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# Energy Systems Research

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# Contents

# Some Generalizations of an Analysis of 2016-2017 Blackouts in the Unified Energy System of Russia

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***Abstract* — The paper presents a brief description of the sequence of events and processes observed during three cascading blackouts that occurred in 2016 - 2017 in the Unified Energy System (UES) of Russia. The key factors that contributed to their occurrence, development, and interruption were determined. The objectives of research on the development of measures to reduce the risk of such system-wide accidents are formulated.**

***Index Terms* — analysis, blackouts, generalizations, recommendations, UES of Russia.**

## I. Introduction

During the years 2016–2017, the UES of Russia went through several major system-wide blackouts with complicated development of emergency processes and massive grave consequences for consumers. The most typical of them in terms of the uniqueness of the cascading development processes, and the consequences for consumers are the blackouts in the Interconnected Power System (IPS) of the Urals on August 22, 2016 (which extended to the entire UES of Russia), in the IPS of Siberia on June 27, 2017, and in the IPS of the East on August 1, 2017 [1–4, a.o.].

Each of the mentioned blackouts, as well as several others, were analyzed in detail by the corresponding Commission of Rostechnadzor (Federal Environmental, Industrial, and Nuclear Supervision Service of Russia). This analysis underlay the conclusions of the Commission about the causes of the blackouts, the inadequate operation of individual components and subsystems, and fostered the recommendations for the measures to prevent such emergencies and their undesirable development. Apart from the official conclusions of the Commission, for each such a serious system-wide accident with consequences for many consumers, there are usually other materials that reveal the specific features of the events and processes of the accident development. This additional information often helps to understand the analyzed system blackout in more detail.

It is worth noting that the ongoing major system-wide cascading accidents are subject to mandatory thorough analysis in all countries, without exception. The findings of such an analysis reveal the general mechanisms of the development of such accidents and the recovery of electric power systems (EPSs) after them. This analysis also facilitates the formulation of generalized recommendations to prevent severe system blackouts, counteract their development, and restore the systems. Examples of such generalizations can be found in [5–12], and in some other publications. Each cascading blackout is unique in terms of a combination of its causes, events, and processes of development. However, individual states and events can manifest themselves in several system-wide blackouts. Such frequently recurring states and events require priority attention and analysis of their causes, and the development of measures to prevent them in the future.

This paper aims to summarize the previously performed analysis of specific system blackouts in the UES of Russia with the view to identifying common factors in their occurrence and development, and, based on this analysis, drawing general conclusions and recommendations to eliminate the impact of these factors.

## II. A brief characteristic of cascading system blackouts

### *A. Blackout in the UES of Russia on August 22, 2016 [1, 2]*

The diagram of the electrical networks of the accident area indicating the cutsets of the emergency separation of the UES of Russia is shown in Fig. 1. Fig. 2 indicates the results of monitoring the electrical frequency in the eastern Fig. 2. Results of frequency monitoring in the eastern part

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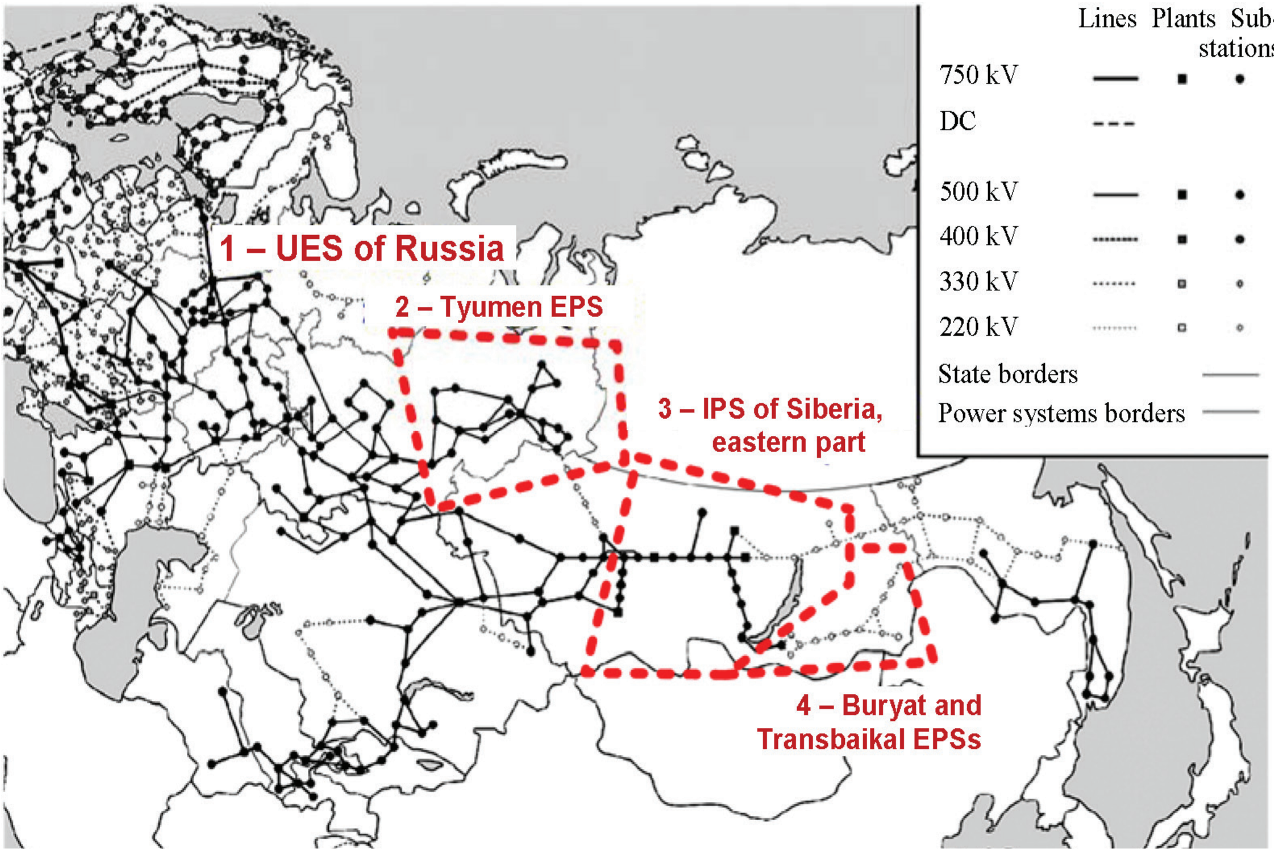



*Fig. 1. A scheme of Russia's UES division into four asynchronously operating parts during the blackout on 08.22.2016.*

of the IPS of Siberia during the blackout on August 22, 2016 (measurement in Irkutsk, frequency [Hz] vs time [s]):

(a) within 50 minutes after the blackout started;

(b) in the initial stage of the blackout;

(c) a sharp rise in frequency due to separation of the eastern part of the IPS of Siberia from the UES of Russia.

Part of the IPS of Siberia. The sequence of the main events and processes during the blackout was as follows:

- The primary cause of the blackout was a short circuit at the outdoor switchgear of the Reftinskaya TPP (thermal power plant) due to the condenser destruction and oil ignition;
- Short-circuit was eliminated by distant redundant protection (due to failures of main and backup protection) with disconnection of outgoing 500 kV overhead lines (OHL). The failed protections include electromechanical protective relays;
- The protection of long-range redundancy 500/220 kV autotransformer (AT) failed;
- The generators of Reftinskaya TPP with a total capacity of 2.3 GW were tripped by process protections due to a prolonged voltage slump during the long short-circuit;
- The out-of-step conditions occurred due to a long time of short-circuit elimination and disconnection of 500 kV overhead lines outgoing from the Reftinskaya TPP by out-of-step protection, which resulted in islanded operation of the Tyumen power system with surplus power of 1.4 GW;
- The frequency in the UES of Russia decreased to 49.742 Hz;
- There were weakly damped slowly decaying synchronous oscillations of generators in the UES of Russia;
- Active power flows increased above the permissible ones in some of the controlled cutsets of the IPS of Siberia due to the uneven loading of power plants because of their unsatisfactory participation in frequency control during the oscillations. Steady-state stability was lost, the out-of-step conditions occurred, the out-of-step protection tripped transit 500 kV overhead lines, and the eastern part of the IPS of Siberia was disconnected for islanded operation with surplus power of 2.1 GW;
- A long transient process in the eastern part of the IPS of Siberia with damped oscillations of the rotors of generators and subsequent overload and stability loss in the cutset of Irkutsk - Buryatia, caused the separation of the Buryat and Transbaikal power systems for islanded operation with a power shortage;
- To restore power balance, in surplus subsystems, the power plant units were unloaded, in deficient ones - the automatic frequency load shedding was involved.

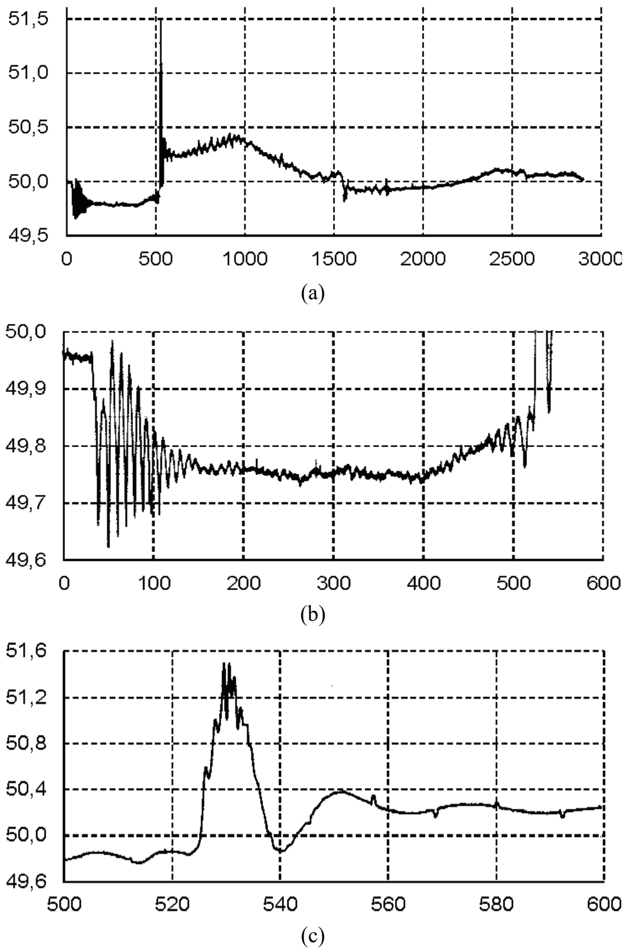



***Fig. 2. Results of frequency monitoring in the eastern part of the IPS of Siberia during the blackout on August 22, 2016 (measurement in Irkutsk, frequency [Hz] vs time [s]):***
***(a) within 50 minutes after the blackout started;***
***(b) in the initial stage of the blackout;***
***(c) a sharp rise in frequency due to separation of the eastern part of the IPS of Siberia from the UES of Russia.***

*B. Blackout in the IPS of Siberia on June 27, 2017 [3]*

The diagram of the electrical networks in the blackout area and the results of monitoring the electrical frequency in the eastern part of the IPS of Siberia are shown in Figs. 3 and 4. This blackout is characterized by the following time sequence of events and processes:

- Emergency control devices at the Bratsk hydropower plant (HPP) falsely generated and implemented control actions to disconnect the load of 825 MW, including 750 MW at the Irkutsk aluminum plant;
- The emergency control devices at the 500 kV Ozyornaya substation (SS) malfunctioned and disconnected the load at the Bratsk aluminum plant of about 650 MW;
- Due to the overload of several 500 kV backbone electrical network components, a multi-frequency out-of-step conditions occurred among four parts of the UES of Russia: the European part, including the IPS of the Urals; the western part of the IPS of Siberia; the eastern part of the IPS of Siberia; and unit 2 of Beryozovskaya TPP;
- The out-of-step protection tripped seven 500 kV overhead lines, which separated the eastern part of the IPS of Siberia (part of the Krasnoyarsk power system, and Irkutsk, Buryat and Transbaikal power systems) for islanded operation with surplus power and a short-term increase in frequency to 52.6 Hz;
- The operation of the over-frequency protection relay and the relays of power units at the Ust-Ilimsk HPP, Bratsk HPP, and Nazarovskaya TPP decreased the total load by 3.28 GW;
- At the same time, the overload protection relays at the Boguchany HPP tripped seven hydroelectric units operating at an increased frequency, which caused a decline in power output from 2 GW to 0 GW;
- Due to false operation of protection relays, Krasnoyarskaya TPP-2, Ust-Ilimsk HPP, and Bratsk HPP were additionally unloaded by about 0.8 GW;
- As a consequence, the frequency in the separated part of the IPS of Siberia went down to 47.7 Hz; the action of the frequency load shedding disconnected a total of 3.4 GW of load at the Irkutsk, Bratsk and Krasnoyarsk aluminum plants to restore power balance in the post-emergency conditions.

*C. Blackout in the IPS of the East, August 1, 2017 [4]*

The scheme of electrical networks of the blackout area and the results of monitoring the electrical frequency in the western part of the IPS of the East are shown in Figs. 5 and 6. The sequence of events and processes during the blackout was as follows:

- During the repair of the electrical network, a single-phase short circuit occurred on the 220 kV overhead line Khabarovskaya SS – Volochaevka traction SS, which caused disconnection of the line, and partitioning of the IPS;
- In the separated deficient eastern part of the IPS of the East, automatic load shedding and the actions of personnel established balanced post-emergency conditions;
- In the western part of the IPS, there were slow frequency oscillations with a period of 2 s, and a range of oscillations from 53 to 47 Hz;
- As a result, the group active power controller at the Zeya HPP was deactivated, and over-frequency protection relay tripped one unit at the Zeya HPP, two units at the Bureya HPP, and one unit at the Neryungrinskaya TPP;
- The arisen active power shortage and frequency decrease triggered the automatic load shedding and disconnection of 500 kV Amurskaya SS - Heihe (China) overhead line;
- Due to a voltage rise to 560 kV in the area of the Bureya HPP, the 500 kV overhead lines of the Bureya HPP - Amurskaya SS and Bureya HPPs – Khabarovskaya No.1 SS were disconnected by the automatic

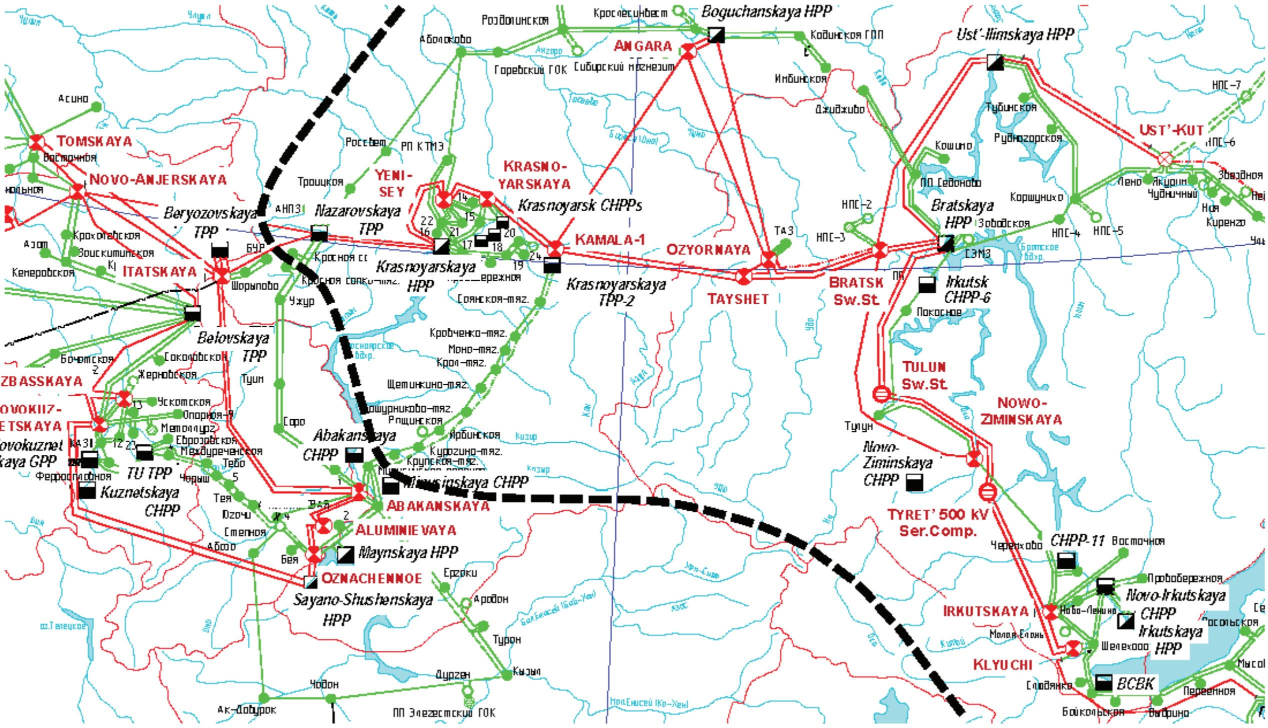



***Fig. 3. The main electrical networks in the area of blackout in the IPS of Siberia on June 27, 2017. The bold dotted line denotes the cutset of separation of the eastern part of the IPS of Siberia for islanded operation.***

overvoltage limiter; and overspeed protection tripped one more hydroelectric unit of the Bureya HPP;

- As a result of an increased active power shortage in the western subsystem of the IPS, the frequency decreased to 46 Hz, and an avalanche-like development of the emergency process occurred with a massive shutdown of power plants and consumers;
- This cascading development of the blackout led to the isolation of the Blagoveshchensk load center with a single source (the Blagoveshchensk CHP) for islanded operation.
- The subsequent unfolding of the emergency caused power shedding of this plant to zero with the auxiliary power loss and complete de-energization of consumers in the Blagoveshchensk load center.

## III. Analysis of key factors of the occurrence and development of the considered blackouts

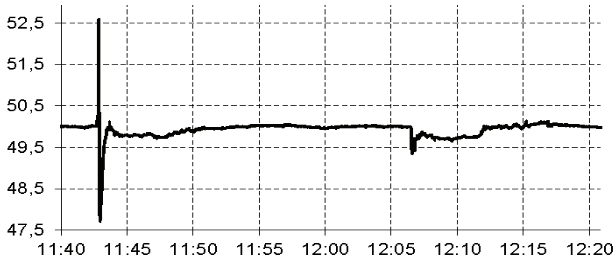
The analysis of the above sequence of events and processes that occurred during the analyzed blackouts allows us to identify the following key factors that determined the specific features of the cascading development of these blackouts:

a) Failures, false operation, actions of relay protection and emergency control devices, which are inadequate to the current state of the system (for example false triggering of emergency control at the Bratsk HPP at the beginning of the accident on June 27, 2017, in the IPS of Siberia; failure of the main and backup protections during liquidation of short circuit at Reftinskaya TPP during the accident in the UES of Russia on August 22, 2016). It is worth noting that the failed relay protection and emergency control equipment have different element bases: at Reftinskaya TPP, it is electromechanical, while at Bratsk HPP, it is microprocessor-based. Therefore, the causes of failures are different;

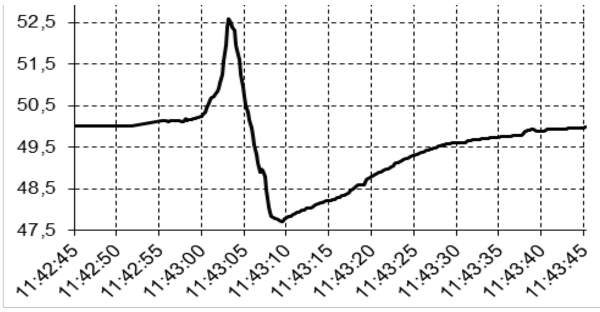
b) Correct operation of emergency control devices, adequate to the current (but off-design) EPS topology and conditions, which aggravates the emergency (for example disconnection of the hydroelectric units at the Boguchany HPP by overload protection when frequency increased during the blackout in the IPS of Siberia on June 27, 2017; tripping of the units at the Zeya HPP, Bureya HPP, and Neryungrinskaya TPP by over-frequency protection during low-frequency steady-state synchronous oscillations in the western part of the IPS of the East during the blackout on August 1, 2017);

c) Correct operation of emergency control devices, contributing to counteraction and termination of a blackout and its development (operation of some emergency control devices in the later stages of the blackout development, out-of-step protection and automatic load shedding in almost all cases of the blackouts at issue);

d) Continuous or weakly damped synchronous oscillations of power plant generators in EPS (for example low-frequency sustained synchronous oscillations of generators at power plants in the western part of the IPS of the East during the blackout on August 1, 2017; weakly damped oscillations in the separated eastern part of the IPS of Siberia during the accident on August 22, 2016).




(a)




(b)

***Fig. 4. Results of frequency monitoring in the eastern part of the IPS of Siberia during the blackout on June 27, 2017 (measurement in Irkutsk, frequency [Hz] vs Moscow time [hh:mm:ss]): (a) from the beginning to the end of the blackout, (b) in the initial stage of the blackout.***

A detailed analysis of factor A) should focus particular attention on the unique case of a cascading failure of the main and backup protections during the elimination of a short circuit at the Reftinskaya TPP during the blackout on August 22, 2016, which requires in-depth scrutiny.

According to the findings of the analysis of several recent system-wide blackouts, the Ministry of Energy of the Russian Federation have stated that the electric power systems have a wide variety of microprocessor-based devices for relay protection and emergency control made by different manufacturers. In many of them, the measuring elements have an unacceptable level of error in the measurements of frequency when it deviates from the nominal one, which leads to failures in operation or false operation of the devices [13]. An important reason for the malfunctioning of microprocessor-based devices of relay protection and emergency control is the imperfection of the algorithms embedded in them [14]. Other factors are discussed in [8, 14, 15, a.o.]. In general, this problem requires thorough research, including the investigation of the statistics of failures of microprocessor-based devices.

