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Contents

Nonlinear Load Modeling for Analysis of Non-Sinusoidal Conditions in Electrical Networks Based on Measurements of Harmonic Parameters

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***Abstract* — Non-sinusoidal conditions in electrical networks need to be calculated for their control and development of technical measures to maintain harmonic parameters according to the requirements of regulatory documents. These calculations are impossible without electrical network and nonlinear load models that adequately reflect them in computational programs. Nonlinear load models have been developed for a long time. Some studies present general modeling principles and models of various nonlinear devices. Others consider some nonlinear devices as equivalent nonlinear loads connected to low and medium voltage networks. A whole host of high-power nonlinear electrical equipment is connected to high voltage networks. Modeling nonlinear loads connected to these networks is a problem. Research of measured parameters of harmonic conditions in electrical networks has shown that they are random values. The probabilistic nature is determined by the network configuration, a range of network components, the number of nonlinear loads, wave and frequency properties of the network, harmonic source phase currents, voltage at terminals of nonlinear electrical equipment, changes in operating conditions and load power, and many other factors. Nonlinear loads can only be modeled based on the measurements of parameters of harmonic conditions due to their unpredictability. The paper presents an overview of existing methods for modeling nonlinear loads, a methodological approach to modeling nonlinear loads based on measured parameters, an algorithm for modeling harmonics of active and reactive currents, a computational program algorithm designed to identify distribution functions of measured current harmonics, and modeling results for current harmonics of railway transformers supplying power to electric locomotives.**

Index Terms: **Harmonics, harmonic parameter analysis, measurements, nonlinear load modeling, power quality.**

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I. Introduction

Operating parameters of electric power systems should ensure economic feasibility, reliability of electrical networks, and quality of power supplied to consumers. When the latter is compromised, electrical power losses in electrical networks increase, the service life of electrical equipment of electrical networks and consumers shortens, the performance of process equipment of industrial enterprises decreases, which causes economic damage. Currently, the most relevant and most acute power quality issue is associated with the non-sinusoidal nature of voltage. This problem is typical not only of Russia but also of many countries around the world. The number of electrical equipment units with nonlinear current-voltage characteristics (nonlinear loads) that are the source of current harmonics and the cause of the voltage waveform distortion at network nodes is rapidly and continuously growing. In addition to the conventional nonlinear electrical equipment of aluminum smelters, railways, pulp and paper mills, and others, the amount of electronic equipment used in the digitalization of all areas of human life is drastically increasing. Nonlinear loads are present in networks of all voltages. Harmonics penetrate from high voltage networks into medium and low voltage networks and vice versa.

Currently, three legislative documents of the Russian Federation (the Civil Code [1], the Law "On Protection of Consumers' Rights" [2], the Law "On the Electric Power Industry" [3]) contain provisions on ensuring proper power quality and the responsibility for it. In real life, the parameters of electrical network operation often differ from those required for electrical equipment [4]. In particular, they do not meet the requirements outlined in [5]. Control of non-sinusoidal conditions in electrical networks, their analysis, and development of engineering measures to maintain the harmonic parameters in line with the requirements of regulatory documents require calculations of harmonic parameters, which cannot be done without models that faithfully represent electrical networks and nonlinear loads in computational programs. At present, increasingly favorable conditions are being created for this, as the objective has been set to establish electric power systems equipped with numerous measuring instruments. Individual devices and systems are installed in electrical networks for long-term continuous monitoring of power quality indices and operating parameters, which allows obtaining information for developing nonlinear load models based on measurement results.

This paper deals with an analysis of existing methods designed to model the nonlinear loads, describes a methodological approach and an algorithm for modeling nonlinear loads based on measured harmonic parameters, a computational program algorithm for identification of cumulative distribution functions of a measured series of random harmonics of nonlinear load currents and calculation of their values with a given probability, as well as the results of modeling backed by the methodological approach, algorithms, and a computational program developed by us for currents of railway traction transformers that supply electric power to nonlinear loads of high-power, i.e., electric locomotives.

II. Analysis of nonlinear load modeling methods available in the literature

Nonlinear load models have been developed for a long time. In some papers, the general principles of modeling are given and models of various individual nonlinear devices are presented on their basis, in others, individual nonlinear devices are considered as equivalent nonlinear loads connected to low and medium voltage networks. A large amount of nonlinear electrical equipment is connected to high voltage networks. Modeling of nonlinear loads connected to these networks remains an unsolved issue.

Models of nonlinear electrical equipment can be divided into three groups according to the principle of its operation: models of ferromagnetic devices, models of arc devices, and models of electronic devices. Ferromagnetic electrical equipment includes power transformers, synchronous machines, and induction motors. To model power transformers, the authors in [6, 7] propose a T-type transformer equivalent circuit. The magnetizing branch is represented as a source of no-load current harmonics, i.e., $\dot{I}_{0n} = I_{cn} + jI_{\mu n}$, where $\dot{I}_{0n}$ is the complex of the no-load current for the nth harmonic, I_{cn} and $I_{\mu n}$ are the active and reactive components of harmonics of the no-load current for the nth harmonic. Their definition is presented in detail in [7–9]. In [10] the transformer is represented as a source of harmonic currents of the two windings:

$$\dot{I}_{1n} = \underline{Z}_{2n} / (k_T^2 \underline{Z}_{1n} + \underline{Z}_{2n}) \dot{I}_{0n}$$

– for the primary winding,

$$\dot{I}_{2n} = \underline{Z}_{1n} / (k_T^2 \underline{Z}_{1n} + \underline{Z}_{2n}) \dot{I}_{0n}$$

– for the secondary winding, where $\underline{Z}_{1n} = R_1 + jnX_1$, $\underline{Z}_{2n} = R_2 + jnX_2$ are complex impedances of the transformer windings; R_1, R_2, X_1, X_2 are the resistance and reactance values of the transformer windings; k_T is the transformer transformation ratio.

The values of the winding resistance are calculated as

$$R_1 = 0.1026KnX_1(J + n)$$

and

$$R_2 = 0.1026KnX_2(J + n),$$

where the coefficients J and K are determined using the expressions in [11].

When developing models of synchronous machines, the authors of [12, 13] propose assuming that synchronous generators do not create voltage harmonics. Synchronous generators can be represented by equivalent impedance with respect to the busbars. The equivalent impedance is determined by the expression in [12] as $\underline{Z}_n = nX$, where $X = 1/2(X_d^{"} + X_q^{"})$, $X_d^{"}$ is the direct-axis sub transient reactance, and $X_q^{"}$ is the quadrature-axis sub transient reactance.

In [14–16] the authors present models of induction motors in the form of T-type equivalent circuits. The model of an induction motor with a single squirrel cage contains the following resistances: R_1, X_1 – resistance and reactance of the stator winding, R_2, X_2 – resistance and reactance of the rotor winding, R_c, X_μ – resistance and reactance of the magnetizing branch, $\dot{I}_{1n}$, $\dot{U}_{1n}$ – harmonics of complex current and complex voltage of the stator winding, $\dot{I}_{2n}$ – harmonics of the complex current of the rotor winding, s_n – the slip for the nth harmonic.

The rotor of a double-deck induction motor has two squirrel cages: one cage is the starting winding; the other cage is the operating winding. The model of this induction motor contains the following resistances: R_1, X_1 – resistance and reactance of the stator winding; X_{2T} – total reactance of the rotor windings dissipation; R_{1O}, X_{1O} – resistance and reactance of the operating stator winding; R_{1S}, X_{1S} – resistance and reactance of the stator starting winding; R_c, X_μ – resistance and reactance of the magnetizing branch; $\dot{I}_{1n}$, $\dot{U}_{1n}$ – harmonics of the complex current and complex voltage of the stator winding; $\dot{I}_{2n}$ – harmonics of complex current of the rotor windings.

Arc devices, whose principle of operation is the electric discharge, are represented in models by piecewise linearized voltage-current characteristics [17] and measured current harmonics [18].

There are several approaches to modeling electronic devices. The most widely used one is the representation of electronic devices by standard spectrum current harmonic sources is [13, 19]. Modeling rectifier converters involves the transfer functions linking the DC and AC sides of the converter [20].

Modeling individual nonlinear devices when analyzing harmonic conditions in electrical networks with a whole host of nonlinear loads is challenging. In such a situation, one should employ models of equivalent nonlinear loads. To this end, two approaches are proposed in the published research for the adoption. The first approach combines several devices [21–23]. The second approach involves developing equivalent load models based on measurements [24–33]. The models are a set of linear multivariate regression equations that relate measured current harmonics to voltage harmonics and the active power of the modeled load [28, 29].

In [30], a probabilistic model of an equivalent nonlinear load is proposed. Depending on the numbers of current harmonics and the value of the total harmonic distortion of current, the authors suggest considering four types of nonlinear loads. Harmonics of complex current at the common connection point are represented as

$$\dot{I}_n = K_E \sum_{i=1}^{4} a_i \dot{I}_n^{(i)} ,$$

where K_E – the share of power of nonlinear loads in the total power of the equivalent load; a_i – the weight coefficient of a nonlinear load of *i*th type in the total power of nonlinear loads; $I_n^{(i)}$, $\varphi_{In}^{(i)}$ – the value and phase of the harmonic current of a load of the *i*th type. All parameters are random variables. This approach requires measuring the current harmonics of each individual load to build the models, which cannot be done because of the large number and complexity of nonlinear loads.

In [31, 32] it is proposed to represent a distribution network with an unknown configuration by the equivalent load, which is modeled by the complex impedance of the distribution network of the *n*th harmonic ($\underline{Z}_{nL}$) and the *n*th harmonic of the complex current source ($\dot{I}_{nL}$). Both of these values are defined as

$$\underline{Z}_{nL} = (\dot{U}_{n1} - \dot{U}_{n2}) / (\dot{I}_{n2} - \dot{I}_{n1}),$$

$$\dot{I}_{nL} = \dot{I}_{n1} + \dot{U}_{n1} / \underline{Z}_{nL},$$

where $\dot{U}_{n1}$, $\dot{U}_{n2}$, $\dot{I}_{n1}$, $\dot{I}_{n2}$, are the measured harmonics of complex voltage and complex current at the node to which the modeled distribution network is connected in two different modes of the electricity supply network.

In [33], the authors propose decomposing the measured current I_n into its deterministic I_{nD} and random I_{nC} components. The expression for the description of I_{nD} is determined by fitting a polynomial function to the measured current I_n using the method of least squares. The component I_{nC} is defined as the difference between the measured current I_n and the deterministic component I_{nD}, i.e., $I_{nC} = I_n - I_{nD}$. The expression for the random component is based on its probability density function. The authors of [33] advise to use the simplest functions, linear and quadratic, to describe I_{nD} and I_{nC}. The authors of [34] note the disadvantage of the latter method of modeling a nonlinear load. It lies in the fact that the random component of the current I_{nC} is rarely captured by one of the known probability distribution laws. This leads to difficulty in describing the measured current I_n and requires the use of special ways of description.

The method of modeling nonlinear loads based on measurements of harmonic parameters, despite the noted disadvantages of the above modeling methods, has significant advantages [35, 36]:

a) it is simpler than the method based on reducing to equivalents and combining individual nonlinear devices because according to the results of measurements, the equivalent load model is obtained directly for the particular node of the network to which it is connected;

b) it can capture changes in the equivalent load over time if measurements are made over a long time;

c) it can be applied to any load and at any node of a network of different voltages;

d) it is best suited for estimating the parameters of the equivalent nonlinear load at busbars with mass loading.

Modeling the nonlinear loads connected to high voltage electrical networks as evidenced by measurements of harmonic parameters is the most effective way. High voltage networks are large-distance networks. They cover a significant area. Many nonlinear loads of high-power, as well as lower voltage networks, are connected to their nodes. Each of the loads is an enterprise with its lower voltage electrical network. The main process electrical equipment of the enterprise generates current harmonics into the network. A large amount of auxiliary equipment, including that with nonlinear voltage-current characteristics, receives electric power from the enterprise network. Current harmonics from these networks flow into the high voltage networks. In networks of all voltages, there are switchings of elements in the network and changes in its configuration. As a result of all processes, the harmonic parameters in the networks of all voltages are random, and are probabilistic in nature. Thus, the modeling cannot factor in all the individual nonlinear devices and loads connected to the high voltage electrical networks. Therefore, the most appropriate way of modeling for high voltage networks is based on measurements of harmonic parameters. Measurement is the only way to obtain accurate information. In what follows, we present a methodological approach, algorithms, and a computational program for modeling nonlinear loads based on the measurements of harmonic parameters.

III. Methodological approach, algorithms, and computational program

The studies of the information on harmonic parameters that was obtained from the measurements [37–42] show that the harmonic conditions are random and their parameters are probabilistic in nature. It is determined by the configuration of the network, the composition of its elements, the number of nonlinear loads, the wave and frequency properties of the network, the phase of harmonic source currents, the values of voltage at the terminals of nonlinear electrical equipment, the changes in operating

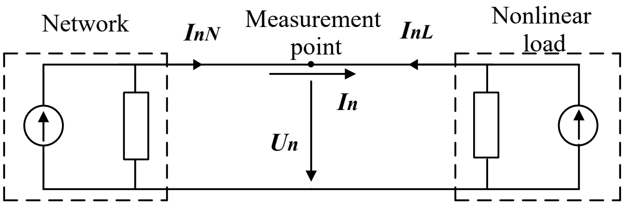


Fig. 1. Diagram of the network and nonlinear load at the nth harmonic.

conditions and power loads, and many other factors. Because of their unpredictability, nonlinear loads in real-life electrical networks can be modeled only relying on measurements of the harmonic parameters.

Harmonic parameters are calculated by solving a system of equations [16, 43]

$$\boldsymbol{U}_n = \boldsymbol{Z}_n \boldsymbol{I}_n, \quad (1)$$

where $\boldsymbol{U}_n$ – a column matrix of the nth harmonic nodal voltages to be determined, $\boldsymbol{Z}_n$ – the square matrix of the self- and mutual impedances of the nth harmonic nodes of the network, $\boldsymbol{I}_n$ – a column matrix of the nth harmonic currents of nonlinear loads connected to the network nodes. The square matrix $\boldsymbol{Z}_n$ is calculated as a result of the inversion of the square matrix of nodal admittance $\boldsymbol{Y}_n$, i.e., $\boldsymbol{Z}_n = \boldsymbol{Y}_n^{-1}$ [44], which is formed based on the known parameters of the network elements. Elements of the matrix $\boldsymbol{I}_n$ are unknown, they have to be determined based on the results of measurements of the harmonic parameters. Each element of the matrix $\boldsymbol{I}_n$ is a complex number $\dot{I}_{ni} = I_{ani} + jI_{rni}$, where i is the number of the network node, I_{ani} and I_{rni} are the active and reactive components of the nth harmonic current. The methodological approach and algorithms presented below are meant for their determination.

The harmonic parameters required for modeling the nonlinear load are measured at the node of its connection to the network, marked as a measurement point in the diagram in Fig. 1, where the network and the nonlinear load are represented as current sources. The diagram denotes the following: $\boldsymbol{I}_{nN}$ – the vector of the nth current harmonic of the network, $\boldsymbol{I}_{nL}$ – the vector of the nth current harmonic of the nonlinear load connected to the node, $\boldsymbol{U}_n$ – the vector of the nth harmonic voltage at the node of the nonlinear load connection to the network. The current vector $\boldsymbol{I}_{nN}$ is the resultant vector of the nth current harmonic of all nonlinear vector $\boldsymbol{I}_{nL}$ of the load modeled.

Thus, current $\boldsymbol{I}_n$ equal to the vector sum of currents $\boldsymbol{I}_{nN}$ and $\boldsymbol{I}_{nL}$ runs through the connection node, i.e.,

$$\boldsymbol{I}_n = \boldsymbol{I}_{nN} + \boldsymbol{I}_{nL}. \quad (2)$$

The following parameters should be measured at the connection node of a nonlinear load: the nth harmonic factor of voltage ($K_{U(n)}$) and current ($K_{I(n)}$), the effective values of voltage and current harmonics: $\boldsymbol{U}_n$, $\boldsymbol{I}_n$ and the values of phase angles of voltage and current harmonics: φ_{Un}, φ_{In}. The arrays of all measured harmonic parameters are series of random variables.

To solve the system of equations (1) it is necessary to determine with a probability of 95% the values of active I_{an} and reactive I_{rn} currents. The parameter values with a probability of 95% are used in [5] to estimate the deviation of voltage from a sine wave. Values of I_{an} and I_{rn} are determined based on the measured effective magnitudes of current I_n and the phase angle $\varphi_{UI(n)}$ between the harmonics of voltages and currents, according to the expressions

$$I_{an} = I_n \cos \varphi_{UI(n)}, \quad (3)$$

$$I_{rn} = I_n \sin \varphi_{UI(n)}, \quad (4)$$

where the phase angle $\varphi_{UI(n)}$ is determined using the measured angles φ_{Un} and φ_{In} as

$$\varphi_{UI(n)} = \varphi_{Un} - \varphi_{In}. \quad (5)$$

Calculation of the current harmonic values with a given probability requires the knowledge of their cumulative distribution functions that can be obtained with the aid of probability density functions identified after appropriate processing of measurement results. Thus, the nonlinear load model is a set of current harmonic cumulative distribution functions that allow calculating with a given probability the harmonic values of active and reactive currents.

A. Methodological approach to modeling the nonlinear loads based on the measurements of harmonic parameters.

The methodological approach consists of seven steps listed below.

1. Check the measured series of random values of harmonic parameters for the presence of outliers. Outliers are elements that differ significantly in value from the other elements of the series. They make the series of measured parameters non-stationary, do not allow constructing a real histogram and correctly determining the distribution law. Their presence can be determined visually by a scatter chart.

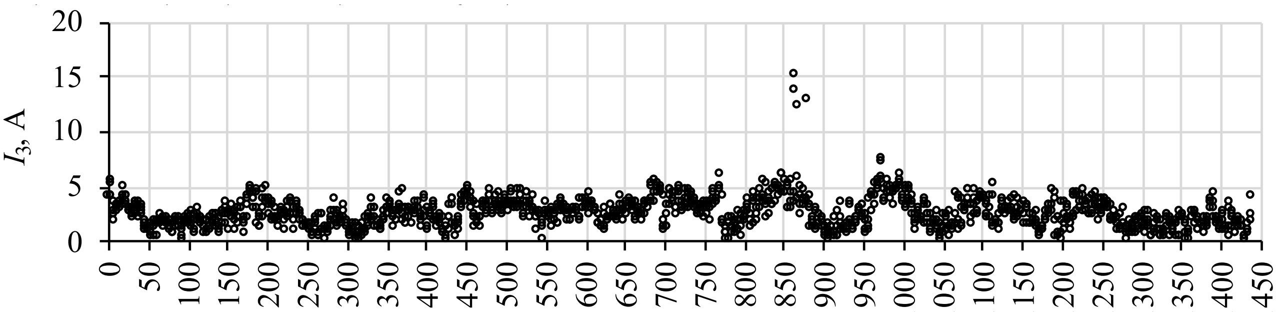


Fig. 2. Scatter chart of the 3rd current harmonic.

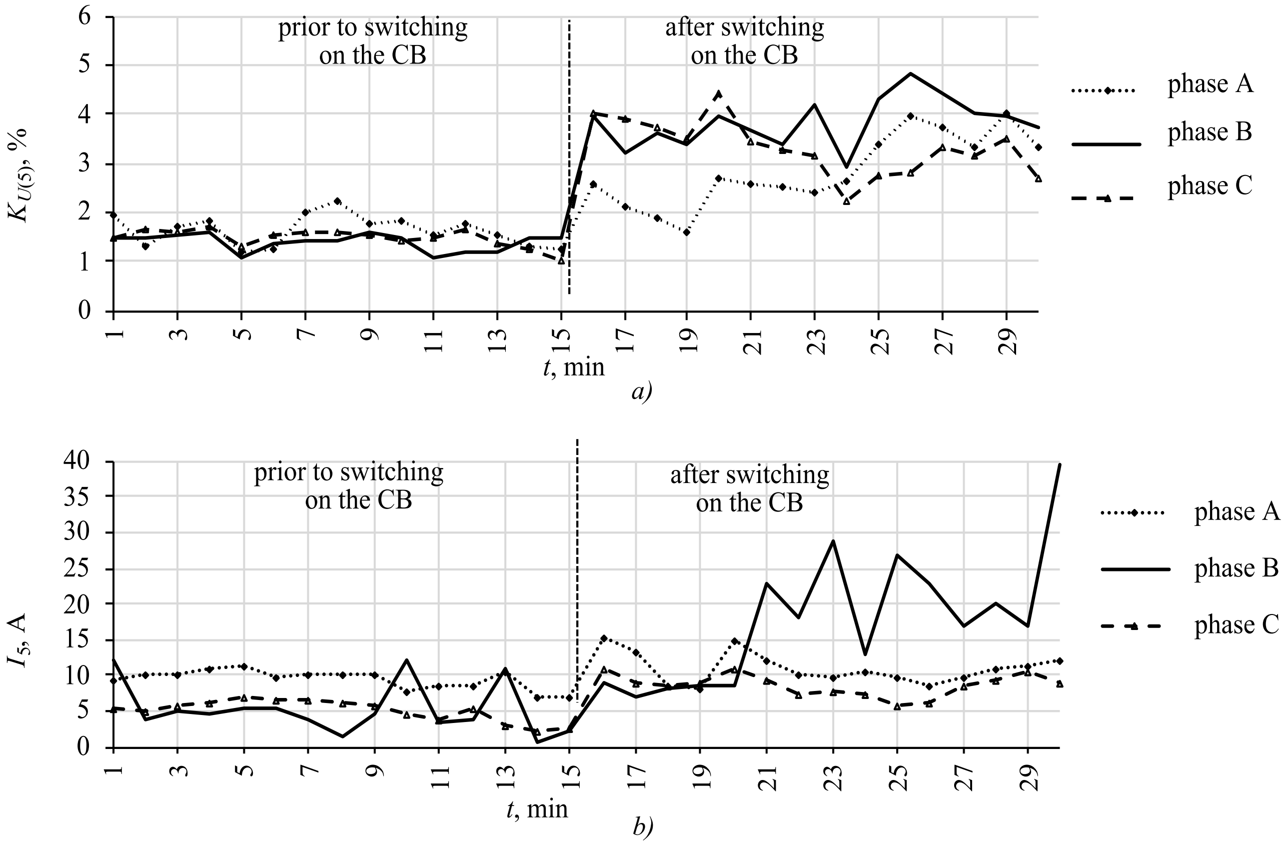


Fig. 3. Changes in a) $K_{U(5)}$ and b) I_5 when the capacitor bank is on.

