Belarus

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Abstract — **The paper highlights and examines the issues related to the limited natural reserves of fossil fuels in the Republic of Belarus. Almost 80 percent of the demand for energy in the economy and social sector of the country is met through the import of energy resources. In this context, one of the priority objectives for the energy development in Belarus is the gradual replacement of imported oil and natural gas with local fuel and energy resources, including nuclear energy. The world's experience in the development of this area is shown. Analysis is made of the measures to achieve the necessary indicators of energy supply to the national economy and the development of the energy sector, in the structure of which the nuclear power plant is beginning to play a significant role. The activities on strengthening the national energy system in Belarus began in June 2021, when the first unit of the Belarusian nuclear power plant was put into commercial operation. The findings show that since then there has been a gradual decline in the shortage of necessary energy resources, reduction in reliance on imported hydrocarbons, and elimination of other threats and uncertainties for sustainable, reliable, and efficient advancement of the energy sector aiming to achieve carbon neutrality of the economy of the Republic of Belarus in the near future.**

Index Terms — **fuel, energy, energy sector, nuclear power plant, sustainable development, energy security.**

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I. INTRODUCTION

Reliable and efficient functioning of the energy sector is one of the overriding and essential objectives of the modern economy in the Republic of Belarus [1]. It can be accomplished by identifying and eliminating factors that pose risks to the sustainable and safe development of the sector. The most important threats, their sources, risk level indicators, methods for their assessment and monitoring standards, as well as the main directions for their elimination are set out in the Concept of Energy Security of the Republic of Belarus [2].

The Republic of Belarus provides about 77.5 percent of domestic gross energy consumption through the import of crude oil and natural gas. The significant reliance of the country's economy on the import of hydrocarbons and the low degree of diversification of primary energy resources represent elements of risk for sustainable development. Since 2020, the republic has faced numerous energy security threats resulting from various political, resource-related, geographical, and economic limitations and circumstances. Moreover, new threats have emerged, including high uncertainty to key indicators of global economic development, which are associated with the COVID-19 pandemic and the escalation of several international and regional conflicts, due to which the enterprises in the country encounter immense pressure from their influential foreign economic partners and experience large fluctuations in the import-export balance. Belarus has also lost the benefits of its strategically advantageous geographical position between large exporters of hydrocarbons and their consumers, which the country enjoyed by attracting investments in the development of the energy sector, including in interregional transport enterprises. There is a noticeable delay in creating conditions for the development of a circular economy and there is no assessment of the impact of carbon border adjustment on the export of a national product dependent on the activities of companies in the energy sector.

In this regard, the strategic objectives of the national energy development should focus on reducing the economy's reliance on the import of fossil fuel and energy resources by increasing the share of local fuels, expanding the capacity of low-carbon and renewable energy sources, and bringing the energy intensity of the gross domestic product (GDP) closer to the world average value of this indicator. In this context, the role of nuclear energy is growing since it belongs to the local types of low-carbon energy resources and contributes to diversification, energy independence, and reliability of the energy sector.

This study aims to comprehensively examine and assess the indicators and risks related to the energy security of Belarus. This assessment is based on the performance of the country's economy over the past 5 years, given the commissioning of the Belarusian Nuclear Power Plant (the BelNPP) in June 2021. The objective is to formulate recommendations that will enhance the national energy security, considering the current trends in international energy policy.

II. Key Features of Contemporary Energy Development

An important trend in global energy policy is the reduction in the carbon intensity of GDP [3]. This fact is evidenced by the changing consumption patterns of low-carbon fuel and energy resources [4] (see Fig. 1). There is also fundamental restructuring of global energy markets with a more diversified balance of energy resources, increased competition between energy producers, an increased role of the energy consumers and their choice in shaping energy policy and in reducing the energy-to-GDP ratio. Major energy companies are actively adopting the modern global energy transition toward renewable energy sources (RES) and nuclear power. The share of the latter in final energy consumption has remained at about 4.4% for ten years due to the commissioning of new nuclear power plants [5], which are considered as a necessary component of the transition period towards a climate-neutral economy. At the end of 2021, the installed capacity of operating nuclear units were 389.5 GW and 58.1 GW was under construction.

Gross consumption of primary fuel and energy resources per unit of world GDP has decreased over the past 20 years

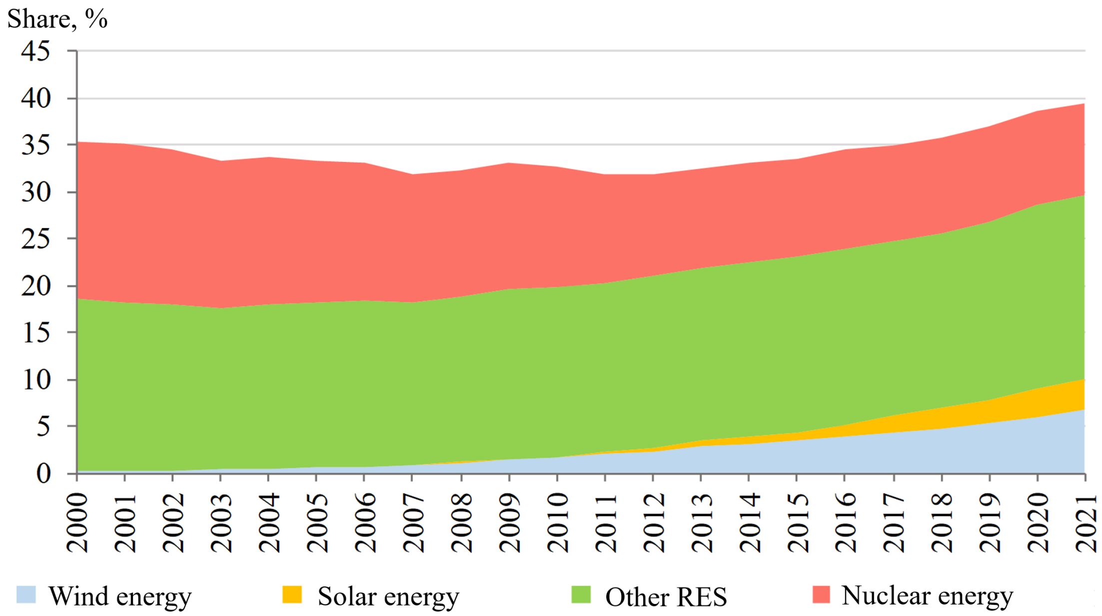

Fig. 1. Consumption of low-carbon energy resources in the world's electricity industry.

annually by an average of 1.5 %, with GDP growing by 3.1% per year [6]. At the same time, the structure and balance of this consumption, as well as the levels, dynamics, and trends in the reduction in energy intensity differ markedly across countries and regions (see examples in Fig. 2 and 3, presented on the basis of data from [7, 8]).

The given examples illustrate the characteristics of the respective climatic zones, the availability and type of primary energy sources, differences in technological development, the structure of the economy, and factors in national energy policy. High energy intensity and its growth in some countries is explained by the presence of inefficient industries, the predominance of a raw material export economy, and low prices for natural energy resources, which do not stimulate a reduction in specific energy consumption.

In the energy sector of leading countries, there is a gradual transition from measures of direct budget support

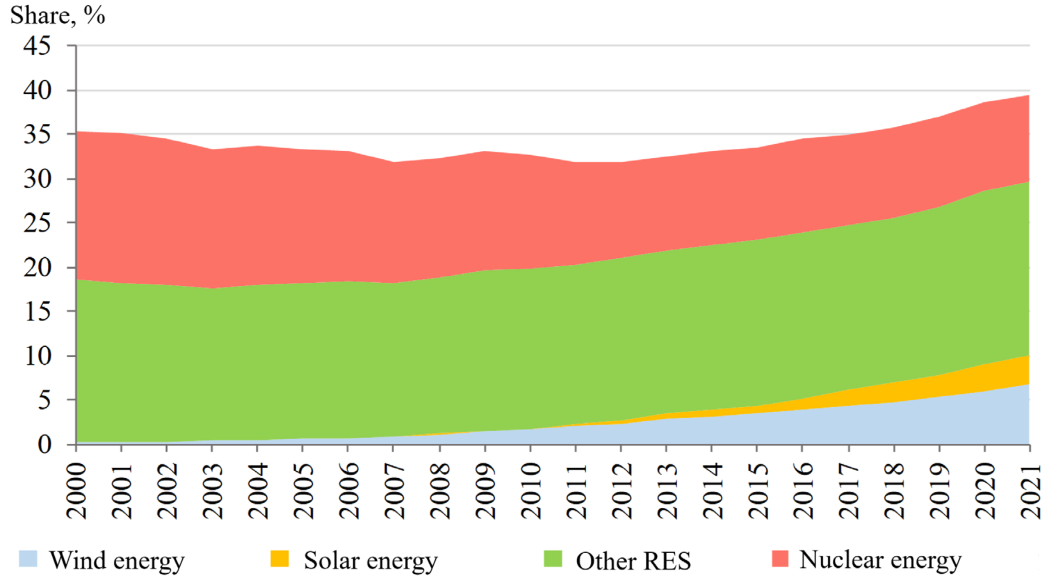

Fig. 2. Examples of changes in energy-to-GDP ratio.