As can be seen from the analysis of the system-wide accidents at issue, the failures and false operation of relay protection and emergency control devices are the root causes of such accidents, along with two others. These

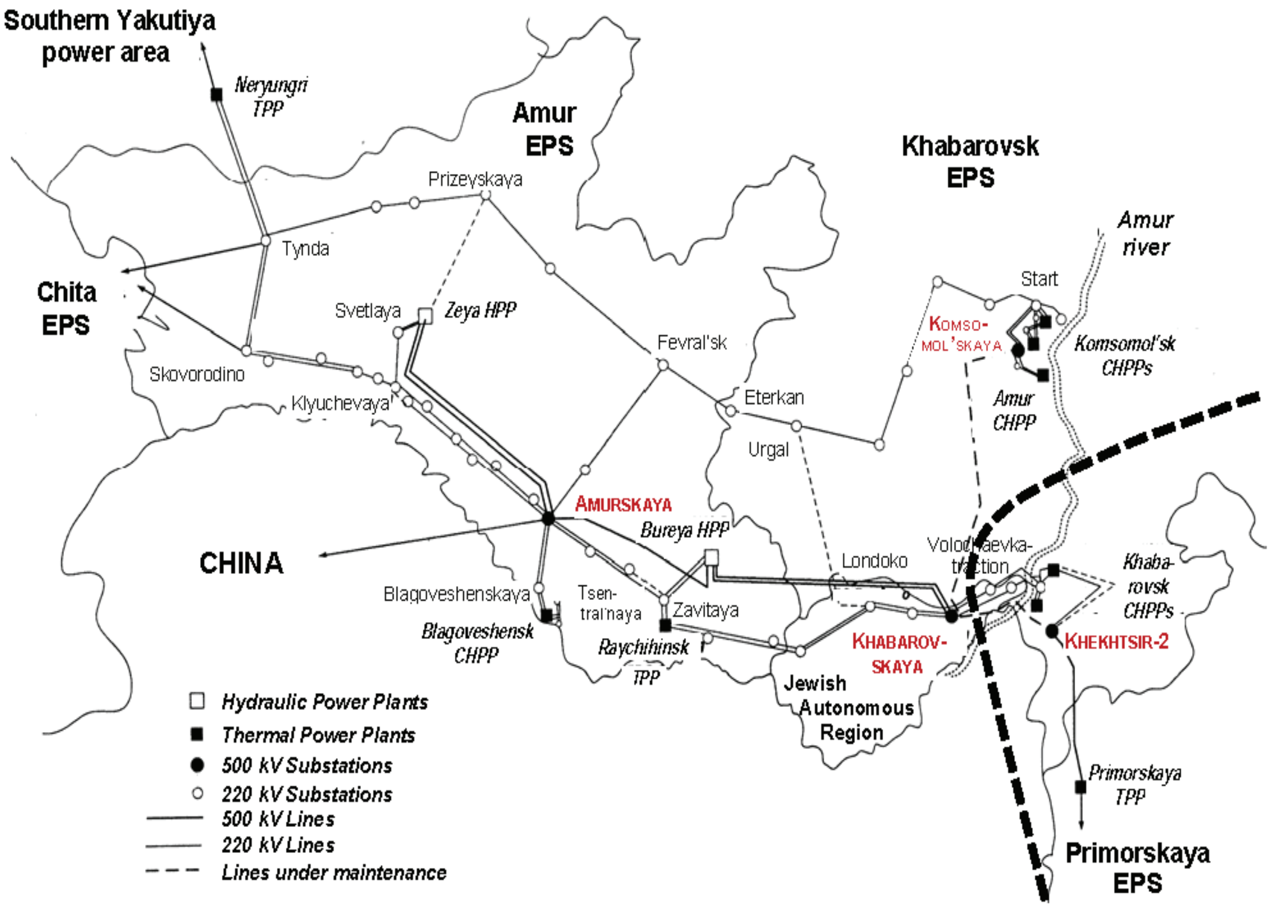



***Fig. 5. A scheme of the main network of the IPS of the East as of 08.01.2017. The bold dotted line denotes the cutset "Crossing through the Amur river" along which the eastern part of the IPS of the East was separated for islanded operation.***

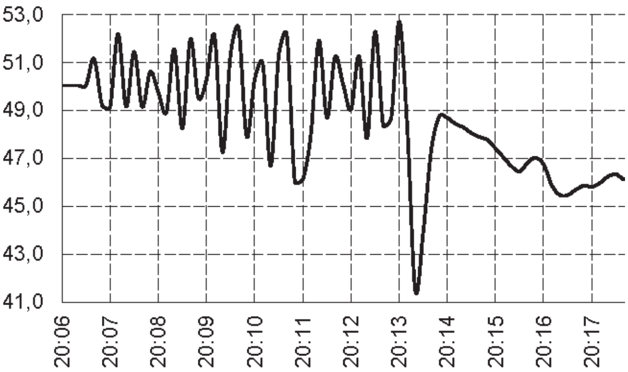



***Fig. 6. Results of frequency monitoring in the western part of the IPS of the East during the blackout on 01.08.2017 (measurement on 220 kV buses of the Blagoveshchenskaya substation, frequency [Hz] vs Khabarovsk time [hh:mm]).***

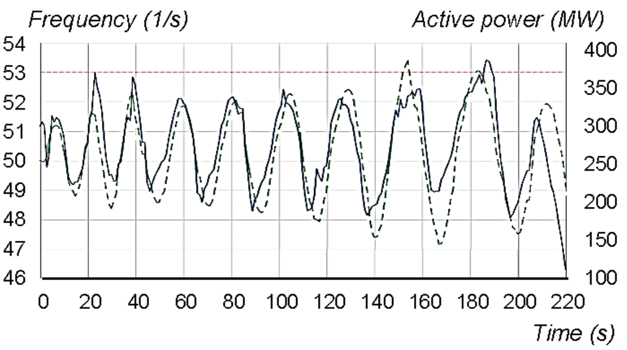



***Fig. 7. Full-scale oscillograms of the rotor speed (dashed line) and active power (solid line) of the hydro-generator of the Bureya HPP during the accident on 08.01.2017.***

are the human factor (erroneous actions of personnel, errors in the design and settings of the relay protection and emergency control, and others), and the off-design extreme external impacts. This fact is confirmed by the statistics of the 1960s - 1980s [8, a.o.].

It is also important to note that the proper (failure-free) operation of relay protection and emergency control devices according to the EPS current topology and operating parameters, which can be off-design (factor B - see above), exacerbates the emergency. A typical example in this regard is the operation of over-frequency protection relay to disconnect the units of the Zeya HPP, Bureya HPP, and the Neryungrinskaya TPP during frequency fluctuations in the separated western part of the IPS of the East during the blackout on August 1, 2017 [4]. The long period of oscillations (2 s), with their large amplitude, created favorable conditions for the operation of over-frequency protection relay, since the frequency at the upper part of the oscillation amplitude appeared to exceed the frequency control settings for a longer time than the automatic response delay required to prevent the relay operation in the case of short-term frequency variations above the trip setting. The avoidance of such conditions is a nontrivial task and requires in-depth research. One of the solutions for the cases like the blackout in the IPS of the East can be measures to eliminate the causes of low-frequency synchronous oscillations of generator rotors in the EPS (Fig. 7).

The positive effect of emergency control devices in the later stages of the blackout, out-of-step protection, and automatic load shedding in all cases (factor C) of interrupting the cascading development of the emergency process does not require comments. This fact once again confirms the well-established opinion of specialists that the out-of-step protection and load shedding are the last frontiers in counteracting the development of cascading emergencies and preventing the complete shutdown of EPS. Meanwhile, in extremely challenging situations, these automatic schemes do not help either, which is demonstrated by the catastrophic uncontrollable development of a system-wide emergency in the IPS of the East on August 1, 2017, with a complete blackout of the town of Blagoveshchensk and the auxiliary power loss at the Blagoveshchenskaya CHP [4].

Of interest is the cause of factor D, which to a greater extent manifested itself in the form of low-frequency sustained synchronous oscillations of generators in the western part of the IPS of the East during the accident on August 1, 2017 [4], and, to a lesser extent, in the separated part of the power system of Eastern Siberia in the accident in the IPS of Siberia on June 27, 2017. [3]. Presumably, such a cause could be the discrepancy between the settings of power system stabilizers of HPP units with respect to the derivatives of operating parameters, the existing topology, and the conditions of the electrical network of the corresponding part of the EPS. Moreover, the relative weakness of the electrical network plays a significant negative role. Similar situations were studied in [16]. As a result, instead of damping the oscillations, the PSSs of HPP and TPP units amplified the system oscillations.

The reliability of the given explanation of the cause of continuous synchronous oscillations of power plant generators under the conditions prevailing in the islanded EPS is also indirectly confirmed by the fact that the current industry standard [17] reflects the requirements for tuning power system stabilizers in a rather fragmentary manner. In particular, this standard suggests voluntary certification of tuning of the power system stabilizers. However, it does not propose a procedure for tuning their coefficients with respect to the derivatives of the power system operating parameters to changing topology and operation conditions. The development of this procedure requires special studies using, for example, frequency methods of stability analysis or modal analysis of EPS [18, 19, a.o.], or other possible approaches. Thus, the industry standard requires adjustment [17].

The elimination of the possibility of weakly damped low-frequency oscillations by using the procedure for adapting the tuning of power system stabilizer will eliminate the non-standard operation of the emergency control devices in the off-design conditions similar to those that developed during the system-wide accident in the IPS of the East.

## IV. Conclusion

The analysis of large-scale system-wide cascading blackouts in the UES of Russia in 2016 - 2017 revealed several factors that determine the occurrence and development of these unique accidents with severe consequences for the system and consumers. The examination of these factors makes it possible to formulate recommendations by area of research with the view to developing the necessary methods and procedures for improving relay protection and emergency control systems (especially those based on microprocessor) and increasing their reliability. Based on this analysis, it is also possible to design the procedures for providing adaptable tuning of regulation coefficients of power system stabilizers by the derivatives of operating parameters and modernize the standards determining the conditions for normal operation and prevention of severe cascading blackouts in the electric power systems.

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# An Express Methodology for Calculating the Reliability of Power Supply Systems with Autonomous Power Sources

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*Abstract* — **Autonomous power sources are widely used in systems for power supply to industrial facilities, especially in the oil and gas industries that have affordable energy carriers. These sources can be used both separately and in combination with centralized power supply, as primary, backup, or emergency sources. Their operation is characterized by the features that affect power supply reliability and must be taken into account when deciding on their use in the stages of designing new power supply systems or modernizing existing ones. The use of methodology and software for calculating the reliability of systems with autonomous power sources in the stage of pre-project research can contribute to more informed decision-making. In this stage, there is no need and opportunity to consider all reliability issues in detail. Here, express methods are enough to take into account the main features of the systems functioning with autonomous or mixed power sources and to compare the proposed system options within a single methodological framework. Based on this, a methodology was developed to calculate the reliability of power supply systems with autonomous and mixed power sources. The proposed methodology employs semi-Markov random processes (Markov chains) and can be used in comparative reliability analysis of power supply options with autonomous and mixed power sources. It was implemented in software and is accompanied by an example of reliability calculation for power supply to a stationary platform for maintaining reservoir pressure in an offshore oil field.**

*Keywords*: **reliability, methodology, random processes, power supply system, autonomous sources.**

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## I. Introduction

Oil and gas production, transportation, and processing facilities characterized by complex continuous processes require a highly reliable power supply. Along with centralized energy sources, autonomous auxiliary power plants based on diesel or gas turbine plants have long been used to power consumers in the oil and gas industry. Depending on the number and type of power sources used, the conditions for their parallel operation with centralized power sources, and constraints on the allowable time for power supply interruption, there can be various types of power supply systems with autonomous power sources in terms of reliability. The reliability assessment in the stage of pre-design surveys and the development of technical specifications for design facilitate the identification of the most rational power supply options in an early stage. In this stage, when the equipment has not yet been selected, it is impossible and unnecessary to consider in detail the reliability of all system elements. It is sufficient to take into account the reliability of the main elements (power sources), the availability of structural and time redundancy, the reliability of automatic systems that ensure the connection of backup and emergency power sources, and the repair restrictions.

This study aims to develop an express methodology for calculating the reliability of industrial power supply systems with autonomous and mixed (centralized and off-grid) power sources.

## II. Selection of a Reliability Calculation Parameter

The method underlying the methodology for reliability calculation was selected given the above features of the operation of power supply systems related to restored and redundant systems, as well as constraints on information support of initial data when identifying power supply options in the stage of designing new systems or modernizing existing ones. The selection of the method involved analysis of the methods of the theory of reliability of engineering and electric power systems [1-9], and their application [10-20], including modeling the reliability of power supply systems for oil and gas production [18-22].

As a result, the methodology is based on the method of mathematical modeling of semi-Markov random processes [7, 8, 12, 13, 16]. This allows factoring in the presence of structural and time redundancy, the reliability of automatic systems that provide the connection of backup and emergency power sources, constraints on repairs of power supply systems, determining stationary reliability indices, and, if necessary, investigating their changes over time.

The specific feature of the proposed methodology lies in the generalization of experience in modeling the reliability of power supply systems [12, 14, 16, 17, 19, 20, 21], the possibility of obtaining a fairly complete set of reliability indices, determining the recoverability of the systems and their differentiation by integral reliability index, i.e., the amount of power undersupply based on the mathematical tool of semi-Markov random processes.

## III. The methodology for modeling and calculating power supply system reliability

The methodology includes the following steps [5, 6, 12, 20, 21]:

- formation of space and state graph of the system;
- mathematical description of the space and state graph of the system;
- determination of the system reliability indices

### *A. The formation of space and state graph of the system*

This stage suggests taking into account working, standby, and repair states of power sources and system tie lines, i.e., power lines that include 6 (10) kV switchgears of technological plants to which generators of autonomous power sources are connected. Along with structural redundancy characterized by backup generating capacities and tie lines, there is also a time reserve in power supply systems [5, 17], which implies that consumers allow a short break in the power supply. The interruption in power supply during the operation of the automatic load transfer (ALT) switch does not stop the process and is not considered a failure. Along with the failures of elements (sources, lines) and failures in switching to a backup source, one should take into account the possibility of system failures, which can be caused by interruptions in fuel supply to generating electric units and the failure of relay protection of power supply systems.

Failures of system elements occur with intensity $\lambda_i$ 1/yr; the recovery intensity $\mu_i$ is 1/yr, ($i=1,\dots,n$). Here $n$ is the number of basic system elements (sources and lines). The intensity of their failure and recovery is inverse to the average time between failures and average recovery time, respectively.

The possibility of an unsuccessful ALT is characterized by probability $q_A$LT. The probability of a successful ALT is 1– $q_A$LT. It allows taking into account the probability $q'$ of failure of the automatic device and the probability $q''$ that the connection time τ will exceed the allowable time $t^*$, as well as the presence of technological (functional) reserve $\delta$ (takes value 1 with technological reserve, and value 0 – without it) [18]. Determining the permissible time of interruption in the power supply to facilities, one should use corporate standards, for example, [23], for PJSC Gazprom. In the absence of a technological reserve, the probability of ALT failure is determined by the sum of probabilities of two events: the automatic devices fail or the connection time of the backup source exceeds the permissible time in case of failure of automati c device $q_A$LT=$q'$+(1 – $q'$)$q''$. The probability $q''$ is determined by the laws of distribution of the connection time $F(t)$ and the permissible time of power outage $D(t)$. The distribution of the random variable is in good agreement with the biased exponential law

$$F(t) = \begin{cases} 0, t \le b \\ 1 - e^{-\frac{t-b}{a}}, t > b' \end{cases} \quad (1)$$

where is the minimum load connection time; is a statistical parameter. The degenerate distribution law corresponds to a fixed value of the permissible time of power outage

$$D(t) = \begin{cases} 0, t \le t^* \\ 1, t > t^* \end{cases} \quad (2)$$

The probability that the connection time exceeds the permissible time is

$$q'' = P\{\tau \ge t^*\} = \int_0^\infty D(t) * dF(t) = \begin{cases} 0, t \le b \\ 1 - e^{-\frac{t-b}{a}}, t > b \end{cases} \quad (3)$$

The probabilities of events allow "sifting" the flow of failures and recoveries [17, 18, 20]. In case of unsuccessful ALT, a generating unit or a system tie line is connected manually by the operator. The power plant unit is put into operation manually with intensity $\mu_{me}$. Manual connection of tie line or sectional switch is carried out with intensity $\mu_{ms}$.

System failures are characterized by the intensity of full failures $\lambda_s$ or the intensity of partialfailures $\lambda_{ss}$ and recoveries $\mu_s$ or $\mu_{ss}$, respectively. The rates of system failures associated with the probability $q_{rp}$ of failure of relay protection are determined by the product of the failure rate in the electrical network of the system $\lambda_{en}$ and the specified probability.

The state and transition graph is formed based on the analysis of possible states and includes a finite set of states $X=\{x_1, x_2, x_3, \dots, x_n\}$, which is divided into subsets of operable states $X_{us}$ and inoperable states $X_{ds}$. The formation of states should take into account the main states and neglect the secondary ones. It is assumed that the combination of independent failures of more than three main system elements is impossible [2, 3]. A subset of inoperable states is divided into several levels, ranked by power shortage in the system.

### *B. The mathematical description of the space and state graph of the system*

Initially, the process is described by the intensity matrix of the system transitions from one state to another. Based on the intensity matrix, the vector of the average residence time of the system in the states and the transition probability matrix between the states are determined. Element of a vector of average residence time in a state is defined as reciprocal of the sum of intensities of transitions leaving this state. Element of the transition probability matrix is defined as the ratio of the intensity of transition from state to state to the sum of the intensities of all transitions leaving state .

Based on the original matrix , vector of stationary probabilities of the process is found. Stationary probabilities are found from the system of equations [5, 18]

$$\pi_i = \sum_{i,j}^{n} p_{ij}\pi_j \qquad (4)$$

and normalization conditions

$$\sum_{i=1}^{n} \pi_i = 1 \qquad (5)$$

The Gauss method is used to solve the system of equations.

*C. Determination of system reliability indices*

The calculation of the power supply reliability is reduced to the determination of reliability indices. A set of reliability indices includes:

$T_H$, *g* is mean operating time to failures;

$T_B$, *h* is mean time to restoration;

$A_F$ is an availability factor;

$F$, 1/yr is an average failure rate;

$\Delta W$, kWh/yr is an average annual power undersupply.

The mean operating time to failures of the system $T_H$ is defined as the average time during which process was in a subset of operable $X_{us}$. The expression $T_H$ is used to calculate

$$T_H = \frac{\sum \pi_k a_k}{\sum \pi_k \sum p_{kl}}, \quad (x_k \in X_{us}, x_l \in X_{ds}), \qquad (6)$$

where $x_k$ is operable; $x_l$ is inoperable.

The average recovery time is defined as the average time during which the process was in a subset of inoperable $X_{ds}$. The expression $T_B$ is used to calculate

$$T_B = \frac{\sum \pi_l a_l}{\sum \pi_l \sum p_{lk}}, \quad (x_k \in X_{us}, x_l \in X_{ds}) \qquad (7)$$

The system availability factor is defined as the

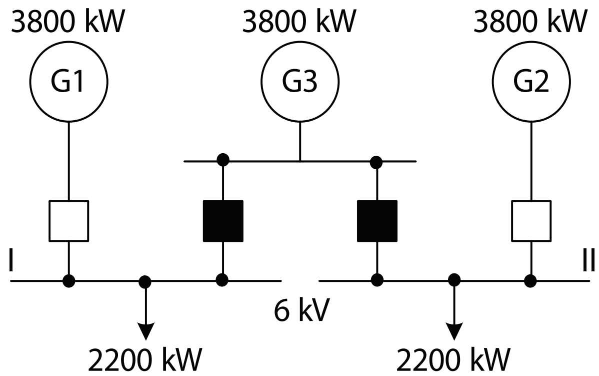


***Fig. 1. Scheme of the power plant of the reservoir pressure maintenance platform.***

stationary probability of a process staying in a subset of operable states . The expression is used to calculate

$$A_F = \frac{T_H}{T_H + T_B} = \frac{\sum \pi_k a_k}{\sum \pi_k a_k + \sum \pi_l a_l} \qquad (8)$$

The average system failure rate is determined from the ratio

$$F_i = \frac{A_F}{T_H} = \frac{\sum \pi_k \sum p_{kl}}{\sum \pi_k a_k + \sum \pi_1 a_1}, \quad (x_k \in X_{us}, x_l \in X_{ds}) \qquad (9)$$

The indices determined by formulas (6) – (9) can be differentiated by the levels of power shortage in inoperable states.

The average annual power undersupply at the i-th level of power shortage in power supply systems is estimated based on the calculated reliability indices according to the formula

$$\Delta W_i = \Delta P_i \cdot F_i \cdot T_{Bi,} \qquad (10)$$

where is the power shortage level, kW; is a failure rate leading to this level of power shortage, 1/yr; is the average recovery time after failure with a given level of power shortage, h. Power shortage is determined by analyzing inoperable states as the difference between the power of consumers and the available generated power, and if there are system tie lines to other power plants, their transfer capability is taken into account.

During scheduled preventive repairs **(SPR)** of the main system elements, i.e., units of power plants and system tie lines, the redundancy of the system decreases, which reduces its reliability during a specified period. The evolution of the

Table 1.Identification of states of the power supply system of the rpm platform under normal operating conditions.

| No. ofstates | The number of units | | | | Power shortage KW |
|---|---|---|---|---|---|
| | In operation | On standby | Under repair | Pending repair | |
| 1 | 2 | 1 | 0 | 0 | 0 |
| 2 | 2 | 0 | 1 | 0 | 0 |
| 3 | 1 | 1 | 0 | 1 | 600 |
| 4 | 1 | 1 | 1 | 1 | 600 |
| 5 | 0 | 0 | 1 | 2 | 4400 |
| 6 | 0 | 0 | 1, S | 1 | 4400 |
| 7 | 0 | 0 | S | 0 | 4400 |
| 8 | 0 | 0 | 1, S | 0 | 4400 |

Note: S is system failure.

Table 2. Identification of the states of the power supply system of the rpm platform under the scheduled repair conditions.

| No. of states | The number of units | | | | Power shortage kW |
|---|---|---|---|---|---|
| | In operation | On standby | Under repair | Pending repair | |
| 1 | 2 | 0 | SPR, 0 | 0 | 0 |
| 2 | 1 | 0 | SPR, 1 | 0 | 600 |
| 3 | 0 | 0 | SPR, 1 | 1 | 4400 |
| 4 | 0 | 0 | SPR, 1, S | 0 | 4400 |
| 5 | 0 | 0 | SPR, S | 0 | 4400 |

Note: SPR is a scheduled preventive repair of the unit

system during SPR corresponds to its graph of states and transitions, which allows calculating the reliability indices of the system in the corresponding period. The resulting system reliability indices are calculated as a weighted average, given the value of the corresponding index and the duration of the system operation throughout the year under normal and repair conditions.

Reliability calculation algorithms are implemented in the **reliability** program, which was used in calculations for the example below.

## IV. An example of calculating the reliability indices of the power supply system of the platform for maintaining the reservoir pressure of an offshore oil field

The power plant of the reservoir pressure maintenance (RPM) platform, shown in Figure 1, includes three units with a rated power of 3800 kW each; there are no system connections with power plants of other facilities of the field. Under normal operating conditions, two units loaded at 57.9% work at separate busbar sections, the third unit is on standby.

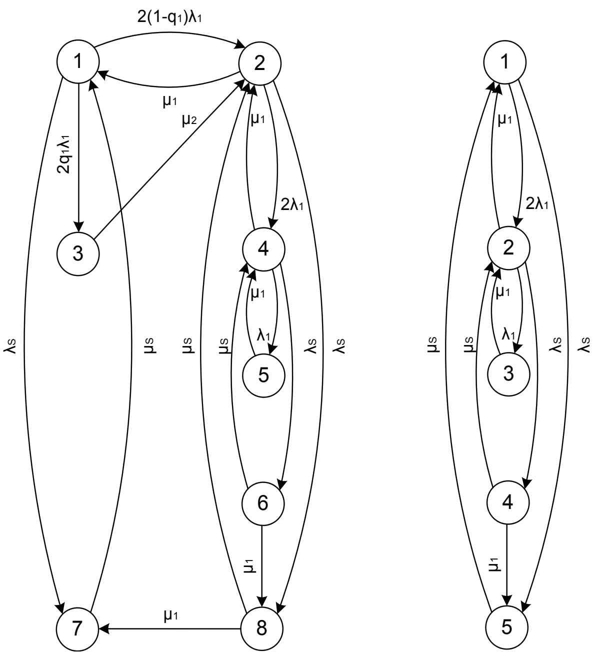


***Fig. 2. The state graph of the power supply system of the RPM platform: a) under normal conditions; b) under repair conditions.***

```
Title: RPM-SR-4400
Power shortage: 4400 kW
Input Data:
L(1) = 6  M(1) = 175      Q(1) = 0.12
L(3) = 1  M(2) = 8760     Q(2) = 0.88
          M(3) = 8760

Inefficient states: 5 6 7 8

The specification statement of the graph:
P(1.2) = 2*Q2*L1P(2.1) = M1     P(3.2) = M2
P(1.3) = 2*Q1*L1         P(2.4) = 2*L1
                P(2.8) = L3
P(4.2) = M1     P(5.4) = M1     P(6.4) = M3
P(4.5) = L1                     P(6.8) = M1
P(4.6) = L3
P(7.1) = M3     P(8.2) = M3
                P(8.7) = M1

Transition probability matrix:
P(1.2) = 0.88   P(2.1) = 0.93085        P(3.2)=1
P(4.2) = 0.96154  P(5.4) = 1P(6.4) = 0.98041
P(4.5) = 0.03297         P(6.8) = 0.01959
P(7.1) = 1      P(8.2) = 0.98041
                P(8.7) = 0.01959

Average time of stay in Vector of probability
of final states:
state Xi (yr):
A[1] = 0.08333       п[1]=0.439746
A[2] = 0.00532       п[2]=0.47236
A[3] = 0.00011       п[3]=0.05277
A[4] = 0.00549       п[4]=0.031353
A[5] = 0.00571       п[5]=0.001034
A[6] = 0.00011       п[6]=0.000172
A[7] = 0.00011       п[7]=4.9E-5
A[8] = 0.00011       п[8]=0.002516

Reliability parameters:
Time between failures TH = 15.58 yr
Average time of recovery TB = 21.63 hr
Availability factor AF = 0.9998
Average failure rate F = 0.064 1/yr
Expected power shortage ΔW = 6106 kW*hr/yr
```

***Fig. 3. A fragment of an output report of the program for calculating system reliability under normal conditions.***

Table 3. The calculated system reliability indices.