Fig. 2 shows a scatter chart of the 3rd current harmonic. The diagram clearly shows the four outliers. During processing, outliers can be replaced by neighboring elements or by their average value, or the methods presented in [45, 46] can be employed to replace them.

2. Analyze the harmonic parameters measured to determine the time intervals, which are characterized by parameters that differ significantly in value.

Analysis of measured data revealed that the values of harmonic parameters differ significantly from each other at certain measurement time intervals. These differences result from the changes in the network layout, the parameters of its elements, powers, the nature of loads, and others arising in the operation of electrical networks. In such cases, the measurement time should be divided into intervals, in which operating conditions characterized by certain values of measured parameters take place. Models of nonlinear loads should be developed for each of these intervals. Fig. 3 shows voltage and current harmonics at the network node with capacitor bank (CB) on. The charts demonstrate that after turning on the capacitor bank, there are sharp increases in the 5th harmonic factor of voltages ($K_{U(5)}$) in the three phases and in the value of the 5th harmonic of currents (I_5) in B and C phases. The parameter changes shown in the Figure are due to the harmonic resonant circuits that occur between the capacitor bank capacitance and the network node inductance [47]. Thus, the entire measurement time interval should be represented by two intervals characterized by operating parameters markedly different in their value: the network parameters before switching on the capacitor bank and the network parameters after switching it on.

3. Establish correlation relationships between current harmonics and corresponding voltage harmonics.

Correlation relationships are analyzed to determine the mathematical methods to be used when modeling current harmonics by measured random variables. The analysis is performed for each of the time intervals established at the second step of the methodological approach. If it is assumed that the random values of current and voltage harmonics are governed by the normal distribution law, then correlation coefficients (r) are calculated to find out the strength of the relationship between them, which are then compared with the coefficients on the Cheddock scale [48]. When the distribution of random variables differs from the normal distribution, methods based on the application of order statistics or the replacement of measured values by their ranks are employed, using the Kenuy test [45, 49], the quadrant test [45, 50], the sign correlation Nelson test [45], and other tests. Table I shows the correlation coefficients r_{UnIn} between current harmonics and voltage harmonics at the nodes of the connection of the aluminum smelter unit (ASU), pulp and paper mill (PPM), and railway substation (RWS) to the electricity supply network.

Table 1. Correlation coefficients rUnIn.

n		3	5	7	9	11	13	17	19	23	25
r_{UnIn}	ASU	-0.04	0.02	-0.05	-0.05	-0.43	0.15	0.45	0.20	-0.06	-0.03
	PPM	**0.61**	0.47	-0.06	**0.62**	**0.74**	**0.56**	0.18	0.40	**0.59**	**0.53**
	RWS	0.29	-0.04	0.37	-0.03	0.12	0.05	0.06	0.10	**0.75**	0.41

The comparison of r_{UnIn} and the coefficients on the Chaddock scale shows that in most cases, except for the coefficients highlighted in bold in Table I, there is either no correlation between the harmonics of currents and voltages or it is insignificant, which attests to the independence or weak dependence of voltage harmonic values on current harmonics, i.e., the probabilistic nature of both parameters, which makes it possible to apply corresponding mathematical methods when modeling current harmonics. If in some cases, there are correlation relationships between current harmonics and voltage harmonics, it is necessary to identify the existing relationships between them through the regression analysis.

4. Analyze the nth harmonic factors of voltage to select harmonic numbers for modeling.

Modeling can be performed not for all harmonics from the range of the 2nd to the 40th recommended in [5]. The numbers of harmonics whose $K_{U(n)}$ exceed the standard values are chosen for modeling [5]. For this purpose, it is necessary to compare the measured values of $K_{U(n)}$ with the standard values for 95% and 100% of the measurement time. Fig. 4 shows as an example the charts of the measured $K_{U(n)}$ at the nodes of the connection to the electricity supply network of the aluminum smelter unit, pulp and paper mill, railway substation, and standard values – $K_{U(3,5)S}$, $K_{U(7,11)S}$, $K_{U(13)S}$, $K_{U(17)S}$, $K_{U(9,19,23,25)S}$ for 95% of the measurement time. The Figure shows that at the node of connection of the aluminum smelter unit, the standard values of $K_{U(11)S}$, $K_{U(13)S}$, $K_{U(23)S}$, $K_{U(25)S}$ are exceeded, at the node of connection of the pulp and paper mill, the same applies to $K_{U(5)S}$, $K_{U(7)S}$, $K_{U(9)S}$, $K_{U(11)S}$, $K_{U(13)S}$, $K_{U(25)S}$, and at the node of the connection of the railway substation, this holds for $K_{U(3)S}$, $K_{U(5)S}$, $K_{U(9)S}$, $K_{U(11)S}$, $K_{U(13)S}$, $K_{U(17)S}$, $K_{U(19)S}$, $K_{U(23)S}$, $K_{U(25)S}$. Thus, at the node of connection of the aluminum smelter unit, one needs to model the 11th, 13th, 23rd, and 25th current harmonic; at the node of connection of the pulp and paper mill: the 5th, 7th, 9th, 11th, 13th, and 25th current harmonic; at the node of connection of the railway substation: the 3rd, 5th, 9th, 11th, 13th, 17th, 19th, 23rd, 25th current harmonic.

5. Analyze active and reactive current harmonic directions through the node of the connection to the nonlinear load network in order to select options for modeling.

The values of current harmonics for $n > 1$ are much smaller than the values of the first current harmonic. Their direction of flow can change for the first harmonic current for many minor reasons. At each time interval defined at the second step of the methodological approach, it is necessary to analyze the directions of the flow of harmonics of active and reactive currents through the node of the connection of the nonlinear load, i.e., relative to the measurement point in Fig. 1. The analysis is performed using the phase angle between the harmonics of voltages and currents $\varphi_{UI(n)}$. The active and reactive currents are directed from the network to the load if the angle $\varphi_{UI(n)}$ is within the range of 0 to $\pi/2$, i.e., in the 1st quadrant of the complex plane [51]. The active current is directed from the load to the network, and the reactive current is directed from the network to the load if the angle $\varphi_{UI(n)}$ is within the $\pi/2$ to π range, i.e., in the 2nd quadrant. Both currents are directed from the load into the network if the angle $\varphi_{UI(n)}$ is within the π to $3\pi/2$ range, i.e., in the 3rd quadrant. The active current runs from the network to the load and the reactive current runs in the

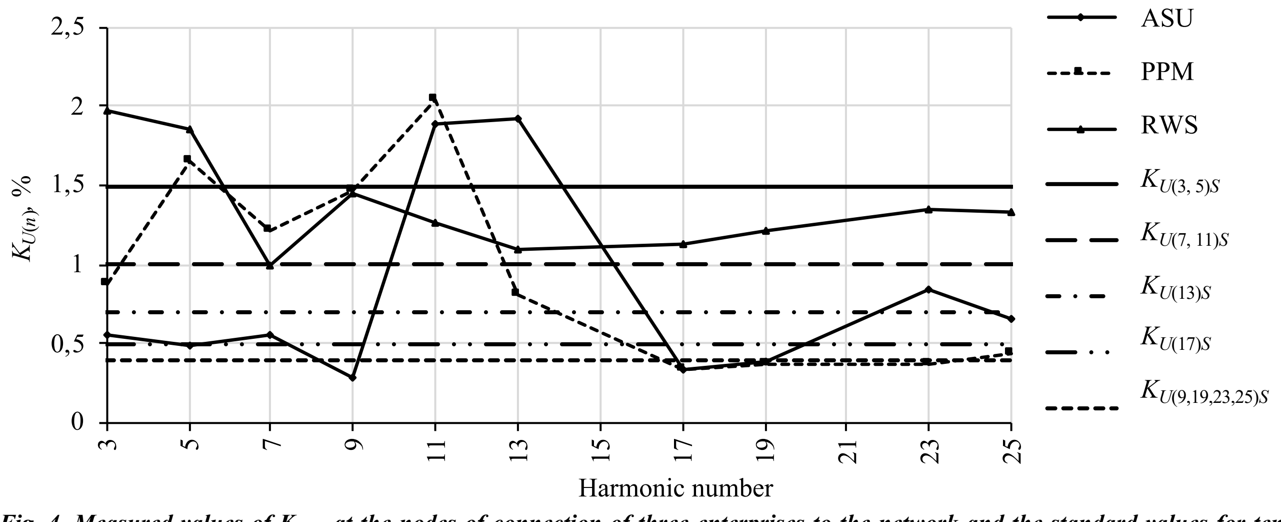


Fig. 4. Measured values of $K_{U(n)}$ at the nodes of connection of three enterprises to the network and the standard values for ten harmonics.

Table 2. Distribution of Harmonic Directions for Active and Reactive Currents of the Railway Substation by the Quadrants of the Complex Plane.

	n	3	5	7	9	11	13	17	19	23	25
The number of $\varphi_{UI(n)}$, % — Quadrants	1	10.3	**81.7**	0.9	**26.2**	21.7	19.5	19.7	17.5	**60.3**	**45.7**
	2	14.7	5.1	19.5	22.4	**32.1**	**26.9**	23.3	21.9	26.8	23.0
	3	**37.5**	0.3	**68.5**	21.9	**29.4**	**33.7**	**31.7**	**34.8**	4.5	11.0
	4	**37.5**	12.9	11.1	**29.5**	16.8	19.9	**25.3**	**25.8**	8.4	20.3

opposite direction if the $\varphi_{UI(n)}$ is within the $3\pi/2$ to 2π range, i.e., in the 4th quadrant. Thus, the time of measurements of the harmonic parameters at each of the time intervals determined at the second step of the methodological approach can be divided into four more time sub-intervals, which correspond to the locations of the angle $\varphi_{UI(n)}$ in the 1st, 2nd, 3rd, and 4th quadrants of the complex plane. Sub-ranges (variants) prevailing over others in terms of the number of measurements, i.e., containing the greatest number of measurements out of their total number are selected for modeling. Table II presents the results of the analysis of the directions of the active and reactive currents of the railway substation using the angle $\varphi_{UI(n)}$. Each cell of the table corresponds to a quadrant of the complex plane. The cell of the table shows the number of measured $\varphi_{UI(n)}$ belonging to the corresponding quadrant as a percentage of the total number of measurements $\varphi_{UI(n)}$, which is 1 440. To model harmonics of active and reactive currents, one should use the options highlighted in bold in the Table II.

6. Develop algorithms for modeling harmonics of active and reactive currents.

Modeling harmonics of active and reactive currents aims to identify their cumulative distribution functions, and then determine the values of I_{an} and I_{rn} with a probability of 95% or other probability and to solve the system of equations (1). Based on the analysis of information from

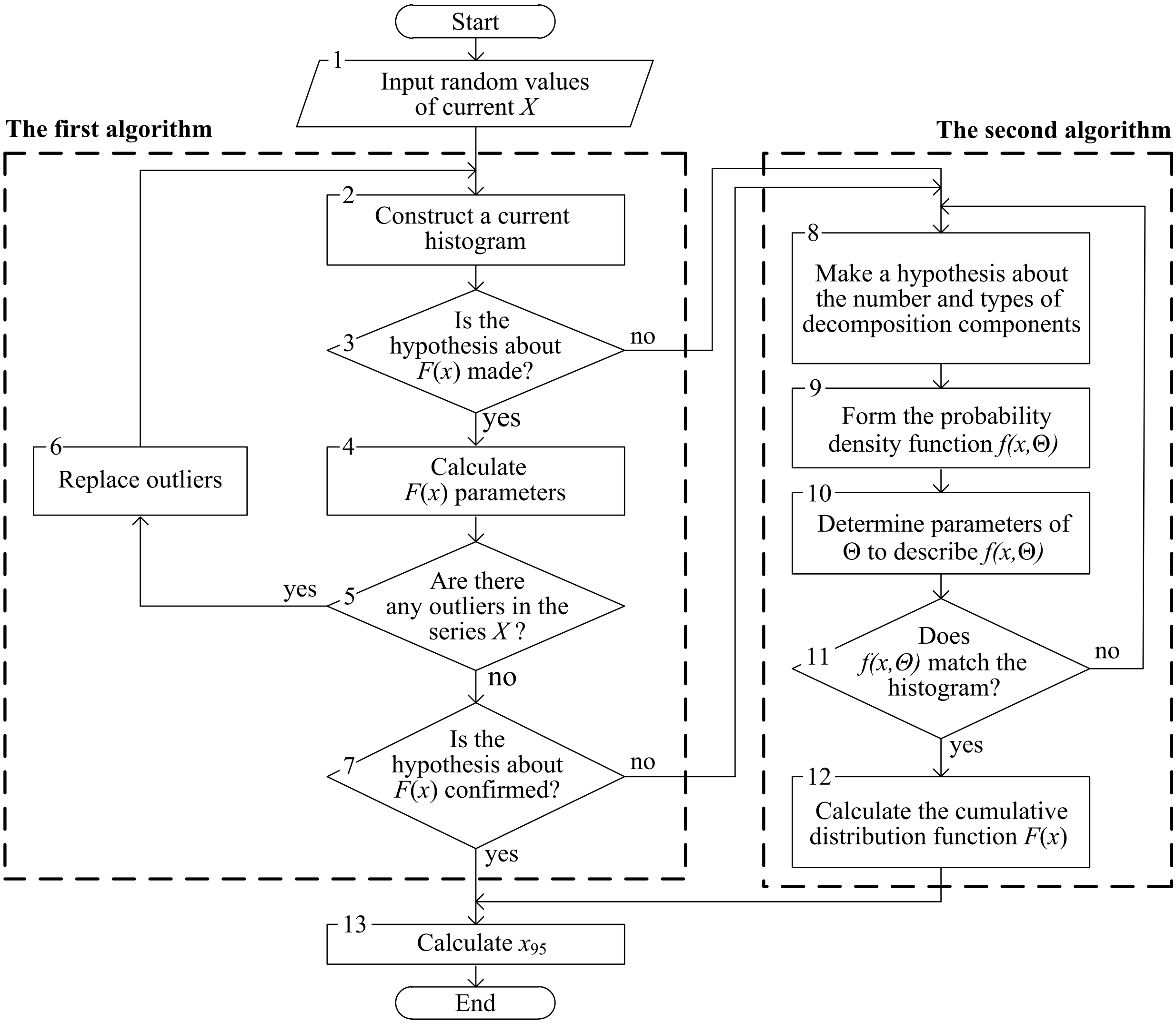


Fig. 5. Flowchart of single current harmonic modeling algorithms.

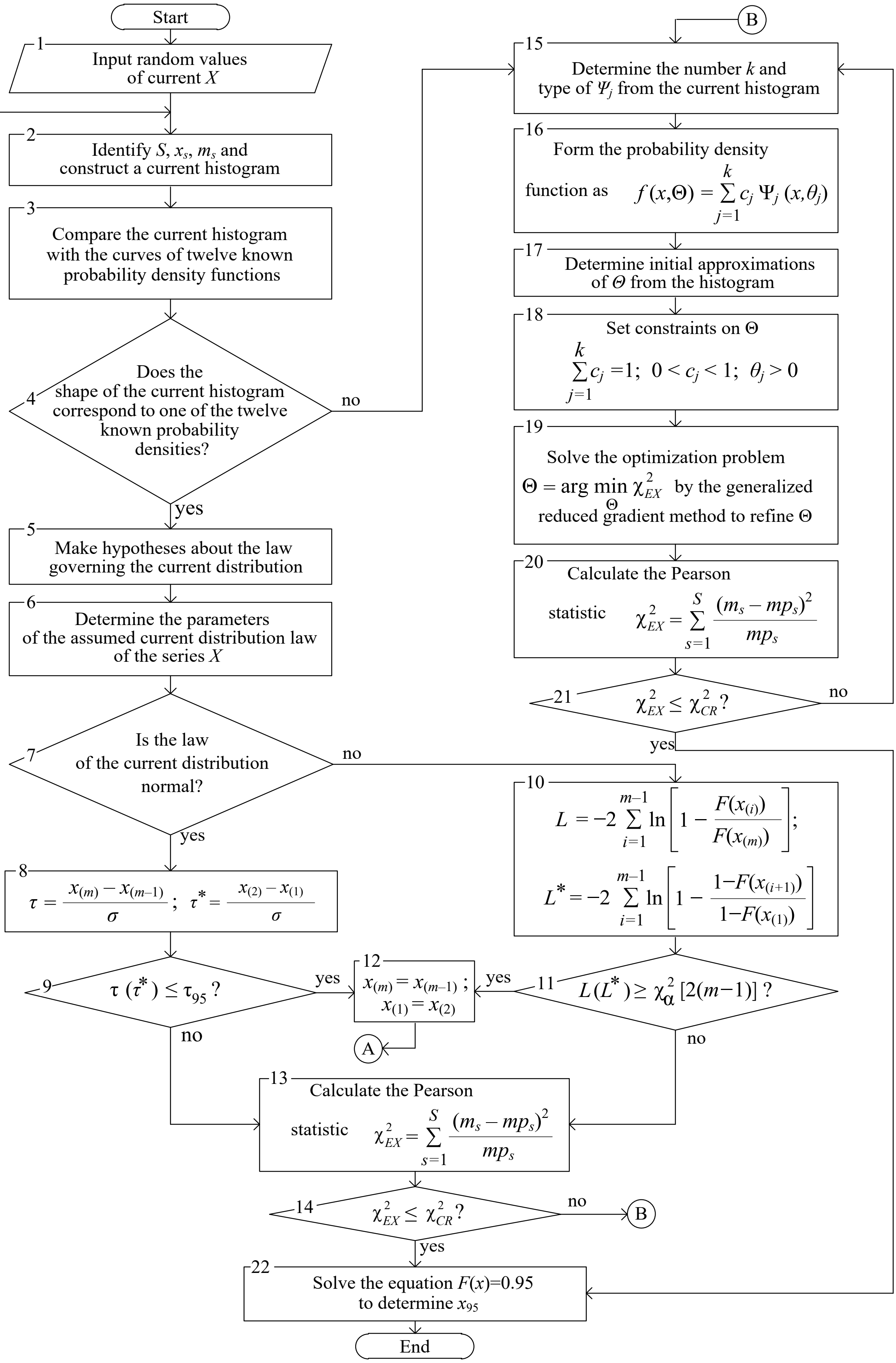


Fig. 6. Flowchart of the computational program algorithm.

numerous measurements of current harmonics, we have arrived at the conclusion that two different approaches should be used to identify their cumulative distribution functions. These approaches are presented in Fig. 5 as two algorithms.

The notations used in the Figure are $F(x)$ – cumulative distribution function, $f(x,\Theta)$ – probability density function, x_{95} – current harmonic value with a 95% probability. The first algorithm, including Blocks 2, 3, 4, 5, 6, and 7, is designed to identify the cumulative distribution functions of random variables of current harmonics corresponding to the known distribution laws. The second algorithm, including Blocks 8, 9, 10, 11, and 12, is designed to identify the cumulative distribution functions of random variables of current harmonics corresponding to mixtures of known distribution laws. Based on the algorithms, we have developed the computational program presented at step *B*.

7. Check the correctness of calculations with a given accuracy of the values of active and reactive currents.

After calculating the values of I_{an} and I_{rn} it is necessary to check the correctness of the obtained values. To do this, one has to calculate the magnitude of current I_n from the values of I_{an} and I_{rn}, and then compare the obtained value of I_n with the measured values of current. The calculated I_n value must not exceed the measured current values. If in some cases the calculated I_n value is out of range, the reasons for it should be found out and, if necessary, the modeling should be performed again. The reasons for the calculated value of I_n to exceed the measured current values can be the rounding of the values of I_{an}, I_{rn}, I_n upwards, insufficiently accurate identification of the cumulative distribution function to describe harmonics of active and reactive currents, even though the identified cumulative distribution function corresponds to the measured harmonic values of active and reactive currents according to the goodness-of-fit tests. In the latter case, it is necessary to choose another distribution law that most accurately describes the distribution of harmonics of active and reactive currents.

B. Computational program for modeling harmonics of currents of nonlinear loads by measured parameters.

The flowchart of the computational program algorithm is shown in Fig. 6. The program identifies the cumulative distribution functions of harmonics of active and reactive currents and calculates their values with a given probability.

Block 1. Input the series of random values of active or reactive current harmonic X: $x_1, x_2, \ldots, x_i, \ldots, x_m$, where m is the number of elements of the X series.

Block 2. Determine the number of histogram intervals S, their boundary values x_s, the number of random variables of the series X that fall into the sth interval m_s, and construct the current histogram. Based on numerous operations of processing the harmonic parameters measurement results and taking into account suggestions available in the published research [52, 53], this study assumes that the number S is 19 if $m > 1000$; S is 15 if $500 \le m \le 1000$; S is 11 if $m < 500$.

Blocks 3–5. Compare the current histogram with the curves of twelve known probability density functions used in the computational program to make hypotheses about the law governing the distribution of current (normal, Weibull, exponential, gamma, Rayleigh, lognormal, beta, minimum value, maximum value, logistic, Maxwell and Cauchy distributions [45, 46, 54, 55]).

Block 6. Calculate the parameters describing the assumed current distribution law of the series of random variables X, according to the expressions presented in [45, 46, 54, 55].

Block 7. Select the test to check the series of random variables X for the presence of outliers depending on the assumed distribution law: 1) if the assumed distribution law is normal, the Irwin test [45, 56] is used to check the series X for outliers; 2) if the assumed distribution law differs from normal, a modification of the Darling test [45] is used to check it.