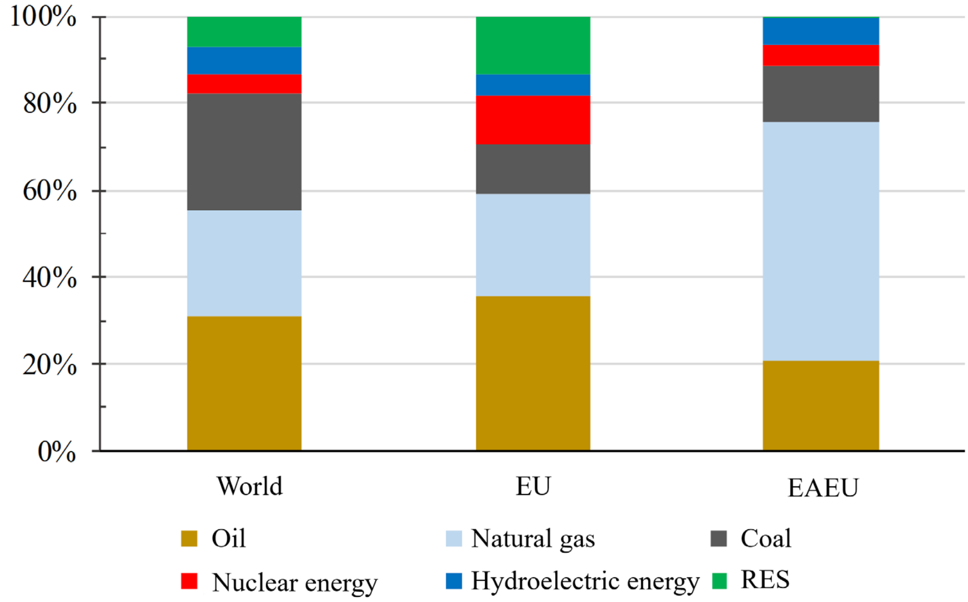

Fig.3. Examples of the structure and balance of consumption of primary energy resources by region (EU – European Union; EAEU – Eurasian Economic Union).

for fossil fuels and implicit subsidies to competitive schemes in favor of nuclear and renewable energy, i.e., auctions, green certificate systems, direct contracts for the supply of energy resources between producers and consumers. These solutions aim to reduce the economy's dependence on the production and consumption of fossil fuels, to diversify the balance of energy resources, which, together with the growing role of consumer choice and expanding competition between different types of energy and fuel, will lead to greater sustainability, predictability, and security of energy development. At the same time, cutting down the fossil fuel consumption per unit product output will become a direct competitive advantage for participants in such schemes.

Analysis of the above trends and existing development programs of the world's leading economies, including their legislation in the field of energy security, allows making the following medium-term forecast regarding the evolution of global energy policy and its target indicators:

- Starting in 2030, the growth of gross primary energy consumption will slow down significantly, in particular due to the enhancement of energy efficiency and the introduction of circular principles of economic development;
- According to all forecast scenarios, the share of fossil fuels in the structure of primary energy resources will begin to decline due to restrictions on the demand side, which will lead to a reduction in their share in primary energy resources by 2050 from the current 82% to approximately 60%, and some scenarios assume such a reduction to their share below 20-30%;
- Among fossil fuels, only natural gas will be able to increase its share in the global energy balance from 22% to 24–26% by 2050, the share of coal will go down from 28% to 19–23%, and oil - from 32% to 25–27%;
- Final energy consumption in the member states of the Organization for Economic Cooperation and Development will be reduced by at least 25% by 2050, and according to some scenarios – by approximately 50%;
- In the rest of the world, final energy consumption will significantly slow down its growth and will be on average no more than 0.3% per year compared to the current 1.9%;
- The overall growth in energy consumption in developing economies will be achieved not through the growth in the fossil fuel and energy production, but through the introduction of new low-carbon energy sources and renewable energy sources;
- The demand for electricity will grow along with the share of electricity in final energy consumption which will exceed 20% by 2040. Moreover, the rapid development of renewable and other low-carbon sources will provide 35–50% of global electricity production by that time;
- The development of distributed electricity generation will accelerate, involving the search for electricity storage solutions;
- Electricity markets will continue to develop to diminish price distortions and foster competition;
- Mobilization of additional investments in sustainable energy, related to technological innovation and energy efficiency, will continue and the amount of $300 billion reached in 2021 is expected to triple by 2030;
- Expansion of international cooperation will persist with a focus on the transfer of technology and the enhancement of human and institutional capacity in developing countries.

III. Parameters and Priorities for Energy Development in Belarus

Important priorities of the national economy of Belarus are to ensure the security, reliability, and efficiency of the energy sector, while simultaneously increasing its financial stability. Following these priorities, which correspond to global trends, and taking into account the unbalanced structure of gross primary energy consumption in the national energy sector (Fig. 4), the strategic objectives of the sector development aim to reduce reliance on imports of hydrocarbons, bring the energy-to-GDP ratio closer to the world average value of this indicator, cut down the gross energy consumption, and increase the capacity of low-carbon energy sources, including nuclear power plants.

The country has always actively planned and fully implemented programs designed to improve energy efficiency, and to date, energy intensity of the country's economy has decreased by 3.5 times compared to the 1990 level. At the same time, the analysis of the rate of decrease in energy intensity reveals that it has decelerated significantly in the last 10 years (Fig. 2). The conclusion follows that low-cost measures to improve the energy efficiency of the national economy have already been exhausted. New political and management decisions are required to motivate the energy sector entities (both

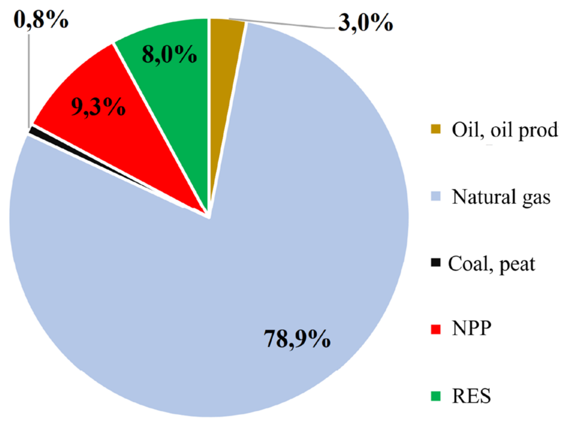

Fig. 4. Gross primary energy consumption in the energy sector of Belarus

producers and consumers) to reduce specific consumption of energy, including fossil fuels.

Over the past 20 years, the gross primary energy consumption has remained virtually unchanged. However, an analysis of the structure of the current balance of primary energy and its comparison with last year's data indicates a good trend in import reduction: imports of electricity decreased by almost 15 times, oil – by 39%, natural gas – by 5.3%, and coal – by 54%. At the same time, in 2022, it became evident that the diversification of imported energy supplies still faces a critical threat. The share of electricity, crude oil, and coal coming from the Russian Federation in the total volume of imports in physical terms continues to grow, replacing supplies of these resources from Lithuania and Ukraine (electricity), Azerbaijan (crude oil), and Kazakhstan (coal).

The government of the country is committed to enhancing energy independence by diversifying primary energy sources, which involves expanding nuclear energy sources, promoting local fuel and renewable energy sources, and reducing energy intensity by a minimum of 7% by 2025.Today, according to the Ministry of Energy, the total installed capacity in energy companies is 11 498 MW. The main part (10 202.5 MW) is connected to the Integrated power grid. The rest of the capacity (1 295.5 MW) are installations operating at various entities. Most energy sources (9 668.2 MW) use gaseous or liquid hydrocarbon fuels converted from primary energy sources. The total capacity of energy plants using renewable energy sources and secondary energy resources is 659.9 MW, which is more than 10 times higher than the figure five years ago. The capacity of each of the two BelNPP units is 1 170 MW.

We must prioritize our attention to the greenhouse gas emissions in the energy sector [9], especially considering their significant growth in the past 5 years, which goes against the global trends observed. In this regard, it must be emphasized that high carbon-intensive export products will no longer be able to compete in the international market due to the restrictions of cross-border carbon regulation. This circumstance poses a certain risk to sustainable development and must be taken into consideration in plans for the development of the energy sector.