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| Indices | Conditions | | |
| | Power shortage under normal operating conditions, kW | | |
| | 600 | 4400 | 600-4400 |
| $T_{H,}$ g | 0.47 | 15.58 | 0.46 |
| $T_{B,}$ h | 18.83 | 21.63 | 18.92 |
| $_{AF}$ | 0.9955 | 0.9998 | 0.9953 |
| $F$, 1/g | 2.108 | 0.064 | 2.172 |
| $\Delta W_,$k. Wh/g | 23821 | 6106 | 29927 |

| 5 | 6 | 7 | 8 |
|---|---|---|---|
| Conditions | | | |
| Power shortage under scheduled repair of the unit, kW | | | Total values with a shortage of 600-4400 |
| 600 | 4400 | 600-4400 | |
| 0,08 | 1.00 | 0.08 | 0.45 |
| 50,05 | 21.63 | 47.86 | 19.91 |
| 0,9358 | 0.9975 | 0.9337 | 0.9932 |
| 11,230 | 0.997 | 12.13 | 2.513 |
| 337269 | 94927 | 432196 | 43705 |

Thus, under normal operating conditions, the power of a power plant is distributed as follows:

– power consumption (including losses) is calculated as follows: 2·3800·0,579≈4400 kW;

- generated power is 4400 kW;
- hot reserve of generating capacity is 3200 kW;
- cold reserve of generating capacity is 3800 kW.

In case of a failure of a power plant unit, it is switched off, and a standby unit is automatically switched on. The failure rate of all power plant units is the same and equals $\lambda_1$. The operational state of failed units is restored with intensity $\mu_1$, according to a limited successive repair strategy, i.e., only one unit is under repair at a time, the subsequently failed unit is repaired after the repair of a unit that failed earlier.

With successful automatic load transfer, the load is not disconnected, or the disconnection is too short to affect the production process and can be ignored. If ALT fails, part of the load is disconnected. Then, the backup unit can be put into operation by operational personnel manually with intensity $\mu_2$. Unsuccessful ALT is characterized by probability $q_1$, successful one — by probability $q_2$=(1–$q_1$). In the process, the failure rate can be $\lambda_S$. The system recovers from failures with intensity $\mu_S$.

For the power supply system to the RPM platform under consideration, the values of the initial parameters are: $\lambda_1$=6 (1/yr); $\lambda_S$=1 (1/yr); $\mu_1$=175 (1/yr); $\mu_S$=8760 (1/yr); $\mu_2$=8760 (1/yr); $q_1$=0.12. The values of the initial data are determined from the operation data of the considered facility.

Figure 2 shows the graph of states and transitions of the power supply system of the RPM platform under normal operating and preventive repair conditions.

Figure 3 presents a fragment of intermediate calculations and calculation results for the system under normal operating conditions. Table 3 indicates the results of modeling the considered system reliability for standard and repair conditions differentiated by power shortage.

The findings indicate that with limited structural redundancy, which normally meets the "N-1" criterion (the failure-free operation is ensured if one of the existing generating units fails), during the period of scheduled repairs, the reliability indices of the system significantly decrease, which results in almost a 1.5-fold increase in the average annual power undersupply. Therefore, alternative solutions for this system can be the installation of an additional generator or additional system tie line, i.e., a cable transmission line connecting the RPM platform with a neighboring technological platform with off-grid power sources that have surplus generating capacity. In this case, the "N-1" criterion is met under repair conditions and the "N-2" criterion is met under normal operation of the system. One more cable line is much cheaper than an additional generator because it does not require extra space, which is crucial due to insufficient space on sea platforms. Moreover, with backup power sources, it provides a faster and more reliable load transfer and reduces the probability of failure when switching to a backup power source. Modeling the reliability of a system with an additional system tie line, given the reduction in the failure probability when switching from the main power source to an emergency one, has been shown twice.

## V. Conclusion

The proposed method for calculating the reliability of power supply systems with off-grid power sources is developed based on analysis of power supply to oil and gas industry facilities and methods for ensuring an appropriate selection of power supply sources of industrial systems when designed and reconstructed. The development of our method involved semi-Markov random processes (Markov chains), which allows an express reliability assessment of systems with off-grid power sources.

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# Issues of Cybersecurity in Electric Power Systems

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***Abstract* — The study deals with the cybersecurity concept of cyber-physical electric power systems (EPSs) as a strategic issue of national importance, which affects all strata of society. The link between the cybersecurity of EPSs and Russia's energy security and information security is analyzed. Data on the number of cyberattacks on control systems of industrial enterprises, power plants, and substations for several years are provided. The consequences of cyberattacks for the operability of the EPS physical subsystem and its facilities are analyzed. Areas of research to counteract external cyber threats are outlined. The key findings of the EPS cybersecurity study carried out at the Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences (ESI SB RAS) are summarized.**

***Index Terms* — Electric power system (EPS), cybersecurity, cyber threats, cyberattacks, counteraction, consequences, key research findings**

## I. Introduction

The electric power system (EPS) is an essential infrastructure that provides the population and the economy with electricity with the required reliability, adequate quality, and at an affordable price. With the growing consumer demands for the reliability of energy supply and quality of energy resources, EPSs are developing based on innovative, intelligent technologies in the context of digitalization and computerization of their production processes. Modern electric power systems and their facilities are complex systems consisting of two closely interconnected layers: physical (process) and information-and-communication subsystems. These subsystems of the present electric power systems, and even more so of the prospective ones, are getting comparable in complexity and responsibility in terms of ensuring the proper operation of EPSs.

Digitalization of the electric power industry implies not only the acceleration of information processing in a digital form but also an increase in efficiency of production processes using the next-generation equipment meeting the IEC standards and the development of new software for control of newly built digital substations, single-area electrical networks, and others. Under these conditions, it is getting increasingly more appropriate to treat EPSs as complex cyber-physical systems (CPS), in which the information-and-communication subsystem can operate inadequately due to internal defects (errors in algorithms, and others), and also can be exposed to unauthorized external actions, i.e., cyberattacks [1-6, and others].

The analysis of events that occur in the process of unfolding of several system accidents in different countries [7] proved the reciprocal influence of failures and disturbances in physical and information-and-communication subsystems (ICS) of EPSs. Invalid information on the current state of EPS and its loss due to cyberattacks on the ICS can lead to the generation and implementation of wrong control actions and the development of emergencies in the physical subsystem. In turn, the failure of a physical infrastructure element can result in an emergency state of the electrical part and contribute to the malfunction of the information-and-communication infrastructure control system.

This paper covers the basic concepts and definitions related to the EPS cybersecurity, analyzes the effects of cyberattacks on the performance of the physical subsystem of the EPS and its facilities, presents the areas for research to counteract external cyber threats, and discusses the key findings of the EPS cybersecurity studies carried out at the ESI SB RAS.

## II. Basic concepts and definitions

Nowadays, cybersecurity is considered a strategic issue of national importance affecting all strata of society. In December 2016, the USA and Russia published almost simultaneously two official documents: "Joint US & Canada electric grid security and resilience strategy" [8]

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and the updated "Doctrine of information security of the Russian Federation" [9]. Similar work is being done in the countries of the European Union, China, and others. The recognition of the cybersecurity importance is evidenced by the significant number of corresponding national strategies. However, these documents show noteworthy differences in the definition of cybersecurity and other key terms.

In [10-12], the authors study the connection between the EPS cybersecurity, on the one hand, and Russia's energy security (ES) and information security (IS), on the other hand. The authors of [11] note that the rapid spread of the computer environment, the development of information technology, and the trend towards the intelligent energy industry make cyber threat one of the most important tactical and strategic threats to energy security, i.e., they consider cybersecurity as an additional threat to energy security that is relevant in today's context.

On the other hand, since there is still no clear-cut definition of the "cybersecurity" term, it is often considered synonymous with information security. According to ISO 27032:2012 [13], cybersecurity is based on five components: application security, information security, network security, Internet application security, critical information infrastructure protection, but is not synonymous with any of them.

Information security is about ensuring confidentiality, integrity, and availability of information needed to meet user needs. Cybersecurity is a broader concept, it is construed as a set of tools, strategies, and technologies that can be used to protect the cyber-environment, resources of the organization, and the user [14]. The cyber-environment is understood here as connected computing devices, infrastructure, applications, services, telecommunications systems, the totality of transmitted and/or stored information, as well as maintenance personnel. Thus, approaching the EPS cybersecurity issue from the standpoint of the CPS, we should emphasize that it is aimed at protecting not only the data and facilities of the information-communication subsystem but also the data and facilities of physical infrastructure, the operation of which can be disrupted due to cyberattacks on the information subsystem.

At present, it is common to have all cyber threats divided into *external and internal ones*. Causes and sources of external threats are located outside the company's computers, usually in the global network: they are viruses, spam, remote hacking, DOD/DDOS attacks, and others. Internal threats depend solely on corporate personnel, software, and hardware. For energy companies, internal threats are no less dangerous than external ones. This issue becomes especially relevant when automating back-office processes in energy companies, for example, when digitalizing the document flow [15]. In Russia, the share of external attacks only slightly exceeds 20%, as estimated by the developers of corporate security systems; the rest of them are hence internal.

The earlier studies on cybersecurity of energy systems introduced the concept of cyber-negligence, which can also be treated as one of the internal cyber threats. Cyber-negligence [16] is the unintentional actions of employees of the organization that can prove harmful. They are due to negligence, poor computer literacy, or disregard for cybersecurity measures, and are comparable in damage to cyberattacks.

As noted in [6], the Dell Security Annual Threat Report published in 2015 by Dell provides the following recorded data on the number of cyberattacks on SCADA systems of industrial enterprises, substations, and power plants: 2012 - 91,676; 2013 - 163,228; 2014 – 675,186. The majority of cyberattacks targeted enterprises in Finland (202,322), Great Britain (69,656), and the USA (51,258), where SCADA systems are widely adopted and, in many cases, connected to the Internet. The authors show that to date, more than 30 countries have developed strategies to combat cyberattacks on energy and industrial facilities.

Therefore, the cyber resilience of energy facilities and EPSs as a whole is a critical and urgent issue to be addressed from the standpoint of the CPS given the interconnection of physical and information-and-communication subsystems [5].

## III. Analysis of consequences of cyberattacks for the operability of the physical subsystem of the EPS and its facilities

Below we present some examples of cyberattacks on power facilities that show that such impacts on the ICS can lead to the destruction of physical subsystems and networks.

*On December 23, 2015, a successful cyberattack was carried out on Ukraine's power grid* [6]. It left about 225 (according to other sources - 600) thousand people without electricity for more than 6 hours. The power supply interruption lasted from 1 to 3.5 hours. Total electricity undersupply was 73 MW / h (0.015% of the daily electricity consumption in Ukraine). Hackers prepared their attack for at least six months. E-mails were sent to utilities, and once they were opened, the BlackEnergy3 malware got downloaded and isolated the infected computers from the control system of the power grid. The operation of the virus makes all information about the information-and-communication subsystem, passwords, and access codes available. After that, it was possible to log in to the SCADA system and shut down 17 substations. Some servers and workstations of automated dispatch management systems of regional EPSs were disabled. At the same time, the company's telephone lines were jammed, which prevented estimating the scale of the outage. Electronic devices used for communication with substation circuit breakers were disabled. Power flow was restored after switching to manual control.

*Kyiv blackout [17]*. On December 17, 2016, there was an outage of one-fifth of the Kyiv power grid together with the Kyiv pumped-storage power plant, which lasted one hour. The failure of the substation's automatic control completely de-energized the 330 kV Severnaya substation (Novi Petrivtsi village) with disconnection of substation auxiliaries from the power supply. As a result, the 144.9 MW loads of Kyivenergo PJSC and 58 MW of Kyivoblenergo OJSC were disconnected. The Kyiv pumped-storage was also de-energized with auxiliaries disconnected from the power supply, which was announced by the National Energy Company Ukrenergo on its Facebook page.

According to experts of the American company Dragos and Slovak ESET, the attack on a part of the Kyiv power grid was carried out by a team of hackers called Electrum. For this attack, the Electrum team used malware called CrashOverride. The researchers believe that the new software based on CrashOverride can automate massive blackouts. Malicious software includes interchangeable plug-in components. With their help, the malware adapts to different types of EPSs and can be easily reused when attacking the same facility or attack several targets simultaneously.

ESET and Dragos experts emphasize the main difference between the attacks on Ukrainian regional EPSs in December 2015 and that on Kyiv's power system. Whereas in the first case hackers had to access the EPS network and disable it 'manually', in the second case, the attack was fully automated. The CrashOverride malware is programmed to send commands directly via special protocols to the grid equipment to turn the power on or off. The experts claim that this feature allows CrashOverride operators to perform much larger and longer attacks than those during the Kyiv one-hour blackout. The consequences of the CrashOverride attack can be much more devastating than a temporary loss of control over the EPS. ESET experts hold that the malicious program has the potential to cause physical damage to EPS equipment. According to their data, CrashOverride can exploit the known vulnerability of Siemens equipment, in particular, the one found in the Siprotec digital relay. Such relays are installed for protection, monitoring, and control of electric power distribution and supply lines. Siemens has already released an update for the Siprotec relay, but if someone has failed to install it, attackers can physically destroy part of the power grid. Mike Assante of SANS Institute, a USA cybersecurity company, says that switching off a digital relay can cause thermal overloads in power lines. This can lead to sagging or melting of wires, damage to transformers, and live equipment.

*Cyberattacks on nuclear power facilities [18].*

1. On January 25, 2003, the Slammer network worm crashed the Ohio nuclear power plant's corporate network in the United States, after which it spread to the plant's safety monitoring and coolant systems. The host computer of the power plant was disabled after that. It took six hours to restore the systems.
2. In September 2010, in Iran, about 30 thousand computer systems of industrial facilities were infected with the Stuxnet virus. The virus was introduced into the computer network of the Bushehr nuclear power plant, which paralyzed the plant, resulting in the suspension of Iran's nuclear program. This virus is distributed through the Windows operating system and is aimed at industrial Siemens software and hardware to cause instability of EPS operation. According to available estimates, this is the first virus created to disrupt real infrastructure facilities such as power plants, waste-water treatment facilities, and industrial plants. Such cyberattacks, based on the invasion of a computer virus targeting industrial power plants, introduce new threats into both cyber systems and physical systems [19].
3. On April 27, 2016, in Germany, the computers of the Gundremmingen nuclear power plant (120 km from Munich) operated by the utility RWE were infected with viruses W32. Ramnit and Conficker. The malware was detected on 18 removable media in the computer system of the plant's B unit, in its data visualization software. The infection did not pose a threat to the safety of the nuclear power plant, since the computers controlling the nuclear power plant systems are not connected to the Internet.

*On August 14, 2003*, most of the Midwest and North-East USA and Ontario, Canada experienced a power outage that in some regions lasted up to 4 days and affected about 50 million people. In total, 61.800 MW of electrical load was disconnected [20]. According to experts, the reasons for this large-scale shutdown are not directly related to malicious activities of cybercriminals; they were caused by errors in the cyber system software [20].

The above incidents show that external cyber threats are the most common causes of emergencies at power facilities (all but the last example). The following section will provide an overview of studies in Russia and abroad on counteracting external cyber threats. As for internal cyber threats, for the information-and-communication subsystem, as noted in [21], until recently, this aspect has not been associated with the issue of cybersecurity of cyber-physical EPSs. Further, the fourth section of this paper provides a brief overview of the research findings in this area.

## IV. Areas of research to counteract external cyber threats

In general, the problem of countering deliberate external cyberattacks is formulated as follows. First of all, one shall identify the most vulnerable points of the information-and-communication subsystem of the EPS in both its components: compiling information for monitoring of operating conditions and control over them (data collection and processing, system state estimation, and others);

development and implementation of control actions (identification, transfer, execution). The most vulnerable point of the given subsystem is identified by simulating cyberattack scenarios that vary depending on the location of their application (data transfer channels, state estimation algorithms, algorithms for developing control actions, and others). Specific measures are envisaged for each of the most vulnerable points or groups thereof to prevent severe consequences for the EPS [22 - 24, etc.].

One of the most common cyberattack scenarios is the false data injection into the EPS state estimation procedure [22]. The state estimation procedure [25] is one of the most important ones in the operational control of the EPS. The results of its calculations serve as the basis for maintaining the current operating conditions of the EPS, planning repair conditions, and making projections. The system state variables, parameters, and topology can be corrupted. The main goal is to make it difficult to identify false data injection by conventional algorithms. We consider the consequences of cyberattacks of this type for the operation of algorithms of electricity market management, algorithms of optimal power flow, and others. To understand "the inner workings" of the mechanism of the data corruption impact on the state estimation and to develop measures to counteract it, researchers model the false data injection process. Thus, in [26, 27], the false data injection scenario is formalized as a combinatorial problem on the graph by minimizing the number of the most affected vulnerabilities. In [28], optimization models based on mixed-integer programming of undetectable and unidentifiable attacks aimed at inputting false data into algorithms of the EPS state estimation are presented. In [29], a semi-Markov model of the false data injection cyberattack is proposed.

Cyber-initiated attacks aimed at information processing, protection, and control systems can be divided into four categories: blocking, imitation and modification, gathering, and privacy [23]. By way of illustration, let us detail the lists of the first two categories of attacks. Blocking attacks are denial of service; jamming during data transmission; sending Trojan horses (malware to trick the recipient) and the like. Imitation and modification attacks include a technique for injecting knowingly incorrect data (fuzzing); masquerading an attacker or malicious program to gain privileges by falsifying information (spoofing); reordering and mixing data (tampering); data cloning; replaying valid data, i.e., making such data resent or delayed.

Each type of cyberattack has negative consequences for the composition and content of data, which is why measures should be implemented to prevent them [23]. Possible consequences of cyberattacks may include loss of data, violation of their confidentiality, integrity, and plausibility. Potential measures to counter the cyber-attacks include antivirus programs, security protocols, passwords as barriers, data duplication, data filtering, time synchronization control for operations, the use of digital signatures to confirm data ownership, and some others.

In terms of countermeasures against cyberattacks, it is important to assess the probability of the success of the attack. For this purpose, two Bayesian graphical models of cyberattacks are presented in [30] for EPS vulnerability assessment. The ultimate goal of any cyberattack on the ICS is to disable physical elements of the cyber-physical EPS. From an attacker's point of view, substations, control centers, data transmission channels, and corporate monitoring centers are considered as potential objects of attack (vulnerability points). The identification of vulnerability points in the information-and-communication subsystem of these objects is precisely aimed at achieving the ultimate goal of a cyberattack. Different combinations of such vulnerability points produce 14 possible cyberattack scenarios. It follows from the above that an important task is the development of complex cyber-physical models (CPM) for the identification of vulnerable points of cyber-physical infrastructure and assessment of the reliability of cyber-physical EPSs and reliability of power supply to consumers [29-31, and others].

Along with computerized cyber-physical models for studies of cybersecurity of EPSs, another important direction is the development of reference physical models. One of them is presented in [32] and includes four interconnected layers: a layer of physical EPS based on the RTDS simulator with multiple ports for connecting physical measuring, protection, and control devices; a sensor layer including the above physical devices; a communication layer implemented using physical channels of data concentration, data transmission, and required protocols; a layers of applications, including, as one of them, monitoring of EPS voltage stability in real-time. In [33], the authors employ the same methodology of building a cyber-physical model (CPM) of EPS based on the application of the RTDS hardware/software simulator and real devices of protection, automatics, and other elements.

In [24], the authors study the impact of the "denial of service" cyberattack on control systems of distributed generation plants, which is aimed at causing instability of the EPS as a whole with the risk of cascading accident development. The research proposes the use of robust control of distributed generation units as a measure to counteract the cyberattack.

An original approach to counteracting cyberattacks is presented in [34] in the form of a package of support for the so-called controlled degradation of the control system of the energy facility in the event of cyber incidents. The essence of the concept is that during an incident, it is possible to consciously give up some functions of information exchange and control, leaving for pre-prepared "limits to degradation" and hence narrowing the environment where a cyber incident may develop. At the level of "maximum degradation" in cases of serious incidents, only the main protection and control functions remain at the stand-alone microprocessor operating condition and the maximum "manual" control mode.

The above analysis of key research findings relevant to the aspect of EPS cybersecurity under examination gives an idea of the state of developments in the world.

## V. Key research findings by the ESI SB RAS

The efficiency of EPS control is ensured by the current regularly updated reliable information, optimal control actions developed on its basis, and their reliable execution. Hardware and software tools of SCADA-systems and WAMS, and the state estimation procedure designed to support the dispatch personnel actions in the course of the EPS operational and emergency control, are the components of the information-and-communication subsystem that are critical and at the same time most vulnerable to cyberattacks. Modern cybersecurity methods aim to prevent or reduce the impact of attacks. Attack prevention is ensured at the level of information technology experts through methods of cryptography, authentication, access control, management, and others. If these measures prove insufficient, actions should be taken to reduce the impact of attacks that occurred in the ICS on the reliability of operation of the physical subsystem.

### *1. Application of statistical methods of information processing in cyberattacks on information collection and processing systems (SCADA and WAMS)*

The studies performed at the ESI SB RAS, along with engineering and organizational measures aimed at improving the cybersecurity of electric power facilities, propose employing statistical methods of processing the measurement information coming from SCADA systems and WAMS to analyze the vulnerability of the information-and-communication subsystem and reduce the impact of cyberattacks on the quality of physical subsystem control. First of all, these are the methods of static and dynamic state estimation [25], measurement verification [35], and other information processing methods used in EPS control.

To assess the ability of a complex engineering system to withstand cyberattacks, the concept of system vulnerability level is introduced, the numerical rating of which is a vulnerability index. In [36,37], the concept of the vulnerability index of the state estimation was introduced, with the latter characterizing the degree of exposure of its results to possible errors in measuring information when cyberattacks are directed at the SCADA system. A set of indicators descriptive of the accuracy of state estimation results was used to determine the vulnerability index. Since these indicators are non-deterministic, the apparatus of the fuzzy sets theory is used to estimate the vulnerability index [38]. It is shown that the joint use of SCADA and PMU measurements for EPS state estimation allows increasing the efficiency of methods for bad data detection and accuracy of obtained estimates, thus reducing the vulnerability of the state estimation task to cyberattacks [39].

A method proposed in [40] for processing and verification of information streams of synchronized phasor measurements (SPMs) involves a wavelet analysis of random processes, which allows detecting both systematic errors and interference maliciously created by cyberattacks. The WAMS structure was studied, vulnerabilities were identified, and possible cyberattacks were analyzed. Attacks of false data injection into the information flows of SPM were modeled, the probability characteristics of distorted data and data not exposed to malicious data streams were analyzed. The SPMs were verified using the wavelet theory.

The study in [41,42] suggests the use of dynamic state estimation algorithms and measurement verification for the detection and correction of data distorted due to cyberattacks in the case of low measurement redundancy. Consideration of the dynamics of changes in the EPS state imparts substantially new properties to the state estimation algorithms, including the ability to work under insufficient information, higher robustness to failures and interference, the ability to adapt and predict. The dynamic state estimation offers more opportunities to detect gross and systematic errors in telemetry due to the use of retrospective and predictive information about the parameters of the operating conditions [42].