Blocks 8–9. Check the largest $x_{(m)}$ and smallest $x_{(1)}$ values of a series of random variables X ($x_{(1)} \le x_{(2)} \le \ldots \le x_{(i)} \le \ldots \le x_{(m)}$) arranged in ascending order for outliers with the Irwin test. The statistics τ, τ^* are calculated using the expressions given in Fig. 6, where $\sigma = \sqrt{\frac{1}{m-1}\sum_{i=1}^{m}\left(x_i - \bar{x}\right)^2}$. Then they are compared with the critical value τ_{95} given in the reference handbooks.

Blocks 10–11. Check the largest $x_{(m)}$ and smallest $x_{(1)}$ values of a series of random variables X ($x_{(1)} \le x_{(2)} \le \ldots \le x_{(i)} \le \ldots \le x_{(m)}$) arranged in ascending order for outliers with a modification of the Darling test.

The statistics L, L^* are calculated using the expressions given in Fig. 6, where, $F(x_{(m)})$, $F(x_{(i=1)})$, $F(x_{(1)})$ – values of the cumulative distribution function for corresponding x. The statistics are then compared with the α-quantile value of the χ^2-distribution $\chi^2_\alpha\left[2\left(m-1\right)\right]$ given in the reference handbooks.

Block 12. Replace outliers with neighboring elements of the series X as $x_{(m)} = x_{(m-1)}$, $x_{(1)} = x_{(2)}$.

Blocks 13–14. Check the fit of the assumed current distribution law to the histogram using Pearson's goodness-of-fit test $\chi^2_{EX} \le \chi^2_{CR}$ [45]. Pearson's goodness-of-fit test statistic is calculated using the expression

$$\chi^2_{EX} = \sum_{s=1}^{S}\frac{\left(m_s - mp_s\right)^2}{mp_s}, \qquad (6)$$

where p_s is the theoretical probability of the random variables of the series X falling into the sth interval, which is calculated as the difference between the values of the cumulative distribution function of the series X at the end and at the beginning of the sth interval

$$p_s = F(x_{s+1}) - F(x_s), \qquad (7)$$

where $F(x)$ is the cumulative distribution function of the series X, calculated as

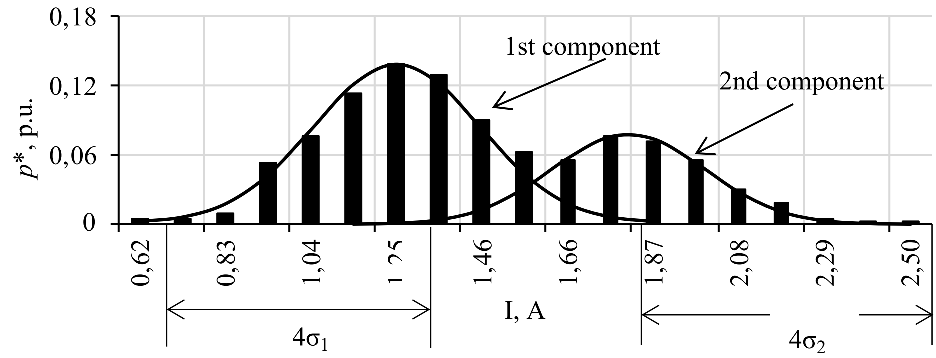


Fig. 7. Current histogram with two peaks.

$$F(x) = \int_{x_{(1)}}^{x} f(x)dx, \quad (8)$$

mp_s is the theoretical frequency of occurrence of random variables of series X in the sth interval. Then the calculated value χ^2_{EX} is compared with the critical value χ^2_{CR} given in [57].

Blocks 15–21. Identify the current probability density function using the methods of decomposing the mixtures of distributions.

First, based on the shape of the current histogram, a hypothesis is made about the number of components in the mixture and the types of their probability density functions. The twelve known probability density functions used in the computational program are proposed as probability density functions for the components of the mixture. Next, a current probability density function is formed as a weight sum of k components of the mixture [55, 58-62]

$$f(x,\Theta) = \sum_{j=1}^{k} c_j \Phi_j(x,\ \theta_j), \quad (9)$$

where $f(x,\Theta)$ is the desired current probability density function; $k \geq 1$ is a natural number; Φ_j is the known probability density function of the jth component of the mixture; $\Theta = (c_1,\ldots, c_k, \theta_1,\ldots, \theta_k)$ is the vector of parameters of the mixture components to be determined; c_j is the weight of the jth component, $c_j > 0, j = 1, ..., k$; $c_1 + \ldots + c_k = 1$; θ_j is the parameter vector of the jth component of the mixture.

The vector Θ is defined using a series of random variables X as follows. The initial approximations of the vector Θ parameters are set based on the histogram analysis. For example, Fig. 7 shows a current histogram with two peaks. We put forward a hypothesis that the histogram has two components, and their probability density functions are captured by the normal distribution law, which is characterized by two parameters: the mean (μ) and standard deviation (σ).

The vector θ_j, in this case, consists of two parameters, i.e., $\theta_1 = (\mu_1,\sigma_1)$ and $\theta_2 = (\mu_2,\sigma_2)$, and the vector Θ consists of six ones, i.e., $\Theta = (c_1, c_2, \mu_1, \mu_2, \sigma_1, \sigma_2)$. The initial values $\mu_1, \sigma_1, \mu_2, \sigma_2$ are determined from the histogram as follows. To determine c_1, c_2, it is assumed that the total area of the histogram under the curves of the mixture components is 1. Values of c_1, c_2 are set by values equal to the fractions of the areas under the corresponding curves of the mixture components. In the case of the normal distribution, the position of the peaks of the histogram relative to the y-axis allows determining the mean for each of the components. Half the width of the shape under the component probability density curve makes it possible to determine the standard deviation since under the normal distribution, the interval of "four standard deviations" covers 99.99% of the values of the series of random variables X [63].

If the histogram components have distribution laws different from the normal law, the initial approximations of the vector Θ parameters are calculated using censored samples obtained from the series of random variables X [46, 64]. Then Θ is refined by solving the optimization problem

$$\tilde{\Theta} = \arg\min_{\Theta} \sum_{s=1}^{S} \frac{(m_s - mp_s)^2}{mp_s}, \quad (10)$$

subject to the following constraints:

$$\sum_{j=1}^{k} c_j - 1 = 0, \quad (11)$$

$$-c_j < 0, \quad (12)$$

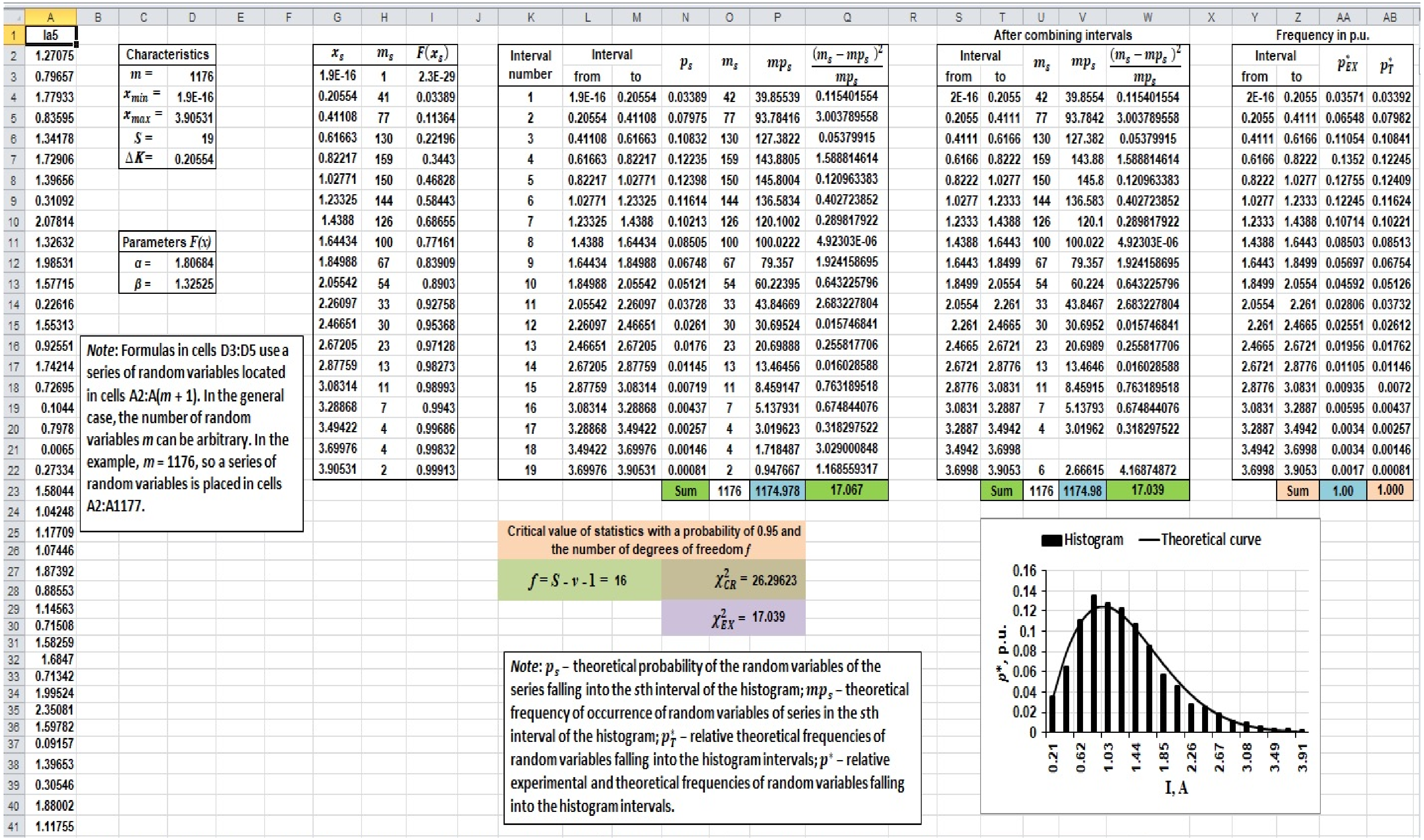
$$c_j - 1 < 0, \quad (13)$$

$$-\theta_j < 0. \quad (14)$$

The constraints correspond to the following: (11) – the sum of all weights must equal 1; (12) – all weights are positive values; (13) – the range that must encompass the values of the weights; (14) – all parameters of the vector θ_j are positive values.

Expression (6) is related to coefficients c_j and parameters of the vector θ_j by expressions (7)–(9), which show that χ^2_{EX} is a nonlinear function of $\Theta = (c_1, \ldots, c_k, \theta_1, \ldots, \theta_k)$, hence, the optimization problem is nonlinear as well. In the computational program developed, the optimization problem is solved by the method of the generalized reduced gradient. As a result of obtaining the solution, the refined parameters of the vector Θ are calculated to describe the law of the current distribution.

After refining the parameters of the vector Θ and substituting them into (9), we check whether the obtained



	A
1	Ia5
2	1.27075
3	0.79657
4	1.77933
5	0.83595
6	1.34178
7	1.72906
8	1.39656
9	0.31092
10	2.07814
11	1.32632
12	1.98531
13	1.57715
14	0.22616
15	1.55313
16	0.92551
17	1.74214
18	0.72695
19	0.1044
20	0.7978
21	0.0065
22	0.27334
23	1.58044
24	1.04248
25	1.17709
26	1.07446
27	1.87392
28	0.88553
29	1.14563
30	0.71508
31	1.58259
32	1.6847
33	0.71342
34	1.99524
35	2.35081
36	1.59782
37	0.09157
38	1.39653
39	0.30546
40	1.88002
41	1.11755

Characteristics	
m =	1176
x_{min} =	1.9E-16
x_{max} =	3.90531
S =	19
ΔK=	0.20554

Parameters $F(x)$	
α =	1.80684
β =	1.32525

Note: Formulas in cells D3:D5 use a series of random variables located in cells A2:A(m + 1). In the general case, the number of random variables m can be arbitrary. In the example, m = 1176, so a series of random variables is placed in cells A2:A1177.

x_s	m_s	$F(x_s)$
1.9E-16	1	2.3E-29
0.20554	41	0.03389
0.41108	77	0.11364
0.61663	130	0.22196
0.82217	159	0.3443
1.02771	150	0.46828
1.23325	144	0.58443
1.4388	126	0.68655
1.64434	100	0.77161
1.84988	67	0.83909
2.05542	54	0.8903
2.26097	33	0.92758
2.46651	30	0.95368
2.67205	23	0.97128
2.87759	13	0.98273
3.08314	11	0.98993
3.28868	7	0.9943
3.49422	4	0.99686
3.69976	4	0.99832
3.90531	2	0.99913

Interval number	Interval from	Interval to	p_s	m_s	mp_s	$\frac{(m_s - mp_s)^2}{mp_s}$
1	1.9E-16	0.20554	0.03389	42	39.85539	0.115401554
2	0.20554	0.41108	0.07975	77	93.78416	3.003789558
3	0.41108	0.61663	0.10832	130	127.3822	0.05379915
4	0.61663	0.82217	0.12235	159	143.8805	1.588814614
5	0.82217	1.02771	0.12398	150	145.8004	0.120963383
6	1.02771	1.23325	0.11614	144	136.5834	0.402723852
7	1.23325	1.4388	0.10213	126	120.1002	0.289817922
8	1.4388	1.64434	0.08505	100	100.0222	4.92303E-06
9	1.64434	1.84988	0.06748	67	79.357	1.924158695
10	1.84988	2.05542	0.05121	54	60.22395	0.643225796
11	2.05542	2.26097	0.03728	33	43.84669	2.683227804
12	2.26097	2.46651	0.0261	30	30.69524	0.015746841
13	2.46651	2.67205	0.0176	23	20.69888	0.255817706
14	2.67205	2.87759	0.01145	13	13.46456	0.016028588
15	2.87759	3.08314	0.00719	11	8.459147	0.763189518
16	3.08314	3.28868	0.00437	7	5.137931	0.674844076
17	3.28868	3.49422	0.00257	4	3.019623	0.318297522
18	3.49422	3.69976	0.00146	4	1.718487	3.029000848
19	3.69976	3.90531	0.00081	2	0.947667	1.168559317
			Sum	1176	1174.978	17.067

After combining intervals				
Interval from	Interval to	m_s	mp_s	$\frac{(m_s - mp_s)^2}{mp_s}$
2E-16	0.2055	42	39.8554	0.115401554
0.2055	0.4111	77	93.7842	3.003789558
0.4111	0.6166	130	127.382	0.05379915
0.6166	0.8222	159	143.88	1.588814614
0.8222	1.0277	150	145.8	0.120963383
1.0277	1.2333	144	136.583	0.402723852
1.2333	1.4388	126	120.1	0.289817922
1.4388	1.6443	100	100.022	4.92303E-06
1.6443	1.8499	67	79.357	1.924158695
1.8499	2.0554	54	60.224	0.643225796
2.0554	2.261	33	43.8467	2.683227804
2.261	2.4665	30	30.6952	0.015746841
2.4665	2.6721	23	20.6989	0.255817706
2.6721	2.8776	13	13.4646	0.016028588
2.8776	3.0831	11	8.45915	0.763189518
3.0831	3.2887	7	5.13793	0.674844076
3.2887	3.4942	4	3.01962	0.318297522
3.4942	3.6998			
3.6998	3.9053	6	2.66615	4.16874872
	Sum	1176	1174.98	17.039

Frequency in p.u.			
Interval from	Interval to	p^*_{EX}	p^*_T
2E-16	0.2055	0.03571	0.03392
0.2055	0.4111	0.06548	0.07982
0.4111	0.6166	0.11054	0.10841
0.6166	0.8222	0.1352	0.12245
0.8222	1.0277	0.12755	0.12409
1.0277	1.2333	0.12245	0.11624
1.2333	1.4388	0.10714	0.10221
1.4388	1.6443	0.08503	0.08513
1.6443	1.8499	0.05697	0.06754
1.8499	2.0554	0.04592	0.05126
2.0554	2.261	0.02806	0.03732
2.261	2.4665	0.02551	0.02612
2.4665	2.6721	0.01956	0.01762
2.6721	2.8776	0.01105	0.01146
2.8776	3.0831	0.00935	0.0072
3.0831	3.2887	0.00595	0.00437
3.2887	3.4942	0.0034	0.00257
3.4942	3.6998	0.0034	0.00146
3.6998	3.9053	0.0017	0.00081
	Sum	1.00	1.000

Critical value of statistics with a probability of 0.95 and the number of degrees of freedom f

$f = S - v - 1 = 16$ $\quad \chi^2_{CR} = 26.29623$

$\chi^2_{EX} = 17.039$

Note: p_s – theoretical probability of the random variables of the series falling into the sth interval of the histogram; mp_s – theoretical frequency of occurrence of random variables of series in the sth interval of the histogram; p^*_T – relative theoretical frequencies of random variables falling into the histogram intervals; p^* – relative experimental and theoretical frequencies of random variables falling into the histogram intervals.

Fig. 8. Sheet 6 of the program - Blocks 13-14.

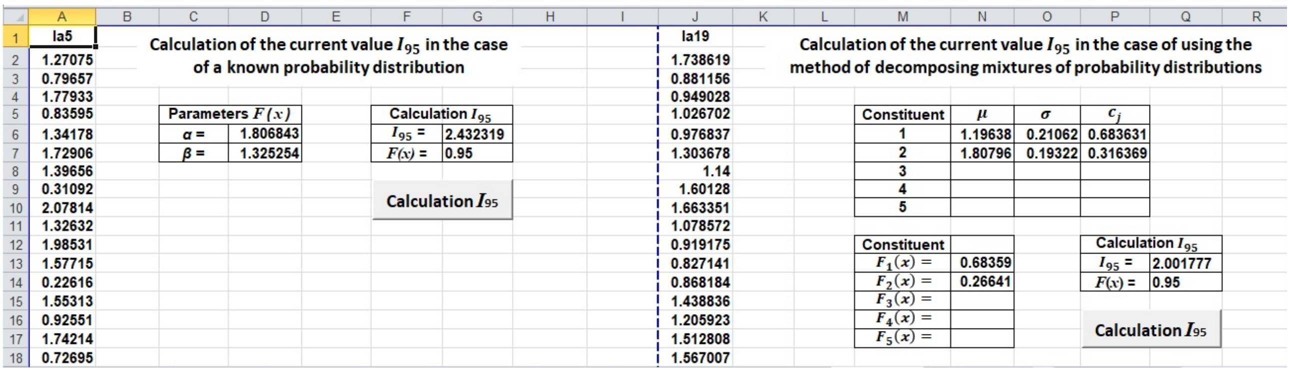


Fig. 9. Sheet 8 of the program – Block 22.

probability density function corresponds to the histogram form using Pearson's goodness-of-fit test [45, 52, 65]. If this test fails, we return to Block 15 to propose other number and/or types of components of the mixture of distributions. If the condition is satisfied, the algorithm proceeds to Block 22 to determine the current value with a 95% probability by solving equation $F(x) = 0.95$.

The computational program developed based on the algorithm shown in Fig. 6 is implemented in MS Excel and Visual Basic programming environment for Windows applications. The program presents probability density function curves of twelve distributions most commonly used in various analyses referred to above. A dedicated program was written in the Visual Basic programming environment for Windows applications to calculate parameters of twelve distributions. This program consists of twelve subprograms, each intended to compute parameters of one particular distribution.

The computational program consists of eight MS Excel sheets. The first sheet implements Blocks 1–2 of the algorithm, the second – Blocks 3–5, the third – Block 6. Blocks 7–11 of the algorithm are implemented on Sheet 4, Block 12 – on Sheet 5, and Blocks 13–14 – on Sheet 6. Sheet 6 is shown in Fig. 8. Blocks 15–21 of the algorithm are implemented on Sheet 7 of the program, and Block 22 is implemented on Sheet 8. The last sheet of the program is presented in Fig. 9.

IV. Application of the developed methodological approach, algorithms, and computational program to modeling current harmonics of railway traction transformers.

Relying on the developed methodological approach, algorithms, and computational program, we have studied and modeled the 3rd and 5th harmonics of active and reactive currents at the nodes of the connection of traction transformers to the electricity supply network for the four substations of the East Siberian Railway: Mysovaya, Tataurovo, Zaigrayevo, and Novo-Ilyinsk. Electrical power is supplied to the traction network through these transformers to cover high-power nonlinear loads, i.e., electric locomotives. The calculations and analysis have indicated that current and voltage harmonics can be considered as independent random variables, and, therefore, the corresponding mathematical methods can be used. The distribution laws of most harmonics of active and reactive currents do not obey the known distribution laws but have more complex forms, i.e., mixtures of known laws, such as normal, Weibull, exponential, and gamma distributions. The distribution laws of the 3rd and 5th harmonics of active and reactive currents are shown in Table III.

The notations employed in the Table are as follows: W – Weibull distribution, G – gamma distribution, E – exponential distribution, W + W – a mixture of two

Table 3. Harmonic Distribution Laws for Active and Reactive Currents.

n	Currents	Substation			
		Mysovaya	Tataurovo	Zaigrayevo	Novo-Ilyinsk
3	I_{an}	W + W	W + G	E	N + G
	I_{rn}	W + G	G	W + G	N + W
5	I_{an}	W + W	W + W + W	W + E	W + W
	I_{rn}	N + W	N + W	W	N + W

Table 4. Harmonic Values of Active and Reactive Currents Calculated with a 95% Probability, A.

n	Currents	Substation			
		Mysovaya	Tataurovo	Zaigrayevo	Novo-Ilyinsk
3	I_{an}	3.7	− 71.0	3.8	− 9.2
	I_{rn}	− 2.8	− 73.5	2.5	− 7.2
5	I_{an}	2.4	− 15.6	2.2	1.7
	I_{rn}	− 2.5	− 55.2	2.9	3.1

TABLE 5. Comparison of $K_{U(3)}$, $K_{U(5)}$ calculated before and after the “Harmonics” software upgrade.