IV. Development of Nuclear Energy in the Republic of Belarus

The decision to build the BelNPP was made on January 15, 2008 at a meeting of the Security Council of the Republic of Belarus. This project is expected to provide about a third of the country's domestic electricity needs, replacing annually 4.5 billion m^3 of imported natural gas and reducing greenhouse gas emissions by more than 7 million tons. The installation of the first generator unit began on January 27, 2016, at the Ostrovets site. On November 3, 2020, it was connected to the Integrated power grid and on June 10, 2021, it was put into operation.

Since the beginning of the commercial operation of the BelNPP, its total output has reached about 14 136 million kWh as of the end of April 2023, which was lower than planned. This was due to the operation of automatic protection of the turbogenerator, diagnostics of technological systems and components, routine maintenance, the first partial reloading of nuclear fuel, and additional tests. On December 27, 2021, the reactor of the second generator unit of the BelNPP was filled with fuel and its physical start-up was carried out on April 26, 2022. Commercial operation is planned to start in the second half of 2023.

To integrate the BelNPP into the country's power system and maintain the baseline operating conditions of nuclear units, it is necessary to ensure the appropriate value and patterns of power consumption. Over the past three years, several decisions have been dedicated to addressing this issue (Table 1).

TABLE 1. Policies and Measures for the Integration of the BelNPP into the Power System

Name of the Resolution	Number and date. Short description
On approval of the Concept for the Development of Electricity Generating Capacities and Electrical Networks until 2030	Resolution of the Ministry of Energy No. 7 of 25.02.2020 includes an analysis of the current state of the power system, the structure and changes in the installed capacity of generating sources, the efficiency of electricity transmission systems, the current and planned energy balance, measures for the further development of electricity generating facilities and electrical networks. The document provides a forecast of the balance of electricity and heat production and consumption, as well as the total installed capacity of energy sources until 2030 for organizations of State Production Association (SPA) "Belenergo."
About the State Program "Comfortable Housing and Favorable Environment" for 2021–2025	Resolution of the Council of Ministers No. 50 of 28.01.2021 includes measures to create and further develop a comfortable and safe living environment and the consumer services sector; to increase the availability of energy supply in populated areas. It also includes the subprogram "Development of the Electric Power Industry and Transition to Gas in Populated Areas," the implementation of which will increase electricity consumption by 2.8 billion kWh a year.
On approval of the State Program "Energy Saving" for 2021–2025	Resolution of the Council of Ministers No. 103 of 24.02. 2021 is aimed at boosting the efficiency of the national economy and strengthening the country's energy security by reducing the reliance on imported fuel and energy resources, bringing the energy-to-GDP ratio closer to the world average value of this indicator. This document establishes energy intensity targets, related objectives and control mechanisms by industry and region, as well as financing principles.
On approval of the Program for Comprehensive Modernization of Energy Production Facilities for 2021–2025	Resolution of the Ministry of Energy No. 19 of 05.04.2021 is aimed at modernizing power plants and boiler houses, electrical and heat networks of the entities of the SPA "Belenergo," given the commissioning of the nuclear power plant. The document presents and justifies a set of measures to achieve power system development indicators, which will increase the availability of electricity for heating and hot water supply both in the existing housing stock and during the construction of new electrified housing. As a result, there will be an increase of 900 million kWh per year in electricity consumption for these needs.
On approval of a Comprehensive Plan for the Development of the Electric Power Sector until 2025, with the BelNPP Put into Service	Resolution of the Council of Ministers No. 169 of 01.03.2016 approves changes (Amendments No. 714 dated October 20, 2022) included in the Comprehensive Plan for the Development of the Electric Power Sector until 2025, with the BelNPP Put into Service and the Cross-sectoral Set of Measures to Increase Electricity Consumption until 2025. The changes concern the deadlines and the list of performers, which were adjusted based on the results of the commercial operation of the first unit of the nuclear power plant.

These measures were aimed at increasing power consumption in various areas, such as industry, housing and utilities sector, construction, and transport. They also concerned the construction and reconstruction of networks and substations of various voltage classes. The increase in electricity consumption is also facilitated by the introduction of the category of "energy-intensive consumers" on January 1, 2021, which involves using a special incentive tariff plan and a system of discounts. Given the fact that households are the main energy consumers, which account for approximately 45% and 21% of the heat and electricity supplied to the market respectively, a special discount system was introduced to encourage them to boost electricity consumption for heating, hot water supply, and cooking. In general, since the beginning of the BelNPP operation, direct and indirect subsidies in support of low-carbon energy have amounted to 46.7 million US dollars [10].

An important and necessary component in the emerging power supply infrastructure, which is aimed at increasing the stability and reliability of the BelNPP equipment and leveling the daily load curve, is the construction of peak-backup sources and electric boilers. The total installed capacity of electric boilers planned by 2025 is 1.12 GW, of which 0.76 GW will be installed at power plants and 0.16 GW – at boiler houses. To date, 170 MW and 26 MW respectively have been put into operation. The construction and commissioning of additional network equipment and new substations are also planned.

To maintain the base-load operation of the nuclear units of the BelNPP, it is necessary to ensure the appropriate value of the final electricity consumption in the country. An accelerated transition to replacing the main volumes of secondary energy resources with electricity in order to achieve the required level of consumption of this resource has become an important priority of the national energy

TABLE 2. Energy Security Indicators of the Republic of Belarus

Name of the indicator and its characteristics	Index of security level		
	Normal	Critical	2022
Energy independence			
1. The ratio of primary energy production (extraction) to gross consumption of fuel and energy resources, %	30	16	22,5
2. The ratio of primary energy production (extraction) from renewable sources to gross consumption of fuel and energy resources, %	14	5	8,0
Diversification of suppliers and types of energy resources			
3. The share of the dominant supplier of energy resources in total imports of fuel and energy resources, %	65	85	98.6
4. The share of the dominant fuel type in gross consumption of fuel and energy resources, %	50	70	59.5
Reliability of supplies, redundancy, processing and distribution of fuel and energy resources			
5. The ratio of the total installed capacity of power plants to the maximum actual load in the power system (redundancy), %	140	95	180.4
6. The share of accumulated depreciation in the initial cost of fixed assets of energy entities, %	45	75	43.4
7. The ratio of the capital investment made in the development of the energy sector to the initial cost of fixed assets of the energy entities, %	6	4	4.7
8. The share of the dominant energy resource (natural gas) in the production of thermal and electrical energy, %	50	80	84.2
9. The ratio of the average daily number of power supply failures in populated areas to the total number of populated settlements, %	0.5	2	0.3
Energy efficiency of final energy consumption and economic sustainability of the energy sector			
10. Energy-to-GDP ratio, kg c.e./million rub.	160	485	361
11. Ratio of the cost of energy commodity imports to GDP, %	15	30	10.4

policy. However, as follows from data analysis, the positive growth in electricity consumption that has emerged over the past 5 years showed negative dynamics in 2022 (a reduction of 6%). At the same time, there is a noticeable trend in the increase in electricity consumption by the population (by 2.1% in 2022). Thus, electrification of the housing sector, service sector, and urban transport holds great potential to enhance the electricity intensity of the economy in the context of commissioning the BelNPP. By 2030, more than 30% of electricity is expected to be consumed by electric houses and electric vehicles.

V. ENERGY SECURITY AND NUCLEAR ENERGY

According to the Energy Security Concept of the Republic of Belarus, in March 2023, the data on monitoring of the energy sector in 2022 were analyzed, and the main risks for its sustainable development in general and for individual sectoral areas were identified. Furthermore, trends in changes in the relevant indices were clarified for the period of 2015–2022 and recommendations were prepared to minimize the risks and ensure the country's energy security in 2023.

Table 2 presents energy security indicators of the Republic of Belarus that cover some characteristics and indices of the energy sector development.

One of the two indicators characterizing the country's energy self-sufficiency (indicator No. 1) shows that the volume of its primary energy production (extraction) in 2022, given the energy generated by the BelNPP, was 8 213 thousand t.c.e. This satisfies 22.5% of national needs (gross consumption of fuel and energy resources), which amounted to 36 559 thousand t.c.e. Analysis of changes in this indicator for the period of 2015-2022 (Fig. 5) demonstrates its significant growth after the commercial operation of the BelNPP started in 2021. This indicator approached the normal level and was noticeably better than the value that was planned to be reached only by 2030. However, it must be taken into account that it still remains within the values of the precritical range.

The second indicator, which represents the share of primary energy produced from renewable energy sources (indicator No. 2), also shows positive dynamics. The ratio of the primary energy production (extraction) from renewable energy sources (2 027 thousand t.c.e.) to the gross fuel and energy consumption in 2022 was 8.0%, which is equal to the value of indicator that was planned to be achieved by 2030.