### *2. Application of the attack tree technique to analyze the cyber vulnerability of EPS facilities [43,44]*

The digital substation (DSS), which is one of the pilot digitalization projects in the electric power industry, was assumed as the object of the cybersecurity study. The study proposes the use of the concepts of "cyber resilience" and cybersecurity indicators to analyze the ability of the DSS to withstand cyberattacks and restore its performance after exposure to them. The structure of the digital substation is studied for the cyber-physical system, and factors influencing the extent of reduction of the digital substation functionality due to cyberattacks are analyzed. Some known cyberattacks were considered, including "denial of service" (DoS-attack), the introduction of viruses and software with "implants", masquerading GPS signals/ stream of transient values (SV stream)/MMS and GOOSE messages, traffic overflow, and others, which are direct threats to DSS performance. The consequences for the DSS cybernetic and physical subsystems under various cyberattacks were analyzed, and measures were proposed for these subsystems to counter cyberattacks.

To coordinate DSS vulnerabilities and cybersecurity threats with measures to counter possible malicious attacks, the study employed the fault tree analysis technique used in the reliability theory of complex engineering systems. As a result, a tree of attacks was formed to analyze the DSS cybersecurity. A tree of attacks can be clearly compiled for each substation. This provides an opportunity to analyze the DSS information-and-communication system with respect to the presence of vulnerabilities, to revise the existing protective cyber-measures, and to develop a policy of further steps to improve the cybersecurity of this energy facility.

*3. Risk-based approaches to cybersecurity analysis*

Theories based on the concept of risk are an important direction in solving the problems of cybersecurity [45]. The risk-based approach takes into account the harm due to damage or destruction of a facility as a result of cyberattacks by using qualitative (complexity of restoration, destruction of the unique natural environment, reputation, etc.) and quantitative (as expressed in monetary terms) indicators, as well as the probability of damage or destruction of a facility with the possibility of cascading emergencies [46].

In [47-49], researchers propose a methodological approach to threat analysis and risk assessment of cyber-security risks in electric power infrastructure based on semantic modeling. The approach includes a system of cyber-security ontologies and a fractal stratified model of the ontology system, a technique for analyzing cyber threats in electric power infrastructure, a technique for modeling scenarios of emergencies in electric power infrastructure as caused by cyber threats, and a technique for assessing cyber-security risks in electric power infrastructure.

The architecture of an intelligent system was developed for threat analysis and assessment of cybersecurity risks in electric power infrastructure. It implements a methodological approach based on the integration of the expert system, Bayesian belief networks, and a visual risk assessment component. This methodological approach was used to develop a technique for cyber threat analysis and risk assessment. The proposed methodological approach allows developing a classification of assets and facilities of the electric power infrastructure to assess potential vulnerabilities in terms of the significance of the facilities and the level of their protection.

In [50, 51], to reveal possible operational failures of the EPS under cyberattacks the authors perform an analysis of cybersecurity risks of the ICS and their impact on control functions, as well as the related consequences for the physical subsystem of EPS.

The information-and-communication infrastructure of the EPS was examined and the cybersecurity properties of SCADA and WAMS, which are part of the infrastructure, were analyzed. An algorithm was developed to assess control risks in the event of cyberattacks on SCADA systems and WAMS. SCADA and WAMS systems were treated as assets, and control losses followed by the EPS malfunctioning were considered as damage.

The algorithm consists of two stages: the first stage is the assessment of control risks for each materialized cyber threat; the second stage is the determination of the resulting risk value.

To assess the risks of losing EPS control, a hierarchical fuzzy system was proposed, which includes four fuzzy inference systems. Factors such as the attacker's capabilities, intentions, and goals were used to assess the probability that the threat will be triggered. Combinations of factors, such as the attacker's capabilities and ICS vulnerabilities, served as the basis for assessing the probability of a threat event as a result of adverse action. A combination of these probabilities was used to determine the total probability of the threat materialization. Combinations of the probability of threat materialization and levels of impact (consequences) on SCADA systems and WAMS determine the risk value for the EPS control.

*4. Ensuring serviceability of the emergency control and relay protection systems in the context of cyberattacks*

In the context of EPS operation under cyberattacks, it is essential to provide the cybersecurity of automatic control systems, including relay protection (RP) devices, the operation and emergency control automatics (ECA) systems, and the automated process control systems (PCS). To this end, the studies performed at the ESI SB RAS [52-55] examined not only the problems of hacker attacks but also the entire array of problems related to the adequate operation of cybernetic systems in EPSs.

The key elements of RP and ECA systems, as noted in [29], as applied to main facilities, i.e., digital substations that can be exposed to cyberattacks with severe consequences, are communication networks, process buses, facility buses, digital systems of RP, ECA, monitoring and control devices, and external digital channels. The researchers propose identifying critical functions of protection and automatic systems and duplicate them on a non-digital basis as the "last tier" of protection, thus excluding the very possibility of cyberattacks on them [53, 54]. Other RP and ECA systems should be able to operate not only in integrated digital information systems but also in a stand-alone isolated condition during the period of a cyberattack or its threat, as well as during the EPS restoration. This "last tier" proposal is practically consistent with the concept of the "controlled degradation" studied in [34].

The research in [53, 54] suggests creating a simulation subsystem at the energy facilities that would automatically simulate the operation of automatic control devices, verifying the adequacy of their work based on information from the emergency event recorders (EER), automatic remote control, and other sources. Given that the hardware and software base of such a simulation subsystem would differ from the hardware and software base of the implementation of RP and ECA devices, in case of cyberattacks, there would be different behavior of real and simulation subsystems observed, which would make it possible to identify cyberattacks as well as to identify potential errors in software algorithms.

The factor of potential algorithm errors realized in the form of software for digital RP and ECA systems is of grave importance and forms internal cyber threats for the information-and-communication subsystem. In [21], this problem is illustrated by case studies of large-scale blackouts of cascade nature in the UES of Russia in recent years. An analysis of the blackouts of August 22, 2016 [55] and June 27, 2017. [7] indicates that the shortcomings of control system algorithms increase the scale of consequences when local accidents become system-wide.

## VI. Conclusion

The case studies of real-life cyberattacks on electric power facilities and systems given in the paper testify to the urgency of the

EPS cybersecurity issue. The issue of cyber resilience of energy facilities and EPSs as a whole is a critical and urgent problem that should be addressed from the cyber-physical standpoint in conjunction with physical and information-and-communication subsystems.

Recent years have seen much effort put in the field of EPS cybersecurity. Analysis of the current state of research indicates a strong interest in this problem and demonstrates significant results in identifying vulnerabilities of the information-and-communication subsystem of the EPS and developing cyber-physical models of the EPS to study the consequences of cyberattacks.

The studies performed at the ESI SB RAS employ statistical methods of data processing to analyze vulnerabilities of the information-and-communication subsystem and reduce the impact of cyberattacks on the quality of control of the physical subsystem of the EPS. The researchers propose applying the methods for verification of the information coming from SCADA systems and WAMS, including the wavelet method, to perform static and dynamic EPS state estimation procedures. The efficiency of cyberattack detection is shown to increase with the combined use of data from SCADA and WAMS. Vulnerability analysis is also performed by building an attack tree for electric power facilities.

The substantiation of measures to counter cyber threats and reduce the negative consequences of their possible materialization involves a risk-based approach for determining the damage from the consequences of materialized cyberattacks. An algorithm was developed to assess control risks under cyberattacks on SCADA systems and WAMS.

Ensuring cybersecurity of automatic control systems, such as relay protection devices, operation and emergency control automatics, and automated process control systems also proves an urgent task in the operation of EPSs under cyberattacks. To fulfill the task, the studies performed at the ESI SB RAS examined not only the problems of hacker attacks but also the entire array of problems of adequate operation of cybernetic systems in the electric power industry.

The process of digitalization of electric power systems; the use of intelligent technologies and complex engineering, information, and communication equipment have increased the cybersecurity risks of EPSs and energy companies. These point to the need to continue multi-faceted studies in this direction so that the recommendations they are to produce would ensure the required level of cybersecurity of digital intelligent EPSs.

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# Support Vector Machines for Providing Selectivity of Distance Protection Backup Zone

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***Abstract* — The development of present-day power systems is associated with the wide use of digital technologies and intelligent algorithms in control and protection systems. It opens up new opportunities to improve relay protection and automation hardware and develop its design principles. Simulation modeling becomes a new tool not only for studying power systems operation but also for designing new relay protection methods.**

**The use of simulation modeling in combination with machine learning algorithms makes it possible to create fundamentally new types of digital relay protections adaptable to a specific protected facility and able to use all the available current and voltage measurements to the fullest extent possible. Machine learning also allows developing auxiliary selective elements for improving the basic characteristics of existing relay protection algorithms such as selectivity, sensitivity, and speed of operation. The paper considers an example of designing an auxiliary element to provide selectivity in the backup zone of distance protection. The problem is solved using one of the most widely known machine learning techniques, i.e., the method of support vector machines (SVM).**

***Index Terms* — multidimensional relay protection, support vector machines, distance relay**

## I. Introduction

Distance protection is one of the most widely spread and effective types of conventional non-unit relay protection. It is usually used in electrical grids with a complex configuration where the use of simpler overcurrent relays is unacceptable due to either their low sensitivity or inability to provide selectivity.Apart from the protection of its main zone, distance protection provides partial or complete protection of the adjoining network components. This approach increases the reliability of relay protection systems and power supply systems in general.

It is worth noting that it is not always possible to provide effective fault detection in the distance protection backup zone with the non-unit protection scheme. Let us consider part of an electrical grid shown in Fig. 1. The second zone of distance protection of the power line $\omega_1$ must cover the entire line $\omega_1$ and partially back up protections of the parallel line $\omega_2$, the adjoining line $\omega_3$, and the transformer $T_1$.

According to the regulations [1], the following restrictions are imposed on the value of reach settings of the second zone of distance protection (Table 1).

To evaluate the efficiency of the distance protection backup zone of line $\omega_1$, we will collect statistical data on faults on the components adjoining the given line. To this end, we will use the Monte-Carlo simulation method. The method suggests multiple simulations of the analyzed objects with a set of parameters randomly generated according to a given distribution law. In the model of the considered electrical grid, these parameters are rms value and angle of voltage in system A (ranges of values are given in Fig. 1, the distribution law is uniform), distance to the fault, and arc resistance. After all the parameters of the current experiment are obtained, a system of contour equations defining the equivalent circuit of the grid is built and solved. This allows determining the currents in branches and voltages at nodes based on which one can calculate the measurement of a distance protection impedance and other parameters of the operating conditions to be simulated.

Let us place a set of simulated short-circuit conditions in the adjoining components on a complex plane of distance protection of line $\omega_1$ and highlight those of them which make it impermissible for the second zone of distance protection of line $\omega_1$ to operate because of the offset conditions (Fig. 2).

Since the power line $\omega_3$ is relatively short (and hence has a low impedance), the condition of adjusting the reach settings $z^{II}_{\text{trip}_{w_1}}$ with $z^{I}_{\text{trip}_{w_3}}$ according to (1) essentially limits the value of $z^{II}_{\text{trip}_{w_1}}$ .

Thus, a large part of faults on the parallel line $\omega_2$ and in the transformer $T_1$ appear to be beyond the second zone of line $\omega_1$ (Fig. 2). Accurate calculations show that only

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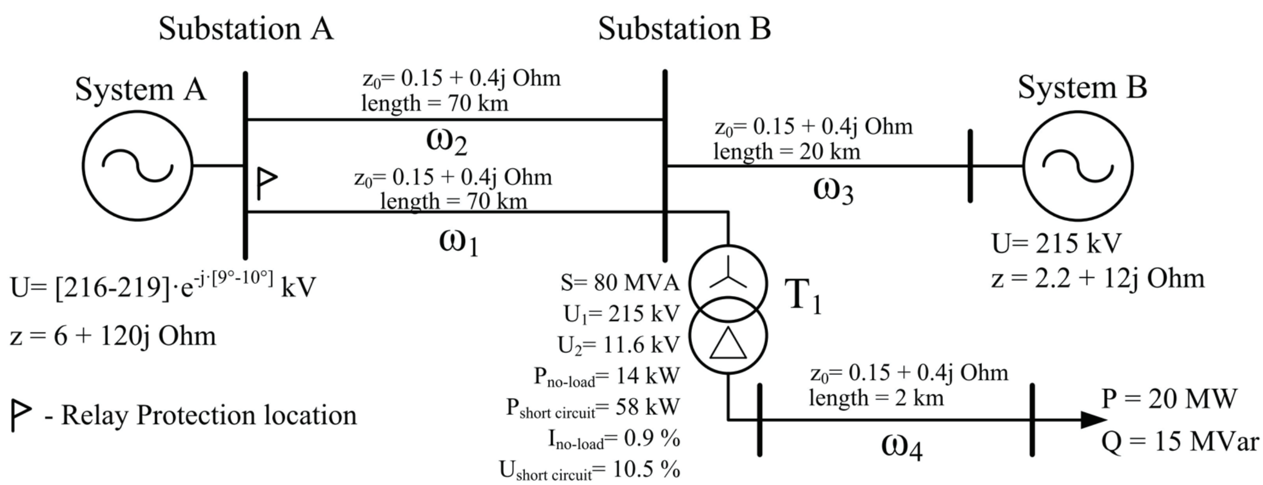
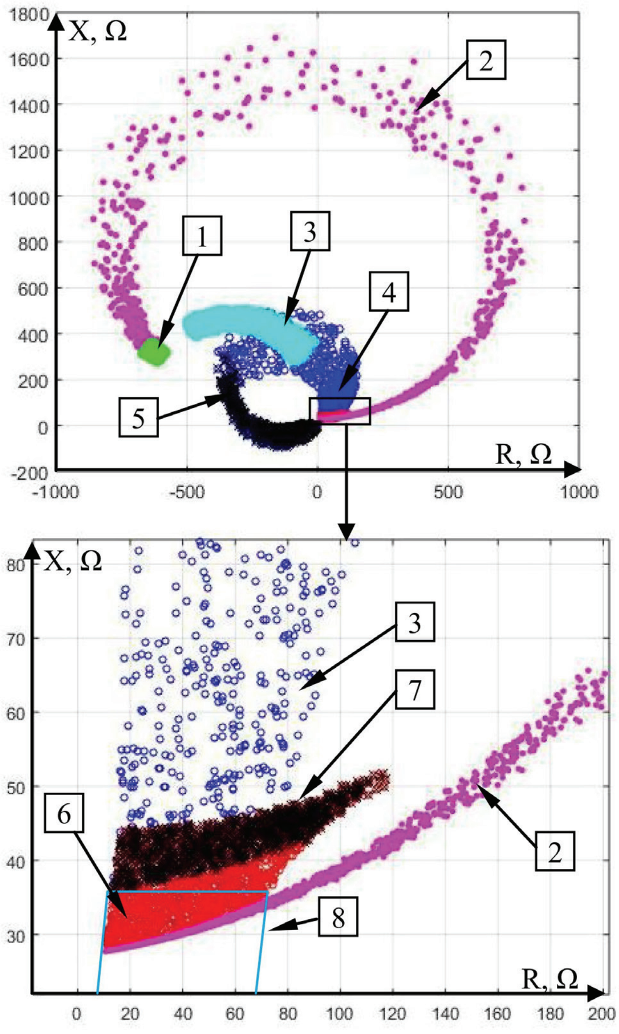



*Fig. 1. The scheme of the analyzed electrical grid section.*




1 – Normal conditions; 2 – Faults on $T_1$ primary winding; 3 – Faults behind $T_1$ (on $\omega_4$); 4 – Faults on $\omega_2$; 5 – Faults on $\omega_2$ (out of $\omega_2$ first zone); 6 – Faults on $\omega_3$; 7 – Faults on $\omega_3$ (out of $\omega_3$ first zone); 8 – $\omega_1$ second zone characteristic;

*Fig. 2. The results of the simulation modeling.*

Table 1. Distance protection second zone reach setting conditions

| Expression | Description | № |
|---|---|---|
| $z^{II}_{trip\omega_3} \le \dfrac{z_{\omega_1} + \dfrac{1-\alpha}{k_{\omega_3}} \cdot z^{I}_{trip\omega_3}}{1+\beta+\delta}$ | Coordination with the first zone of line ω3 distance protection; | (1) |
| $z^{II}_{trip\omega_1} \le \dfrac{z_{\omega_1} + \dfrac{1-\alpha}{k_{\omega_2}} \cdot z^{I}_{trip\omega_2}}{1+\beta+\delta}$ | Coordination with the first zone of line ω2 distance protection at substation B; | (2) |
| $z^{II}_{trip\omega_1} \le \dfrac{z_{\omega_1} + \dfrac{z_{T_1}}{k_{T_1}}}{1+\beta+\delta}$ | Coordination with the faults behind the transformer; | (3) |

42.7% of faults in the primary winding of the transformer and 5.8% of faults on line $\omega_2$ fit this characteristic. It means that in the cases where the main protections fail, most of the faults on the parallel line and in the transformer will be cleared only by the third zone of distance protection of line $\omega_1$. Since the third zone has a longer operation time, the protected components are more likely to suffer severe damage caused by long-lasting overcurrent.

The improvement of distance protection and its reach zone expansion can be achieved by using special fault detection systems able to indicate a faulted component in the grid. With such systems, the second zone of distance protection of line $\omega_1$, which is set according to (1-3), can be replaced by three independent zones. These zones will have the same time settings, and their reach settings will meet one of the conditions (1-3), respectively. By combining the mentioned zones with the selection elements as shown in Fig. 3, the reach point of the distance protection can be shifted further in the backup zone (increase sensitivity), which will completely exclude the possibility of false operation.

Thus, to provide efficient backup protection of the electrical grid components with sufficient operation time it is appropriate to use special algorithms for identification of emergency states. The concept of multi-dimensional

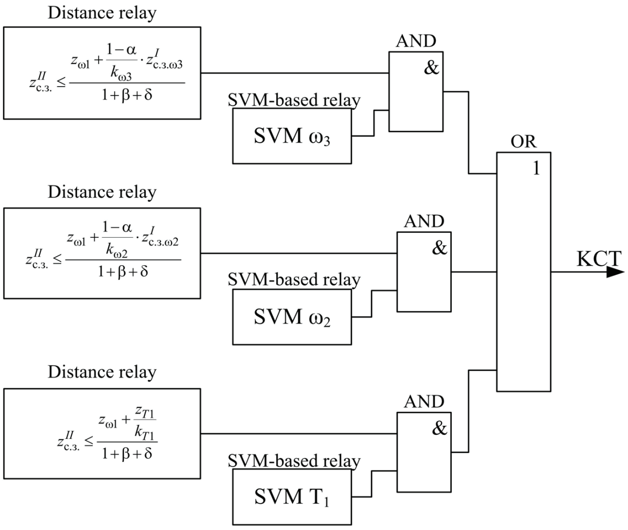



***Fig. 3. The principle of combining the distance protection zones with the selection elements.***

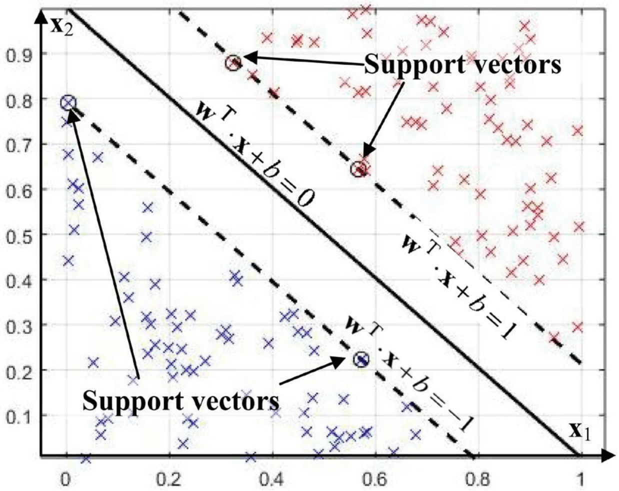



***Fig. 4. Separating border in a two-dimensional space.***

Table II α- and β-states for the designed elements.

| Element | α-states | β-states |
|---|---|---|
| *SVM* $T_1$ | Faults on $T_1$ | Faults behind $T_1$; Faults on $\omega_2$ outside $\omega_2$ zone 1; Faults on $\omega_3$ outside $\omega_3$ zone 1; Normal states. |
| *SVM* $\omega_2$ | Faults on $\omega_2$ | Faults behind $T_1$; Faults on $\omega_3$ outside $\omega_3$ zone 1; Normal states. |
| *SVM* $\omega_3$ | Faults on $\omega_3$ | Faults behind $T_1$; Faults on $\omega_2$ outside $\omega_2$ zone 1; Normal states. |

(multi-parameter) relay protection can be used to develop such algorithms.

This concept views relay protection as a discriminative system monitoring a specific set of information features, including operating parameters of the protected facility, which are available for measurement. The features are integrated into a feature space, and possible states of the protected facility (both feasible and unfeasible) constitute regions in the feature space similar to those on the impedance plane in Fig. 2. Unlike distance protection, however, the multi-dimensional approach uses features selected individually for a specific task, and their number (dimension of the feature space) can also vary. The features and their number should be selected based on the simplicity, illustrative representation, and sensitivity of the protection algorithm.

The decision rule of the multi-dimensional relay protection is usually obtained from an automated analysis of simulation data of the protected component. The procedure for classification of any observed state involves calculating coordinates of a point, which corresponds to a state in the selected feature space, and determining whether the obtained point is within the operation range set by the decision rule. In terms of machine learning, the implementation of multi-dimensional relay protection is a supervised classification problem, which, among other things, can be solved by the method of support vector machines.

The paper considers an example of using the support vector machines to design selective elements providing increased sensitivity of the second zone of distance protection.

## II. Literature review

The approach presented in [2-5] proposes a mapping of possible states of a protected facility onto one or several setting planes formed by arbitrary features. Similarly to machine learning methods, this approach assumes the protection decision rule to be formed via supervised classification. The simulation model of a protected component is usually used as a teacher. Based on the simulation results, the regions of normal and fault conditions are displayed on predefined setting planes. Unlike most of the machine learning techniques, this approach does not suggest the formation of regions in feature spaces with more than two dimensions.

There are also solutions providing transformer backup protection using both one-sided [6] and two-sided measurements [7] based on simulation data analysis. Like [2-5], the studies in [6] and [7] suggest dividing the N-dimensional feature space into several setting planes. Also, the study discussed in [6] proposes a criterion for assessment of a feature space, which is based on the ratio of average Euclidean distance between the representatives of one class to the distance between representatives of different classes. The problem of feature space assessment was further developed in [8] where apart from the method that estimates the separability of states via metric functions, the authors describe the methods based on “separating functions” that explicitly define the border surface (linear or non-linear) between different classes in the feature space.