Substation	n	$K_{U(n)\text{-}P}$, %	$K_{U(n)\text{-}A}$, %	$\Delta K_{U(n)}$, %
Mysovaya	3	1.12	1.10	1.79
	5	1.16	1.06	8.62
Posolskaya	3	1.25	1.28	2.40
	5	1.19	1.07	10.08
Kamensk	3	1.27	1.31	3.15
	5	1.22	1.09	10.66
Selenginsky pulp and paper mill	3	1.29	1.32	2.32
	5	1.23	1.10	10.57
Tataurovo	3	1.37	1.44	5.11
	5	1.29	1.14	11.63
Severnaya	3	1.36	1.41	3.68
	5	1.38	1.26	8.70
Rayonnaya	3	1.37	1.42	3.65
	5	1.39	1.29	7.19
Motornaya	3	1.38	1.43	3.62
	5	1.41	1.32	6.38
Zaigrayevo	3	1.49	1.56	4.70
	5	1.76	1.73	1.70
Novo-Ilyinsk	3	1.66	1.58	4.82
	5	2.07	2.02	2.42
Kizha	3	1.69	1.74	2.96
	5	2.27	2.24	1.32
Petrovsk-Zabaikal'sky	3	1.70	1.73	1.76
	5	2.56	2.54	0.78

Weibull distributions, W + G – a mixture of Weibull distribution and gamma distribution, N + W – a mixture of normal distribution and Weibull distribution, W + W + W – a mixture of three Weibull distributions, N + G – a mixture of normal distribution and gamma distribution, W + E – a mixture of Weibull and exponential distribution.

Table IV presents the values of the 3rd and 5th harmonics of active and reactive currents calculated with a 95% probability at the substation connection points with regard to the direction of flow. In the Table, the minus sign “–” means that the active or reactive currents are directed from the load to the network. Unsigned (positive) currents are directed from the network to the load. The correctness of the calculations of the harmonic values of active and reactive currents has been verified by checking as described at Step *B*.

The developed method of modeling nonlinear loads is implemented in the “Harmonics” software package [66] developed at the Melentiev ESI, SB RAS, for the purpose of improvement of the original package.

Table V shows the results of the comparison of $K_{U(3)}$, $K_{U(5)}$ for a segment of the network supplying twelve substations of the East Siberian Railway as calculated before ($K_{U(n)\text{-}P}$) and after ($K_{U(n)\text{-}A}$) upgrading the “Harmonics” software.

In the previous version of the software, the harmonic parameters were modeled considering the results of $K_{U(n)}$ measurements at the four substations listed above. We used the harmonic values of active and reactive currents given in Table V to calculate $K_{U(n)\text{-}P}$, $K_{U(n)\text{-}A}$. The last column of Table V shows the differences $\Delta K_{U(n)}$ of indices $K_{U(n)\text{-}P}$ from indices $K_{U(n)\text{-}A}$, calculated as $\Delta K_{U(n)} = 100\,|K_{U(n)\text{-}A} - K_{U(n)\text{-}P}| \,/\, K_{U(n)\text{-}P}$. The table shows that the differences in the $K_{U(3)}$, $K_{U(5)}$ indices are insignificant.

V. CONCLUSION

The methodological approach, algorithms, and computational program developed for modeling nonlinear loads to analyze non-sinusoidal conditions in high voltage electrical networks based on measurements of harmonic parameters, as evidenced by long-term modeling experience, can significantly reduce the time of modeling the nonlinear loads and harmonic parameters and improve the accuracy of harmonic values determined for active and reactive currents of nonlinear loads. With the help of the tools developed, we have performed the analysis and modeling of the 3rd and 5th current harmonics at the nodes of the connection of transformers of four substations of the East Siberian Railway to the electrical network that supplies electric power to high-power nonlinear loads, i.e., electric locomotives. The modeling results obtained indicate that the values of current harmonics are distributed according to different laws, including normal, Weibull, exponential, and gamma distributions, and the laws described by mixtures of distributions. The calculation results demonstrate that the approach developed to model nonlinear loads is effective and appropriate. The obtained results will be instrumental in developing the theory of non-sinusoidal operating conditions of electric power systems.

Acknowledgment

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Analysis of the Electric Power Potential as Illustrated by the Ues of Russia

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***Abstract* — The paper presents an analysis of the current state of the Unified Energy System (UES) of Russia, which aims to identify "weak points," regional shortage and excess energy systems, locations of the electricity consumption growth, and seeks to determine the technical potential of the power grid for electricity transmission. This analysis relies on the models developed for optimization in terms of the maximum excess capacity for the entire Unified Energy System of Russia and for individual regions of the country in the context of the existing mix of generating capacity and cross-regional structure of the power grid. Calculations were made for the conditions corresponding to the reported performance of the Unified Energy System of Russia in 2020. The cross-regional power grid of the Unified Energy System of Russia is capable of covering the capacity needs of all the country's power systems, and almost everywhere has a significant available transfer capability of power transmission lines.**

***Index Terms*: Unified Energy System of Russia, region, generation, power grid, analysis, model, excess capacity, potential, bottlenecks.**

I. Introduction

One of the significant stages in formulating the strategies for the development of electric power systems [1–3] is an analysis of their existing state. In the process of this analysis, it is necessary to identify «bottlenecks» in the system, the power systems with a capacity shortage or excess, the technical potential of the power grid for power transmission, possible locations of power consumption growth, and others [4–7]. The results of this analysis are employed to form alternatives for levels and territorial distribution of power consumption, options for construction of power plants, and power grid expansion. This information is also needed to assess the energy security of the country's regions [8].

The importance of quantitative analysis of the potential of the existing electric power industry in Russia is also determined by the current situation, i.e., the presence of significant excess generating capacity in the country.

The assessment of the technological potential of the existing power grid depends on the electricity transmission capability to cover additional demand for electricity at grid nodes, whereas generating capacity potential is determined by the relationship between the capacity demand and the available capacity of power plants in the regions of the country.

Let us consider the problem of determining the maximum possible electricity consumption in the power systems across the country, without expansion of grid and generating capacity (problem 1).

Problem statement: find the maximum total excess capacity (or maximum generation) in the system

$$\max \sum_i (g_i - s_i),\ i \in I\,, \qquad (1)$$

where g_i is the load coverage at the node i:

$$g_i = p_i + \sum_k t_{ki}(1-d_{ki}) - \sum_k t_{ik},\ i,k \in I\,, \qquad (2)$$

provided that the electricity demand of all nodes is covered

$$g_i \ge s_i,\ i \in I\,, \qquad (3)$$

at the given maximum generation at the nodes

$$0 \le p_i \le P_i,\ i \in I\,, \qquad (4)$$

and constraints on power flows

$$0 \le t_{ik} \le T_{ik},\ i,k \in I\,. \qquad (5)$$

The optimized variables p_i, g_i, t_{ik} (power plant load, load coverage, and power flow from node i to node k) are non-negative here, I is a set of power system nodes.

The given variables are s_i – existing consumption at nodes, P_i – limit load of operating power plants at nodes, T_{ik} – transfer capability of existing transmission lines, d_{ik} – specific power losses during transmission from node i to node k.

The obtained values of excess power determine the

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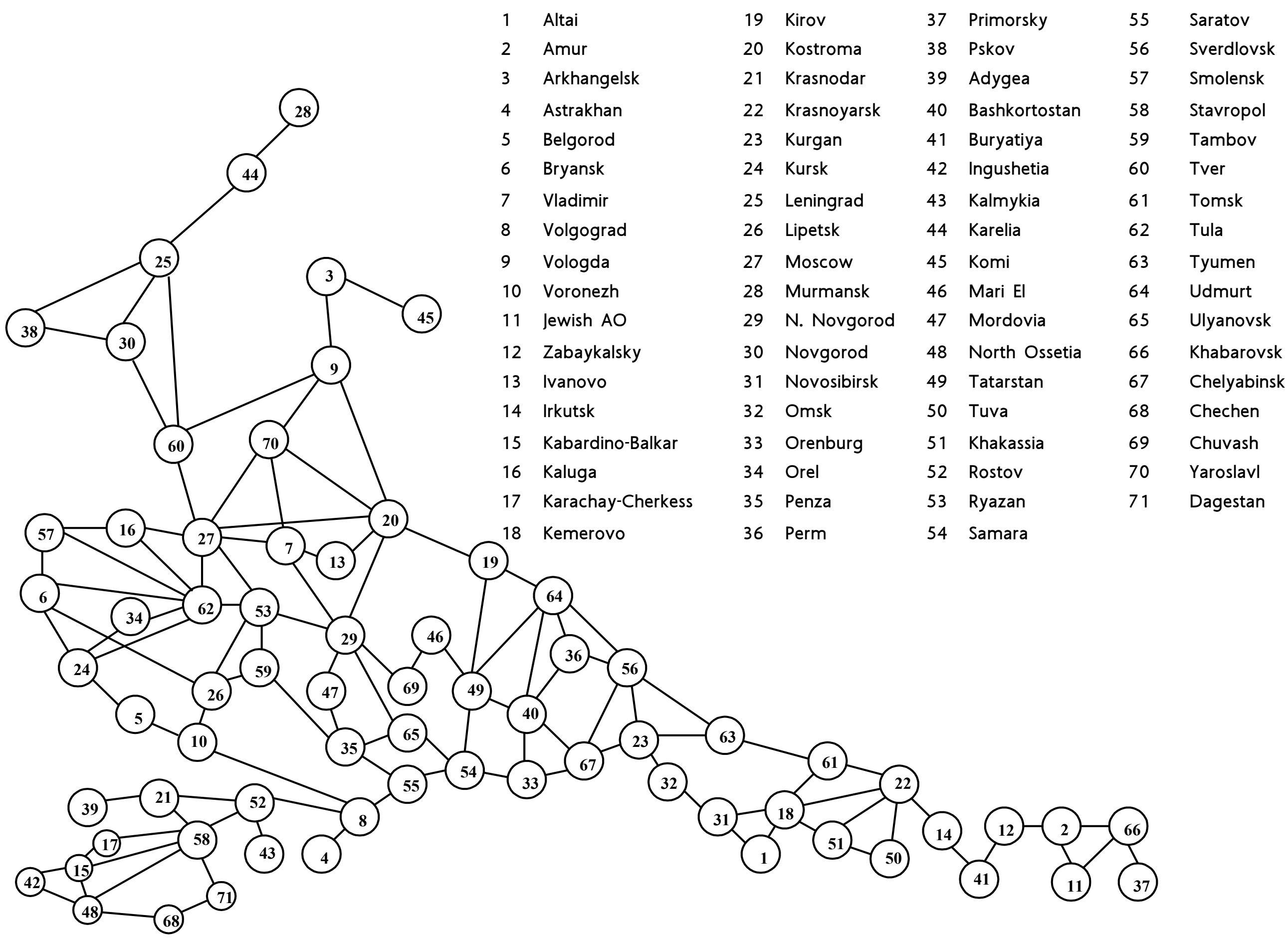

Fig. 1. Equivalent circuit of the UES of Russia

locations of possible growth of consumer loads in the system without reinforcing the grid and power plant capacity additions. Transmission lines where power flows were at the limit of transfer capability form a set of loaded grid elements, i.e., possible candidates for expansion.

Under normal (shortage-free) conditions, maximum total surplus power will be achieved with minimum losses in the grid, i.e., these criteria are identical.

Mathematical models similar in their statements to the above are used to minimize power shortages in the process of analyzing the adequacy of power systems [9–16].

The optimization criterion (1) in the considered model assumes equal importance of possible load growth at all system nodes. If it is necessary to single out certain regions because of their particular importance (for example, those of the Russian Far East), appropriate weighting coefficients can be introduced into criterion (1).

Apart from this statement (placing new consumers to maximize the total consumption in the system, given the capabilities of the existing generation and power grid with minimal energy construction), there can also be another statement. Namely, it is necessary to maximize consumption at a single system node, considering the grid capabilities. In this case, the losses in the grid will naturally be higher than in the first problem. The statement of this problem is as follows. Determine the maximum excess capacity at a single *i*-th node (problem 2):

$\max\,(g_i - s_i)$, (6)

subject to constraints (2)–(5). This problem is solved for all nodes of the power system equivalent circuit.

II. Practical application

The above problem statements were applied in the corresponding analysis of the Unified Energy System (UES) of Russia. An equivalent circuit of UES was built for the calculations (Fig. 1).

The circuit includes 71 nodes, each corresponding to a power system of a constituent entity of the Russian Federation, and cross-system (cross-regional) power lines connecting them (with a voltage of 220 kV and above). We considered the state of the UES for the year 2020.

Background information on generation and transmission lines is taken from the Scheme and Program for the Development of the Unified Energy System of Russia in 2020-2026 [Order of the Ministry of Energy of the Russian Federation No. 508 of June 30, 2020]. The reported load plus a 20% capacity reserve, the same for all nodes, is taken as the node load s_i. The limit load of power plants P_i was assumed to be equal to the reported available capacity at the nodes of the equivalent circuit. The transfer

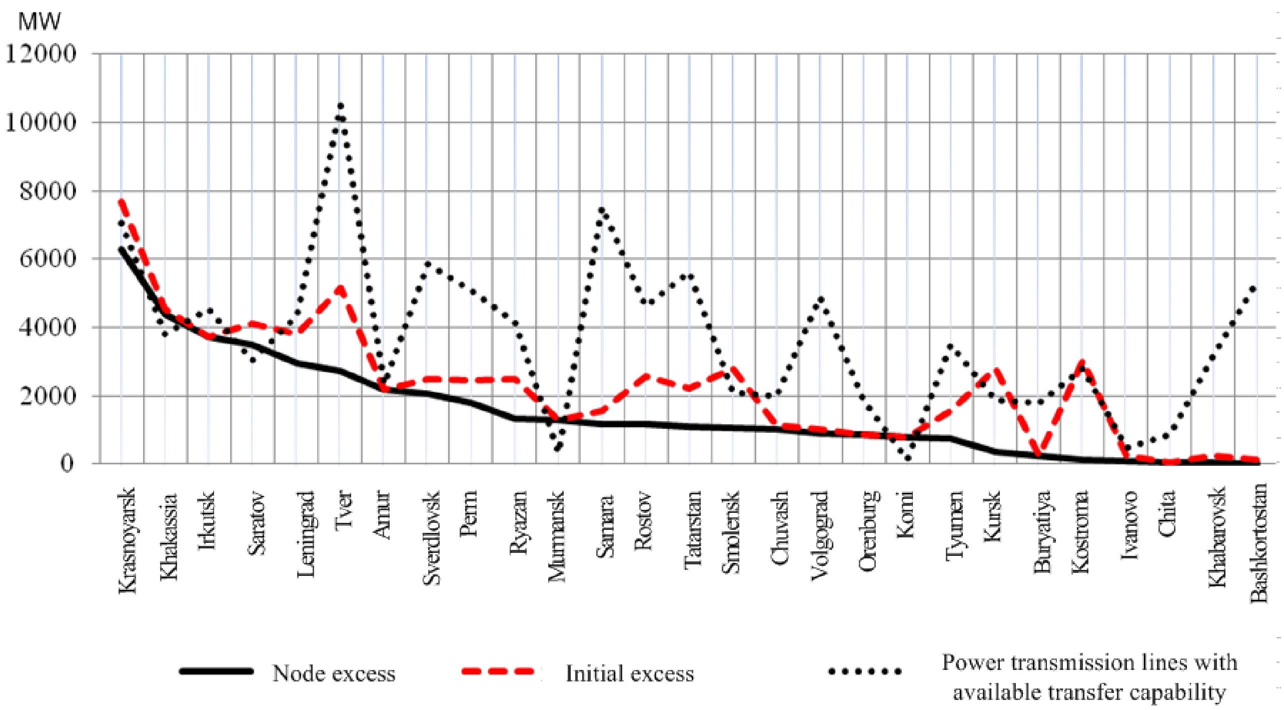

Fig. 2. Excess capacity of Russian power systems (MW), given maximum total excess of the UES of Russia.

capability of transmission lines T_{ik} is assumed to be equal to the natural power of the lines of corresponding voltages, reduced by 20% to ensure static stability. The value of specific power losses during power transmission is assumed to be 6% per 1 000 km, which is the same for all types of transmission lines.

The main results of the model 1 (1)–(5) calculations for the maximum total excess of Russia's power systems are shown in Fig. 2. Only power systems with positive values of calculated excess capacity are shown. The rest of them have zero excess. We provide the values of calculated and initial excess capacity and transfer capability of transmission lines incoming to the power systems and the remaining available transfer capability for power flows.

The total generating capacity of Russian power systems assumed in the calculation was 234.8 GW, the overall load of consumers was 192.5 GW, their difference or initial excess capacity was 42.3 GW.

Calculated total excess capacity of all Russian power systems was 42.0 GW or 18% of the total generating capacity. This is 0.3 GW less than the total initial excess due to the need to cover a load of power systems with an initial capacity shortage and the corresponding power losses in cross-regional power tie lines.

Table 1 shows the regional power systems with the highest values of calculated excess capacity (the top ten of them).

The power system of the Krasnoyarsk Territory has the maximum calculated excess capacity (6.3 GW). The power systems shown in this Table are the prime candidates for possible load growth without generating capacity additions and with the minimal expansion of the power grid. The total capacity of these ten nodes is 31.0 GW, which accounts for most (74%) of the excess of all power systems of the UES of Russia.

The structure of these systems and the systems with the highest excess capacity partially overlap; the first six systems are on both lists, i.e., a large calculated excess capacity is determined by the presence of a significant initial excess. There was a positive initial excess in 33 systems (out of 71). The remaining 38 systems initially had a shortage of capacity. The calculated positive excess was found in 27 systems, each with a positive initial surplus. The calculated excess in the remaining 44 systems was zero. In all systems with the positive calculated excess, its value was less than the initial excess, and after some surplus power was supplied to adjacent nodes, there was an available transfer capability of the connected power lines for almost all excess nodes.

Fig.3. shows in an aggregated way the power flows formed to cover a load of the systems initially experiencing a capacity shortage.

The left-hand side of the Figure shows systems that

Table 1. Excess capacity (GW) at the first ten nodes with the highest excess.

Krasnoyarsk	Khakassia	Irkutsk	Saratov	Leningrad	Tver	Amur	Sverdlovsk	Perm	Ryazan	**Total**	**UES of the Russian Federation**
6.3	4.4	3.7	3.5	3.0	2.7	2.2	2.1	1.8	1.3	**31.0**	**42.0**

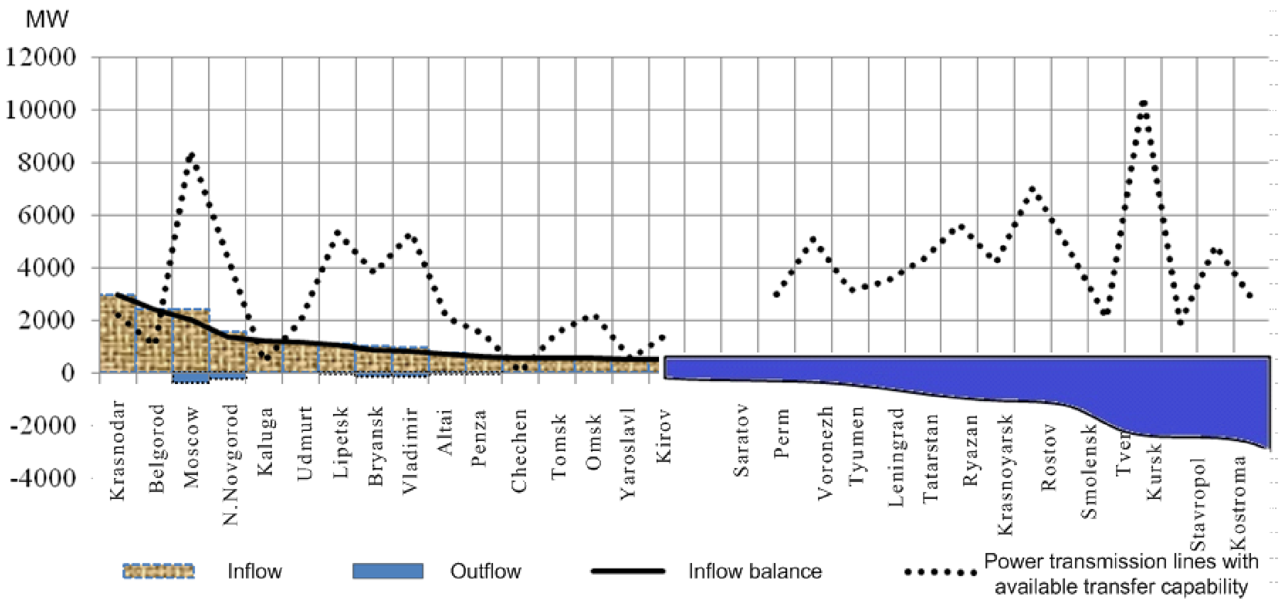

Fig. 3. Cross-system power flows (MW).