The commissioning of the first unit of the BelNPP significantly improved the redundancy indicator (indicator No. 5), which is in the range of the normal threshold level. Thus, it becomes possible to gradually decommission

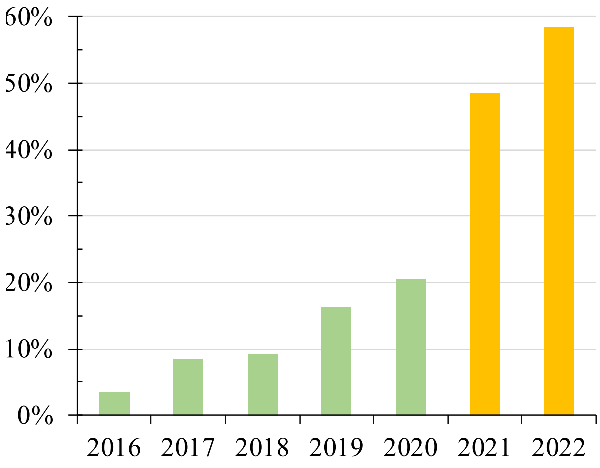

Fig. 5. Change in the indicator “Ratio of primary energy production (extraction) to gross energy consumption,” as a percentage of the 2015 level.

obsolete power units of thermal power plants, thereby expanding the room for the utilization of renewable energy sources and increasing the country’s electric power export potential.

Furthermore, given the cost of fixed assets of the BelNPP and the upgrade of technical equipment at some enterprises of the SPA “Belenergo,” the calculations suggest that the accumulated depreciation accounts for 43.4% of the initial cost of fixed assets, which indicates that the corresponding indicator (indicator No. 6) is within the normal threshold level.

Natural gas is still the dominant primary energy source. Its share in energy production is 84.2%. Compared to the 2015 level, this share decreased by 7.1%, which is the result of the commissioning and gradual increase in the load of the BelNPP and the development of renewable energy sources. This indicator (indicator No. 8), however, still remains at a critical level.

VI. Conclusion

The launch of both BelNPP power units at full capacity, anticipated by the end of 2023, along with the expansion of renewable energy sources will enhance our energy security indicators by 2035 as follows:

• The share of primary energy production in the volume of gross consumption of fuel and energy resources will rise from the current 22.5% to 70%;

• The share of natural gas in gross fuel and energy consumption will decrease from the current 59.5% to 40%;

• The ratio of the installed capacity of power plants to the maximum actual load will increase from the current 180.4% to 200%.

The connection of the BelNPP to the Integrated power grid of the national energy sector significantly improved the country's energy security indicators, providing, together with renewable energy sources, a guarantee of a sustainable and consistent increase in the energy independence of the national economy.

The operation of the BelNPP contributes to the diversification of the balance and final consumption of fuel and energy resources, thereby reducing the share of fossil fuels. In doing so, the country not only fulfills its international obligations under the Paris Agreement, but also stays in line with the latest trends and development programs of global economies.

Putting the BelNPP into service boosts the availability of electricity for the end consumer, which, in turn, will provide the corresponding demand for electricity and initiate an increase in the share of renewable energy sources and other low-carbon sources in final energy consumption. This will also accelerate the development of decentralized electricity generation, including search for storage solutions, motivation of the participation of the national energy sector in international and regional energy markets and integrated power systems.

The BelNPP as part of the energy sector makes the infrastructure for the production, conversion, transmission, and consumption of energy resources more reliable, sustainable, and efficient. With this plant, we can reduce the carbon intensity of the national GDP and attract investments in the further development of the energy sector infrastructure.

On the other hand, there are some certain aspects of the current economic and energy development, both internal and external, which could potentially hinder the future progress of nuclear energy and jeopardize the energy security of the Republic of Belarus. These are as follows:

• Potential disruption of financial stability and decline in the financial health of end energy consumers;

• Increased inflation and devaluation risks jeopardizing the ability to finance investment programs, modernization and ongoing maintenance of the energy infrastructure;

• Reduction in the possibility of concluding long-term agreements on the export of electricity from the Republic of Belarus, given its low competitiveness compared to neighboring countries, where, significant electricity surpluses are growing;

• Sanctions impose restrictions on the import of crucial equipment and technology, which may pose a threat to the planned maintenance and repair of the existing energy infrastructure due to its high reliance on imports and credit financing, with the BelNPP being no exception.

Therefore, given the significance of the BelNPP in enhancing the energy security of the Republic of Belarus, it becomes imperative to conduct a comprehensive technical and economic feasibility analysis to determine the future progress in this area, make a projection of long-term demand for electricity in the country, and perform a subsequent calculation of the energy security level based on relevant indicators.

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The Influence of Unbalanced Loads in the Electrical Network on the Operation of Transneft PJSC Power Consumers

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***Abstract* — The study focuses on an assessment of the power quality of electrical consumers of Mariinsk substation of the Transneft–Western Siberia JSC and Skovorodino OPS-21 of Transneft–East LLC in the power systems adjacent to the Trans-Siberian Railway and Baikal–Amur Mainline. The dynamics of bringing the power quality indices at the OPS-21 to the normalized values of the State Standard (GOST 32144-2013) when using SVC-20/20-10 at this station is shown. The design solutions of the Round Table "Low quality of electricity in 35-220 kV electrical networks supplying electrified railways and public consumers. Technologies for its normalization" were noted within the framework of the International Forum "Electrical Networks", Moscow, November 22–25, 2022.**

***Index Terms* — power quality, electric network, unbalanced loads, power consumers.**

I. Introduction

The quality of electricity in the electrical networks of electric power systems and power supply systems is one of the most important aspects determining the reliability and efficiency of power supply to consumers. This is especially true for the electricity consumers of Transneft PJSC in the power systems adjacent to the Trans-Siberian Railway (Transsib) and Baikal-Amur Mainline (BAM). A significant share of the load of the trunk networks of Siberia and the Far East, feeding the Transsib and BAM, is electrified traction of "Russian Railways" JSC.

The dynamic development of railways, including high–speed ones, leads to a significant increase in the share of traction load in the load of the power system. This is especially relevant at present in relation to the instructions of the President of the Russian Federation V.V. Putin to expand the capacity of the Eastern Section (Vostochny Poligon in Russian): BAM and Transsib.

Currently, the modernization of the Eastern Section is one of the largest infrastructure projects in the Russian Federation. The first stage of the project provides for an increase in the carrying capacity of the BAM and Transsib in the direction of seaports and border crossings of the Far East to 144 million tons in 2021. The implementation of the second stage will increase the annual capacity of the railways to 180 million tons by 2024.

II. Traction Power Supply System Case Study

The traction power supply system of the railway has a negative impact on the electrical networks. This is because the electric rolling stock is a sharply alternating single-phase load having a low power factor and causing current and voltage distortion both in the traction power supply system and in the external 110 kV and 220 kV networks feeding traction substations. The specific features of the traction load include the oscillatory uneven nature of the load during the day and a significant distortion of the sinusoidal current and voltage waveforms.

The second negative factor aggravating the effect of traction load on voltage quality is the large length of power

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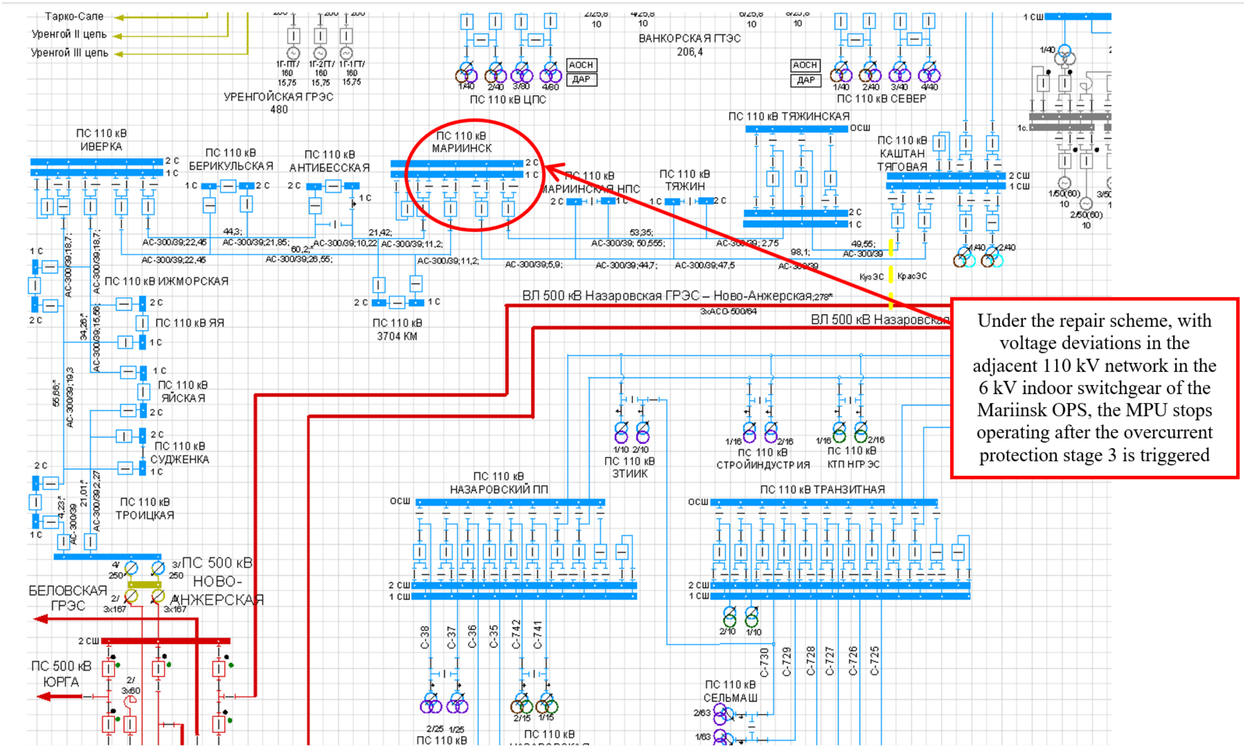