Different ways of fault detection in power systems based on machine learning methods are analyzed in various research papers. In [9], the authors compare the efficiency of classification algorithms such as Naïve Bayes’ Classifier,

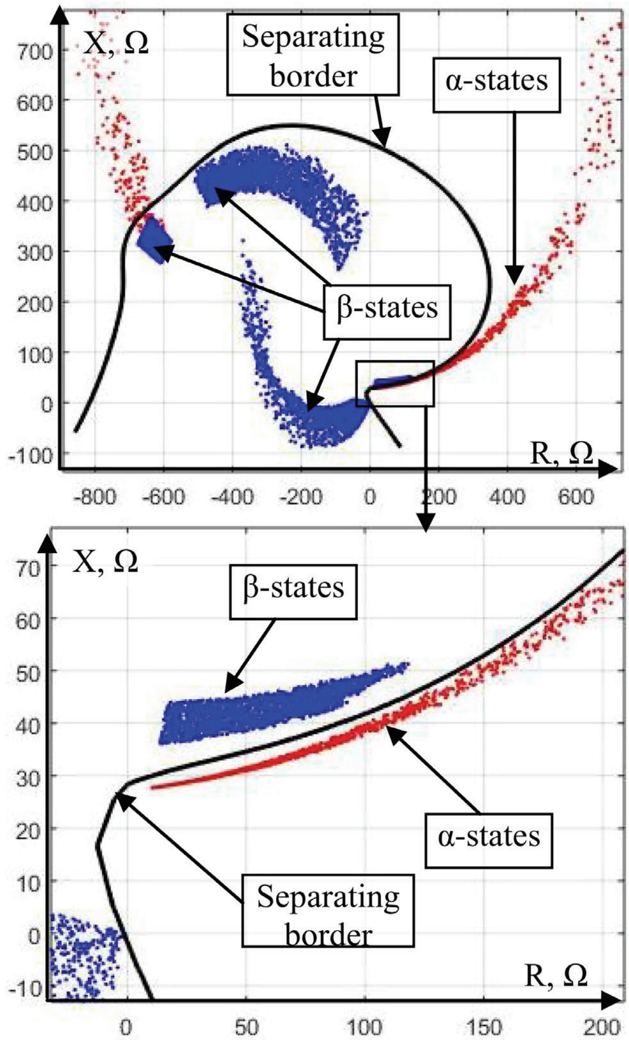



*Fig. 5. Training set and separating border of the "SVM T1" element.*

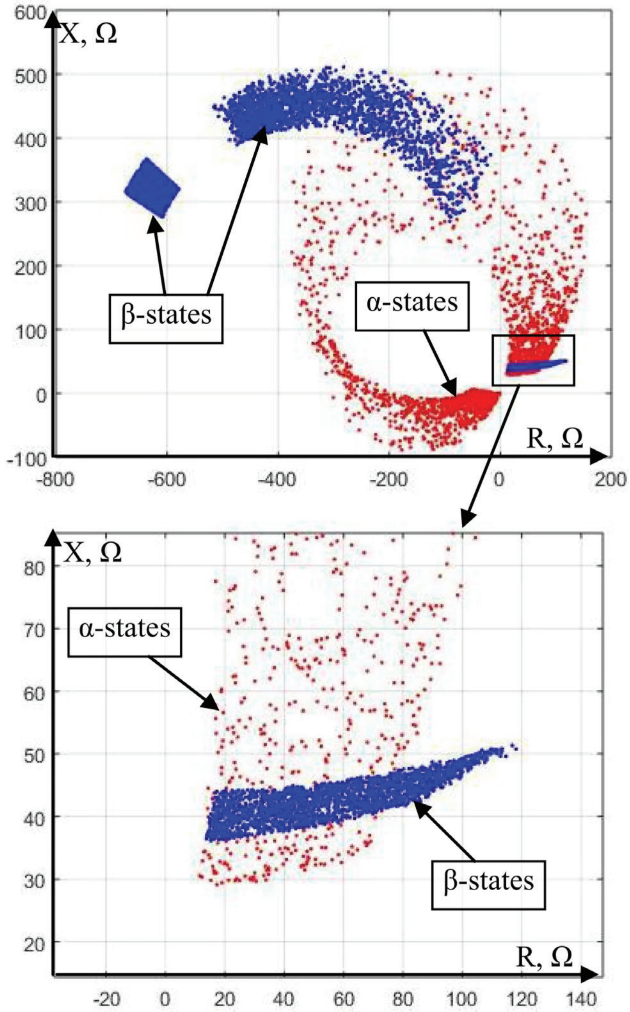



*Fig. 6. Distribution of α- and β-states of the "SVM ω2" element on the impedance plane.*

Radial Basis Function Classifier, Bagging and Boosting in the problem of identifying the type of a fault on a power line. In [10], the focus is on the relay protection based on the support vector machines in distributed networks with distributed generation. The authors used a feature space consisting of active and reactive power flows.

## III. The application of support vector machines

In its simplest form, the support vector machine (SVM) technique is used for binary classification. The learning procedure assumes setting a hyperplane in the feature space to divide the training set elements related to different classes (denote the classes by α and β, respectively). Thus, the feature space is divided into an operation region and a non-operation region. The procedure for the state classification is to determine on which side of the hyperplane the considered state is.

The training set is said to be linearly separable if a hyperplane can be drawn so that all the points belonging to class α will lie on one side of it while all the points

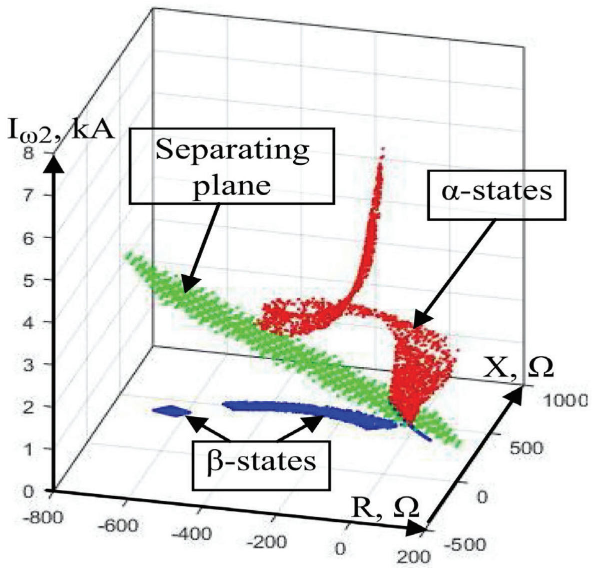



*Fig. 7. Separating plane of the "SVM ω2" element in a three dimensional space.*

belonging to class β will be on the other side. This condition can be formalized as follows:

Let there be a training set $\mathbf{x}_1, \ldots, \mathbf{x}_N$ consisting of $N$ vectors in a multi-dimensional space. For each element of the training set there is a class tag $y_1, \ldots, y_N$ so that $y_i = 1$ if the $i^{th}$ element belongs to the class α and $y_i = -1$ if the $i^{th}$ element belongs to the class β. Then the hyperplane $\mathbf{w}^{\mathrm{T}} \cdot \mathbf{x} + b = 0$ separates the classes if the condition is met:

$$\forall i \in 1,\ldots,N,\;\; y_i \cdot \left(\mathbf{w}^{\mathrm{T}} \cdot \mathbf{x}_i + b\right) > 0. \quad (4)$$

An example of a separating hyperplane is shown in Fig. 4. Sum of distances between the plane and the closest representatives of both classes is called “margin”. It is obvious that the most optimal hyperplane is the one that gives maximal margin provided that the condition (4) is met. It is proven [11] that equation of such a hyperplane can be obtained by finding the constrained minimum of the system of expressions:

$$\begin{cases} \min\limits_{\mathbf{w},b} \dfrac{1}{2}\mathbf{w}^{\mathrm{T}} \cdot \mathbf{w}, \\ \forall i \in 1,\ldots,N,\;\; y_i \cdot \left(\mathbf{w}^{\mathrm{T}} \cdot \mathbf{x}_i + b\right) \geq 1. \end{cases} \quad (5)$$

In most cases, however, the training set is not linearly separable, which means that there is no hyperplane satisfying the system of inequalities (4). In this case, the SVM allows misclassification of some elements from the training set but introduces a penalty for it. The optimization problem takes the following form:

$$\begin{gathered} \min\limits_{\mathbf{w},b,\xi_1,\ldots,\xi_N} \frac{1}{2}\mathbf{w}^{\mathrm{T}} \cdot \mathbf{w} + C \cdot \sum_{i=1}^{N} \xi_i, \\ \forall i \in 1,\ldots,N,\; y_i \cdot \left(\mathbf{w}^{\mathrm{T}} \cdot \mathbf{x}_i + b\right) \geq 1 - \xi_i, \\ \forall i \in 1,\ldots,N,\;\; \xi_i \geq 0, \end{gathered} \quad (6)$$

where  is a slack variable describing the classification error of the $i^{th}$ element of the training set; C is a coefficient defining penalty for the misclassification.

The coefficient C defines what will be more important for the classification algorithm: margin maximization or classification error minimization.

In practice, instead of the primal SVM problem (6), the dual form is solved, which provides the same answer but can be solved with faster numerical methods. Solving the dual SVM problem involves optimization of the variables $\lambda_1, \ldots, \lambda_n$ (expression (7)), i.e. Lagrange multipliers. The dual form is derived from the primal form [12] and is written as follows:

$$\begin{gathered} \min\limits_{\lambda_1,\ldots,\lambda_n} \left( \sum_{i=1}^{n} \lambda_i - \frac{1}{2} \cdot \left( \sum_{i=1}^{n} \sum_{j=1}^{n} \lambda_i \lambda_j y_i y_j \mathbf{x}_i^{\mathrm{T}} \mathbf{x}_j \right) \right), \\ \forall i \in 1,\ldots,N,\;\; 0 \leq \lambda_i \leq C, \\ \forall i \in 1,\ldots,N,\;\; \lambda_i y_i = 0. \end{gathered} \quad (7)$$

The quadratic programming problem (7) can be solved via one of the known methods [e.g. 13].

Having obtained optimal Lagrange multipliers $\lambda_1, \ldots, \lambda_n$ – by solving problem (7), one can restore separating hyperplane equation (8).

$$\begin{gathered} \mathbf{w} = \sum_{i=1}^{n} \lambda_i y_i \mathbf{x}_i, \\ b = \frac{1}{y_s} - \mathbf{w} \cdot \mathbf{x}_s, \end{gathered} \quad (8)$$

where $s$ is an index of a vector such that $0 < \lambda_s < C$. The classification algorithm can be expressed in terms of the coefficients $\lambda_1, \ldots, \lambda_n$ as follows:

$$a(\mathbf{x}) = \operatorname{sign}\left( \sum_{i=1}^{n} \lambda_i y_i \mathbf{x}_i^{\mathrm{T}} \mathbf{x} - b \right). \quad (9)$$

Another way to classify the linearly inseparable data is to use a kernel trick. Its idea is to transform the original feature space $X$ to a higher dimensional space $H$ via a special kernel function $H = \varphi(X)$ in which the training set would be linearly separable. With such an approach, the optimization problem takes the form (10) and a new object is classified according to expression (11).

$$\begin{gathered} \min\limits_{\lambda_1,\ldots,\lambda_n} \left( \sum_{i=1}^{n} \lambda_i - \frac{1}{2} \cdot \left( \sum_{i=1}^{n} \sum_{j=1}^{n} \lambda_i \lambda_j y_i y_j \varphi(\mathbf{x}_i, \mathbf{x}_j) \right) \right), \\ \forall i \in 1,\ldots,N,\;\; 0 \leq \lambda_i \leq C, \\ \forall i \in 1,\ldots,N,\;\; \lambda_i y_i = 0. \end{gathered} \quad (10)$$

$$a(\mathbf{x}) = \operatorname{sign}\left( \sum_{i=1}^{n} \lambda_i y_i \varphi(\mathbf{x}_i, \mathbf{x}_j) \right). \quad (11)$$

The most widespread kernel functions used in practice are the polynomial (12) and the radial (13) ones.

$$\varphi(\mathbf{x}_i, \mathbf{x}_j) = (\mathbf{x}_i \cdot \mathbf{x}_j + 1)^d; \quad (12)$$

$$\varphi(\mathbf{x}_i, \mathbf{x}_j) = e^{-\gamma \cdot \left|\mathbf{x}_i - \mathbf{x}_j\right|^2}, \quad (13)$$

where $d$ is the degree of the polynomial; $\gamma$ is a regulation parameter.

It is worth noting that for the classification according to (9) it is sufficient to summate only those $i$, for which $\lambda_i \neq 0$, i.e. only the support vectors whose quantity is much smaller than the size of the whole training set.

## IV. Design of the SVM-based state classifiers for relay protection

The most important part of designing multi-parameter relay protection is the identification of states to be detected by the algorithm (α-states) and also the states (β-states), at which the algorithm operation must be excluded. The composition and size of the training set will depend on this decision. Usually, α-states are specific types of faults inside the reach zone, whereas β-states are operating conditions and faults outside the reach zone where tripping can lead to non-selective behavior of the protection.

Using the above-described Monte-Carlo-based approach, we will form training and testing sets for the auxiliary elements to be designed.

The “*SVM $T_1$*” element (Fig. 3), which has to detect faults in the power transformer, should use simulation results of faults at $T_1$ as α-states. The β-states should consist of the following scenarios:

- Faults behind $T_1$;
- Faults on the part of line $\omega_2$ outside the reach of the distance protection first zone of line $\omega_2$;
- Faults on the part of line $\omega_3$ outside the reach of the distance protection first zone of line $\omega_3$;
- Normal states.

Note that the behavior of the “*SVM $T_1$*” element in the situations that are not included in the training set is not pre-defined. For example, this element can operate in case of a fault at the beginning of line $\omega_3$, but this is permissible because it will not lead to non-selective switching off.

Similarly, we can identify α- and β-states for the "*SVM* $\omega_2$" and "*SVM* $\omega_3$" elements (Table II).

Location of α- and β-states of the “*SVM $T_1$*” element in the feature space formed by the impedance plane is shown in Fig. 5. An analysis of the Figure shows that in the given feature space, the regions of the states are linearly inseparable. Thus, the efficient classification via SVM is possible only by using a kernel function. Let us implement the procedure for learning the given training set with the aid of the polynomial kernel with a degree of 6. The obtained separating border is also shown in Fig. 5.

The distance protection combined with the implemented “*SVM $T_1$*” element detects 95% of phase-to-phase faults in the transformer primary winding and excludes only the faults that are close to the transformer neutral and practically do not differ from the normal state.

Location of α- and β-states of the “*SVM* $\omega_2$” element in the same feature space is shown in Fig. 6.

As evidenced by analysis, Fig. 6, unlike Fig. 5, has overlays of α- and β-states, which makes it impossible to find a border that would accurately separate the studied and alternative states. One of the possible options to improve accuracy is to increase the dimension of the feature space. The rms value of the line $\omega_2$ current measured at the substation, where the designed protection should be installed, can be added to the feature space as the third dimension. In the resulting three-dimensional feature space, it becomes possible to place a separating plane providing unmistakable differentiation of the considered states (Fig. 7).

Figure 8 indicates a distribution of α- and β-states on the distance protection two-dimensional impedance plane for the “*SVM* $\omega_3$” element designed to detect faults on line $\omega_3$. In terms of the classification, the case in Fig. 8 is the simplest because the accurate classification of states can be performed in the two-dimensional feature space without a specific kernel function. However, the use of a polynomial kernel function, for example, is preferable, since in this case, the separating border settles further from the complex values of both α- and β-states.

The use of a more complex kernel function guarantees a higher probability of appropriate work of the classifier in situations where the observed complex values go slightly beyond the regions formed by the simulation results.

Thus, the results presented in the paper allow us to conclude that the designed SVM-based auxiliary elements for distance protection identify the faulted components of the grid almost unmistakably and provide selectivity of the distance protection in the backup zone.

It is worth noting that the obtained separating borders in the feature spaces and their discriminative ability are characteristic only of a specific scheme and operating situation of a particular power grid. Therefore, the use of the SVM method in relay protection is limited despite its obvious benefits.

## V. Conclusion

1. The advent of digital technologies and intelligent algorithms in the energy industry opens up new opportunities not only for the improvement of relay protection hardware but also for the development of its design principles. Simulation modeling becomes a powerful tool for the research into power system operation and the development of new relay protection algorithms.
2. The SVM application to relay protection problems is promising in both the formation of new protection algorithms and the use of SVM as an additional tool for increasing selectivity and speed of existing types of protection. An increase in the dimension of feature space to identify the electrical grid states significantly increases the probability of correct classification.
3. The proposed approach to the state recognition based on electrical grid simulation modeling and SVM allows the decision rule of protection algorithm to be adapted to an arbitrary grid configuration. It may be particularly appropriate for the grids of a complex configuration with the state parameters influenced by many factors (circuit breakers states, load power, and others), which cannot be handled manually.
4. Despite the high recognition ability of machine learning algorithms in general and the SVM in particular their application in relay protection is limited for several reasons:

- Trained algorithms are only applicable to a particular power grid section;
- Simulation modeling is required for setting the algorithm parameters;
- The use of a feature space with more than two dimensions makes it difficult to visualize the simulated states and the operation boundary obtained by implementing the algorithm.

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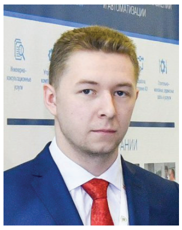

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# A Methodology to Calculate the Supply and Demand Balance by Region for Vietnam's Energy Systems

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*Abstract* — **The energy supply and demand balance is one of the important issues to address when proposing options for energy system development. Currently, several tools are utilized for calculating the supply and demand balance for Vietnam's energy systems. These tools are instrumental in developing the national energy system. However, most of them treat the national energy system as a unified whole, with no specific focus on regional energy supply and demand balances. This paper presents a methodology to calculate the supply and demand balance for Vietnam's energy systems by region, with the practical application of Corrective Module1, a piece of software which is a result of the joint research and development effort by the Institute of Energy Science, Vietnam Academy of Science and Technology (VAST) and the Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences (RAS). The findings of this study demonstrate that the energy system supply and demand balance calculated by region is the scientific basis for researchers, managers, and policymakers to get a clear vision of possible energy system development at the national and regional scale and to provide directions and policies that are consistent with the conditions of each region and the country. This approach is appropriate for Vietnam's geographical conditions, infrastructure, energy resources, load distribution, and policy framework.**

*Index Terms* — **energy supply and demand balance, energy system, software package, environment**

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## I. Introduction

The supply and demand balance is one of the important issues in the energy system (ES) optimization. Results of the supply and demand balance calculation provide inputs enabling researchers to select and propose energy system development options that are suitable, economically feasible, and environmentally sustainable. They provide the scientific basis for assessing the structure, utilization factor, and capacity of fuel/energy sources, and involve the stages of mining, exploitation, processing, conversion, importation, exportation, and consumption. Moreover, these data are instrumental in assessing the substitution of each fuel and energy source in the system to achieve the highest economic and energy efficiency.

## II. Literature review

calculation of the ES supply and demand balance requires dedicated software. The software will model the ES as mathematical expressions and equations, and solve the problem of balancing supply and demand in line with the optimal planning methods. Currently, several software packages are used across the world, depending on the objectives and characteristics of each country. Researchers in Vietnam use some of the software packages in developing the long-term ES development strategy. These are MESSAGE, LEAP, MARKAL, EFOM-ENV, and TIMES [1, 2, 3, 4, 5].

MESSAGE (Model of Energy Supply Strategy Alternatives and General Environmental Impacts) is provided by the International Atomic Energy Agency (IAEA) to support energy analysis and planning in the member states. MESSAGE describes the ES according to the energy flows from exploitation, processing, and production to consumption as objective functions and constraints. It solves the problem of the supply and demand balance by linear programming methods [1]. This software does not support the evaluation of the strengths and weaknesses of the region as part of the country in the overall development of the national ES.

LEAP (Long-Range Energy Alternatives Planning System), developed by the Stockholm Environment

Institute, is the analytical tool for energy development scenarios that address environmental issues. This software is widely used by thousands of organizations in more than 190 countries around the world at different levels, including the levels of the city, state, national, regional, and global [2]. However, the software requires detailed information on all employed energy technologies, which is difficult to implement in a developing country with a limited budget and human resources. Therefore, in Vietnam, this program is only applied at the national scale due to insufficient data on energy technologies.

MARKAL was developed by the International Energy Agency back in the 1980s for modeling the energy sector at the levels ranging from local to national. The key objective of MARKAL is to analyze and plan the energy system according to the least-cost approach [3]. MARKAL can be regarded as the prototype model for the energy sector, from which other complex and integrated models were developed.

EFOM-ENV was developed by the European Commission to explore the energy supply, subject to technical, environmental, and political constraints. The strength of EFOM-EVN lies in its ability to integrate renewable technology and calculate emission reduction, thus supporting the development of energy and environment policy. Similar to MARKAL, EFOM-ENV employs the least-cost criterion for a mix of energy conversion technologies to meet energy demand over the period considered. However, it covers both the energy production and consumption sectors [4]. Given that the environmental data on Vietnam's energy production and consumption are not fully covered in available studies, it proves unfeasible to collect the data and apply this model in the current situation.

TIMES (The Integrated MARKAL - EFOM System) is developed by the International Energy Agency (IEA) with the main objective of analyzing the potential development of energy technologies and fuel resources. TIMES describes the ES in terms of production technologies, conversion, and energy consumption; it calculates and compares scenarios based on the minimum cost. This software can be employed to study energy development at the national or regional scale by means of describing thousands of technologies for energy production, conversion, transportation, and consumption [5]. However, the development of constraints and classification of demand is complicated and requires much effort, which is unsuitable in the context of Vietnam.

Currently, the application of these software packages in Vietnam is limited to the studies that deal with the national scale. Moreover, analyzed energy technologies include only the key ones adopted in some industries and economic sectors. The obtained results lay the foundation for studies and development of the national ES. Meanwhile, there are differences in resource distribution, formation, development level, technical capability, and financial and economic conditions across regions in Vietnam, which generates the need to divide the ES into regions to accommodate region-specific conditions. The regional division of the ES fits the governmental plan of economic development with its division of the whole country into key social and economic regions. As a result, we propose studying and developing a model for the ES supply and demand balance calculation by region to describe the national ES in a way suitable for individual regions' current conditions and future development of Vietnam's economy.

The division of the ES into energy regions will allow both the modeling to be conducted at the national scale and the detailed results to be produced for the regions. The results of the energy supply and demand balance calculation by region will provide the information for assessing the scale, development, and structure of the mix of fuels and energy sources, hence meeting the demand of each region and being consistent with the overall development context of the national ES. The study will propose methods for modeling and solving the problem of Vietnam's ES supply and demand balance by region, which are implemented as the Corrective Module 1 software package[6]. The model is capable of describing the ES regardless of the number of regions, provided that the number of regions is more than one. This is the result of cooperative research between the Institute of Energy Science (VAST) and the Melentiev Energy Systems Institute (RAS) in 2011-2015.

By analyzing the characteristics of the primary social and economic regions, the ES structure, and some other related issues, we proposed calculating Vietnam's ES supply and demand balance in 2015-2030 for eight regions [7]. The region was established based on six economic regions, with the division of two economic regions, including the North and Central Coast regions, into four. Thus, eight energy regions are the Red River Delta (V1), Northeast (V2), Northwest (V3), North Central (V4), the South Central Coast (V5), Highlands (V6), Southeast (V7), and Mekong Delta (V8).

Input data include energy supply (costs and volume of production, imports, and exports), conversion and transportation of energy, energy consumption by type of fuel/energy source (Figure 1,) including coal, oil and gas, and power systems [8, 9, 10, 11]. Specifically, the regional parameters of production capacity, costs of production, transportation capacity, transportation costs are set based on the data from individual production and transportation facilities. The data on regional energy consumption are extracted and calculated with respect to the energy consumption of five key economic sectors, namely, industry, agriculture, transportation, tertiary sector, and households. The export/import data are retrieved from global price forecasts.

## III. Methodology

A methodology for calculating Vietnam's ES supply and demand balance by region is proposed based on the study of the basic characteristics of the ES and its internal and external relations. The methodology covers a comprehensive model of the region, models of subsystems (coal, oil, gas, electricity), objective functions, and constraints. The problem of calculating the supply and demand balance is solved by the linear programming method.

*1. Modelling methodology*

Each region is modeled according to three main factors, including inputs (energy production, imports, and trans-regional transportation [transportation between regions], conversion and regional transportation [refineries, gas processing, power generation, and regional transportation (transportation within one region)], and outputs (energy to meet regional demand, energy transportation to other regions). The regions are connected through trans-regional transportation, which makes up the comprehensive (national) ES.

The overall regional modeling of ES is based on modeling of three sectoral subsystems, including coal, oil and gas, and power systems of the region. Figure 1 presents the model of Vietnam's ES for one region.

With regards to the coal system, the inputs include coal produced in the region, coal delivered from other regions, and imported coal; conversion and regional transportation include thermal power plants using coal and coal transportation in that region; the outputs include coal supplied to that area, transportation to other regions, and export.

For the oil and gas system, the inputs include crude oil and natural gas produced in the region, petroleum products imported and transported from other regions; conversion and regional transportation include refineries, gas processing, power plants using gas and oil, and their transportation in that region; outputs include crude oil, gas and refined petroleum products consumed in that region, transportation to other regions, and exports.

With regards to the electric system, the inputs include power from hydropower plants and renewable energy production in that region, the fuel type for thermal power, transportation from other regions, imports; conversion and regional transportation include the thermal power plant and power transportation in the region; outputs include power demand in that region, power transportation, and export to other areas.

In Figure 1, all three subsystems of coal, oil, and gas, and electric power are linked to the supply and demand of a regional energy system. The connection among regions through road transportation will constitute overall Vietnam's ES.