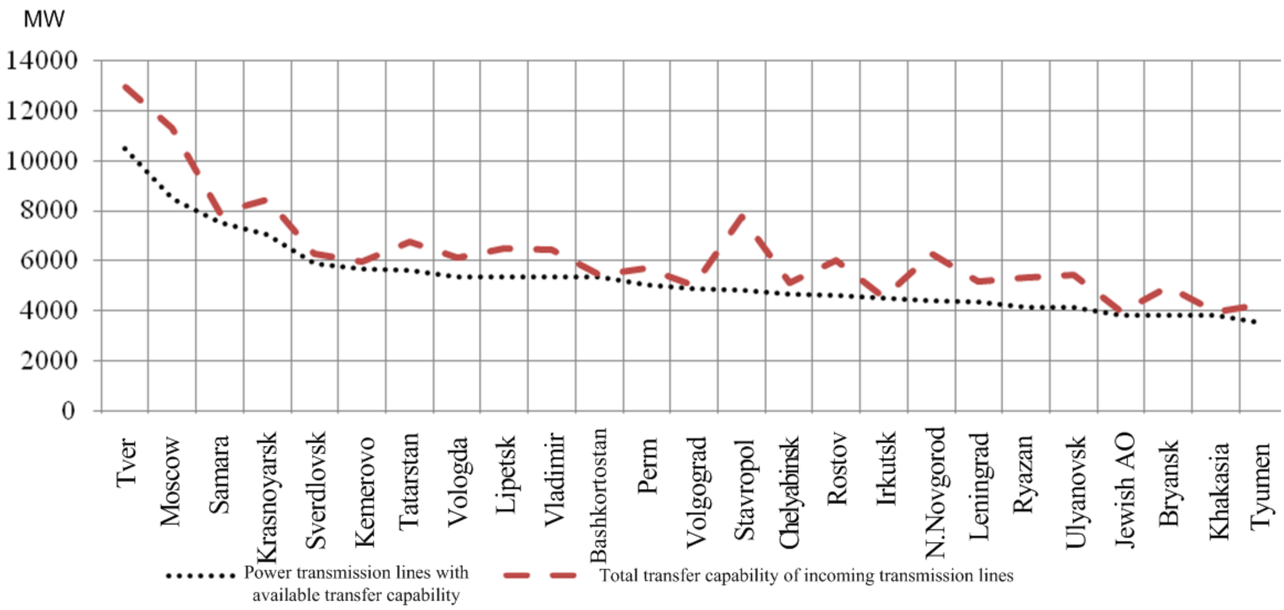

Fig. 4. Transfer capability of incoming transmission lines (MW).

initially have a power shortage and receive flows from the outside. The right-hand side shows redundant systems. The systems with relatively small flows in the center are not indicated in the Figure. As seen in the Figure, systems receiving the greatest power inflow are those of the Krasnodar Territory, the Belgorod Region, and Moscow Region; and the systems of the Kostroma Region, Stavropol Territory, and the Kursk Region show the greatest output. At the same time, almost all systems have the available transfer capability of their incoming power lines.

The value of the available transfer capability of the transmission lines incoming to regional systems, as shown in Fig. 4, is used to identify the power systems that are most suitable for placing generating capacity with subsequent power output to neighboring systems without significant expansion of the power grid. These are the systems of the Tver Region, Moscow Region, Samara Region, Krasnoyarsk Territory, and others.

To determine the power systems with the lowest cost of connecting new consumers, we performed a series of calculations with the criterion of maximum excess values of individual systems (model 2). The results of these calculations are shown in Fig. 5.

We give the values of excess power during local optimization of regional power systems, their values during optimization of the total excess in Russia (based on the previous calculation), and the difference between these values, i.e., an increase in excess capacity.

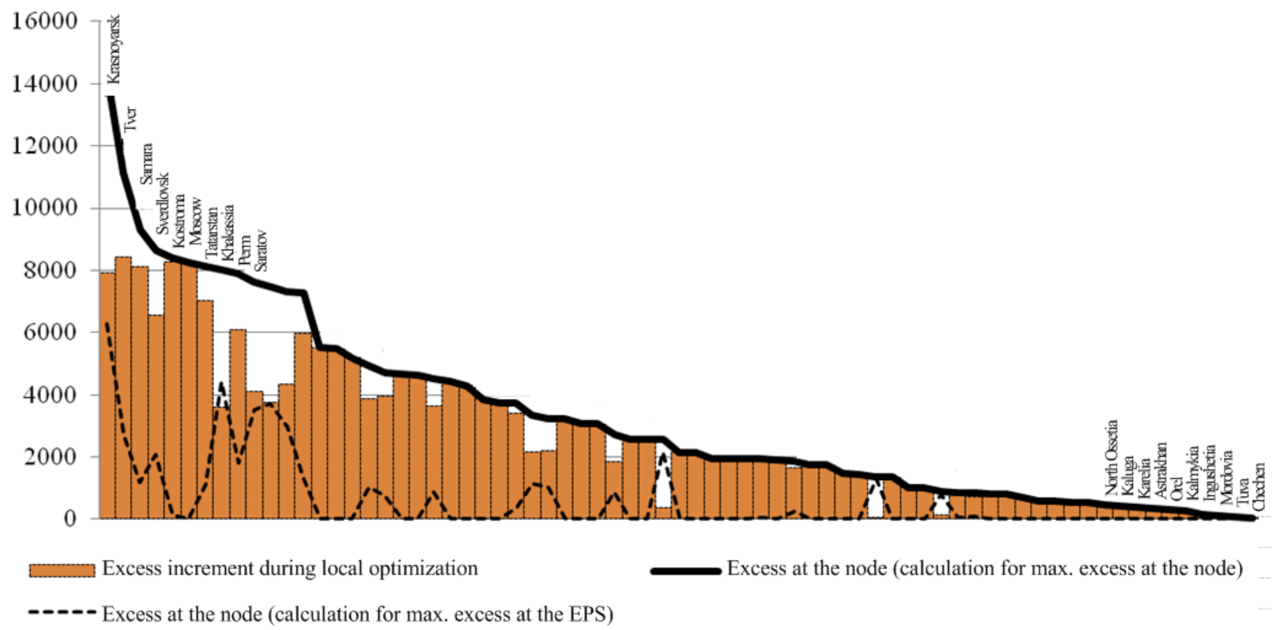

Fig. 5. Results of local optimization of excess capacity of regional systems (MW).

This Figure indicates that there is maximum excess capacity in the systems of Krasnoyarsk Territory, the Tver Region, Samara Region, Sverdlovsk Region, and others. The top ten of these power systems coincide with the list of the top systems identified according to the global optimization results only partially (6 out of 10) (see Fig. 2). Changes in this list are determined by the transfer capabilities of the power lines incoming to these nodes.

The largest values of the growth in local excess capacity relative to excess capacity in the case of global optimization are in the systems (the Tver Region, Moscow Region, Kostroma Region, and others) with maximum power output and the highest available transfer capability of the connected lines shown in Figures 3 and 4.

III. Conclusion

1. We have proposed a methodology for assessing the energy potential of Russian regions using mathematical models for calculating the excess capacity of power systems.
2. Under the assumed initial conditions, there is a significant excess capacity of about 42 GW or 18% of the total available capacity of power plants in the existing Unified Energy System of the country as of the end of 2020.
3. The calculations have revealed the regions with the highest energy potential. These are the Krasnoyarsk Territory, Tver Region, Samara Region, Sverdlovsk Region, Kostroma Region, and Moscow Region. The total potential of the ten nodes being the best in terms of this characteristic is high and amounts to about 75% of the overall potential of Russia's power systems.
4. The least potential is available in the Chechen Republic, Mordovia, Ingushetia, Kalmykia, Orel Region, Astrakhan Region, and others.
5. The cross-regional power grid of the UES of Russia can cover the power needs of all the country's power systems, and almost everywhere has significant available transfer capabilities of power transmission lines.

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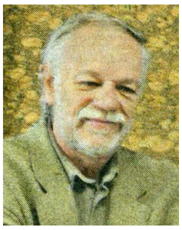

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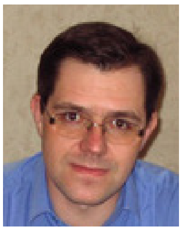

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Prospects for the Development of Geothermal Energy Supply

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***Abstract* — The paper addresses methodological and technological issues of building environmentally friendly and efficient energy supply based on geothermal energy sources. Geothermal potential in the world, accentuating that in Russia (areas of the Baikal natural territory) and Mongolia, is analyzed considering the possibility of its implementation in the thermal power industry.**

Geothermal areas of Central Mongolia are characterized by increased heat flows and occurrences of thermal waters. The most promising thermal spring occurrences are the Shivert, Shargalzhuut, Tsenkher, Otgontenger, and Khuzhirt, to name some of them. Currently, the thermal energy potential of the Khangai arched uplift in Central Mongolia is employed to heat industrial, agricultural, and civil facilities. There are also plans to consider the possibility of large-scale employment of thermal waters of the region for electricity generation.

An example of using geothermal waters for electricity generation is given, and the possibility of establishing a heating system in the city of Tsetserleg based on a geothermal heat pump unit with a wind power plant is assessed.

***Index Terms*: geothermal energy, heat pumping stations, heat supply, geothermal power plant, integrated energy system**

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I. Introduction

The research and practical use of geothermal resources have been increasingly attracting the attention of the world community lately. They seem relevant for both the study of resource reserves and their extraction and the expansion of the scope of practical application. Depending on the temperature difference, geothermal resources can be used to generate either electricity or heat. The greatest field of geothermal heat application as hot water is heating, which requires a lower heating agent temperature. Expansion of such heat application becomes possible with the development of the market for non-conventional equipment and its availability. A heat pump is often installed to increase the temperature potential in the heating system to coordinate the temperature charts of the heat carrier supplied and used by consumers. Renewable energy sources can be employed in integrated sources with gas turbines and fossil fuel cogeneration plants. This paper considers their design solutions and possible use.

II. Potential of Geothermal Resources in the World

One of the current trends in global renewable energy development is the involvement of geothermal energy resources in the energy supply. The total installed capacity of geothermal power plants is currently 16 GW. It is certainly a low value compared to the capacity of other renewable energy sources, not to mention fossil fuel energy. In many regions, however, only the energy of the Earth can provide the population with cheap heat and electricity. The potentialities of different types of geothermal energy resources by region are shown in Table 1 [1].

According to Rystad Energy (Rystad Energy is an independent energy research and business intelligence company providing consultancy services, an located in Oslo, Norway), the industry will receive $ 25 billion in investments over the next five years and increase its

TABLE 1. Potential of different types of geothermal sources in the world

Continent	Geothermal source type		
	High-temperature, used for power generation, TJ/year		Low-temperature, used as heat, TJ/year (lower limit)
	Conventional technologies	Conventional and binary technologies	
Europe	1 830	3 700	>370
Asia	2 970	5900	>320
Africa	1 220	2 400	>240
North America	1 330	2 700	>120
Latin America	2 800	5 600	>240
Oceania	1 050	2 100	>110
World potential	11 200	22 400	>1 400

TABLE 2. Geothermal power plants in Russia (2017)*

Name of geothermal power plant	Installed capacity	Generated electricity, MWh	Year of commissioning the first unit	Year of commissioning the last unit	Owner	Location
Mutnovskaya	50.0	329 180	2003	2003	JSC “Geoterm”	Kamchatka Territory
Pauzhetskaya	12.0	42 896	1966	2006	JSC “Geoterm”	Kamchatka Territory
Verkhne-Mutnovskaya	12.0	62 876	1999	2000	JSC “Geoterm”	Kamchatka Territory
Total	74	434 952				

* – based on the data of 6 TP

capacity to 24 GW, which will lead to large-scale drilling operations and positively affect the workload of oil and gas service companies. Whereas the number of wells drilled in 2019 was more than 220, in 2025, this figure will grow to 400 [2]. Preparation of wells accounts for up to 40 percent of the costs of a geothermal plant, whereas the other part is the costs of surface infrastructure.

In general, more than 60 countries use geothermal energy in economic activity around the world. The same number of countries conduct research and experiments on its use. Geothermal sources, for example, meet a third of Iceland’s energy demand and account for 27 percent of the Philippines’ energy production.

III. Development of geothermal energy supply in Russia

Russia is not among the leaders in harnessing geothermal and renewable energy in general (wind, solar, and earth heat). In 2020, their share in the country’s energy balance was no more than 1 percent. As mentioned above, the world’s total installed capacity of geothermal power plants in 2020 exceeded 16.0 GW. In Russia, the capacity of geothermal power plants is 74 MW, which is also less than one percent in the capacity structure after decommissioning the two geothermal power plants on the Kuril Islands of the Sakhalin Region (in 2010, this figure was 81 MW) [3].

At the same time, the geothermal sources in Russia seem to be a rather promising strand and can be a serious alternative to fossil fuels according to economic and environmental criteria. The technical potential of geothermal resources is about 100 million t.c.e./year, and the economic potential reaches 30 million t.c.e./ year.

The geothermal energy reserves in Russia are tremendous. According to expert estimates, they are 10-15 times higher than the reserves of fossil fuels in the country. There are geothermal energy reserves throughout almost the entire country, with temperatures ranging from 30 to 200 °C. About 4 000 wells have been drilled to a depth of 5 000 m, which allows switching to large-scale adoption of the most advanced technologies for local geothermal heat supply. Given that the wells already exist, energy production in most cases proves to be an economically efficient technology [4].

Despite the high potential, most geothermal sources in Russia are located economically irrationally. The Kamchatka Territory, Sakhalin Island, and the Kuril Islands are characterized by poor infrastructure development, high seismicity, hard terrain, and scarce population, which is justified by the lack of fuel resources and their complicated delivery scheme (Table 2).

Currently, three geothermal power plants (Paratunskaya, Mendeleevskaya (under reconstruction), and Okeanskaya) are removed from service.

The geothermal resources of the Krasnodar Territory, Stavropol Territory, and the Kaliningrad Region, which have reserves of thermal waters with a temperature up to 1 100 °C, are of much greater interest. There are also geothermal energy reserves in Chukotka, including those

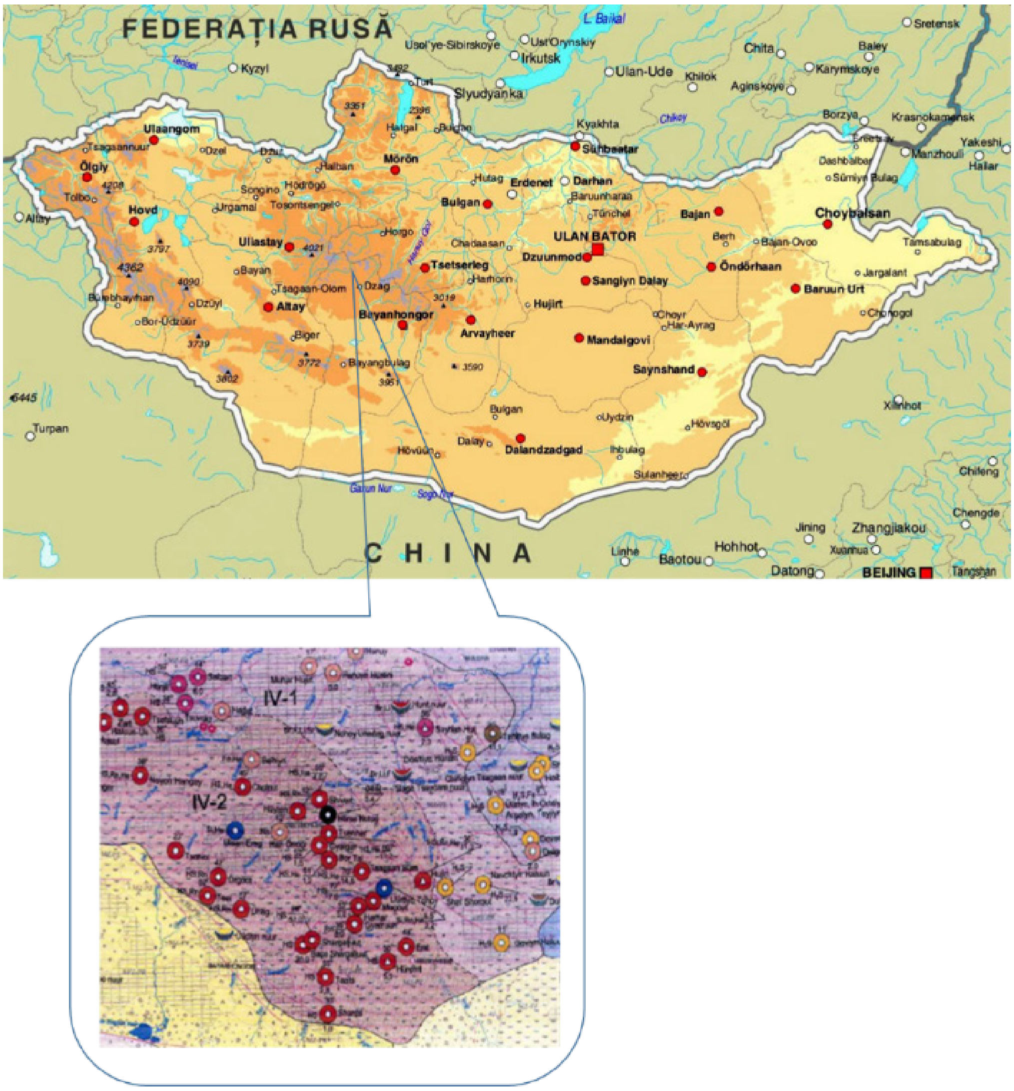


Fig.1. Map of Mongolia, Khangai hydrothermal system.

already discovered that can be actively used to supply energy to nearby settlements.

In the North Caucasus, there are well-studied geothermal deposits located at a depth of 300 to 5 000 m, with a temperature in the reservoir ranging from 70 to 1 800 °C. Geothermal resources have been used here for a long time for heating and hot water supply in agriculture, industry, and everyday life. For example, today, more than 30 percent of the housing stock in Dagestan is heated and supplied with hot water from geothermal sources, and this figure can rise to 70 percent.

Currently, about fifty geothermal deposits have been explored in Russia. Their use for geothermal energy development requires stimulating motivation and conditions for attracting investments. The introduction of geothermal energy into the energy balance of the country will, on the one hand, increase its energy security, and on the other hand, reduce the negative environmental impact compared to the conventional sources [5].

IV. Geothermal resources in the Baikal territory of Russia

The hydrogeological region of the Baikal rift zone is one of the world's hugest rift zones holding numerous thermal springs (up to 60 springs). The depth of the thermal waters varies from 750 m to 2 900 m, the water temperature of the springs is 20 to 82 °C, the flow rate is 1 to 85 l/s, the salinity rarely reaches one g/l. The largest and most heated springs are Alginsky, Allinsky, Bauntovsky, Garginsky, Goryachinsky, Gusikhinsky, Insky, Kotelnikovsky, Kuchigersky, Mogoisky, Pitatelevsky, Umkheisky, Khakussky, Cheloleksky, to name some of them [6].

There are four most noticeably distinguished such hydromineral areas in the territory of the Baikal region (*Torgashina MA Mineral springs of the Republic of Buryatia*). These are East Sayan (thermal and cold carbonic waters), Baikal (nitrogen and methane thermal waters), Selenginskaya (cold non-carbonated radon waters), and Daurskaya (cold carbonic and radon waters) regions.

The maximum heat flow in the territory under

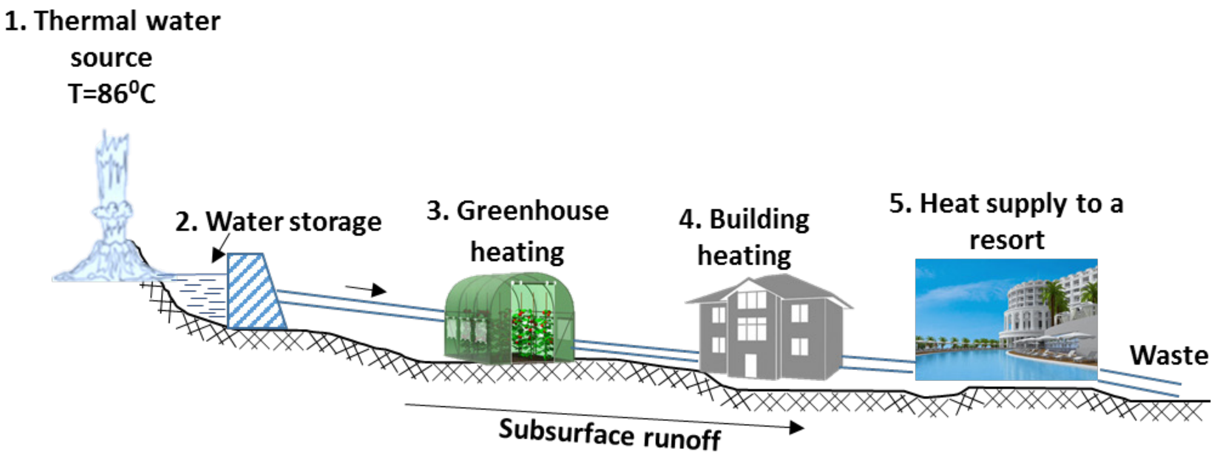


Fig.2. A diagram of a heat supply system based on a geothermal source.

consideration falls on the northern part of the Barguzin depression, in the area of the Allinsky, Kuchigersky, and Umkheisky thermal springs. However, the water temperature for these sources differs significantly because thermal springs are diluted by surface and ground waters due to fracture and vein formations.

V. Geothermal resources in the Republic of Mongolia

Over the past two decades, researchers have conducted general studies regarding the geothermal conditions in Eastern Siberia and Mongolia, including the southern part of the Siberian Platform, the Baikal rift zone, the Baikal fold region, and Mongolia (four areas differing in geological and tectonic conditions). The structure of the continental crust in the provinces of Mongolia is highly heterogeneous – its age varies from the early Riphean to the late Cenozoic era. Nearly 43 geothermal sources have been discovered to date in the country, but their use is very limited [7].

Reserves of thermal springs in Mongolia (in particular, in the Khangai open-pit mine) significantly exceed the energy demand of consumers. Fig. 1 shows a map of Mongolia with a dedicated zone of geothermal sources, which has prerequisites for switching from boilers running on fossil fuel to thermal power plants operating on geothermal energy to provide heating to consumers.

It is worth noting that the thermal water (TW) parameters depend on several factors:

- the depth of extraction, which is associated with capital expenditures for the construction of well;
- the location of the wells and the distance of the heating agent transportation to the consumer;
- geothermal parameters of thermal water (flow rate, temperature, and pressure at the outlet, mineralization of thermal water, chemical composition, and others).

An important parameter characterizing the thermodynamic efficiency of a thermal source is the temperature gradient for every 100 m of depth, which is very important to arrange heat supply to local and dispersed consumers.

When extracting thermal water of the said well outlet temperatures, the temperature can vary significantly depending on the well drilling depth. The range may depend on the well location and other hydrogeological conditions.