Fig. 1. Power supply scheme of the Mariinsk OPS.

transmission lines and their distance from power sources, which determines the low short-circuit power in the electrical network and, accordingly, the high sensitivity of voltage to distortion currents from nonlinear, asymmetric, and sharply alternating consumers. At the stage of implementation of the Eastern Section project, the power of the distorting load of Transsib traction substations will only increase in the near future.

Currently, there are problems with the quality of electrical energy at the facilities of Transneft–Western Siberia JSC, which lead to failures (emergency shutdowns of the OPSs). For example, at the Mariinsk OPS under repair conditions (when the transit transmission is interrupted, the 110 kV “Tyazhinskaya” substation and 110 kV “Kashtan” traction power substation (TPSS) are disconnected (due to the withdrawal of the 110 kV Iverka–Mariinsk overhead line with a branch)), we fix significant distortions of power quality indices (PQI):

- negative voltage deviations (the standard is no more than 10%):

dUA(−) = 28.66% (18.07.2022);

Alice(−) = 13.55% (18.07.2022);

- positive voltage deviations (the standard is no more than 10%):

dUC(+) = 10.13 (19.07.2022);

dUVS(+) = 10.04 (07.19.2022);

- the unbalance factor (the standard is no more than 4%):

K2 U% 11.46 (21.07.2022)

- the total harmonic distortion of the voltage (the standard is no more than KU(95%) = 5, KU(100%) = 8):

KU(A) = 17.60 (07.19.2022);

KU(AB) = 18.40 (07.19.2022);

- the harmonic factor of phase voltage of order n.

Excess by 3, 5, 6, 7, 9, 11, 13, 15, 17, 19, 21, 23, 27, 33 harmonic components of the voltage. The greatest distortion is caused by harmonics 9, 11, 13, and 15.

In some operating conditions, the value of these harmonics is more than 6 times higher than the standard value. The power supply scheme for the Mariinsk OPS is shown in Fig. 1.

During the period from 09.2007 to 08.2022, there were 26 shutdowns of main pump units at the Mariinsk pump station and 17 failures, which led to its stopping.

The deviation of the power quality indices causes the uninterruptible power supply (UPS) to freeze, with further transition of microprocessor-based automation system (MAS) of the automated production process control system to power supply directly from the network with low power

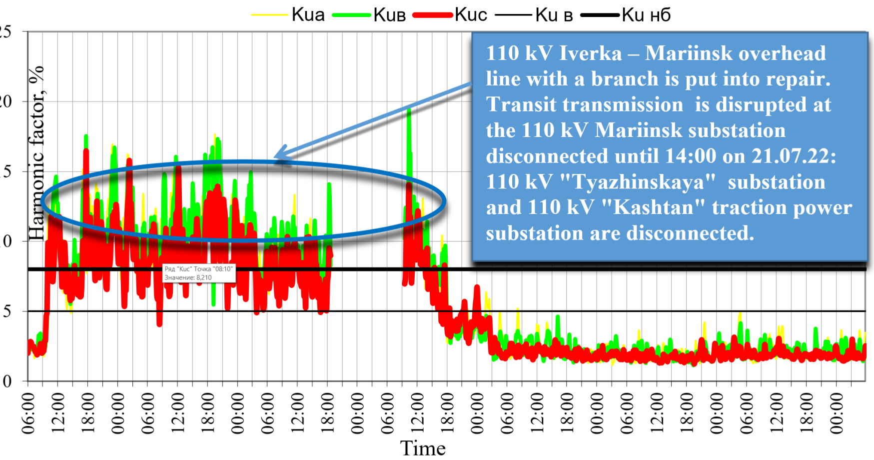

Fig. 2. Graphs of harmonic factors of phase voltages averaged over a time interval of 10 minutes for input No. 1 for the period from 07.18.2022 to 07.25.2022.

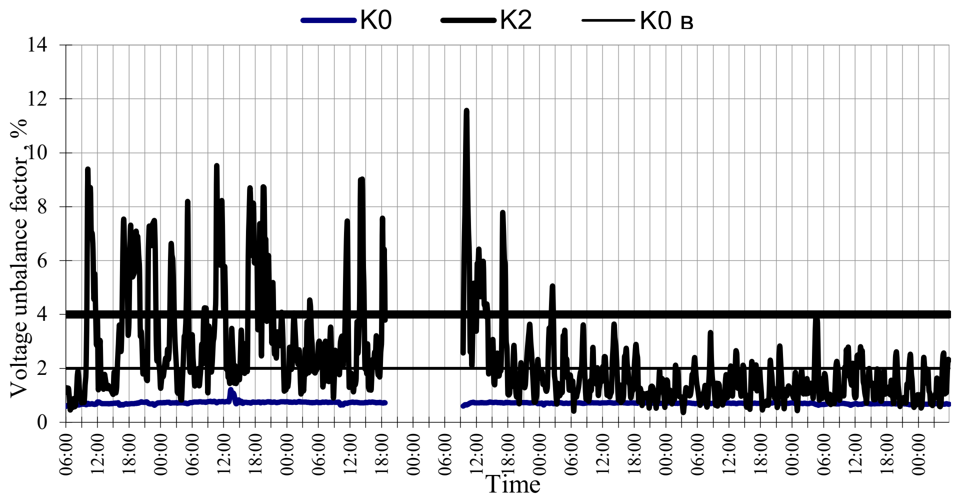

Fig. 3. Graphs of the unbalance factor for the zero sequence and negative sequence voltage averaged over a time interval of 10 minutes for input No. 1 for the period from 07.18.2022 to 07.25.2022.

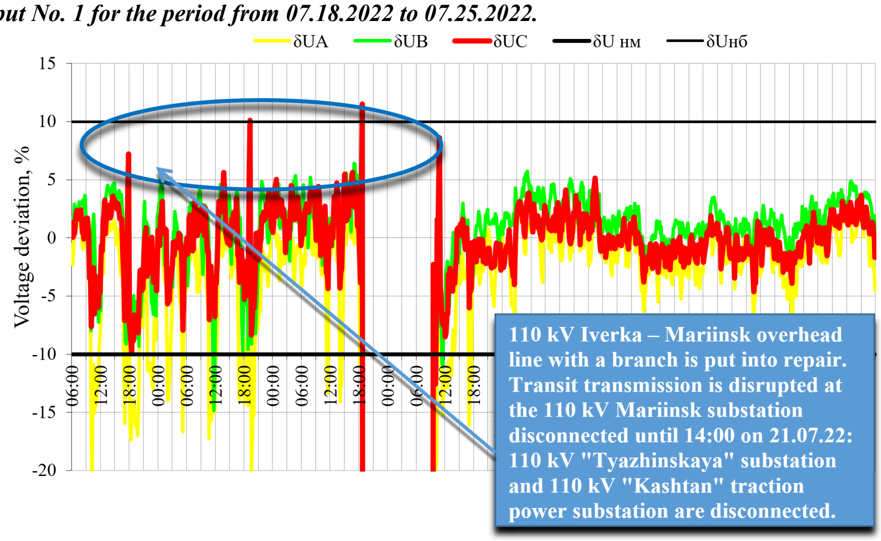

Fig. 4. Graphs of phase voltage deviations averaged over the time interval of 10 minutes for input No. 1 for the period from 07.18.2022 to 07.25.2022.