The ES modeling diagram allows the construction of the objective function and constraints to solve optimization problems to develop Vietnam's ES by linear planning methodology.

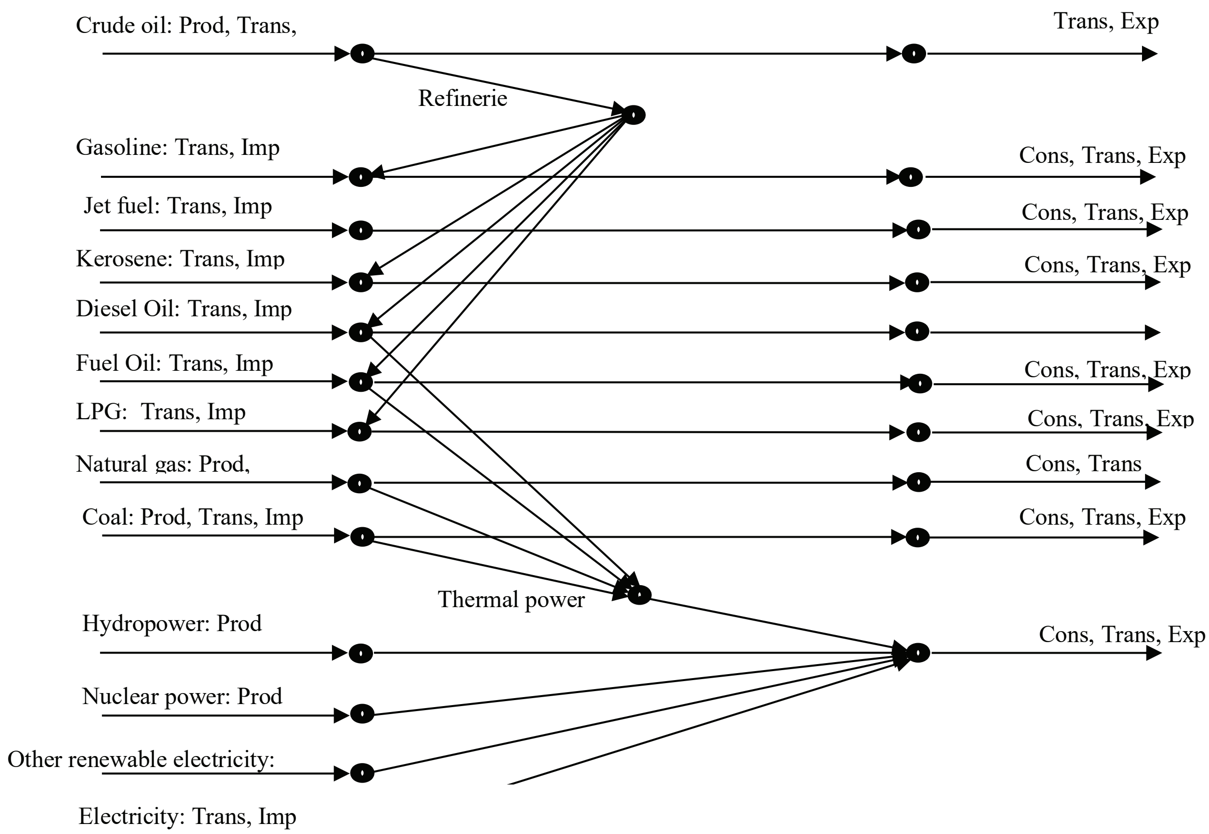


***Figure 1. Modeling of Vietnam's ES by region; Prod: Production; Trans: Transportation; Imp: Import; Exp: Export; Cons: Consumption; Nu: nuclear power; RE: Renewable energy; Nat: Natural gas***

*2. Objective function*

$$\sum_{i=1}^{I}\left[\sum_{j=1}^{J} c_{ij}^{n\ln l}.Q_{ij}^{n\ln l} + \sum_{k=1}^{K} c_{ik}^{pd}.E_{ik}^{pd} + \sum_{l=1}^{L} c_{il}^{vt}.F_{il}^{vt} + + \sum_{m=1}^{M} c_{im}^{pxk}.F_{im}^{pxk} + \sum_{n=1}^{N} c_{in}^{pnd}.F_{in}^{pnd}\right] \to \min \quad (1)$$

Where:

$c_{ij}^{n\ln l}$, $Q_{ij}^{n\ln l}$ is the cost ratio of fuel/energy source and production volume (excluding power), USD/KTOE

$c_{ik}^{pd}$, $E_{ik}^{pd}$ is the cost ratio of fuel/energy source and production volume, USD/KTOE

$c_{il}^{vt}$, $F_{il}^{vt}$ is the cost and volume of transportation of fuels/energy sources, USD/KTOE

$c_{im}^{pxk}$, $F_{im}^{pxk}$ is the calculated cost ratio and export volume that can be met, USD/KTOE

$c_{in}^{pnd}$, $F_{in}^{pnd}$ is the calculated cost ratio and domestic demand that can be met, USD/KTOE

*I* is the number of geographical energy regions

*J* is the number of types of fuel/energy sources (excluding electrical power)

*K* is the number of inputs for power generation, including hydropower and renewable energy

*L, M, N* is the number of *N* ln *L* transportations of fuel/energy sources (including electrical power).

*3. Constraints*

The energy demand and supply balance constraints of the region, including production, transportation, import, and export constraints:

- The constraints of the energy demand and supply balance of the region include the constraints on the power demand and supply balance and the balance of energy demand for other needs.

+ the fuel and energy balance for other needs in the regions:

$$Q_{sx}^{n\ln l} + Q_{vtv}^{n\ln l} - Q_{vtr}^{n\ln l} - Q_{pd}^{n\ln l} - D_{nck}^{n\ln l} \geq 0 \quad (2)$$

Where:

$Q_{sx}^{n\ln l}$ is fuel/energy produced in the region, KTOE

$Q_{vtv}^{n\ln l}$ is the fuel/energy transported to the region (including domestic transportation and import), KTOE

$Q_{vtr}^{n\ln l}$ is the fuel/energy transported from the region (including domestic transportation and exports), KTOE

$Q_{pd}^{n\ln l}$ is the fuel/energy for power generation in the region, KTOE

$Q_{nck}^{n\ln l}$ is the fuel/energy for other needs of the region, KTOE

The number of constraints equals the total number of types of fuel/energy sources (excluding power), multiplied by the number of regions.

+ regional power balance:

$$E_{sx}^{dn} + E_{vtv}^{dn} - E_{vtr}^{dn} - E_{nc}^{dn} \geq 0 \quad (3)$$

Where:

$E_{sx}^{dn}$ is power generated in the region, including all types of power plants, KTOE

$E_{vtv}^{dn}$ is power transported to the region, including domestic transportation and import, KTOE

$E_{vtr}^{dn}$ is power transported from the region, including domestic transportation and export, KTOE

$E_{nc}^{dn}$ is the power demand in the region, KTOE

The number of constraints equals the number of regions.

production, transportation, import, and export constraints:

$0 \leq Q_{s}^{n\ln l} \leq Q_{\max}^{n\ln l}$ (4)

Where:

$Q_{s}^{n\ln l}$ is the required volume of fuel/energy source, KTOE

$Q_{max}^{n\ln l}$ is the upper boundary of the required fuel/energy source volume, KTOE

This constraint is used for all types of fuel/energy sources at all stages of production, import, export, and transportation. The number of constraints equals the number of produced fuels/energy sources + the number of energy transportations x types of transportation + the number of energy exports x types of exports + the number of energy imports x types of imports.

Power generation, import, and export constraints:

$$0 \leq E_{s}^{dn} \leq E_{\max}^{dn} \quad (5)$$

where:

$E_{s}^{dn}$ is the volume of required electrical power, KTOE

$E_{max}^{dn}$ is the upper boundary of required power, KTOE

These constraints are used for all types of power plants, except for transported, imported, and exported power calculated inclusively. The number of constraints equals the number of power plants + the number of domestic electrical power transportations + the number of imported power transportations + the number of exported power transportations.

Transportation means transportation equivalent between two regions or between a region and an importing or exporting country. For example, power transmission from region 1 to region 2 is performed through numerous lines; however, in this model, only one transportation equivalent is calculated.

## IV. Calculation results for Vietnam's energy systems

collected data are entered into the Corrective - Module1 software package, and Vietnam's ES supply and demand balance for the year 2020 is calculated as the reference case. Calculation results are presented by type of fuel/energy sources, with two Tables of results for each type (the Table of overall results and the Table of the fuel/energy transportation). In the case of electrical power, three tables are the table of overall results, the table for electricity transmission and, the Table of electricity generation by types of power plants. Types of fuel/energy sources with two tables of results are anthracite, lignite, natural gas, crude oil, liquefied petroleum gas, gasoline, oil, fuel oil, kerosene, jet fuel, and biomass. These types of fuel/energy sources have a similar structure of the result Table, as is shown in Table 1.

Table 1. Supply and demand balance of coal in 2020 - Reference case (KTOE)

Table 1 presents the supply and demand balance of coal in 8 regions. The total production, import, export, and consumption of the whole country is the sum of the corresponding values of 8 regions. The main difference is the detailed results for each region. Coal is produced in region 2. In 2020, it needs to be imported into V4, V5, and V8. The difference between the transportation to and from the region illustrates the transported energy used within the region or the destination of energy transportation.

Table 2. Transportation of coal in 2020 - Reference case (KTOE)

The coal is transported from region 2 to region 1; after satisfying the needs of region 1, the remaining coal will be transported to region 3 and region 4. Coal is imported into region 4. Thus, the imported coal, in addition to domestic coal, will enable region 4 to meet its demand. The remaining coal will be transported to region 6. Signs of the values in Table 2 stand for the transportation direction (to be read as the «column» to «row» direction). For example, transportation from V1 to V2 is 15.937.8 (positive), while transportation from V2 to V is -15.937.8 (negative).

Similar Tables of results can be obtained for other types of fuel/energy sources such as gas, crude oil, refined petroleum products, renewable energy, and electricity. For electric power, apart from the two Tables that are similar to those used for coal, there are detailed results of electricity generation for different types of power plants (Table 3).

Table 3. Electricity generation by type of power plants in 2020 – Reference case (GWh)

Table 3 indicates that Vietnam possesses diverse resources for electricity generation, where coal, gas, and hydropower account for the largest share of 39.49%, 26.55%, and 29.28%, respectively. The share of renewable energy resources such as wind, solar, and biomass in the energy mix is very small - 0.82%, 0.01%, and 0.32%, respectively. Power output is evenly distributed between regions, ranging from 7% to 18%, while region 2 holds the largest share (18%), and region 6 has the smallest share (7%). The results of the ES supply and demand balance calculation by region provide the same amount of information as those obtained with the aid of other software packages. Moreover, we get detailed results for each region, which assists the assessment of capacity, role, advantages, and limitations of the regions in the energy production and supply.

## V. Discussion

### *1. Discussion of calculation results*

The modeling and solving the problem of the energy supply and demand balance provide not only overall results applicable to the national scale but also detailed results by region in terms of the ES capacity and structure required to meet the regional and national demand while being suitable for the conditions specific to each region and consistent with the overall development context of the national ES.

The total volume of domestic coal production in 2020 is 27492.3 KTOE, which is exported from region 2 to meet the national demand. Moreover, three regions, including V4, V5, and V8, need to import coal. Regarding transportation, coal is transported from region 2 to region 1.

Table 1. Supply and demand balance of coal in 2020 - Reference case (KTOE)

| **Types of power plants** | **Region** | | | | | | | | **Total** | **Share** |
|---|---|---|---|---|---|---|---|---|---|---|
| | **V1** | **V2** | **V3** | **V4** | **V5** | **V6** | **V7** | **V8** | | |
| Anthracite-fired thermal power plant | 32120.0 | 42470.0 | 0.0 | 20000.0 | 1106.8 | 0.0 | 1860.0 | 3766.4 | 101,323.2 | 39.49 % |
| Brown coal-fired thermal power plant | 0.0 | 0.0 | 0.0 | 1855.4 | 0.0 | 0.0 | 0.0 | 0.0 | 1855.4 | 0.72% |
| Gas turbine power plant | 150.0 | 0.0 | 0.0 | 0.0 | 2475.0 | 0.0 | 32240.4 | 33252.1 | 68117.5 | 26.55 % |
| Hydropower | 0.0 | 2669.3 | 30526.7 | 6264.3 | 12216.1 | 18546.4 | 4909.2 | 0.0 | 75132.0 | 29.28 % |
| Wind power | 0.0 | 0.0 | 0.0 | 100.0 | 1065.0 | 0.0 | 300.0 | 630.0 | 2095.0 | 0.82% |
| Solar power | 0.0 | 5.5 | 5.0 | 2.0 | 1.3 | 6.4 | 3.8 | 13.3 | 37.2 | 0.01% |
| Biomass power | 55.7 | 31.4 | 15.5 | 162.3 | 91.2 | 50.2 | 122.0 | 301.7 | 830.0 | 0.32% |
| Nuclear power | 0.0 | 0.0 | 0.0 | 0.0 | 7200.0 | 0.0 | 0.0 | 0.0 | 7200.0 | 2.81% |
| Total | 32325.7 | 45176.1 | 30547.2 | 28384.0 | 24155.4 | 18602.9 | 39435.5 | 37963.5 | 256590.3 | |
| Share | 13% | 18% | 12% | 11% | 9% | 7% | 15% | 15% | | |

Table 2. Transportation of coal in 2020 - Reference case (KTOE)

| Region | V1 | V2 | V3 | V4 | V5 | V6 | V7 | V8 | Imports |
|---|---|---|---|---|---|---|---|---|---|
| V1 | 0.0 | -15937.8 | 709.3 | 4649.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| V2 | 15937.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| V3 | -709.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| V4 | -4649.8 | 0.0 | 0.0 | 0.0 | 0.0 | 354.3 | 0.0 | 0.0 | 4373.9 |
| V5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 967.7 |
| V6 | 0.0 | 0.0 | 0.0 | -354.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| V7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | -2202.4 | 0.0 |
| V8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2202.4 | 0.0 | 4210.2 |

Table 3. Electricity generation by type of power plants in 2020 – Reference case (GWh)

| Types of power plants | Region | | | | | | | | Total | Share |
|---|---|---|---|---|---|---|---|---|---|---|
| | V1 | V2 | V3 | V4 | V5 | V6 | V7 | V8 | | |
| Anthracite-fired thermal power plant | 32120.0 | 42470.0 | 0.0 | 20000.0 | 1106.8 | 0.0 | 1860.0 | 3766.4 | 101,323.2 | 39.49 % |
| Brown coal-fired thermal power plant | 0.0 | 0.0 | 0.0 | 1855.4 | 0.0 | 0.0 | 0.0 | 0.0 | 1855.4 | 0.72% |
| Gas turbine power plant | 150.0 | 0.0 | 0.0 | 0.0 | 2475.0 | 0.0 | 32240.4 | 33252.1 | 68117.5 | 26.55 % |
| Hydropower | 0.0 | 2669.3 | 30526.7 | 6264.3 | 12216.1 | 18546.4 | 4909.2 | 0.0 | 75132.0 | 29.28 % |
| Wind power | 0.0 | 0.0 | 0.0 | 100.0 | 1065.0 | 0.0 | 300.0 | 630.0 | 2095.0 | 0.82% |
| Solar power | 0.0 | 5.5 | 5.0 | 2.0 | 1.3 | 6.4 | 3.8 | 13.3 | 37.2 | 0.01% |
| Biomass power | 55.7 | 31.4 | 15.5 | 162.3 | 91.2 | 50.2 | 122.0 | 301.7 | 830.0 | 0.32% |
| Nuclear power | 0.0 | 0.0 | 0.0 | 0.0 | 7200.0 | 0.0 | 0.0 | 0.0 | 7200.0 | 2.81% |
| Total | 32325.7 | 45176.1 | 30547.2 | 28384.0 | 24155.4 | 18602.9 | 39435.5 | 37963.5 | 256590.3 | |
| Share | 13% | 18% | 12% | 11% | 9% | 7% | 15% | 15% | | |

After satisfying the needs of region 1, it will be transported to region 3 and region 4. Imported coal and domestic coal ensures that region 4 meets its demand for coal. The remaining coal will be used in region 6.

These results are essential for planning regional energy development and identifying regional energy demand, production, transportation, and imports. Moreover, these results can be used to evaluate the contribution of each region (in cooperation with other regions) to the overall energy supply and demand balance through the amount of energy transported to and from each region. On the national scale, in addition to the information on the structure and makeup of energy production, imports, and exports, these data provide some details on energy imports and show which region is the most economical and efficient in terms of energy import. Moreover, a comparison of different development scenarios allows identifying the location for new energy projects to achieve the most efficient implementation.

With regard to power systems, they are complex and play an essential role in the energy system. Their capacity and structure directly influence the development of the coal and gas industries as these two industries contribute the majority of raw materials to electricity generation. The calculation results show that all regions generate electricity, but there is a difference in the resources used for electricity generation, depending on the potential and capacity of each region. The regions vary in demand for electricity, which requires its transmission. Regions 2, 3, 4, and 5 generate a sufficient amount of electricity to satisfy internal demand and supply it to other regions. At the same time, regions 1 and 7 mainly receive electricity from other areas.

Results of the electricity supply and demand balance calculation are instrumental in assessing the scale and structure of power plants in each region. For example, region 3 hosts many hydropower plants, while the electricity demand is low there; therefore, there is no need to build large thermal power plants in this region. Meanwhile, region 2 has large coal reserves, which is a favorable condition for building large coal thermal power plants. Region 1 has a high electricity demand, and its natural characteristics are suitable only for developing thermal power; therefore, the volume of transported electricity is large. This allows developing a specific regional plan based on its capacity. On the national scale, the results are supportive of the priority of power plants, their capacity, and their location. Thus, the results of the regional supply and demand balance calculation will serve as the scientific basis to assist scientists, managers, and policymakers in getting a clear outlook of the potential to develop the ES not only on the national scale but also on the regional one, which can underlie suitable and efficient regional policies.

*2. Preliminary evaluation of the proposed methodology*

Based on the evidence provided by the analysis and study of the situation, along with the calculations of the development plan, we state that the model needs to be revised and completed with respect to modeling the transportation system and integrating environmental emissions. As to the transportation system description, this model describes the new transportation system between two regions by a single transportation line. In fact, there are five existing lines of energy transportation in Vietnam, including waterway, railway, road, pipeline, and power transmission line transportation. Therefore, a single transportation line is inadequate and needs to be supplemented by other transportation lines in the model. Moreover, the cost of local transportation is not fully described due to the incompleteness of the database on types of energy sources, transporting distance, load distribution, and others.

In terms of the environmental aspect of the ES, while the environmental standards and regulations are available for the design and construction of energy systems and power projects, there is no constraint on the environment integrated into the model. There is a need for further research to incorporate environmental impacts, specifically environmental emissions of energy systems into the model.

## VI. Conclusion

Simulation and calculation of the ES supply and demand balance by region is an appropriate approach consistent with the natural geographical conditions, economic and engineering infrastructure, energy resource potential, load distribution, and development policies of Vietnam in the current context. This model is capable of handling any number of regions greater than one. The modeling results will serve as the scientific basis for scientists, managers, and policymakers to enable them to get a clear perspective on the possibility of developing the ES on the national and regional scales. Some issues, however, need further research, including regional and trans-regional transportation systems and environmental emissions.

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# 50 Years of Systems Analysis of Energy Development In The USSR And Russia

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***Abstract* — This year replete with so many anniversaries related to the energy sector sees the centenary celebration of the GOELRO Plan. This event is remarkable for energy studies: a complex energy method that backed up the Plan development half a century later became one of the preconditions for the development of the methodology of systems analysis of the energy development. The groundwork of this methodology was laid at SEI/ESI SB RAS (Siberian Energy Institute. Melentiev Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences) founded by Academician L.A. Melentiev; the institute celebrates its 60th anniversary this year. Half a century ago, an 'off-site' department of the SEI was established in Moscow and 15 years later it was reorganized into ERI RAS (Energy Research Institute of the Russian Academy of Sciences) and GKNT (State Committee for Science and Technology).**

**The paper focuses on the background of the development of the theory and methods of systems analysis of energy development, covers its main theoretical and applied contributions in two stages of social and economic development of the country, discusses evolution of this research area and its possible adoption in the alternative (mobilization-type and liberal) concepts of shaping 'the information society' of the future.**

***Index Terms* — GOELRO plan; systems analysis of the energy sector; methods and applications; further research directions.**

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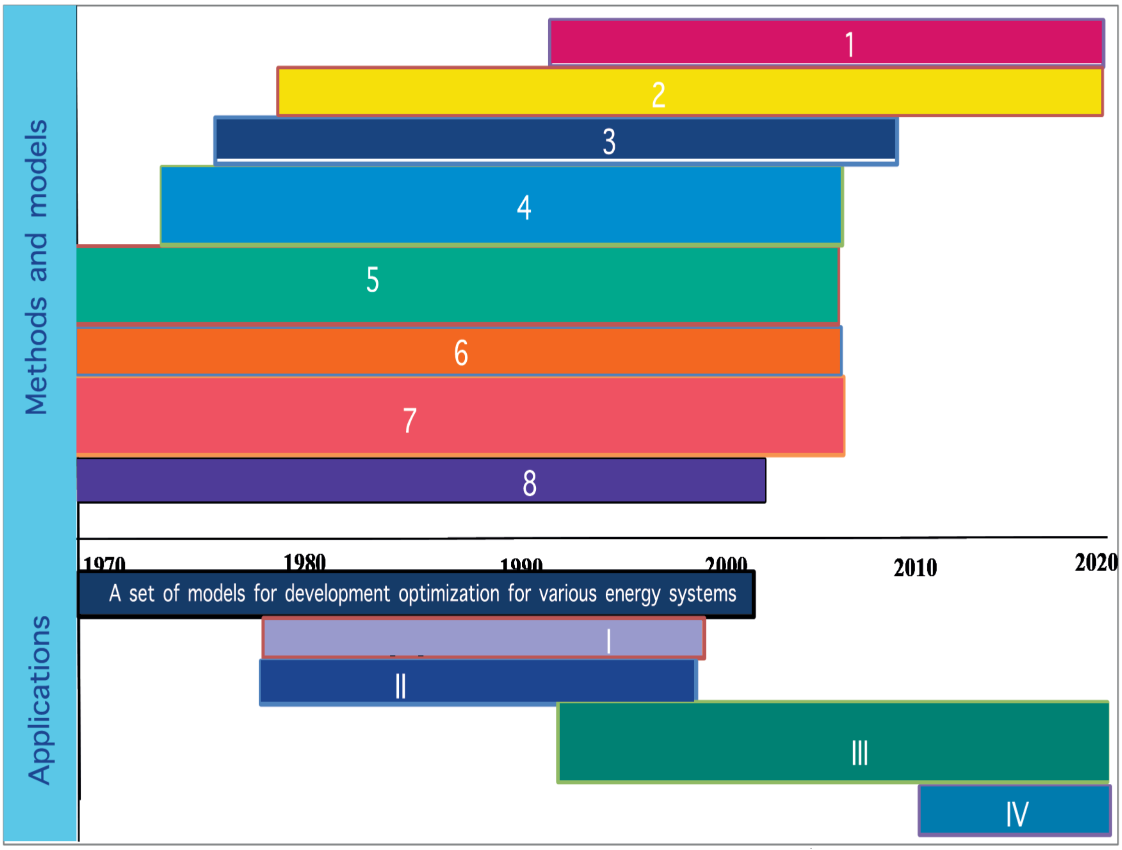
## Introduction

The first-ever long-term outlook of the energy development as treated in conjunction with the economy, the plan of the State Commission for Electrification of Russia (GOELRO Plan) [1], proved a game-changer in managing the economy. Materials backing up the Plan attest to the back then advanced statements of scientific problems and techniques for validation of efficient solutions. Sixty years later, L.A. Melentiev would note that the GOELRO Plan laid foundations of "...the main ideology behind economic planning based on scientific understanding of the energy industry as a unified whole and electrification as the key driver of economic development" [2].