Natural resources of thermal waters on the territory of the Khangai arch in Mongolia are estimated at 17 044 m^3/day. Hydrothermal fluids emerging from the depths to the surface have a value of 1 880.926 GJ/day of energy potential.

Geothermal areas of Central Mongolia are characterized by increased heat flows, outlets, and deposits of thermal waters. The most promising areas for exploring hydrothermal waters are those that have experienced the intense influence of the newest tectonic movements and volcanism, mainly located in folded areas. Thermal waters here have local development and are of a fraction-vein type. The areas of the Khangai arched uplift, where the Shivert, Shargalzhuut, Tsenkher, Otgontenger, Khuzhirt deposits, and other hydrotherms are located, should be considered the most productive ones [8, 9]. Their operational thermal water reserves are approved by the State Commission for Reserves in the highest categories (A, B, C). At present, in Central Mongolia, the heat and power potential of the Khangai arched uplift is used insignificantly for heat supply to industrial, agricultural, and civil facilities, which is why the possibility of an integrated large-scale use of the region's thermal waters is considered.

The proposed schematic diagram of a heat supply system intended for heating greenhouses, and providing heating and hot water to residential buildings and health resorts is shown in Fig. 2.

Thermal waters of granite massifs in the region are widely distributed but limited in resources that do not exceed 3–5 l/s or amount to 10 l/s in exceptional conditions, with their (outlet) temperatures about 90–96 °C.

Geothermal resources of Mongolia can be divided into four types in terms of their use: balneology and sanatorium

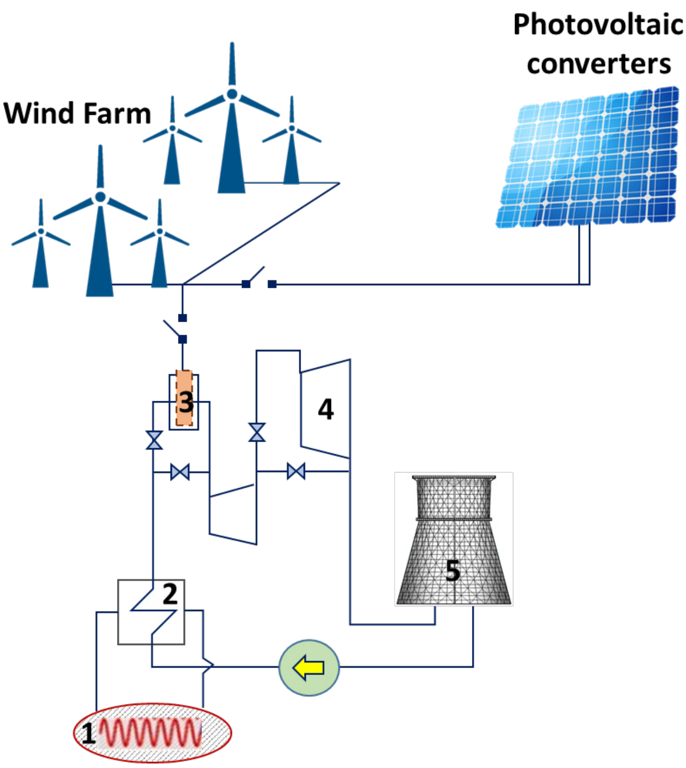


Fig. 3. Combination of GeoPP with WPP and PVP: 1 – geothermal heat source; 2 – steam generator; 3 – low-temperature heating elements; 4 – parts of high and low-pressure steam turbine; 5 – «dry» cooling tower as condenser.

services, heat supply, agriculture, power supply. Heat supply based on thermal waters in Mongolia was provided mainly through the construction of small heating facilities, hot water supply, and balneology. In 2016, Japanese specialists, for the first time, installed a plant at the Tsenkher resort and produced electricity for hotel facilities [10].

The term «thermal energy water» usually means natural hot groundwater that can be used in the national economy as a source for heat or thermal energy production. At the same time, the main criterion for classifying thermal water as a thermal energy resource is its temperature. Like other types of groundwater used in the national economy, thermal waters are minerals and belong to the complex raw material to be used not only for medicinal purposes but also as a source of extraction of valuable elements and their compounds for various technological needs.

Water used for thermal energy has a temperature above 35–40 °C. In this case, the lower value of the water temperature for heating the protected ground during balneological procedures is 35 °C, and the lower limit of the water temperature for hot water supply is 40–45 °C. Based on the experience of using thermal waters, they are divided into low- and medium-potential ones. Medium-potential waters (with a temperature of 70–100 °C) are used for the needs of heat supply. These waters can be effectively used for heat supply to industrial, agricultural, and municipal facilities. The efficiency of using such waters for heating can be significantly enhanced by equipping heat consumers with heating and ventilation systems optimized for low and medium-potential heating agents, including their combination with heat pumps.

VI. Current Challenges for Geothermal Energy

There is a great deal of positive experience in using geothermal energy for energy supply to consumers. However, some issues limit the scope of this renewable energy resource and need resolving. The most significant of them are:

1. A relatively low temperature potential of a heating agent, which significantly depends on geothermal conditions of the area and the depth of occurrence of a productive natural or artificial reservoir. The temperature of the heating agent supplied to the consumer can be controlled by raising it in peak boiler houses or with heat pumps, which increases the costs and decreases the competitiveness of geothermal power plants.
2. The limited range of the heating agent transport due to its low heat content and high cost of heat pipelines for energy transmission over long distances.
3. The difficulty in heat storage. Heat storage in the form of hot water in tanks is possible only to smooth out the temporary irregularity of the daily heat load curves or in the event of a short-term shutdown of the geothermal circulation system [11].

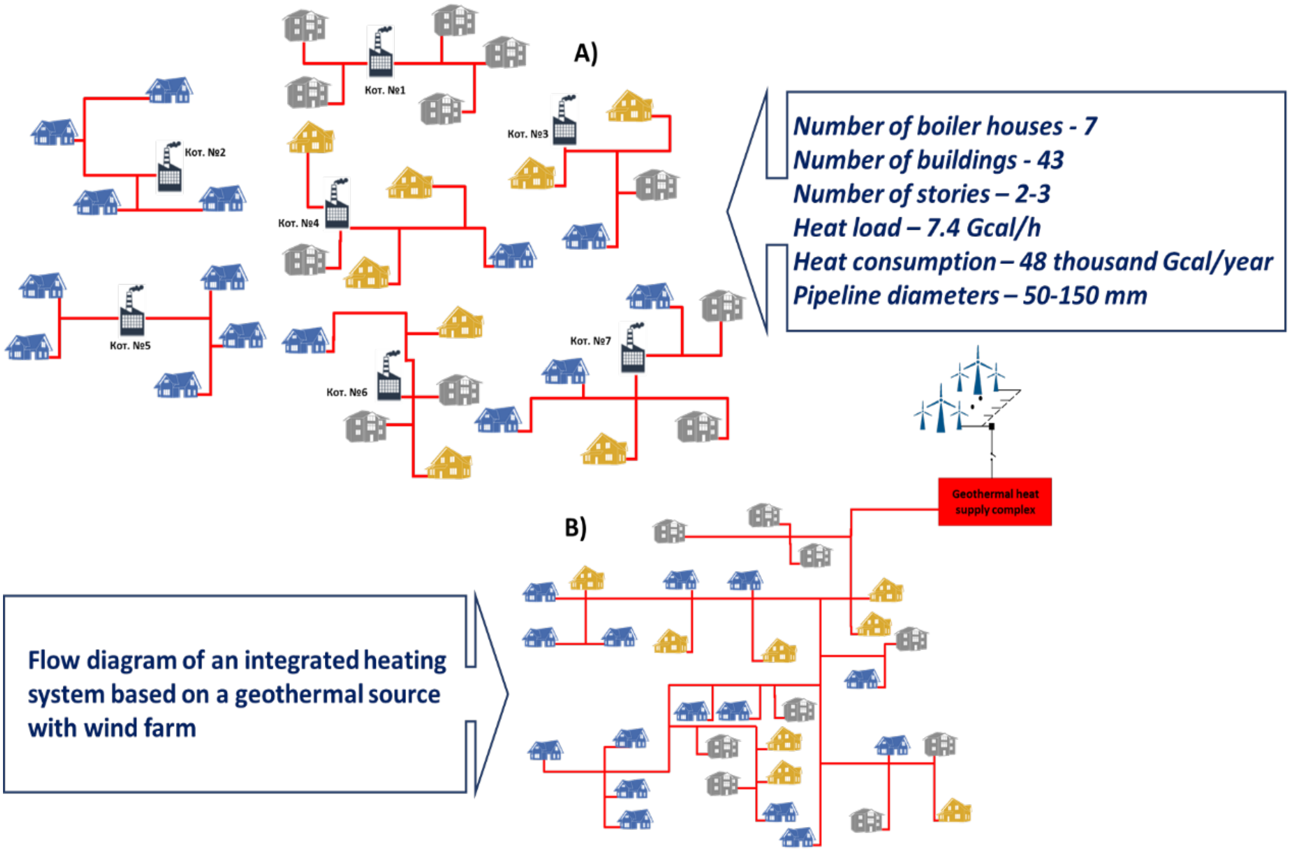


Fig. 4. Flow diagram of heat supply in Tsetserleg: (A) existing and (B) proposed.

4. Large amounts of work and costs due to the lack of effective technologies to explore and develop new deposits.
5. Significant content of minerals, which leads to high levels of salt deposition and corrosion of materials and equipment.
6. Low heat content of geothermal resources, which complicates their use for electricity generation.
7. Substantial environmental impact.

The above issues of using geothermal energy suggest that its practical use requires considerable capital investment in the construction of wells. High mineralization of thermal waters leads to corrosion that destroys the structures of geothermal power plants, which is why it is necessary to develop systems for periodic and constant cleaning of pipes, pumps, and shut-off valves, which increases the cost of operating geothermal plants.

VII. Creation of Integrated Systems to Improve the Efficiency of a Geothermal Power Plant

The increase in the efficiency of geothermal heat and expansion of its application scope can be achieved by integrating double-circuit geothermal power plants (GeoPPs) [12] with wind power plants (WPP) and solar plants based on photovoltaic converters (PVP). This integration allows additional steam superheating for a steam turbine unit (STU) operating on a working medium with a low boiling point. The use of low-quality electricity from WPP and PVP for superheating steam in low-temperature heating elements (HE) eliminates many problems that arise when they are directly connected to the power system (Fig. 3) [13–17].

The efficiency of such a geothermal power plant increases to a boost in the efficiency and power resulting from the rise in upper temperature of the STU cycle and a decrease in the lower temperature of the cycle (possibly to negative values) in winter since admissible steam humidity in the last turbine stages is provided even under increased degrees of its expansion. Thus, the temperature difference between the geothermal source and the surrounding air is more fully used. This plant can be equipped with a low-pressure turbine part (LPP), which is used only in the winter period, by analogy with T-type turbines, in which LPP is used for condensing power generation. The STU operates at sliding steam pressure at the bottom of the thermodynamic cycle (at the turbine outlet), as in conventional steam turbine TPPs working at sliding steam pressure at the top (at the turbine inlet). Operating conditions of the plant are regulated by redistributing the WPP/PVP electricity among heating elements of GeoPP, peak electric boiler houses, and energy storage devices if the latter are available.

Recently, there has been a significant decrease in the cost of PV plants. However, this decrease is insignificant

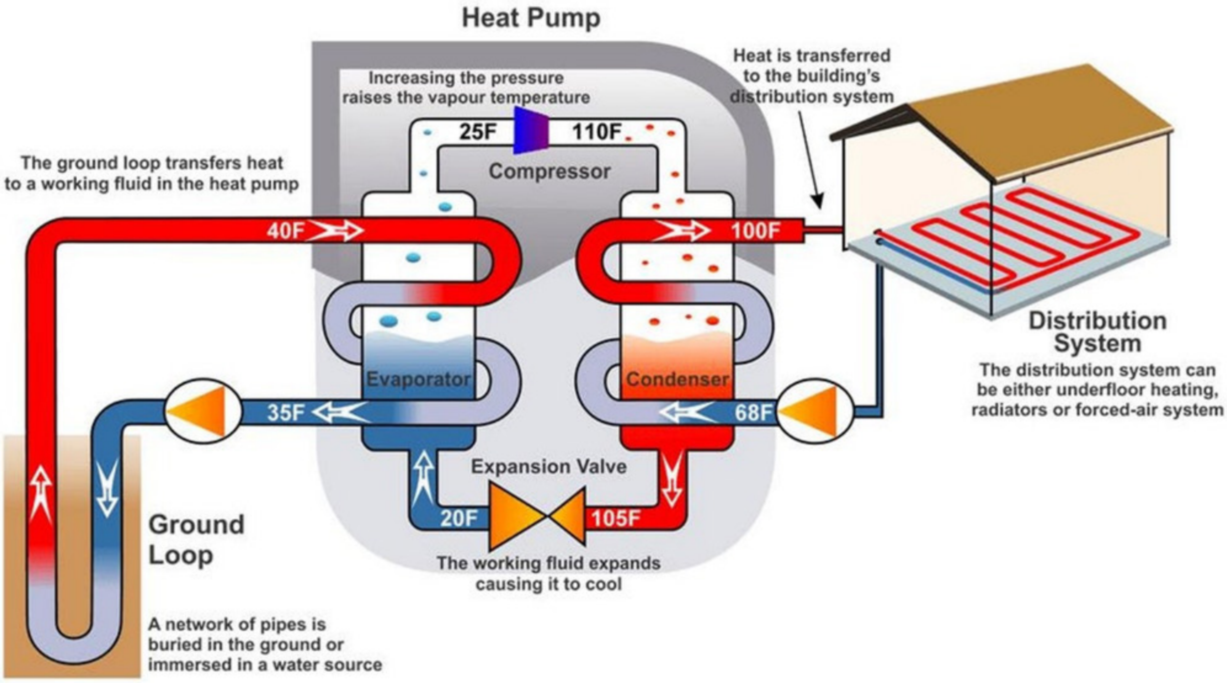
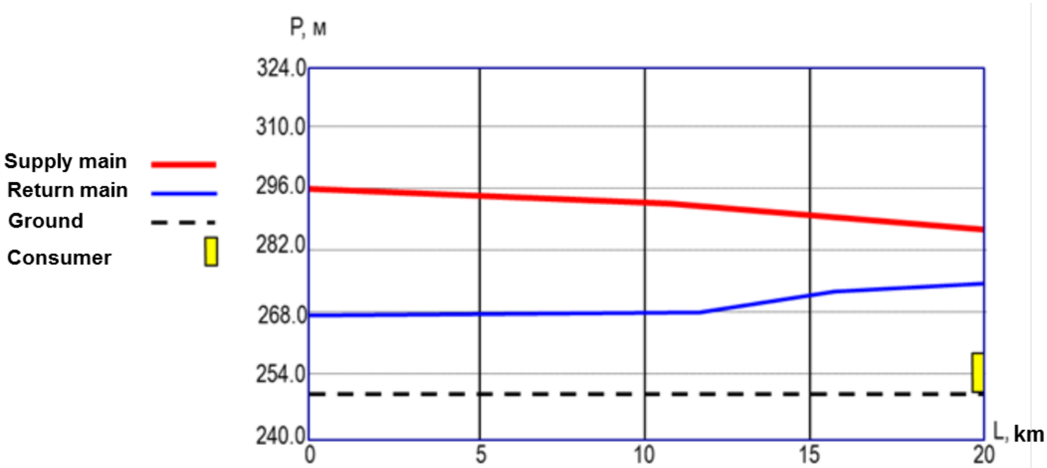


Fig. 5. Flow diagram of a heat pump using thermal waters.



	HPI	tc-1	tc-2	tc-3	Consumer-4
Diameter (sup./ret.) (mm)	250/250		250/250	150/150	150/150
Flow rate (sup./ret.) (t/h)	260/260		217/217	78/78	43/43

Fig. 6. Piezometric graph between HP valve vaults, consumer 4.

due to the need to have expensive rectifiers, inverters, transformers, switches, and others. Since the proposed diagram suggests that GeoPP should replace storage, inverter, and step-up transformer, it is logical to include PVP in the GeoPP through STU. Solar and wind energy is most efficiently used together in one power complex since the change in their active operation usually occurs in antiphase. When GeoPP operates on steam, the erosion effect on turbine blades goes down due to its overheating with a corresponding decline in humidity. Working medium (low-temperature or water vapor) can be tapped from the turbine extractions to the heating system water heaters.

The use of heat pumps in geothermal power supply technology seems to be an effective measure to increase the efficiency and scope of application. Heat pumping units (HPUs) can significantly reduce either the consumption of thermal water from debit wells or their number (all other things being equal). Thus, the combined thermal power plant based on a thermal source and an HPU may become more technically accessible for heat supply according to the temperature chart of the heat output (depending on the outside air temperature).

Table 3. Payback period of the heat pump-based heating system in Tsetserleg versus the distance to the geothermal source

Option No.	Distance from the source to the city, m	Cost of the pipeline network, given the intracity networks, RUR mln	The cost of HPU with a pipeline network, RUR mln	PAYBACK period, years
1	0	9.2	68.5	3.9
2	1 300	39.7	99	5.6
3	2 500	76.3	135.6	7.7
4	5 000	152.5	211.8	12.1
5	7 500	228.8	288.1	16.4
6	8 000	244	303.3	17.3

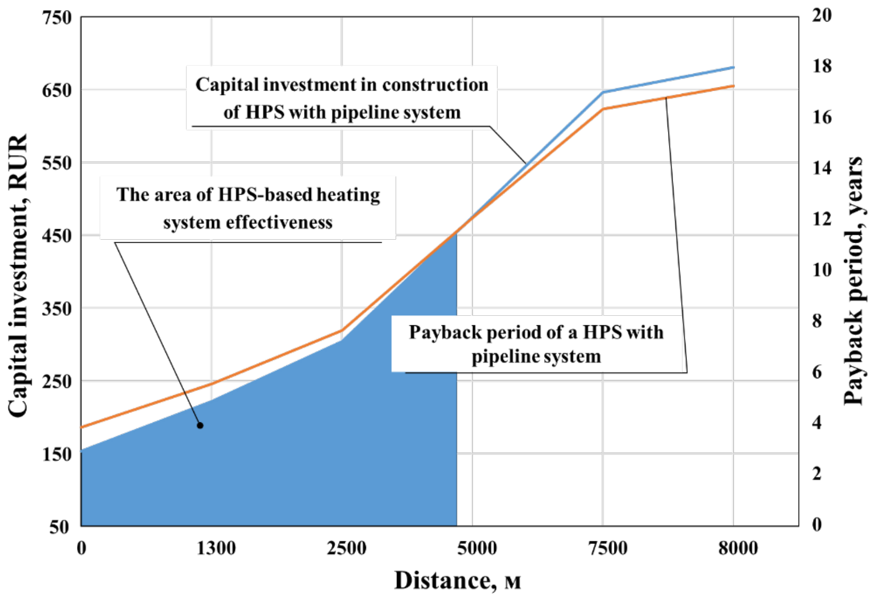


Fig. 7. Investment and payback period for HPS with a pipeline network.

A feasibility study on the efficiency of heat pumping stations (HPS) for heat supply purposes should consider that HPS characteristics should be calculated for the longest period of low ambient temperatures in the region. With this approach, the consumption of thermal water and electricity for the drive of the heating pump motor will lead to the overestimation of cost indices, which may not always be justified. For example, if the continuous duration of low temperatures does not exceed 10–15 days.

Heat pumps can provide heat energy needs with specified parameters both for an individual consumer (autonomous) and for local group consumers (4–10 private buildings) or district heating (for urban-type settlements).

VIII. Geothermal heat supply system design

Within the cooperation between the Siberian Branch of the Russian Academy of Sciences and the Mongolian Academy of Sciences, the research team considered several localities in Siberia of the Russian Federation and Mongolia that were supposed to be provided with geothermal power. The city of Tsetserleg, with low-efficiency coal-fired boilers (with geothermal deposits located in its area), proved to be the most preferable.

At present, the city receives heat from 7 coal-fired boiler houses located in the city center (Fig. 4), which significantly pollutes the environment. The distance of coal transportation is 253 km. The heating system is dead-end. There are 4–6 buildings connected to each boiler house, with the tallest building 8.4 m high. The diameter of the heat network pipelines varies from 50 to 150 mm.

The annual heat consumption of the city is about 47.6 thousand Gcal/year. Construction of HPS running on geothermal water and its commissioning will provide thermal energy for heating, ventilation, and hot water supply to the city.

The heating system of Tsetserleg can be converted to a geothermal system with the help of an HPS, which includes four heat pumps connected in series. In this case, three circulation circuits of heating agents are formed (Fig. 5), including:

1 – geothermal water;

2 – working fluid of the heating pump;

3 – network water of the city heating system.

Calculations of the heat supply system from a single source show that such a system has good operability but requires a relatively considerable investment in the heat pipeline construction from the geothermal sources «Tsenkher» and «Shivert» to the city, 15 km and 20 km long, respectively. Fig. 4 shows a diagram of the existing heat supply system of the city and a diagram of heat supply from a single geothermal source with a WPP.

The piezometric graph (from this source to the most distant urban consumer) obtained from the calculation is shown in Fig. 6. It testifies to the feasibility of the thermal-hydraulic conditions of such a heat supply system.

A long-range heating agent transport significantly increases investment in the geothermal heat supply system and leads to insufficient competitiveness versus coal heat sources.

In recent years, new large reserves of geothermal resources with a relatively high water temperature, sufficient for heating, have been discovered. Some of them are located at a shorter distance from the city (about 8 km), and others are located directly on its territory. The close location of geothermal sources from the heat consumption centers can significantly reduce investment in the heat networks construction and enhance system efficiency. New geothermal sources have good technical and economic indices:

- considerable resources at the accessible depth;
- the proximity of deposits to the consumption center;
- transportability without significant heat loss.

Relatively shallow drilling of wells (50–100 m) and high water temperature contribute to a significant reduction in the cost of the geothermal heating system for the city.