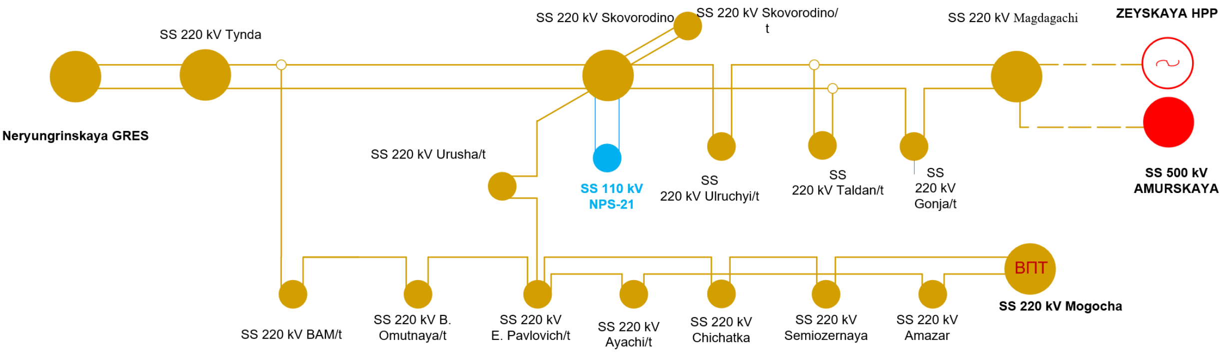

Fig. 5. Power supply scheme of the Skovorodino OPS-21 of the Transneft–East LLC.

Fig. 6. A general view of two static var compensators at the Skovorodino OPS-21 of the Transneft–East LLC.

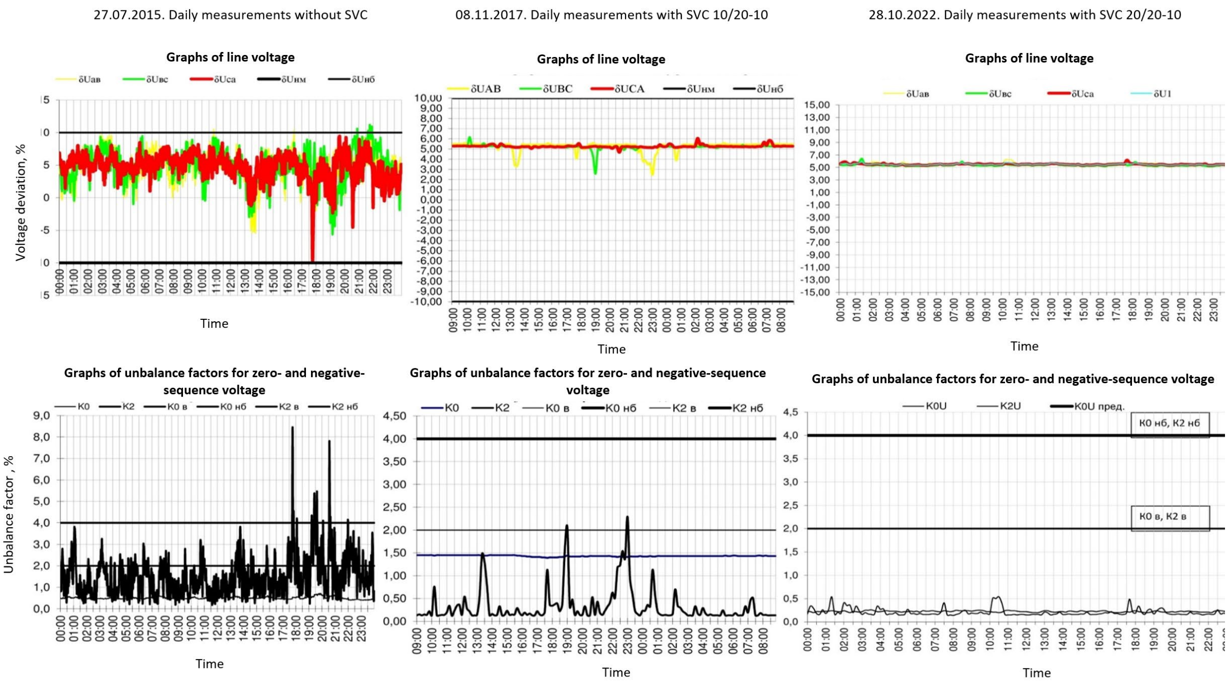

Fig. 7. Dynamics of bringing the PQI of the Skovorodino OPS-21 of Transneft–East LLC to the standard values with SVC on the first section of 10 kV buses.

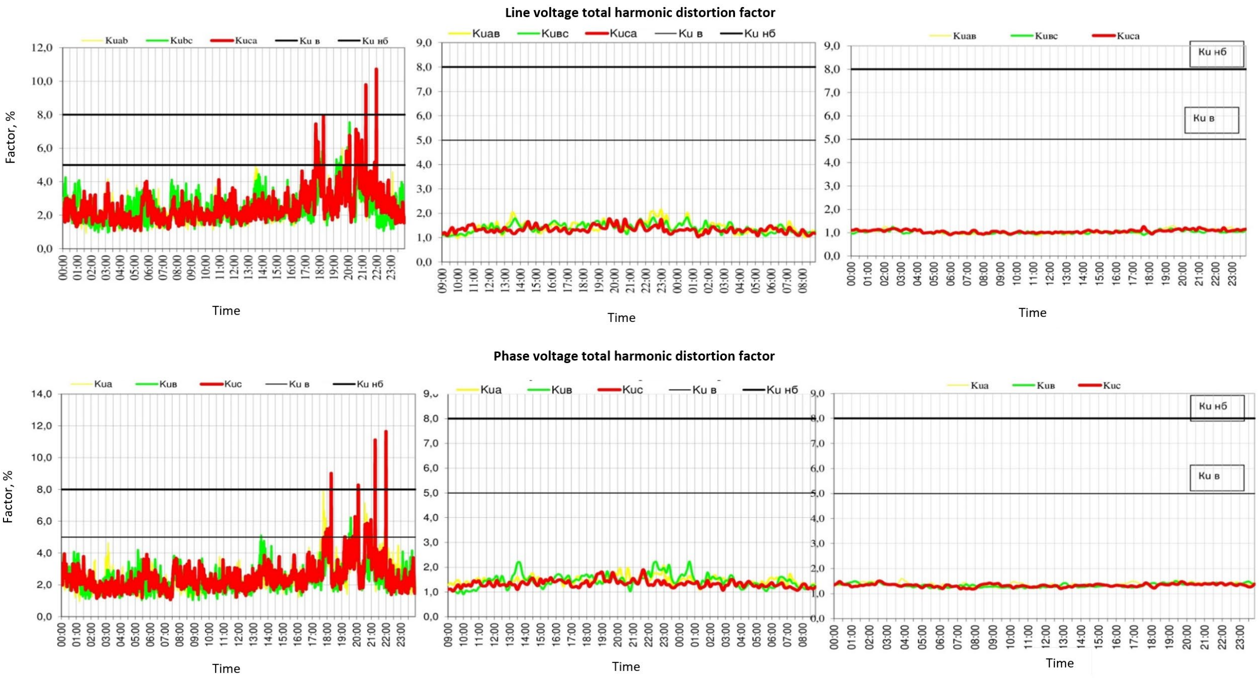

Fig. 8. Dynamics of bringing the PQI of the Skovorodino OPS-21 of Transneft–East LLC to the standard values with SVC on the first section of 10 kV buses.

quality indices, which results in generation of the false signal "Malfunction of vibration monitoring devices" and the subsequent shutdown of the main pump unit (MPU) No. 2 and MPU No. 4 with the restart of the UPS MAS.

Mariinsk station is located on the Trans-Siberian Railway and is the gate of the Eastern Section of the Russian Railways JSC. It is unique in that there is a change in the type of traction from DC (3 kV), on which the railways of the western part of the Russian Federation operate, to AC (25 kV), used in its eastern part of the Russian Federation. This requires changing the locomotives of all transit trains passing through the station.

Currently, the Mariinsk station handles up to 128 freight trains daily, including up to 32 combined container trains. After the reconstruction, the capacity of the station will increase to 140 freight trains per day in total for the eastern and western directions. Accordingly, the inter-train interval of electric rolling trains will be reduced and the load on traction substations, and hence on the 110 kV transit overhead lines feeding the 110 kV Mariinsk substation will increase. A similar situation will occur at all traction substations.

Due to the terrain features, loaded trains can go up (phase "A") and down with electricity recovery (phase "C"), therefore, both negative and positive voltage deviations are observed.

Since VL80R electric locomotives (25 kV AC) are equipped with collector electric motors NB-418Kb with a thyristor inverter driven by the network, the electricity recovered by electric locomotives in braking mode distorts PQI in terms of harmonic composition.

The most promising option is to reconnect the 6 kV indoor switchgear (IS-6 kV) of the Mariinsk substation to the 110–500 kV substation, which does not directly supply traction substations of Russian Railways JSC.

The paper presents graphs of PQI deviations for the other facilities of Transneft – Western Siberia JSC.