Harsh experience of Stalin's five-year plans, the Second World War, and restoration of the national economy that followed all demonstrated the huge mobilization potential of the planned economy and that of its fuel-and-energy basis but failed to contribute to any breakthroughs in the development of the methodology and means of planning. As late as in the mid-1960s the conditions for a quantum leap in methods and tools for planning the energy development as a prerequisite for economic development, namely:

- The awareness of the energy industry as an aggregation of processes of production, conversion, distribution, and consumption of energy resources (fossil fuels, hydropower, wind and solar energy, etc.) and all types of energy on a par with understanding the energy balance as a method for the complex quantitative and qualitative depiction of the production and consumption of all types of energy and fuels in the national economy as a whole, its industries, and the country's districts [3];
- The mathematical theory and methods developed by L.V. Kantorovich for searching the extreme points of convex functions in the multi-dimensional space of linear constraints and their economic interpretation [4] opened the way to stating and solving challenging problems of the optimum management and planning of economic development, including optimization of fuel and energy balances;




1 Models of Russia's energy sector development as part of the world energy

2 Models of the energy industry impact on economic development as an integral part of the latter

3 Methods for optimization of LES development under uncertainty

4 Decomposition of LES development models with reconciliation of the primal and dual solutions, and use of the iterative aggregation method

5 Optimality criteria for LES development: comparing running and capital costs against each other, factoring in other criteria as constraints

6 Modeling the dynamics of LES development and operation modes

7 Modeling area-specific energy balances, technologies, transportation links, economy (costs and results), and constraints put on LES development

8 Concept and theory of systems analysis of energy industry development

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I Model for development of the EP and the CP for SEP

II Energy sector" subsystem ASPS by Gosplan of the USSR

III MIS for drafting documents on strategic energy development in Russia

IV MIS 'SCANER'

*Fig. 1. Evolution underwent by the methodology and application of systems analysis of the development of large energy systems in the USSR and Russia.*

*Legend: I – Long-term energy program of the USSR; Comprehensive program for scientific and technological progress in the USSR; II - Automated system for planned calculations by the USSR Gosplan; III – Modeling-and-information system; IV – Supersystem for energy-related decision analysis.*

- The introduction of computers [5], their application to research and development reduced computational efforts needed for implementation of the first (calculation of energy balances of production and consumption for all types of energy resources throughout the country) and especially so of the second prerequisites (optimization of the above processes in the course of energy sector development and operation).

The novel methodological and computational basis made the 1960s the "Sturm und Drang" age in the development of economic and mathematical models and methods for optimization of decisions, on a par with efforts to apply them to the country's energy industry management. Researchers at the Siberian Energy Institute of the Siberian Branch of the USSR Academy of Sciences proposed a mathematical model for optimum energy development planning that was adapted to industries of the energy sector and country's regions.

## II. Theory, methods, and applications of systems analysis of the energy development in the USSR

Methodologies behind systems analysis study such objects and phenomena of the real world that:

Possess properties of the whole that cannot be reduced to a sum of properties of their elements;

Have elaborate internal and external relations and synergy effects of interrelations of elements that constitute the main factors of the system's efficiency growth: concentration, centralization, combination, and specialization of the main components of their economic activity;

Include an object, organizational bodies, and mechanisms (including financial ones) of control that are, as a rule, have a sophisticated hierarchical structure;

Obey the principle of least action, which requires optimization of the decisions to be made;

Have an uncertain future, which generates risks with respect to decisions made and requires adaptive control over their operation and development.

Identification of a mix and interrelations of systems that serve as a backbone of human activities by supplying all types of energy and the study of their current state and prospects to improve their efficiency are the subject of energy systems analysis. Focus on the mathematical statement (modeling) of a specific problem while factoring in all its aspects and relations underlies the methodology for systems studies in general and for those of energy development in particular.

It took several years to correctly represent the diversity of fuel and energy types, sources of their production, transportation routes to consumers, the variety of technologies and modes (daily, weekly, yearly) of their production, processing, and consumption in terms of a formal linear programming problem solved by the L.V. Kantorovich [4] method. It was even more difficult to formalize the unfolding of those processes in time to take into account the renovation and decommissioning of operating plants and construction of new ones, which, in turn, required a description of products and processes in the linked economic sectors. The optimum solution to this enormously complex problem had to be searched under uncertain values of all the numerical indicators used in the model (Fig. 1). The complete problem statement does not exist, and up to the early 1970s, we saw the chaotic proliferation of the problems of optimization of different parts of energy industry development.

An All-Union Symposium held at the SEI in 1970 initiated the process of creating the theories and methods of systems analysis of energy industry development. Large energy systems (LES) were construed as hierarchically organized man-machine systems of complex structures that operated under incomplete information [6]. Dozens of articles and local publications followed, they discussed theoretical problems, methods, and tools (mathematical models) for studying the LES structures and properties and solving a wide range of problems related to their development. Scientific and methodological aspects of those works as applied to the optimum planning of energy development were generalized in the monograph [7], and the possibility of their use in planning and engineering were first formalized in guiding documents. Efforts to build the automated system for plan calculations (ASPC) of the USSR Gosplan (State Planning Committee) opened the way to a radical change in the economic development planning, and the energy industry was a leader in the development of systems of cross-industry complexes.

As a result, by the end of the 1970s, a coherent and full-fledged school of systems research as applied to the energy industry was established in the USSR. The focus of the research was on the current state of the energy sector and power industry of the USSR and prospects for their development for 10-15 years, the features of fuel supply to the country's regions. The research also involved an analysis of the stability of marginal fuel costs by country' region, and the identification of values to be recommended as a tool for coordinating the results of various fuel and energy calculations in the energy sector subject to its optimum development. The systems approach extended its scope to control over the development of the electric power and heat industries, to the nuclear energy system, to gas supply systems, and to relations between energy and economic development. Preparation for the adoption of systems analysis methods for energy development was finalized by the elaboration of the first phase of the "Energy sector" subsystem of the ASPC of the USSR Gosplan.

The active involvement of Soviet experts in the energy project hosted by the IIASA (founded in 1972) attested to the leading role the USSR played in the development of the theory and methods for systems analysis of energy industry development.

Methods and models for systems analysis of the energy industry development were tested back in 1979-1980 during the development of the USSR Long-term Energy Program. Different scenarios of optimal energy development to 2000 were computed at the central computing facility of the USSR Gosplan and analyzed in terms of their impact on the national economy. The findings of those studies were generalized in an aggregated form in [8] and included in commitments of the subsequent five-year plan of the USSR national economy development. They established themselves as prescriptive with methodological guidelines on the identification and use of reduced and marginal fuel and energy costs and on feasibility studies of engineering solutions in energy under the uncertainty of input data. The experience thus gained was reflected in SEI and ERI research monographs on theoretical grounds of systems analysis in the energy industry, on methods for studying and controlling energy systems, and on solutions to challenges of the country's energy development [9-11].

However, by the mid-1980s the USSR lost its leading positions in the development of methods and tools (especially in terms of computer performance) for systems analysis of the energy industry development. The USA came up with the national energy model MARKAL, and the International Energy Agency adopted these and more and more powerful means of systems analysis for projections of the energy development in the world and its regions.

At the end of the 1980s, the Comprehensive Program for Scientific and Engineering Progress (section "The Energy Sector") was developed with the aid of systems methods that provided for the minimization of green gas emissions by the energy industry and investigated the survivability of large energy systems. The continuous economic slowdown and radical change in the foreign policy of the country at the end of the 1980s, however, devaluated the main provisions and projections of the USSR Energy Program.

An analysis of the results of applying the methods and systems analysis of the energy development in the USSR leaves a mixed impression. Theoretically, they were immanent to the system of centralized planning and were successfully used for elaborating long-term programs of energy and technological development. However, the development of the most significant (annual and five-year) plans of energy development using the ASPC in GOSPLAN focused on validating the contingency calculations only. Hopes of the 1970s that the methods of systems analysis would accelerate the economic growth were not fulfilled. Poor economic discipline in the 1980s following the market reform championed by A.N. Kosygin and growing distortion of reported information by enterprises defied the purpose of using formalized methods for energy development planning.

## III. Methods and applications of systems analysis to the energy sector development in Russia

The USSR collapse with the transition of Russia to a market economy dismantled the system of planned economy and its organizational bodies. As early as in 1992, the Academy of Sciences developed (in a joint effort with the Ministry of Energy) the Conceptual foundations of Rusia's energy policy in a new economic environment, which was adopted by the Government. Methods and tools of systems analysis of energy development started to be adapted to market conditions (Fig. 1).

Those studies favored the development of Russia's energy strategy to 2010 (ES-2010) and identified the roles of energy sector industries in the medium-term program of economic development in Russia, in the former USSR countries, in shaping the Eurasian energy space, and in ensuring the energy security of Russia.

The increased role the energy sector played in the economy of the country and the challenges of reforming it called for changes in the policy documents. Russia's energy strategy to 2020 (ES-2020), along with energy sector development problems under market conditions focused on energy efficiency and security, the regional energy policy, and on the environmental issues.

Monitoring of ES-2010 and ES-2020 implementation demonstrated that scenarios and projections of the energy sector and its industries development adopted in the Program were met by five-year plans by 82% and 80%, respectively. Projections of subsequent strategic documents were, unfortunately, met to a much lesser extent.

The transition to market relations was instrumental in having the capabilities of Soviet methods for systems analysis of energy development to be adjusted and expanded, while computer technology enhancement (especially the availability of more powerful personal computers interconnected into networks) allowed the development of larger and more sophisticated (by an order of magnitude) mathematical models. Bulky optimization models were framed and completed by simulation models created by experts for working in their specific fields. Distributed databases ensured the integration of numerous individual models into a single tool of systems analysis of energy industry development.

Russia's energy strategy to 2020 was developed using the novel modeling-and-information system StraTEK (Fig. 1). With the abandonment of the centralized planning system, the energy experts lost the required information sources on economic development and there were no historical data in the country that could prove adequate for proper application of statistical methods of forecasting. For this reason, the toolkit of systems analysis of energy development was to be supplemented by a full-blown system of economic development models.

New economic conditions called for a significant extension of mathematical models of development of the energy sector industries. Previously, their purpose was the optimization of development and utilization of the production capacities and relations, while in the new contexts, they were to optimize financial flows and organizational structures of the energy sector and major companies. This fact necessitated the transition from multi-dimensional problems of linear programming to non-linear problems of larger dimensionality to be able to study the options of forming energy markets and reforming natural monopolies, primarily in the electric power and gas supply industries.

The perfection of the organizational structure of the energy sector and shaping the competitive environment in gas and electric power industries served as major drivers of the structural policy of ES-2020. Those recommendations, however, were implemented to a lesser extent than projections of the development of industries that made up the energy sector.

The world economic crisis of 2008 crashed the GDP of the country by almost 8%, the production of energy resources fell by 5%, thus crowning the 'golden decade' of the development of Russia's economy and energy. The change in the country's leadership led to the substitution of the earlier objectives of accelerated economic growth for a paradigm of sustainable development. Works on the planning of energy industry development constituted little more than a proforma effort, and the market-oriented transformation of the industry was substituted for the state capitalism gaining momentum. Russia's energy strategy to 2030 was approved by inertia, but its scenarios of economic development happened to be too optimistic, which made projections of domestic fuel and power demand unrealistic and hence distorted the outlook of the energy sector development.

Fewer commissioning contracts as initiated by authorities and the global economic crisis revived the interest in methodological studies, notably, in projecting the relations between energy and economy and in the prospects of the world energy development. The ERI RAS completed the development of the SCANER modeling-and-information system. It complemented StraTEK with models on the development of the world energy and energy markets and was regularly used for projecting the coordinated energy development in Russia and the world to 2035-2040. Special attention was paid to the dynamics of European and Asian fuel markets that are of primary importance for the country.

In 2014, Russia eventually adopted the law on strategic planning to regulate the body and contents of planning processes in the country. Mostly satisfactory fulfillment of provisions and compliance with the scope and deadlines for development of high-level strategic documents that were provided for by that law were in contrast to slow implementation of provisions on planning the development of the economy and its sectors, the energy industry in particular. The revision of the energy strategy to 2030 (initiated in 2013) and its extension to 2035 were not supported by real-time projections of the social and economic development of the country. The Government lost interest in the studies on perfecting energy markets and energy security, which diminished the number of contracts for such research. As a result, academic efforts focused on the generalization of ten-year results of using the methods and models for the energy industry development and on validating the long-term projections of the energy sector development.

Description of the development of production and economic systems as a manifold of agent-based models and their application within SCANER to medium- and long-term projections of the energy development in interaction with other sectors of the economy proved a breakthrough. The authors investigated the methods and 'cost' of energy adaptation to post-crisis economic development; outlined the foundations of economic aspects and management of the present-day electric energy industry of Russia; and discussed the impact of technological progress on the world energy development and the intensification of the transition from fossil fuels to carbon-free energy resources. Threats to energy development (reduction in fuel exports) and the Russian economy conditioned by those factors were estimated, and measures to mitigate their negative impact were proposed.

However, the recently adopted Energy strategy of Russia to 2035 neglected those results.

## IV. What are the prospects?

Systems analysis of the energy industry development is appealing, but its results are used poorly and spontaneously. This fact is demonstrated in Table 1, where 16 rows of the main body of works on planning the energy and economic development are grouped based on three aspects: stages and means of planning, sources of the required information, and the body of deliveries of the planning process.

As was noted, the application of systems methodology in the energy industry under socialism failed to go beyond the development of proposals on long-term plans and optimization calculations to accompany the five-year plan in the USSR Gosplan (see Column 1).

Under state capitalism, the use of tools of systems analysis (mathematical models) for the planning of the energy industry development in Russia extended to the development (once in every five years) of the national energy strategy, master plans, and programs of long-term energy sector development and included drafting of corporate strategies of the companies partially owned by the state. All the levels of planning are currently supported by computers, email, and the Internet. Large companies make planning decisions based on their projections of the market dynamics (Column 2 in Table 1).

According to the law, strategic economy and energy planning in Russia was re-oriented from standardized planning (the detailed plan for each enterprise) to indicative planning of the development objectives, tasks, and means for their achievement given a limited mix of quantitative indicators of the plan implementation success. The forecasting activity in the USA in the 1990s was organized in this very manner. In the early 21st century, China changed over to a similar concept of strategic

Table 1. Aspects and stages of applying systems analysis to the energy industry development*.

| **Aspects and the make-up of works on development management** | | **Stages of the evolution of society** | | | |
|---|---|---|---|---|---|
| | | Planned economy (the USSR, S1980–1991) | State capitalism (Russia, 2000-2020) | Information society (2035–2050) | |
| | | | | Mobilization-type | Liberal |
| Stages and means of planning | Level of detail of plans | Down to individual companies | State, ministry | Planning down to households | No planning |
| | Application of mathematical models | Gosplan, ministries | From the country down to companies | **A set of energy development models and/or artificial intelligence** | **Agent-based models of energy and economy entities** |
| | Use of computers | Sporadic | **Same** | | |
| | Communication means | Mail, telephone | Mail, telephone + Internet | **Super Internet** | **Super Internet** |
| | Approval of decisions in the energy industry | State, ministry, companies | State, ministry | **From the national level to households** | **Modeling the market operation under incomplete information** |
| | Factoring in energy and economy relations | Ministry (detailed) | Ministry (aggregated) | Integration of energy into the economy | |
| | Approval of planned decisions | Ministry | **State, companies** | Top management level | **Decentralized** |
| Data sources | From linked companies | Limited | Limited | **Integral databases on the energy industry, subcontractors, and consumers** | **Formed under simulation of the market operation under incomplete information** |
| | From the upper level in an aggregate form | Ministry | Ministry + state-owned company | | |
| | Company’s projections | Limited | **Most of the companies** | | |
| Planning deliveries | Prescriptive plan | For the most part | – | **Optimized production development plans and setting of standards of energy consumption** | **Market players make planned decisions and assess development risks** |
| | Taxes | State | State | | |
| | Prices | State | State (partially) | | |
| | Investment plans of companies | Ministry | Ministry for state-owned companies | | |
| | Economic rules | State | State | State | Economic council |
| | Planning enhancement | Same | Same | Same | Same |

*Aspects of planning activities that make use of the tools of systems analysis are given in bold.

planning of the economy (and the energy as its integral part). Implementation of the indicative economy and energy planning in Russia is impeded by the biased nature and low validity of the drafted documents along with the process casuality as mentioned above. All the hierarchy of indicative planning in the USA (and, to a much lesser extent, in China) is accompanied by publicly discussed modeled projections that are developed by well-funded powerful research organizations on a competitive basis. Justification of economy and energy development strategies and programs in Russia is of fragmented nature (they are validated mainly by academic institutions weakened by the reform), their optional discussion is a mere formality and is mainly ignored in the planning documents.

Meanwhile, the development of 'digitalization' concepts and programs for the industries and companies in Russia to 2024, which started recently, is aimed at acquiring and identifying accessible information and using it only in the operational management of the company or sector of the economy. The fourth (digital) technological revolution, however, leaves no alternatives to the broad adoption of methods and means of systems analysis for managing the economic development in general and that of the energy industry in particular.

Let us consider the alternative concepts of applying the systems methodology and tools to the planning of the development of the energy sector (15 to 25 years ahead) as a constituent part of the country's economy, omitting the social implications of the information society.

Given an unfavorable geopolitical situation, the mobilization-type digital economy may be formed in certain countries when centralized planning extends down to households (see Column 3 in Table 1). Plans for the economic (and energy) development within this concept are computed by the computer networks using megasystems of production and area-specific mathematical models. Input information for the models is obtained using neural networks based on the databases of reported data and assessment of their errors. Following the results of optimization calculations, other neural networks will generate representative scenarios of systems development and will form a prescriptive matrix of indicators corresponding to them. On this basis, the authorized bodies make decisions that are automatically disaggregated into production and investment plans, prices and taxes for the companies, and consumption standards for the population.

An alternative concept is that of liberal economy and it reflects the optimistic outlook [12] of experts with respect to development trends and adoption of information technology (see Column 4 in Table 1). It implies the lack of even an indicative plan and availability of the self-organization of all the market players in the sophisticated process of managing the future. Input information for these is acquired with the help of neural networks and subsequently used for the development (in computer networks) of a set of economic development scenarios based on the manifold of agent-based models of market players. Based on those scenarios, the Market Moderator (Economic Council) forms a preferred (in terms of criteria of maximum volume and growth quality given minimum system risks) high-low lines of economic development (including the energy industry). Each player, as a decentralized independent company (DIC), can control all the information processes and identify its probable future risks using blockchain technology [13]. Collegial bodies of the market adjust the rules of its operation and perfect requirements to be met by the tools.

Thus, with the liberalized digital economy, the long-established methods of analysis should be complemented with the following:

- Neural networks, pattern recognition techniques, and other artificial intelligence means;
- Agent-based models and methods of agent interaction;
- Blockchain technology.

The extent of implementation of this concept remains uncertain, but mastering the means described above would enhance the methodology of systems analysis of energy industry development as an integral part of the economy and the production base of the society.

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# Civilization as a Large-Scale Energy-Information System

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### Dear Readers!

This issue of the Energy Systems Research journal is opened by a paper which was unexpected for our journal both in the ideas discussed and in the conclusions drawn. The author, V.V. Bushuev, is a well-known power engineer, Doctor Habilitatus in Engineering, Professor, Director-General of the Institute of Energy Strategy, former Deputy Minister of Energy of the Russian Federation, who philosophically addresses the global issues of civilization (who are we, where do we come from, where are we going to?) and interprets these issues in terms of energy development (foresight). The author's target vision relies on the tools for analyzing the cyclical development of civilization as a large-scale energy-information system on the example of its East Eurasian type for the time horizon until the middle of the 21st century. It is worth placing emphasis on the constructiveness of the 'cyclical' approach to long-term forecasts of energy development used by the author. This approach, as evidenced by the practice of its application, in most cases, provides more reliable results compared to the traditional long-term forecasting methods. This paper will undoubtedly arouse interest among the readers of the journal. Depending on the breadth and depth of this interest, the journal is ready to continue the discussion of the issues raised in the paper.

***Abstract* — The world is a triadic meta-system: nature - society - man, in which all components are linked by material, energy, and information relationships. These system subjects and their relationships are civilization structures represented by a "community" in our planetary House, i.e., Ecos (from the Greek 'oikos' – dwelling in various zones of the earthly oecumene). Civilization is a set of socio-natural factors, the system of life, and cultural-and-mental relations in the eco-system in its certain evolution stage. Regional and mental features (like apartments in an apartment house) characterize certain historical and geographical types of civilization, among which the Atlantic, East-Eurasian, and Islamic ones stand out. All of them are in different stages of their evolution and differ in their material level, the organization of social life, and the target vision of their arrangement. The current stage of the civilization development is characterized by a thorough transformation of all its types under the influence of regular cyclicality and change in the dominant factors of socio-natural relations in the planetary House, given the qualitatively new features of modernity - massive digitalization as a way of integrating the real (material and power energy) and verbal (subtle-energy and information) worlds.**

**The paper briefly examines historical aspects of the cyclical development of civilization (using the example of its East-Eurasian type) and presents the author's target vision (foresight) of its future for the time horizon until the middle of the 21st century.**

***Index Terms* — civilization, features, transformation, cyclical development, target vision (foresight), East-Eurasian civilization system, energy prospects of East Eurasia.**

## I. Specific features of the primary civilization systems of the world are presented in Figures 1 and 2.

These civilization communities are shaped as the corresponding structures - the Atlantic Alliance, the SCO, and the Arab League, shown in Fig. 2. [1-3].