Pipelines with polyurethane foam insulation were considered for heat transportation in the heating system of Tsetserleg. They have low heat losses (within 2%), high reliability, and guaranteed service life of up to 50 years. These factors make it possible to reduce the cost of maintaining heat pipelines by nine times and cut the capital expenses of constructing heat networks by 1.2 times compared to the traditional construction of pipelines. The construction time of heat networks with polyurethane foam pipelines laid without channels is reduced by 2.5–3 times.

Systems of operational remote control (ORC) to be installed in pipelines with polyurethane foam insulation allow additional remote monitoring of the heating main state to prevent accidents and their prompt elimination. The ORC system sensors, based on time-domain reflectometers, detect the place of occurrence of a steel pipe defect with an accuracy of one meter.

Depending on the distance between the geothermal source and the heat load center, investment in the pipeline network can vary from RUR 9.2 to 245 million.

The efficiency of a heating system to be based on a geothermal source will be determined by a decrease in the fuel component in the heat cost price.

Table 3 shows payback periods for the heating system of the city of Tsetserleg versus the distance between the geothermal source and the heat load center.

Calculations show that the closer the geothermal source to the load center, the more efficient is a heating system based on it.

Fig. 7 shows graphically the relationship between the costs and payback periods depending on the distance between the geothermal source and load center, along with the efficiency zone of adopting the HPS-based heating system.

With a payback period of up to 8 years, it is efficient to transport geothermal energy at a distance of up to 4 km from the heat load center.

Heat pumping station using geothermal heat will reduce harmful emissions of SOx, NOx, particulate matter, and fluoride compounds, which will decrease the environmental impact significantly. The improvement in the environmental situation, displacement of expensive imported coal will pay off the investment and make this project economically attractive.

IX. Conclusions

The generalization of the experience of using heat pump technology in the world practice and the technical and economic calculations performed in this work to assess the HPS feasibility for heat supply to consumers allowed formulating the following:

- for geothermal energy to be used in heating and hot water supply, it is advisable to employ heat pumps. They allow the use of sources with low-temperature geothermal water, which makes it possible to involve not only large high-potential geothermal deposits but also local low-potential sources of geothermal waters located near the consumer;
- heat pumps fit well into the existing heat supply system, as they are environmentally friendly, reliable, safe, durable plants that can reduce both the consumption of geothermal water supplied from a well and the number of these wells (all other things being equal);
- inclusion of HPS in the geothermal heat supply system ensures the technical and economic availability of heat supply with the possibility of regulating thermal energy supply to consumers, according to the output temperature chart, depending on the outside air temperature;
- the HPS efficiency potential can be increased, and the scope of applying renewable resources in Mongolia and other territories can be expanded by involving wind energy in an integrated energy complex to be established.
- Assessing general situation in geothermal energy, it is worthwhile to note that despite the existing issues, it has seen significant advancement in recent years, which is largely due to the improvement in technologies and the expansion of the market for new equipment:
- the efficiency of geothermal sources rises significantly with their integrated use, which provides the completest implementation of the geothermal water thermal potential, including residual one, in various technological processes, and allows the production of

valuable components contained in this water (iodine, bromine, lithium, cesium, sodium sulfate, boric acid, and many others) for their industrial use;

- the development and application of new effective methods of water purification from toxic compounds and metals continuously reduce capital costs of producing heat from geothermal sources;
- the geothermal resources of the Shivert, Shargalzhuut, Tsenkher, Otgontenger, Khuzhirt, and other deposits of the Khangai arched uplift are currently most promising for practical use. They can be widely employed in heating and hot water supply to resorts, various populated areas, including large cities, and in the development of greenhouse farms and balneological centers;
- the intermittent electricity from WPP and PVP for steam superheating can boost the efficiency of GeoPP by increasing the upper and average integral temperature of heat input in the cycle, enhance the efficiency and power of the power plant, reduce erosion damage to turbine blades, and extend the life of wells and deposits;
- the concept of an integrated power system removes technological restrictions on the level of wind and solar energy in power systems, which increases the environmental safety and economic viability of geothermal energy and makes it competitive in relation to conventional methods of electricity and heat generation. In addition, the integration of energy technologies helps reduce the consumption of fossil fuels, expands the use of renewable energy sources without the expensive batteries, and fosters the reduction of CO2 emissions without using expensive technologies for their disposal.

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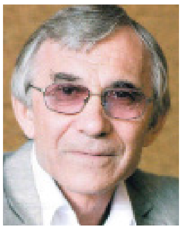

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Thermodynamic Analysis of Air-Blown Staged Gasification of Coal in a Flow

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***Abstract* — One of the ways to environmentally friendly use coal is an integrated gasification combined cycle. The most common oxidizing agent employed in gasification is oxygen. It is feasible to use air instead of oxygen to reduce the cost of generated electricity. The air gasification downsides can be reduced by using heated air and organizing a staged process. The paper is concerned with a thermodynamic analysis of the MHPS (Mitsubishi Hitachi Power Systems) air-blown staged gasifier. The analysis relies on an original approach that suggests investigating experimental data on a set of calculated ones. The experimental run nears the thermodynamic optimum, which coincides with the carbon boundary line. Cold gas efficiency can be increased from 78.6 to 81.5% by reducing the equivalence ratio. Thus, the temperature will decrease from 1 200 to 1 100 °C. The experimental run of the MHPS gasifier is not optimal thermodynamically, but it is probably optimal kinetically. The fact is that the rates of heterophase reactions decline near the carbon boundary, which leads to a sharp increase in fuel underburning and a decrease in efficiency. The experimental run is also located close to the region with the maximum thermal efficiency of the process, which is indicative of the high efficiency of converting air heat into chemical energy of producer gas.**

***Index Terms*: coal gasification, entrained-flow, thermodynamic modeling.**

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I. Introduction

Gasification is the thermochemical fuel conversion, which involves gaseous oxidants, solid oxidants, or supercritical water [1, 2]. The main product of this process is combustible gas used for energy purposes or as a chemical raw material. One of the main options for environmentally friendly use of fossil coal is the technology of its integrated gasification in combined cycle (IGCC) [3, 4]. Most operating IGCCs include an entrained-flow gasifier operating on oxygen or its mixtures with steam (Table 1). Two large plants use air as a gasification agent. These are the Nakoso IGCC plant in Japan and Kemper Country energy facility in the USA. Such a small spread of this type of gasification agent is due to the following air gasification downsides:

- low degree of coal conversion in the reactor, which requires coke recycling;
- low heating value (LHV) of the produced gas and the related problem of its stable combustion in the combustion chamber of a gas turbine [5];
- relatively low cold gas efficiency of air gasification;
- the complexity of organizing the removal of liquid slag in comparison with the high-temperature oxygen process.

A significant advantage of air gasification is the absence of an air separation unit. It increases capital costs of the construction of a plant and auxiliary power supply. The relatively low gas temperature at the gasifier outlet makes it possible to use the high-temperature part of the recovery boiler for gas cooling.

Compressed air can be supplied to the gasifier from the turbine compressor. It heats up to 500 °C when compressed [10]. Further heating of air to 700-1 000 °C can reduce the above air gasification disadvantages, thereby improving the gas heating value, the degree of coal conversion, and cold gas efficiency. Some researchers work on gasification with heated air [11-13]. These studies use biomass and wastes as fuel.

TABLE 1. Characteristics of the main operating IGCCs [6-9].

Year of commissioning	Plant	Country	Size, MWth	Gasifier type	Agent type
1994	*Buggenum*	Netherlands	253	Shell, entrained-flow	Oxygen/steam
1995	*Wabash River*	USA	262	E-Gas, two-stage entrained-flow	Oxygen
1996	*Tampa Polk*	USA	250	Texaco, entrained-flow	Oxygen
1998	*Puertollano*	Spain	335	PRENFLO, entrained-flow	Oxygen
2002	*Wakamatsu*	Japan	170	EAGLE, two-stage entrained-flow	Oxygen
2005	*Vresova*	Czech	400	Lurgi, fixed-bed updraft	Oxygen/steam
2007	*Nakoso*	Japan	250	MHPS, two-stage entrained-flow	Air
2014	*Kemper County*	USA	524	TRIG, entrained-flow	Air

Another method for improving air gasification is a staged organization of the process. Since 1981, the two-stage air gasification technology has been developed by Mitsubishi Heavy Industries jointly with the CRI (Central Research Institute of Electric Power Industries) [5]. These organizations have developed and tested several gasifiers of various sizes. These are a demonstration stand with a capacity of 2.4 t/d (1983-1995, location of Yokosuka Lab.), a semi-industrial gasifier with a capacity of 200 t/d (1991-1995, the Nakoso station, Fukushima), and an industrial plant with a capacity of 1 700 t/d (since 2007, Nakoso station) [14].

The paper aims to analyze the operation of the MHPS (Mitsubishi Hitachi Power Systems) gasifier. A thermodynamic analysis of this reactor was carried out earlier [10]. One-dimensional kinetic models were employed in numerical studies of the gasifier [15, 16]. The current work is grounded on an original thermodynamic approach, which makes it possible to analyze one or several experimental conditions on a set of modeled ones, and allows:

- estimating the efficiency of reactor and outlining ways to improve it;
- identifying the constraints preventing process optimization;
- evaluating the influence of various process parameters in terms of thermodynamics to identify primary and secondary ones among them.

This approach was previously used to analyze the conditions of biomass downdraft gasification [17].

II. METHODS AND APPROACHES

A. A thermodynamic model with macrokinetic constraints

A thermodynamic model that factors in the equilibrium in a closed reaction system [18] was used for modeling the experimental run (Table 1). The model maximized the entropy of the system. The constant parameters were pressure and enthalpy. Equilibrium is referred to as a convex programming problem:

find

$$\max S(x,T) = \sum_j S_j(x,T)\,x_j \tag{1}$$

subject to

$$\sum_{j=1}^{n} a_{ij} x_j = b_i,\ i = \overline{1,m}, \tag{2}$$

$$x_j \geq 0,\ \forall j = \overline{1,n}, \tag{3}$$

$$H_{hr} = \sum_j H_j\left(T^{in}\right) x_j^{in} - H, \tag{4}$$

$$H = \sum_j H_j\left(T\right) x_j, \tag{5}$$

$$x_k \geq \varphi\,(x, x^{in}), \tag{6}$$

where $S(x, T)$ is the total entropy of substances in the system and $S_j(x, T)$ is the specific entropy of substance. Index j refers to substances, whereas index i refers to chemical elements; $x = (x_1,\ldots,x_n)^T$ is the vector of substances amounts. Material balance is determined by equation (2), where a_{ij} is the number of atoms of element i in a molecule of substance j; b_i is the amount of substance of element i in the system.

The energy balance of the system is found by equations (4) and (5), where $H(x, T)$ is the total system enthalpy, and $H_j(T)$ is the substance enthalpy; H_{hr} is the heat exchange between the system and environment.

Expression (6) is a generalized macrokinetic constraint on the formation or response of a substance in the system [19]. The model takes into account the experimentally observed methane yield exceeding the equilibrium value with this constraint.

A software package consisting of two modules was implemented for calculations. The first module is a C++ program used to calculate chemical equilibrium. The second module is written in PHP and is used to form a computational matrix, optimize process conditions, process and output data in a client-server application.

Cold gas efficiency (%) is calculated as [20]:

$$CGE = \frac{LHV_{gas} V_{gas}}{LHV_{coal} m_{coal}} 100, \tag{7}$$

where LHV_{gas} (kJ/m^3) and LHV_{coal} (kJ/kg) are the low heating values of gas and coal, respectively; V_{gas} (m^3) is the gas volume; m_{coal} is the mass of coal. The thermal efficiency (%) of the process is calculated using equation (8), where Q_{air} (kJ/m^3) and V_{air} (m^3) are the heat and the volume of air, respectively:

$$TE = \frac{LHV_{gas} V_{gas}}{LHV_{coal} m_{coal} + Q_{air} V_{air}} 100, \tag{8}$$

TABLE 2. MHPS gasifier testing results

PARAMETER	VALUE	REF.
COLD GAS EFFICIENCY, %	77.2	[21]
COAL CONVERSION DEGREE, %	99.9	[22]
DRY GAS COMPOSITION, % VOL.		[22]
CO	30.5	
CO_2	2.8	
H_2	10.5	
CH_4	0.7	
N_2 AND OTHERS	55.5	
PRODUCER GAS TEMPERATURE AT THE GASIFIER OUTLET, °C	1 200	[23]
GASIFYING AIR TEMPERATURE, °C	500	[10]
HEAT LOSS THROUGH THE REACTOR WALL, % (OF COAL LOW HEATING VALUE)	2	[10]
REACTOR PRESSURE, MPA	2	[10]

Equivalence ratio (ER) is determined by equation (9) as the ratio of the actual amount of air ($V_{air,actual}$, m^3) to the amount required for complete (stoichiometric) combustion of coal ($V_{air,comb}$, m^3). In general, the equivalence ratio is characterized by the air/fuel ratio:

$$ER = \frac{V_{air,actual}}{V_{air,comb}}. \quad (9)$$

B. Equilibrium model input data

Data on a single start of the gasifier at the Nakoso plant with a capacity of 1 700 t/d are shown in Table 2. This experiment was carried out on Chinese coal with the following characteristics (% mass): C^{daf}: 82.00, H^{daf}: 4.86, O^{daf}: 12.05, N^{daf}: 0.92, S^{daf}: 0.17, A^d: 6.1, W^r: 5.6, V^d: 35.28 [10]. The high heating value of the coal was 30.2 MJ/kg (dry).

The input data of the equilibrium model are the initial composition of the reaction system, the intensity of its heat exchange with the environment (or temperature), and pressure. The initial composition of the reaction system is set following the chemical composition of the coal and air, and the equivalence ratio. The last parameter is not given in open sources. To calculate it, one should make the mass balance in the experiment or find it using a thermodynamic model. The latter was used since it opens up additional possibilities for analyzing the gasifier operation.

We can use the redundancy of available experimental data to search for the equivalence ratio. The task is reduced to finding an equivalence ratio (air/fuel ratio) such that the process temperature is 1 200 °C, and the heat loss is 2%, i.e., the temperature in the reactor rises with an increase in the air/fuel ratio and at a constant value of heat exchange. A decrease in this ratio leads to a decline in the reactor temperature. The temperature in the reactor will be 1 200 °C for a particular value of the equivalence ratio.

III. RESULTS AND DISCUSSION

A. Model verification.

The equilibrium composition of reaction products is compared with the experimental one in Table 3. The producer gas temperature at the reactor outlet is 1 200 °C. Concentrations of gas components are numerically the same. The model underestimates the carbon dioxide yield by 1.1 percentage point and overestimates the cold gas efficiency accordingly. The closeness of the modeled yield of substances to the experimental one is due to the reaction conditions favoring the attainment of

TABLE 3. Comparison of modeled and experimental results.

Parameter	Experiment [21, 22]	Equilibrium
Cold gas efficiency, %	77.2	78.6
Equivalence ratio, –	n.d.	0.406
Coal conversion degree, %	99.9	100
Dry gas composition, % vol.		
CO	30.5	30.5
CO_2	2.8	1.7
H_2	10.5	10.5
CH_4	0.7	0.7
N_2 and others	55.5	56.7
The gas temperature on the gasifier outlet, °C	1 200	1 200

a close-to-equilibrium state by the chemical system. These are a sufficient residence time of substances in the reactor, high temperature, and pressure.

B. Analysis of the experimental run on a set of equilibrium data.

A set of possible operating conditions of the gasifier can be calculated by varying two model parameters. These are the equivalence ratio and the heat exchange between the reactor and the environment. The result of this calculation is shown in Fig. 1. The equivalence ratio is changed with a step of 0.01, while heat exchange is altered with a step of 1% to accurately show the isolines in the Figure.

The isoline that reflects the zero equilibrium yield of the coke residue is called the carbon boundary line [17]. To the left of this line, a thermodynamically stable carbon residue is formed in the reacting system. Its yield increases to 0.1–0.4 kg/kg (coal) as the equivalence ratio decreases, and the thermochemical conversion process shifts to pyrolysis (region A) in this case. The cold gas efficiency of the process is reduced because carbon residue does not convert to a combustible gas.

Thermodynamic conditions for complete fuel consumption should be to the right of the carbon line. The equivalence ratio increases and the conversion process goes to the combustion region (region B). In this case, excessive oxidation of the gas combustible components with air occurs. The efficiency of the process also decreases.

The conditions located on the carbon boundary line are characterized by the maximum cold gas efficiency attainable at a certain level of heat transfer between the reaction system and the environment [17]. The Figure also shows temperature isolines that limit the conversion area to an interval of 300–2 000 °C. Fuel does not ignite below 300 °C. There is a problem with the thermal stability of structural materials of the reactor above 2 000 °C.

The experimental run of the MHPS reactor (point 1 200 °C) is not optimal from the thermodynamic point of view. It is located slightly to the right of the carbon boundary line but can be shifted to the boundary line when the equivalence ratio decreases to 0.384 and the temperature in the gasifier drops to 1 100 °C. This action will increase the cold gas efficiency of the process from 78.6 to 81.5%. Reaction system motion to the carbon boundary line, however, will considerably slow down the rates of the heterophase reactions between carbon residue and gas at the gasifier outlet [17]. This phenomenon is natural. The boundary line corresponds to equilibrium between a fuel (solid) phase and a gas phase. There is an insufficient difference in thermodynamic potentials for the occurrence of chemical reactions. The degree of fuel conversion in the test run was 99.9% (see Table 2). Optimization of this run towards a decrease in the equivalence ratio will lead to appreciable fuel underburning due to the kinetic limitations of the carbon residue reactions. The cold gas efficiency will also decline. The experimental operating conditions of the MHPS reactor are likely to prove optimal kinetically but not thermodynamically.

Apart from the equivalence ratio, the position of the experimental run relative to the carbon boundary line is influenced by the heat exchange between the reactor and the environment. It is equal to the sum of the heat losses of the reactor minus the amount of external heat input with heated air. Fig. 2 shows the isolines of thermal efficiency, which factors in the efficiency of converting both the coal chemical energy and the external heat supplied to gas

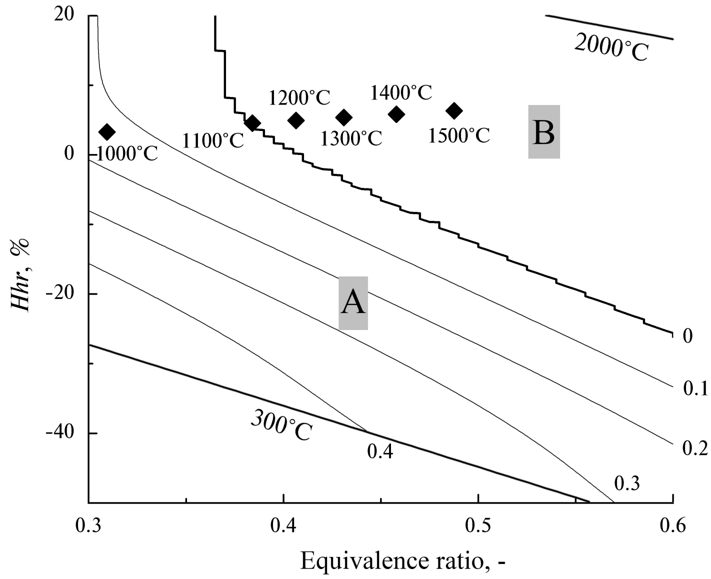

Fig. 1. Modeling the operating conditions of the MHPS gasifier. Isolines indicate the equilibrium yield of the carbon residue (kg/kg (coal)). The point 1 200 °C corresponds to the experiment [23]. The rest of the points are calculated for the indicated reactor temperatures.

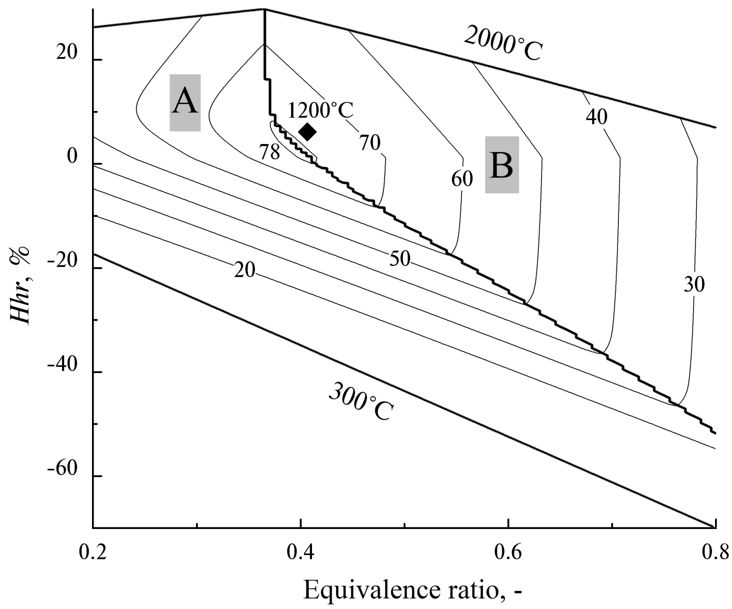

Fig. 2. Results of modeling the air gasification process in the MHPS reactor. Isolines indicate thermal efficiency levels. Diamond corresponds to the experimental run [23].

energy. Thermal efficiency is characterized by an optimum localized within the 78% isoline and equal to 79.2%. The experimental run of the MHPS reactor is located near this optimum. External heat in the experiment is supplied with compressed air heated to 500 °C.

IV. Conclusions

The thermodynamically optimal gasification conditions are located near the carbon boundary line corresponding to the equilibrium between the gas and coke phases. Achievement of optimal conditions turns out to be kinetically limited. The free energy of the reaction system approaches the equilibrium value when nearing the carbon boundary. Such restrictions increase coke underburning and decrease cold gas efficiency of gasification.

As evidenced by the analysis performed, the MHPS gasifier operates in near-thermodynamically optimal conditions. Kinetic limitations turn out to be insignificant in this case. The fuel conversion rate is 99.9%. These limitations can be removed by increasing the equivalence ratio relative to its optimal thermodynamic value.