It is worth noting that to normalize the PQI at the oil pumping station (OPS), Transneft–East LLC introduced static var compensator STK-10/20-10 at the Skovorodino OPS-21 in 2017, which was followed by the modernization of the equipment (installation of STK-20/20-10) in 2020. The power supply scheme of the Skovorodino OPS-21 of the Transneft–East LLC is shown in Fig. 5.

The 110 kV OPS-21 of Transneft-East LLC is powered by two 110 kV overhead lines from the 220 kV Skovorodino SS of the power system of the East - a branch of FGC UES PJSC. The length of the 110 kV supply lines is 23 km. The 220 kV Skovorodino TPSS of the Trans–Baikal Railway branch of the Russian Railways JSC is powered from the 220 kV Skovorodino SS by two 220 kV overhead lines, the length of the 220 kV supply line is 5.2 km. The nearest power source for the 220 kV Skovorodino SS is power system of the East – a branch of FGC UES JSC (155.2 km), for 220 kV Tynda SS, the power source is Neryungri GRES. In addition, the 220 kV Skovorodino SS provides power to the nearby 220 kV traction substations (BAM TPSS, Urusha TPSS, Ulruchyi TPSS, and Gonzha TPSS) via 220 kV overhead line. Thus, the 110 kV OPS-21 substation is connected according to a radial dead-end scheme, in which the quality of electrical energy depends on the distance between the supply center and the consumer.

At the 220 kV Skovorodino SS, single-phase loads of varying magnitude with heterogeneous harmonic composition prevail, which is caused by the operation of five traction substations. The 220 kV Skovorodino TPSS, located at a distance of 5.2 km from the 220 kV Skovorodino SS, has the most significant impact on the quality of electrical energy.

A general view of the two static var compensators at the OPS-21 is shown in Fig. 6.

The dynamics of bringing the PQI at the OPS-21 to the normalized indices of State Standard (GOST 32144-2013) is shown in Fig. 7 and 8.

Thus, the SVC 20/20-10 when used at the OPS-21:

- improves the harmonic composition of the 10 kV bus voltage;
- compensates for slow and fast voltage changes (dips) up to 13% of the rated voltage of 10 kV, with a three-phase balanced voltage reduction of 10 kV and a short-circuit power of 152.69 MVA;
- ensures reliable operation of the equipment under the voltage unbalance in the network.

III. Conclusion

In order to enhance the reliability of the electrical equipment of the Transneft facilities along the Trans–Siberian railway and Baikal–Amur mainline, it is crucial to take measures to improve the PQI in the transmission and distribution networks of the power system of Siberia and the East by ensuring electromagnetic compatibility of the traction load with the supply network. This process involves converting an unbalanced non-sinusoidal load current with a significant proportion of reactive component into a balanced sinusoidal current that ensures such electromagnetic compatibility. Power factor correction units (SVC and STATCOM) can provide this.

The issues addressed in the paper were thoroughly discussed at the Round Table “Low quality of electricity in 35-220 kV electrical networks feeding electrified railways and public consumers. Technologies of its normalization” within the framework of the International Forum “Electrical Networks,” Moscow, November 22–25, 2022.

The following points are important to highlight:

1. The most effective solution to the problem of low power quality in the transmission networks adjacent to the Transsib and BAM is the installation of three-phase compensators with phase-by-phase control of the SVC and STATKOM type at traction substations of Russian Railways JSC. In order to stimulate their application, the contracts for the connection of traction substations to the electric grid must not only specify the requirement for their installation, but also provide a system of discounts and surcharges for the use of electricity for the execution of this paragraph in an amount that ensures the regulatory payback period of the power factor correction unit. This can be helped by rationing in terms of encumbrance of technical conditions for connecting distorting loads in the network, depending on the ratio of the short-circuit power at the point of connection to the installed load capacity, as is done in electric companies abroad.

2. In order to carry out the Federal Project “Development of the railway infrastructure of the Eastern Section of Railways,” to achieve its goals and accomplish the objectives set, it is crucial to develop and implement the program for installing reactive power compensators and other necessary equipment at the traction substations of the Russian Railways JSC. This program plays a vital role in future ensuring reliable supply of electric power in Transbaikalia, Eastern Siberia, and the Far East.

3. High quality of electricity in the unified power system networks can be ensured only if the use of advanced reactive power compensators by consumers is stimulated at the state level, which requires the adoption of appropriate laws that underlie the tariff policy of the Russian Federation in this area.

According to the solutions proposed at the Round Table, on 10.02.2023, a joint meeting of the Scientific and Technical Council of the ROSSETI FGC UES and the section “Electrical Equipment” of NP STC UES was held at the Rosseti Science and Technology Center. Based on the results of the meeting, some measures were recommended to formulate a regulatory act and make changes to the existing regulatory documentation, and conduct a separate in-depth study to address the power quality challenges.

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Using of Evacuated Solar Tube Collectors for Heating in Central Yakutia Conditions

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***Abstract* — In the Department of Energy Problems of the IPTPN SB RAS an experimental stand for a solar heat supply system based on the evacuated solar tube collector was assembled. During the experiment the incident solar radiation on the collector surface and the corresponding thermal energy received from the evacuated solar tube collector were measured. Data collection began at the end of 2021 and is still ongoing. The obtained experimental data will allow to study the efficiency of the evacuated solar tube collectors in the climatic and natural conditions of Yakutsk (Central Yakutia) and measure the intensity of solar radiation. The obtained research results will make it possible to determine the effectiveness of using solar heating systems based on evacuated solar tube collectors in the conditions of Yakutia, as well as their feasibility. Features of the solar heating system operation in extremely low temperatures have been identified. Recommendations to take these features into account are given. Based on the data received the database of the solar heating system operation and the database of solar insolation were developed and registered.**

***Index Terms* — Evacuated solar tube collector, solar heating, solar radiation intensity, experimental stand, cloudiness, low temperature.**

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I. Introduction

Harsh climatic conditions, remoteness of populated areas, and complex transport schemes impose significant restrictions on the development directions of the Sakha Republic (Yakutia) in general and energy supply in particular. The current situation in the heat supply sector of the Republic is characterized by serious problems: low technical level, low economic efficiency of heat supply facilities and high fuel costs [1]. On average the duration of the heating season in Yakutia is 8-9 months a year and in some settlements of the Arctic zone it is almost all year round. Due to the influence of climate the amount of energy for heating 1 sq. meter of housing is required two times more than the average for the Russian Federation and accordingly economically justified tariffs for utilities significantly exceed their average Russian level [2].

Expenditures from the state budget of the Sakha Republic to provide subsidies to organizations in the public utility complex are growing every year. On average for the period from 2015 to 2018 90.8% of the economically justified tariff for heat energy is subsidized from the regional budget. Accordingly, the part of the economically justified tariff paid by the population was 9.2%. Subsidies for heat energy only in the Arctic zone were 5.7 billion roubles [3].

In the current situation of high costs for heat supply to hard-to-reach settlements of the Republic huge potential for the introduction of energy-saving technologies is created. Hybrid solar heating with vacuum solar collectors is a promising technology for implementation due to the presence of significant natural heliopotential. The long-term average of photovoltaic power potential at some solar power plants in Yakutia, in particular in the settlements of Dulgalakh, Batamai, Yuchyugey reaches 1000-1100 kWh/kW per year, and on average more than 800 kWh/kW per year for all solar power plants of the Sakha Republic

TABLE 1. Solar power plants characteristics

Settlement	POWER, KW	Long-term average of photovoltaic power potential at year, kWh/kW
Batagay	1000	833
Kybergene	20	1023
Batamai	60	1009
Yunkyur	40	836
Yuchyugey	30	1181
Orto-Balagan	50	909
Dulgalakh	20	1051
Kudu-Kyuyol	20	920

[4]. The long-term averages of photovoltaic power potential of several solar plants located in different parts of the Sakha Republic are shown in Table 1. For more efficient operation, such systems include thermal energy storage tanks that store it for further use at night time. The economic success of installing solar heating can be ensured by a combination of two main factors: high costs for heating and the availability of a significant amount of solar energy.

II. EXPERIMENTAL STAND

Studies of the working processes of a solar heat supply system based on a evacuated solar tube collector were carried out under natural conditions in Yakutsk at a specialized stand of the Department of Energy Problems of the IPTPN SB RAS. The experimental stand allows monitoring the operating parameters of a solar heating system and solar radiation falling on the ground for a long time. Measuring the resulting useful thermal energy using an ultrasonic heat meter allows you to evaluate the efficiency of the solar collector depending on climatic conditions (Figures 1-2).