The fundamental difference between the proposed consideration of various types of civilization in the territory of Eurasia is the focus on natural factors that determine not

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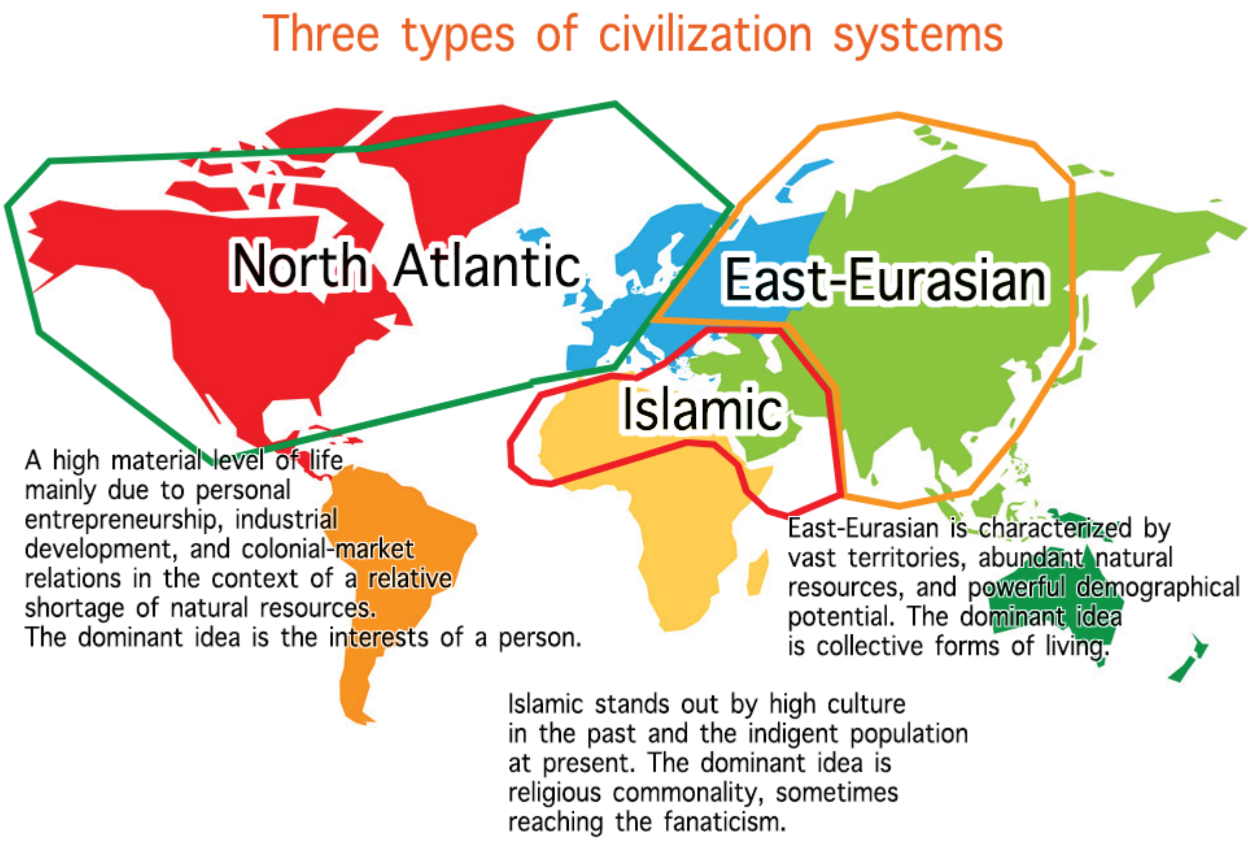


*Fig.1. Three types of civilization systems.*

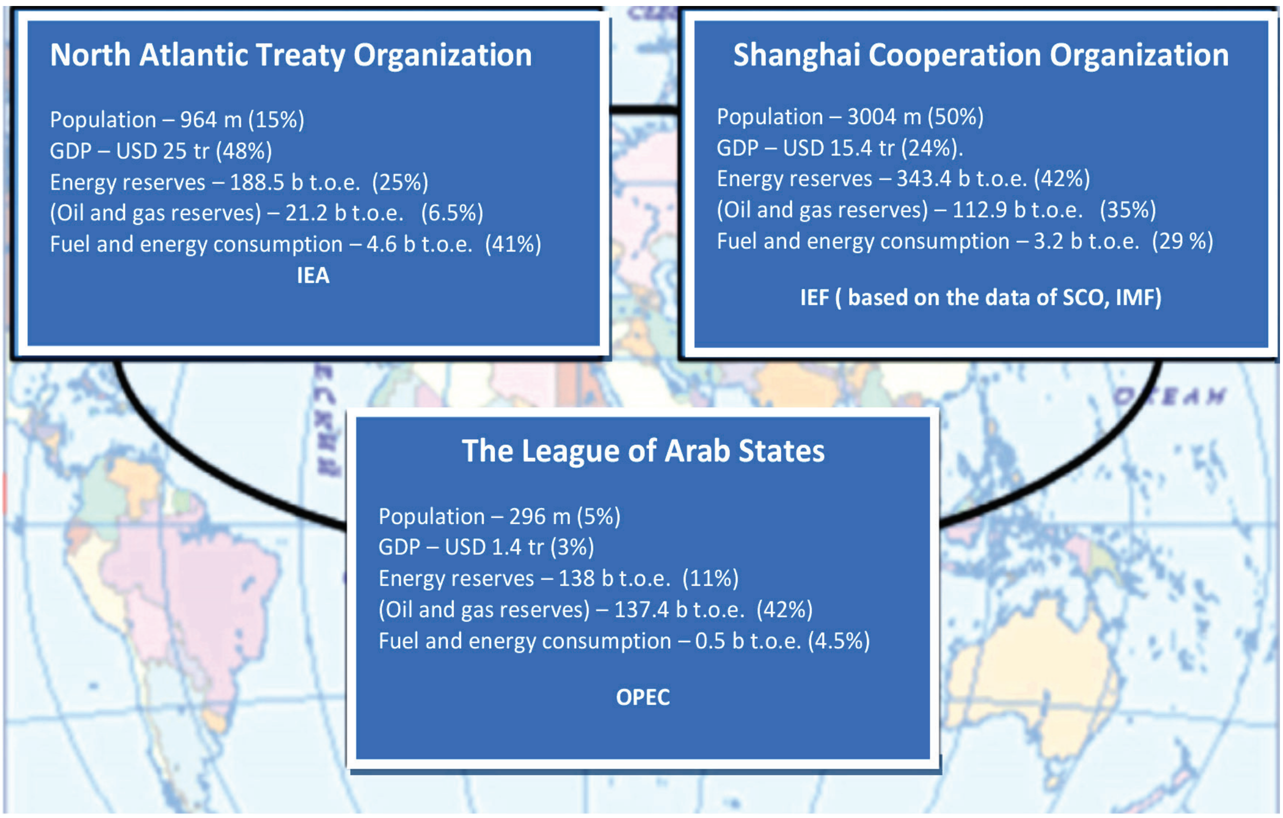


*Fig.2. Characteristics of different civilization communities.*

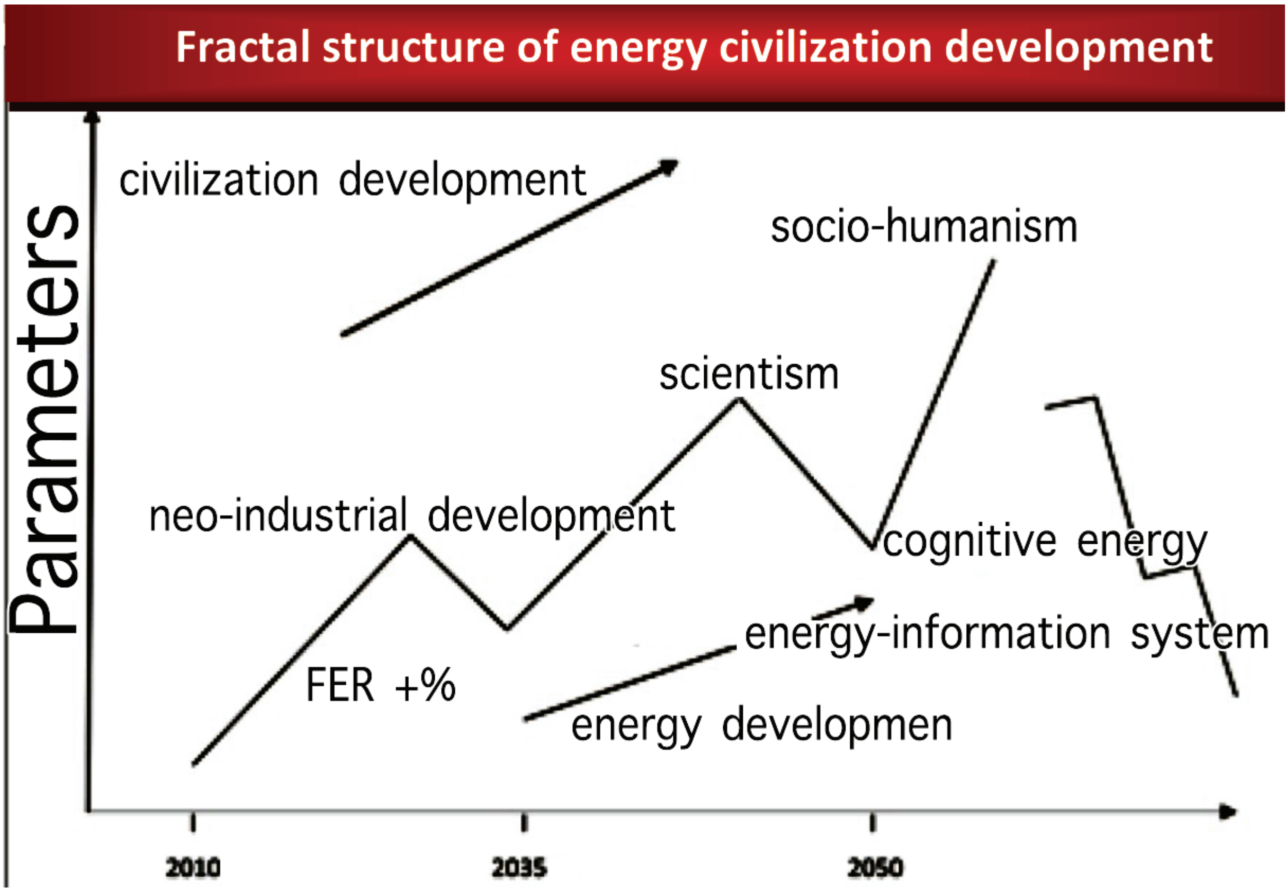


*Fig. 3. Waves of civilization and energy.*

only geographical and demographic features but also the related mental, social, and technological features of their historical and future development [1].

Vast territories with rich natural resources, high but unevenly distributed demographic capital, a sharply continental and rather harsh climate in most of the East-Eurasian oecumene determined the collectivist mentality of the local population and the centralization of management of its social structures. Natural resources of East Eurasia (furs and timber in Siberia, fuel and energy resources of the region, tea, and silk of China) have always been an item of export, which also influences the characteristic features of the enclave (island, oasis) economic development of the territory and the great attention to the organization of internal and external infrastructure. Despite rather significant differences in different countries, the East-Eurasian civilization had a fundamental commonality. The collectivist mentality, inherent even in distributed cattle breeding and seasonal production over a large territory, determined the organic perception of communist ideology in the USSR and China, and the "imperial" (autocratic) planned management contributed to the successful progress of the countries in the region. Thus, the Soviet Union had become one of the military-political leaders of the world, and China, in recent years, having retained its historical characteristics, has become a "world factory" that has caught up with the United States in terms of its economic development. The economic development of the Central Asia countries made a colossal breakthrough in the 20th century while maintaining their resource potential, distinctive national culture, and centralized management. India, whose industrial development was not aimed at catching up with Western countries, has become one of the leaders in information innovations. No wonder its programmers are among the most in-demand IT specialists in the world. And it is precisely due to centralization (India has established the world's only Ministry of Renewable Energy), the country is successfully transitioning to new energy sources while maintaining large nuclear power plants and coal-fired thermal power plants. This facilitates a reasonable diversification of the socio-economic life in the region. Further development of the East-Eurasian civilization led to its new structure shaped into the SCO and the EEU [4-5].

The specific features of various civilizations manifest themselves most acutely during the periods of exacerbation of the socio-political, resource-technological, and information-technological situation in the world. Even the current pandemic crisis has shown the versatility and global nature of the world dynamics manifestation, on the one hand, and, on the other hand, it has demonstrated the fact that the countries of the East-Eurasian civilization with a dominant collectivist mentality and centralization of public life cope with crises much more effectively than the Atlantic countries with a cult of individualism and decentralization of management. This is indicative of the fact that the market copes well with fluctuations in global dynamics, while active government interference is required to resolve crises.

## II. Spatio-temporal (fractal) semblance of civilizational development

Any development is always cyclical. There are daily, annual, and more extended recurring periods in nature and society. The end of one stage and the beginning of the next are as a rule accompanied by crisis phenomena. Crises are not only a catastrophic manifestation of socio-natural, man-induced, and civilization destruction but also the "night before the birth" of new ways of life. Since we all "live in the arms of the Sun" various types of terrestrial processes are subject to cosmic cyclicality [1].

There are **three types of crises** [6] in civilization development, separating some cycles from others:

- The current **parametric crisis** is characterized by changes in parameters rather than changes in the basic structure of the dynamic system. Examples of such crises are recurrent natural disasters and man-made accidents (including those at nuclear power plants), intermittent ups and downs in world oil prices, economic recessions, technological transitions to other voltage levels in high-voltage power transmission lines. Such crises are usually separated by 10-12-year periods of cyclical development of the system (Jupiter cycle).
- The **structural crises** result in changes in the very organization of the system of management and power in society. For example, the transition from the dominant planned management of the economy to the market (economic reforms in China in the 1980s, Gorbachev's perestroika in the USSR). The priorities of technological development change, for example, the beginning of the atomic-space era and oil and gas energy in the USSR in the 1960s. Such turning points have a historical recurrence of 36 (three of 12 years each) years (Saturnian cycle).
- The **civilization crises** determine radical changes in the dominant type of resource energy potential, a new technological and social way of life in several neighboring countries, and rearrangement of the world structure. Such crises are separated by the so-called "imperial" cycles of 144 years [2] and their subharmonics (two 72-year-long periods, four Jupiter cycles of 36 years, and twelve Saturnian cycles of 12 years).

Such a clear quantitative periodization of world dynamics associated with cosmic cyclicality, of course, does not always correspond to strict time intervals, nevertheless, it reflects the qualitative changes in the development of civilization.

Over the past century, the world has witnessed 4 major oil crises, more than 20 economic crises, 8 virological pandemics with an approximately 12-year periodicity; two global socio-political revolutions (1917 and 1989-1991), separated by the 72-year period of the USSR establishment and disintegration, which had a worldwide resonance.

Despite the significant historical features of various countries of East Eurasia (USSR - Russia, and China) in the 20th and 21st centuries, there are common 36-year cyclical periods of their development. Years from 1917 to 1953 in the USSR, and from 1949 to 1985 in China were the time of the authoritarian leadership (by Stalin and, accordingly, Mao Zedong and his successors) characterized by the formation of socialist ideas and temporary repressive actions. The period from 1953 to 1989 (from Khrushchev to Gorbachev) in the USSR saw the establishment of the atomic and space industry; the development of virgin lands; the construction of the BAM, the hydroelectric power plants of the Angara-Yenisei cascade, and the West Siberian oil and gas industry. China, pursuing Deng Xiaoping's ideas, went through a course of economic reforms, and in 36 years (from 1985 to 2021) has become the second economic power in the world. Post-Soviet Russia (from 1989 to 2025) has gone through a series of difficult transformations in the transition to a market economy, and the restoration of the national defense and economic level.

All the countries of East Eurasia are experiencing, albeit with a shift by one cycle, the general dynamics of civilization transformations, relying on their resource capabilities, including demographic ones, and on an authoritarian organization and their mentality.

Following this logic of cyclical development, by the beginning of the 2060s, we should expect the end of the 144-year "imperial" cycle in Russia (1917–2061), which will correspond to the 36-year "night before the birth" (2025 –2061) of the new arrangement of the country. This time will correspond to the 36-year stage of economic stability in China (2021 –2057) with subsequent stagnation and the stage of economic prosperity in India (and other SCO countries).

In the Atlantic civilization, this period will be characterized by the collapse of the military-political NATO bloc, the loss of the monopoly leadership by the United States, and a change in the dominant idea of economic development with the rejection of material consumerism in favor of the "green world".

After that, there can be a transition from the state model to the network model of public life organization, i.e., a change in the civilization development paradigm itself. This is already beginning to be seen in the development strategies discussed both in the Atlantic world and in the East-Eurasian civilization.

The coming period will be the time of radical transformations not only in the material and energy sphere of life but also in the sphere of information and intellectual development. The key factor of such transformations will be the **common energy of nature, society, and human**.

The transition from one structure of civilization to another (from industrial development to socio-humanism) (Fig. 3) is inevitably accompanied by the transformation of energy as a potential for development, and a system of life. The forthcoming transformation is related not only to a change in the dominant energy carriers, i.e., the transition from coal and oil to gas and electricity but also to the integration of power, bio- and "subtle" energy, which ensures the unity of the material and mental worlds.

The spheres of cognition and life in the East have always relied on the energy-based similarity of Man and the Universe [7]. The very expression "qi" (energy) was the root basis for such concepts as a cycle - an energy wheel (the principle of the cyclicality of all world processes), a figure (another form of energy), information (another form of action) and even the concept of civilization - a system of energy ownership. No wonder it is in the East where qigong is widespread as a method of treating people by controlling their energy. The very image of Man and the Earth is a multidimensional energy representation of both the physical body and the seven surrounding energy spheres of the etheric, astral, mental, and other bodies. Through these spheres, man and the Earth carry out energy communication with the surrounding world, when cosmic energy interacts with internal biophysical and cognitive energy through the corresponding chakras, and the results of the intellectual life of the system ascend into the noosphere, replenishing the overall potential of the World-system [7].

Even today, cosmic energy is involved in building the energy potential of the subsoil, water, and atmosphere. Therefore, all energy resources of the planet, including hydrocarbons, gas hydrates, and heat of the deep layers of the Earth (and not only solar and wind renewable energy sources), are renewable energy potential. The energy of the Sun participates in the accumulation of the creative spiritual potential of people, which is an important component of the human potential of civilization. Solar activity creates conditions for the formation and manifestation of the passionarity of the human community leaders, who are most responsible for the accumulation of the potential and the active life of society. Moreover, it is the energy interaction of the anthroposphere and technosphere with the environment that determines the harmonious co-development of nature and society.

Energology, as a general science about various types of energy, their commonality, and transformability, about the general energy laws of the universe, allows us to better understand the energy unity of the world and use this concept to establish the future energy-information system of civilization.

## III. The main directions of energy foresight for the forthcoming 36-year period of the civilization cycle.

The current crisis, whose distinctive feature is simultaneous manifestation of coronavirus pandemic, economic crisis and plunge in prices in the world energy markets, which are accompanied by the collapse of the main ideological and socio-political foundations of society and their changes, is only an overture to the global break in the world order to be expected by the end of the forthcoming 36-year stage (up to the beginning of the 2060s), according to the general cyclical dynamics of the World-system.

For some obvious reasons, such as the desire for self-isolation of states in the context of anti-quarantine measures, the rapid development of the “online” principles in many areas of activity, the partial rejection of hydrocarbon energy due to fears of global warming, the development of new waste-free nature-like technologies, and the active advancement of the Internet of Things and the Internet of Knowledge, we can claim that the upcoming transformation of life will affect many basic foundations of civilization and will require qualitative changes in the technological, informational and organizational ways of life. All these changes are in one way or another connected with the energy of the future - its transformation from a system of energy supply to society into a system of its vital activity. After all, energy is every action, work, including life itself, while the energy potential (natural and man-made) is only an opportunity for life. The 20th century was a period of active industrial advancement of the entire civilization system, including the East-Eurasian one, based on the massive electrification of production and everyday life. With the beginning of the millennium, the world entered a qualitatively new period of its development characterized by the integration of the physical (energy) and information patterns of life. The upcoming 36-year Saturnian cycle (from 2025 to 2061) of civilization development will be the heyday of this hybrid world.

## IV. Major changes in the structure of the world energy and its East- Eurasian wing.

The current ideas about the forthcoming energy transition that are widespread among representatives of the Atlantic civilization system and imposed on the whole world require critical rethinking in terms of specific features of the development of various civilization systems. The general recipes for the three Ds (decentralization, decarbonization, and digitalization) of the world energy can hardly be applied by all regions of the Earth's oecumene due to their historical and geographical features. Centralization in the development of the East-Eurasian civilization, as shown above, is caused by its natural (resources, including demographic ones) characteristics, extended territory, and collectivist mentality. Therefore, East Eurasia will still have both a high degree of life urbanization and a significant role of raw materials in the economy and centralized energy sector. This does not mean energy stagnation. Undoubtedly, the refining sectors will also actively expand here, including oil, gas, and coal chemistry. However, the need for more comprehensive development of the still sparsely populated territories of the Russian Far East and Western China will require corresponding large-scale energy development, which cannot be pursued only through decentralized systems [8, 9]. In addition to the development of energy-intensive mining resources, including not only the exploitation of hydrocarbon reserves but also the extraction of rare earth materials, the centralization of energy supply will be required to create territorial-production clusters, which have been and will be the main type of organization for the economic development of extended and sparsely populated areas. It stands to reason that small-scale energy will find a wide application here in organizing the life of individual regions, but it will not become an alternative to large-scale energy - it will only become its supplement. To select certain development options, an empirical relationship is quite suitable: with a load concentration of more than 40 kW per km$^2$, two-thirds of the demand will be met by centralized energy sources, and one-third - by distributed energy, including local and renewable energy sources. At a load density of less than 10 kW per km$^2$, the relationship is inverse.

For East Eurasia, the main energy issue is the infrastructural development of the territory [10, 11]. It is not about expensive energy transport communications, pipeline or power grid, rail or road, connecting individual districts of industrial and energy production and consumption, which are located far from one another. It is impossible and impractical to provide the same density of infrastructure in the extended territory of East Eurasia as in Europe. Here it is quite appropriate to employ another infrastructural principle, such as network structures or energy rings that connect separate oases (as in the old days) or individual modern and future territorial production complexes (TPC).

The Asian energy ring proposed in the works by researchers from the Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences [12], in our view is a "busbar system" that represents various transport and energy communications, to which both large generating units (nuclear, thermal, hydraulic and tidal power plants) and load centers (TPC) are connected. Elements of these rings can be various communications (oil and gas, coal and electric, hydrogen and methane-hydrate), in the form of mutually complementary now and hybrid system-wide energy transmissions in the future. According to the same principle, hydropower and water-transport links of East Eurasia can and should develop in the future. At the same time, using the example of the Casa-1000 project [1], we can talk about the transfer of water resources from Siberia to Central Asia for irrigation, and the use of the Pamir hydroelectric power plants for generating electricity and its subsequent transit to Pakistan and India. And hydro-energy and transport communications in the Arctic and the South China Sea will make it possible to effectively use the water resources of Eurasia for infrastructural, irrigation, and climatic support of the sustainable development of civilization.

For the development of infrastructure systems in the region, of great importance will be storage systems - converters that make it possible not only to store energy for a long time but also to transform various energy types into each other, creating a common interregional energy interconnection for the integration of resources and centers of various energy consumers. In particular, integrated power complexes in the region of the Sea of Okhotsk, which consist of tidal hydroelectric power plants and local use of their energy for electrolysis of seawater, production, and liquefaction of hydrogen, with its subsequent export to other regions of Eurasia, can play the role of such storage devices.

In the future, energy rings can also be transformed into energy-information communications, where physical flows can be partially replaced by virtual (financial and information) ones, contributing to the integration of individual regions of the East-Eurasian civilization.

The principle of decarbonization in East Eurasia in connection with the sufficiently large gas resources available here (including those produced during the gasification of coal deposits, gas hydrate and biogas reserves from the processing of wood waste and agricultural waste, and the disposal of organic waste) should lead not to the widespread transition to renewable energy sources, but to the replacement of the “green energy” paradigm with “blue energy” one [13]. The contribution to solving environmental problems will not be less, but it will provide more efficient use of existing resources, those, which are not available in Europe and which make up the invaluable wealth of East Eurasia.

## V. The main directions of development of energy-information systems

The main directions of development of energy-information systems in the era of transition to a new structure of civilization development suggest not just the expanded use of digitalization for processing large amounts of data (Data-systems) but the organic adoption of computer capabilities into our life. The world of physical realities is changing to the world of the Internet of Things and the Internet of Knowledge. Even here, however, it is necessary to take into account the specific features of the East-Eurasian civilization. The material interests of people, the desire for an excess of things and goods have never dominated it. In Russia, in China, and in India, people's interest in the virtual world, the world of spirituality and illusions, the world of noospheric knowledge, the cosmic unity of Man and the Universe have always predominated and survived. It is the countries of this region, primarily Japan, that have recently started to follow the principle of material poverty and immaterial happiness. It is not without reason that India is one of the leading countries in the world in self-reported happiness, despite the low level of material wellbeing. Therefore, by the middle of this century, one should expect the energy-information world advancing towards socio- and cosmo-humanism focused not on the dominant idea of material development, but on the completeness of the human view of life. The catch-up path of material development, which is followed by China and which Russia is trying to follow, is a dead-end of evolution for the countries of Eurasia. The energy-information virtual world, which has already become the world of the younger generation, is the world of new energy-cosmism. The end of the "imperial" development cycle of the East -Eurasian civilization is not the end of its centralized development, but a turn of the vector towards the Cosmos.

The Cosmos is viewed not as a place for the extraction of new resources, new sources of energy, and interplanetary travel, but as our past, where we all came from, and our future. K.E. Tsiolkovsky wrote at the dawn of cosmonautics: “in the future, humanity will turn into radiant energy and set off to explore new outer spaces” [14]. Russia is not a bridge between east and west, north and south; it is a bridge between the Earth and the Space. Cosmic energy will be closely connected with the use of bio- and cognitive energy of man, who is going through the transition from Homo sapiens (intelligent man) to Homo faber (man the maker). The noosphere is not a mythical notion of Russian cosmists, but the virtual energy-information world from where we draw natural forces and inspiration, where we bring our creative concepts and ideas for future generations. Digitalization and informatization as new forms of energy activity will allow us to integrate (albeit in a virtual form) the Earth oecumene and the noospheric Cosmos.

The East-Eurasian civilization is an energy-cosmic civilization of the future, which will become the leader of world development by the middle of the 21st century.

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