The experimental stand is installed on the roof of the IPTPN SB RAS main building in Yakutsk. Thermal energy source is an evacuated solar tube collector SILA R5-15 with 15 tubes. The total collector area is 2.41 m2, the aperture area is 1.64 m2. The collector is installed at a height of 22 meters from the ground surface. The azimuth angle corresponds to the location of the roof of the building and is equal to 217°, the angle of inclination to the horizon is 65°, the roof slope is 10°. The system is divided into two separate circuits. Solar circuit with antifreeze liquid (ethylene glycol) and heating circuit with rainwater as a liquid. Heat exchange takes place in a storage tank with a volume of 200 liters with one heat exchanger. The useful thermal energy received from the collector is measured using the SPT940 heat meter with a stationary ultrasonic

Fig. 1. Solar collector, pyranometer.

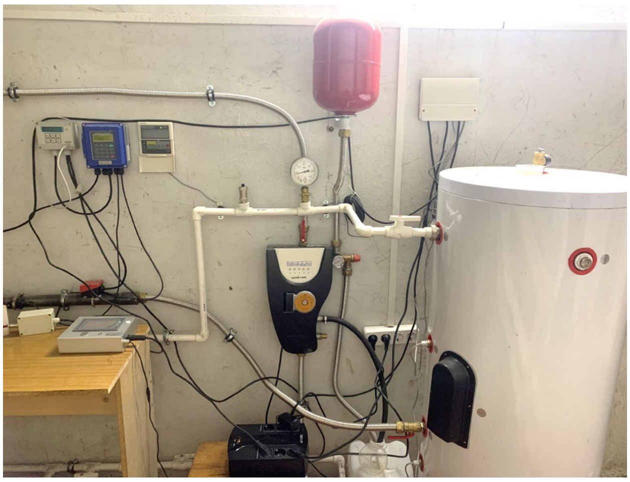

Fig. 2. Measuring stand.

flow meter Streamlux SLS-720F. The heat meter records the temperature data of the supply and return pipelines, the volume and mass flow of the liquid. The amount of incoming solar radiation on the collector surface is measured using a RK200-04 pyranometer. The experimental stand scheme is shown in Figure 3.

III. DATABASES

Based on the data obtained, as well as open sources of information on the climatic characteristics of the region, a database of useful thermal energy of a solar heating system with an evacuated solar tube collector with 15 heat pipes was compiled. At the beginning of the experiment until September 2022 indications were read off for a collector with 11 operating tubes, after September 2022 the experimental stand operated at full capacity. The amount of incoming solar radiation on the collector surface was recorded with a measurement period of 5 minutes. To carry out calculations of the system efficiency these parameters of climatic conditions were added to the database according to the meteorological station of the Yakutsk airport: ambient temperature, atmospheric pressure, relative humidity, wind speed and total cloudiness. Software was created to process the large amount of data obtained from the pyranometer and heat meter. This program received a certificate of state registration of the computer program №2023669993 [4]. State registration of the database №2022622548 of total solar radiation using a pyranometer installed on the roof of the IPTPN SB RAS main building was also completed [5]. The difference between the developed database is the frequency of measurements of 5 minutes in contrast with the data from weather stations in Yakutsk with a measurement period of 3 hours and data from satellite actinometric measurement systems with a measurement period of 1 hour.

IV. Installation Features and Operating Experience

Additional difficulties arise in the design and installation of equipment on inclined surfaces, in the manufacture of the frame and in fine-tuning the angle of inclination of the collector. It is best to provide a mechanism for smoothly adjusting the angle of the frame or, if possible, install the equipment on a flat surface.

Flexible, cold-resistant wires should be used to transfer pyranometer data. The braid of conventional wires breaks in severe cold even with a slight change in the position of the wire.

The measuring equipment is located in the utility room under the roof, the length of the pipe branch is about 15 meters which is quite a lot. The length of the solar collector circuit should be minimized to reduce heat loss in the pipe, the load on the circulation pump, the volume of expensive antifreeze used and save material.

When designing an installation special attention should be paid to the correct selection of the storage tank volume. Excessive volume of the storage tank leads to inefficient operation of the entire system; insufficient volume will lead to boiling of the antifreeze liquid in the solar collector circuit. It is also very important to take into account the operating mode of the circulation pump in the solar collector circuit, the length of the solar collector circuit, the characteristics of the heat exchanger of the storage tank and the solar collector.

During the operation of the stand, it was revealed that it is better to place the expansion tank of the solar collector circuit directly at the entrance to the solar collector. In case of circulation pump failure incorrect settings of the circulation pump, interruptions in the power supply without backup, the antifreeze liquid in the solar collector

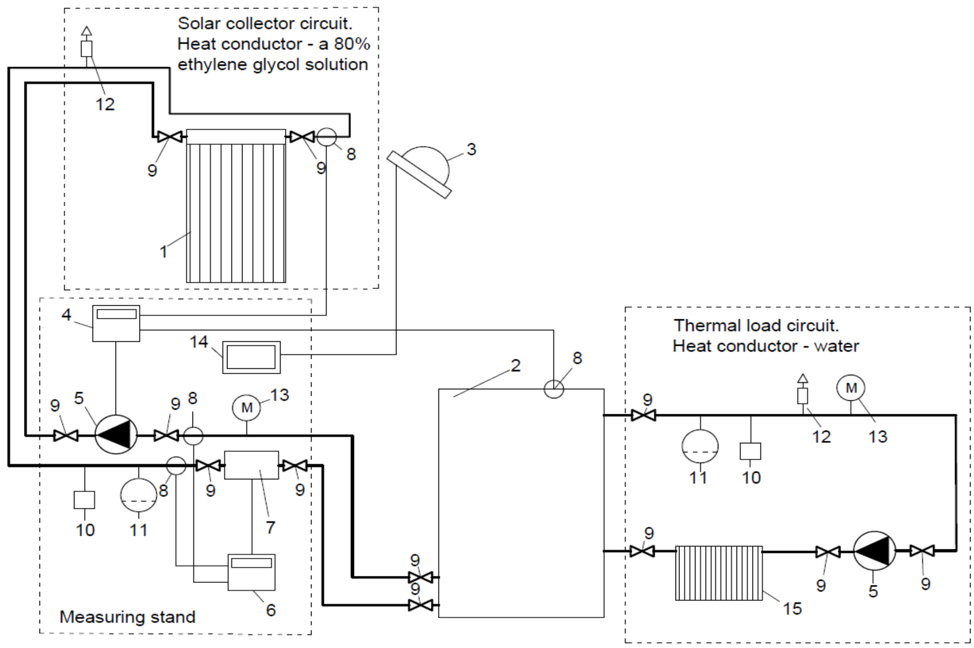

Fig. 3. Scheme of the experimental stand.
1 – evacuated solar tube collector; 2 – storage tank; 3 – pyranometer; 4 – controller; 5 – pump; 6 – heat meter; 7 – flow meter; 8 – temperature sensor; 9 – ball valve; 10 – dump valve; 11 – expansion tank; 12 – air vent; 13 – pressure gauge; 14 – data logger; 15 – heating radiator.

circuit quickly heats up which causes its release into the atmosphere in the presence of an emergency coolant discharge valve. Without valve the system will overheat which can lead to operational incident.

During the night with high humidity especially if sewer pipes or ventilation are located nearby frost forms on the collector tubes which interfere with the heat exchange process. After sunrise with sufficient intensity of solar radiation the frost melts and collector begin to operate normally.

There is an assumption that a system with a storage tank for heat exchange fluid directly on the top of a solar collector will work better due to the inertia of the heat transfer process from the heat exchange fluid of the solar collector circuit to the water in a tank.

V. CONCLUSION

Evacuated solar tube collectors have shown positive results when operating in low temperature conditions subject to certain requirements. When designing the installation it is necessary to minimize the length of the solar collector circuit, provide expansion tanks and an emergency coolant discharge valve, and pay special attention to the correct choice of the volume of the storage tank. It is also very important to take into account the operating mode of the circulation pump in the solar collector circuit, taking into account the length of the solar collector circuit, the characteristics of the heat exchanger of the storage tank and the solar collector. During the operation of the stand, it was revealed that it is better to place the expansion tank of the solar collector circuit directly at the entrance to the solar collector. During the winter season, frost forms on the surface of the vacuum manifold tubes, which reduces the efficiency of the manifold.

Evacuated solar tube collectors have shown positive results when operating in low temperature conditions, subject to certain requirements. When designing the installation, it is necessary to minimize the length of the solar collector circuit, provide expansion tanks and an emergency coolant discharge valve, and pay special attention to the correct choice of the volume of the storage tank. Setting the operating mode of the circulation pump in the solar collector circuit should be done taking into account the length of the solar collector circuit, the characteristics of the heat exchanger, storage tank and the solar collector. The solar circuit expansion tank must be installed directly at the entrance to the solar collector. During the winter season, frost forms on the surface of the vacuum manifold tubes, which reduces the efficiency of the manifold.

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