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Why IEEE Xplore Matters for Research Trend Analysis in the Energy Sector

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***Abstract* — The paper aims to briefly compare and analyze the results of queries to IEEE Xplore and the leading abstract databases Scopus and Web of Science to identify research trends. Some errors were revealed in the Author Keywords in Web of Science. Therefore, a more detailed analysis that involved comparing various types of key terms was made only for IEEE Xplore and Scopus platforms. The study employed IEEE Access journal metadata as indexed on both platforms. Sample matching for IEEE Xplore and Scopus was achieved by comparing DOI. The IEEE Xplore metadata contains more key term types, which provides an advantage in analyzing research trends. Using NSPEC Controlled Terms from expert-compiled vocabulary provides more stable data, which gives an advantage when considering the change of terms over time. Apriori, an algorithm for finding association rules, was used to compare the co-occurrence of the terms for a more detailed description of sample subjects on both platforms. VOSviewer was used to analyze trends in scientific research based on IEEE Xplore data. The 2011-2021 ten-year period was divided into two sub-intervals for comparing the occurrence of Author Keywords, IEEE Terms, and NSPEC Controlled Terms. Bibliometric data of the IEEE conference proceedings was used to illustrate the importance of context in estimating the growth rate of publishing activity on a topic of interest.**

***Index Terms*: bibliometric analysis, IEEE Xplore, INSPEC Controlled Terms, keywords co-occurrence, research trends, Scopus.**

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I. Introduction and Objectives

The increasingly sophisticated and competitive landscape of scientific works demands an in-depth analysis of research trends for decision-making in developing an innovation development strategy.

This topic is very diverse and is well represented in scientific publications that address various aspects relevant for identifying research trends. For example, the research in [1] relied on bibliometric methods to map intellectual structures and research trends. Data was collected from citations and co-citations found in Science Citation Index Expanded, Social Science Citation Index, and Arts and Humanities Citation Index. The application of bibliometric analysis allowed the authors to identify research trends related to innovative entrepreneurship. Multicriteria decision analysis (MCDA) approaches to incorporating social criteria and evaluating participatory mechanisms in the decision-making process for renewable energy projects are discussed in [2]. The authors expect that in the future, developing countries with a high potential for energy production from renewable sources will face problems in assessing the potential social implications of the decisions made. According to [3], science plays a significant part in decision-making on the sustainable development of renewable energy. The study applies a textual analysis approach to 2 533 Scopus-indexed metadata published from 1990 to 2016, based on a Latent Dirichlet Allocation Topic Model. The models created include up to 1 100 topics. The most developed ones are energy storage, photonic materials, nanomaterials, and biofuels. The establishment of sustainable energy systems will require future research to focus not only on technical energy infrastructure but also on related economic, environmental, and political issues. The analysis presented in [4] aims to identify the major trends in research on artificial intelligence (AI) in business. The authors conduct a bibliometric analysis of Web of Science and Scopus data. They identify 11 clusters and the most common terms used in AI research whose analysis has shown a growing scientific interest in synergies between AI and business. Identifying research trends helps make decisions on the selection of prospective research topics. Citation and publication delays constrain such analysis. Therefore, the authors of [5] use an approach called predicting the frequency of author-specified keywords to identify research trends. A long short-term memory neural network (LSTM) is used for the analysis. It is noted that the feature characterizing the potential for community development is especially significant in the long-term prediction.

The energy transition to low-carbon power sources requires significant development of the power grid infrastructure and optimization of its operation.

Grid infrastructure topics are well represented in the Scopus abstracts database. For example, the query TITLE-ABS-KEY ("grid infrastructure") yields 3 157 papers (as of September 2021).

Therefore, only a brief list of publications that reveal relevant issues of this topic will be given.

Key aspects affecting the integration of microgrids in the broader context of energy transformation are presented in [6]. In contrast to other decentralized energy systems, microgrids interact with centralized grid infrastructure. The authors' analysis shows that California's path to microgrids is mostly driven by legislative and regulatory pressures toward clean energy and symbiotic relationships between regime influencers and the microgrid niche. The authors of [7] analyze the spread of solar energy in Portugal, both nationally and locally. They note that the energy transition must be implemented in a multiscale, multilateral, and intersectoral perspective. Since solar power plants require access to land and electric grids, the establishment of the solar energy infrastructure involves interaction with local communities. In [8], the authors present a macroeconomic assessment of planned investments in power grid infrastructure in Germany. Investments in power grid infrastructure are mainly aimed at achieving environmental and energy policy goals. Using a statistical analysis, the authors show how the multiplier effect of grid investments impacts macroeconomic outcomes: production, added value, employment, and tax revenues. The net multiplier effect on production volume is positive, whereas the other effects are negative. Research related to smart grids as forerunners of the Energy Internet, which should connect producers and consumers of electricity with renewable energy sources and storage units, is discussed in [9]. The paper presents a systematic review of the literature related to the current state of the Energy Internet. The authors found that although the infrastructure, technology, and system design are reasonably ready for the transition to the Energy Internet, the major obstacles are defined by regulations.

These tasks are classical for the experts of the Institute of Electrical and Electronics Engineers (IEEE). Research trends in this area are reasonable to justify the use of the metadata of the IEEE Xplore platform, which is currently insufficiently used in the bibliometric analysis.

Each abstract database has its strengths and weaknesses to be considered in the bibliometric analysis to identify the trends in scientific research. There is extensive literature dedicated to comparative analysis of capabilities of abstract databases, as well as the errors and issues that arise in them.

The study presented in [10] examines 3 073 351 citations found by Web of Science, Scopus, Google Scholar, Microsoft Academic, Dimensions and Open Citations Index of CrossRef of 2 515 English-language highly cited papers (from 252 subject categories) published in 2006. The authors conclude that in terms of coverage Microsoft Academic and Dimensions are good alternatives to Scopus and WoS in many subject categories. However, it is worth noting that the metadata structure of these sources differs significantly, especially in terms of the keywords offered by the systems and the classification of subject categories. Authors of [11] claim that the original purpose of scientific publications was to provide a global exchange of scientific results, ideas, and discussions among the academic community to achieve better scientific results. Nowadays, many of the most crucial decisions on industrial and economic growth priorities, allocation of financial resources, educational policies, creation of opportunities for collaboration, acquisition of status, employment of academic staff, and others rely on the evaluation of scientific results and research quality approximated as publication impact has become the most significant criterion. The authors aim to provide all potential users with a comprehensive description of the two main bibliographic databases – Web of Science and Scopus. The variety of publications devoted to comparing individual abstract databases is enormous; one can find a suitable comparison for the most famous databases. For example, the authors of [12] have found that Google Scholar indexed the most recent papers indexed in WoS, and now they can be found through Google Scholar. The ratio of quantity and quality of citations, threats to WoS, and weaknesses of Google Scholar are discussed. Some publications compare abstract databases by specific indicators. For example, in [13], a comparative analysis of journal coverage is made for three databases (Web of Science, Scopus, and Dimensions) to understand and visualize their differences. The analysis employed the most recent lists of major journals from the three databases. Findings indicate that the databases differ significantly in journal coverage with Web of Science being the most selective and Dimensions - the most comprehensive. Comparison of the data presented in abstract databases indicates that the specific direction of research and authors' affiliation are also important. In [14], the authors compare three resources (Web of Science, Google Scholar, and Scopus) to determine the resource with the most representative coverage of citations of South African environmental research. The study has found that Web of Science extracts most citation results, followed by Google Scholar and Scopus. WoS shows the best results in terms of overall coverage of journal samples and also extracts the largest number of unique articles. A multiple-copy study shows that WoS and Scopus find no duplicates, whereas Google Scholar finds a few of them. Scopus provides the fewest inconsistencies in terms of content verification compared to the other two citation resources.

When conducting bibliometric research, it is essential to understand what errors and inaccuracies a researcher may encounter when using the metadata of leading abstract databases. A wide range of studies is devoted to this issue. We will cite some of them, which reveal this problem to the greatest extent. In [15], the authors focus on a systematic analysis of duplicate entries in Scopus, and [16] presents empirical analysis and classification of database errors in Scopus and Web of Science. The study in [17] analyzes the so-called “phantom citation” (i.e., articles about which the WoS reports that they are citing an article when, in fact, they are not). An analysis of citations (and article references) in two English-language and two non-English-language sources shows that phantom citations and other indexing errors are about twice as common in non-English-language articles. These and other errors affect about 1% of citations in the WoS database. This factor influences the calculation of h-indices or other indicators of research impact. Another aspect of citation problems [18] is missing citations, i.e., the lack of links between the cited article and the corresponding citing article. This study is based on an extensive sample of scientific articles concerned with engineering and manufacturing and focuses on the old data in Scopus and WoS databases. The main results of this study are as follows: 1) both databases are slowly correcting old missed citations, and 2) a small fraction of initially corrected citations may suddenly disappear from the databases over time.

The developers of the free software VOSviewer, widely used in bibliometric research, made a significant contribution to an analysis of issues with the metadata of leading abstract databases. In [19], they present a large-scale comparison of five interdisciplinary sources of bibliographic data (Scopus, Web of Science, Dimensions, Crossref, and Microsoft Academic) for 2008-2017. Scopus was pairwise compared with each of the other data sources. The authors emphasize the importance of combining comprehensive coverage of scientific literature with a flexible set of filters for its selection.

Both the citation rate and the impact factor of a journal are significant to assess individual articles and their authors. Authors of [20], using computer modeling, show that under certain conditions, the impact factor is a more accurate indicator of the value of articles, whereas, under other conditions, the number of citations received by an article is a more precise indicator of its value than the impact factor, i.e., it is crucial to critically discuss research assessment criteria. This statement is especially significant for new publications whose citations have not yet been formed in abstract databases.

Systematic bibliometric analysis of metadata of scientific publications and conference proceedings reveals major R&D trends. Traditionally, abstract databases - Scopus and Web of Science (WoS) - are used for this purpose, however, there are a growing number of specialized platforms that allow collecting information for such analysis, such as OnePetro, IEEE Xplore, and Semantic Scholar.

Specialized abstract databases may better reflect the opinions of experts in the field than general databases.

This paper aims to highlight some of the IEEE Xplore features, which, along with its openness, may provide additional benefits compared to closed access databases Scopus and WoS.

On the underestimation of IEEE Xplore as a source of bibliometric metadata

Document topics are most commonly defined by a set of terms that describe the subject area well and frequently occur in them. This approach makes it possible to assess research trends by the occurrence of key terms describing published documents. Terms can be the author’s keywords, documents text mining terms, or experts-controlled terms from a subject vocabulary [21-23].

The paper focuses only on this aspect of bibliometric analysis.

To clarify the underestimation of IEEE Xplore as a source of publication metadata, several comparisons are made for the queries containing the basic terms bibliometrics OR scientometrics and the names of leading abstract databases. The following results are obtained

For queries in Scopus:

- TITLE-ABS-KEY ((bibliometric* OR scientometric*) AND “ieee xplore”) → 11 results;
- TITLE-ABS-KEY ((bibliometric* OR scientometric*) AND “scopus”) → 3 797 results;
- TITLE-ABS-KEY ((bibliometric* OR scientometric*) AND (“WoS” OR “web of science”)) → 5 919 document results.

For queries in Web of Science Core Collection:

- (bibliometric* OR scientometric*) AND “ieee xplore” (Topic) → 10 results;
- (bibliometric* OR scientometric*) AND “scopus” (Topic) → 3 026 results;
- (bibliometric* OR scientometric*) AND (“WoS” OR “web of science”) (Topic) → 4 840 results.

No results were found for “All Metadata:” bibliometric* OR “All Metadata:” scientometric* AND “All Metadata:” “ieee xplore” on the IEEE Xplore platform.

IEEE Xplore platform provides a comprehensive list of metadata for publications, which enables a comprehensive bibliometric analysis (https://ieeexplore.ieee.org/Xplorehelp/searching-ieee-xplore/advanced-search.)

The list of IEEE Xplore platform metadata can be used to analyze the topics of published materials:

- Abstract;
- Author Keywords;

Table 1. Examples of mismatches between Author Keywords on the Web of Science platform and the keywords in the publications themselves [24-26].

Author Keywords by WoS	Correct Keywords	DOI of article
Big Data; Data analysis; Tools; Social networking (online); Computer languages; Companies; Big data analytics; Data analytics; Deep learning; Machine learning	Big data analytics; data analytics; deep learning; machine learning	10.1109/ACCESS.2019.2923270
Text categorization; Semantics; Feature extraction; Natural language processing; Bit error rate; Task analysis; Neural networks; Text classification; Text representations; Label embedding	label embedding; Text classification; text representations	10.1109/ACCESS.2019.2954985
Task analysis; Rehabilitation robotics; Lighting; Clutter; Computer vision; Training; Machine intelligence; Robotic vision systems	Machine intelligence; robotic vision systems	10.1109/ACCESS.2019.2955480

Table 2. Top 25 key terms according to Scopus for 1 250 records.

Author Keywords	N	Index Keywords	N
deep learning	112	deep learning	181
machine learning	67	learning systems	156
blockchain	61	internet of things	114
convolutional neural network	37	convolutional neural networks	92
internet of things	37	network security	84
security	36	5g mobile communication systems	75
iot	32	blockchain	69
5g	30	classification (of information)	64
edge computing	25	convolution	64
covid-19	23	deep neural networks	64
artificial intelligence	21	energy utilization	62
optimization	21	feature extraction	62
feature selection	19	energy efficiency	61
image encryption	18	forecasting	61
feature extraction	17	surveys	61
particle swarm optimization	17	learning algorithms	60
smart grid	16	particle swarm optimization (pso)	56
classification	15	cryptography	54
cloud computing	14	machine learning	51
energy efficiency	14	digital storage	47
data privacy	13	electric power transmission networks	47
anomaly detection	12	long short-term memory	47
energy management	12	network architecture	46
intrusion detection	12	support vector machines	46
lstm	12	internet of things (iot)	45

- Document Title;
- Index Terms;
- INSPEC Controlled Terms;
- INSPEC Non-controlled Terms;
- Standard Dictionary Terms;
- Standards ICS Terms.

INSPEC Controlled Terms, Keywords from the INSPEC expert-edited dictionary are of particular interest (https://ieeexplore.ieee.org/Xplorehelp/searching-ieee-xplore/command-search#summary-of-data-fields.)

The list of publishers whose publications are indexed in Xplore is the second feature of this platform: IEEE (2 477 765); OUP (39 031); IET (21 473); MIT Press (11 958); VDE (10 124); Wiley (3 564); SMPTE (3 022); SAE (2 942); River Publishers (2 351); BIAI (1 517). No giants such as Elsevier and Springer Nature are on the list, but the publications of the IEEE itself dominate. The platform focuses on industry interests. When analyzing research trends, it is important to understand the priorities of the IEEE community.

The feature of IEEE Xplore is the high number of conference materials metadata compared to journal articles and standards-related documents.

Out of 2 582 653 papers in 2011-2020, there were those of Conferences (1 992 101), Journals (482 568), Magazines (66 809), Books (25 937), Early Access Articles (9 611), standards (5 297), and courses (330).

Conference proceedings reflect industry interests more than peer-reviewed publications. For example, the major Publication Topics for IEEE Xplore in 2011-2020 were learning (artificial intelligence) (103 944), feature extraction (67 483), optimization (64 359), neural nets (46 323), the Internet (43 459), cloud computing (40 371), mobile robots (36 370), image classification

Table 3. Top 25 key terms according to IEEE Xplore for 1 250 records.

IEEE Terms	N	INSPEC Controlled Terms	N
feature extraction	209	learning (artificial intelligence)	307
optimization	143	feature extraction	155
machine learning	114	internet of things	122
task analysis	92	optimization	116
mathematical model	80	convolutional neural nets	111
training	80	neural nets	81
computational modeling	75	cryptography	78
internet of things	68	pattern classification	72
deep learning	67	diseases	64
predictive models	63	power engineering computing	62
wireless communication	63	5g mobile communication	59
data models	62	image classification	58
5g mobile communication	60	cloud computing	56
cloud computing	57	particle swarm optimization	54
computer architecture	57	mobile computing	53
heuristic algorithms	55	power grids	52
support vector machines	54	probability	52
security	53	recurrent neural nets	51
neural networks	50	security of data	48
blockchain	47	support vector machines	48
encryption	46	data privacy	47
monitoring	46	search problems	47
reliability	46	internet	46
sensors	44	medical image processing	46
protocols	43	distributed power generation	45

(36 029), control system synthesis (35 968), medical image processing (35 231), wireless sensor networks (33 215), and power grids (32 965), which are distinct engineering challenges.

In bibliometric research, it is advisable to choose the topic relevance according to the materials of conferences or patent studies and analyze peer-reviewed articles to assess the scientific validity of the topic. The choice of the goal and methods of its achievement must not rest on a closed set of data. These sets should overlap but not coincide.

II. Analysis and results

A. Comparison of keywords of IEEE Xplore and Scopus platforms.

Let us briefly explain why Scopus but not Web of Science was chosen for comparison.

The comparison of the expressiveness of keywords in different platforms has revealed that the Web of Science system contains many errors in the Author Keywords field, and the Keywords Plus field has few terms. This issue requires additional, more comprehensive study and is beyond the scope of this paper. Therefore, Table 1 provides only a few examples to illustrate it.

The examples are taken from the IEEE Access journal, which provides access to the full text, making it easy to compare the author's keywords in the system and in the article. Last accessed July 10, 2021.

Such an issue, however, has not been encountered on the IEEE Xplore and Scopus platforms, which is why these systems are used further in the study.

To compare the key terms in different systems, one must establish a set of publications indexed in both systems. The IEEE Access journal, which is indexed in all the above systems, has a whole host of publications and fits the bill, for example, according to Scopus 18 073 publications in 2020.

IEEE Xplore and Scopus allow the export of 2 000 metadata for a single query, which is enough for a qualitative comparison. To select 2 000 articles out of 18 000, they are sorted by citation on each platform, and then the first 2 000 pieces of bibliometric metadata are exported. Citation rate of the articles is determined based on the platform's data,

Table 4. The 25 most commonly co-occurring key terms in the Author Keywords and Index Keywords fields of Scopus metadata records

Author Keywords	%	Index Keywords	%
machine_learning*deep_learning	7.32	learning_systems*deep_learning	25.93
convolutional_neural_network*deep_learning	6.50	convolutional_neural_networks*deep_learning	15.74
feature_extraction*deep_learning	3.25	deep_neural_networks*deep_learning	12.65
artificial_intelligence*machine_learning	2.85	convolutional_neural_networks*learning_systems	10.80
covid-19*deep_learning	2.85	convolution*deep_learning	10.19
intrusion_detection*deep_learning	2.44	convolution*convolutional_neural_networks	9.57
cnn*deep_learning	2.44	long_short-term_memory*deep_learning	8.95
artificial_intelligence*deep_learning	2.44	learning_algorithms*learning_systems	8.64
classification*deep_learning	2.44	support_vector_machines*learning_systems	8.33
lstm*deep_learning	2.44	forecasting*learning_systems	8.02
security*machine_learning	2.03	convolutional_neural_networks*learning_systems*deep_learning	8.02
anomaly_detection*deep_learning	2.03	convolution*convolutional_neural_networks*deep_learning	7.41
data_analytics*machine_learning	2.03	deep_neural_networks*convolutional_neural_networks	7.41
cnn*lstm	2.03	classification*learning_systems	7.10
covid-19*machine_learning	2.03	deep_neural_networks*learning_systems	7.10
q-learning*reinforcement_learning	1.63	learning_algorithms*deep_learning	7.10
natural_language_processing*deep_learning	1.63	convolution*learning_systems	6.79
neural_network*deep_learning	1.63	feature_extraction*learning_systems	6.48
internet_of_things*machine_learning	1.63	classification*deep_learning	6.48
pandemic*covid-19	1.63	deep_neural_networks*convolutional_neural_networks*deep_learning	6.48
sentiment_analysis*deep_learning	1.63	deep_neural_networks*learning_systems*deep_learning	6.17
cnn*lstm*deep_learning	1.63	convolution*deep_neural_networks	5.86
artificial_intelligence*machine_learning*deep_learning	1.63	decision_trees*learning_systems	5.56
image_classification*deep_learning	1.22	reinforcement_learning*deep_learning	5.56
attention_mechanism*deep_learning	1.22	network_security*learning_systems	5.56

hence the difference in the lists of articles in the 2 000 most cited ones for each platform. Articles with the same DOI are sampled to resolve this issue. There are 1 250 such articles. For comparison, in 2020, the intersection of 2 000 most cited journal articles between the Web of Science and IEEE Xplore systems was 1 207, which compares with 1 250 and indicates the consistency of the results.

It is worth noting that for a sample of 1 250 records, there is no discrepancy between the Author Keywords in both systems. For this reason, the following two Tables list them once. Tables 2 and 3, each, show the 25 most common key terms: Author Keywords and Index Keywords (https://service.elsevier.com/app/answers/detail/a_id/21730/supporthub/scopus/) for Scopus; IEEE Terms and INSPEC Controlled Terms for IEEE Xplore. N in the Tables denotes the occurrence of the term.

The general topics of the terms presented in the Table can be described as deep learning, machine learning, blockchain, convolutional neural network, and the Internet of things. Data from the Table can be used to generate new queries for further collection of literature.

The terms: feature extraction and distributed power generation, power grids, data privacy are more pronounced in IEEE Xplore metadata than in Scopus, but in general, the coverage of topics in both cases is close in nature.

IEEE Xplore data is in the public domain, Author Keywords on this platform and in Scopus coincide, and INSPEC Controlled Terms reflect the subject of publications no less expressively than Index Keywords, thus the features of IEEE Xplore are attractive for bibliometric analysis to detect research trends. An additional advantage is that experts in a narrower subject area moderate the INSPEC Controlled Terms vocabulary, and therefore, it better reflects engineering topics.

The study on the trends in topics of scientific publications assessed by frequency of occurrence (or co-occurrence) of terms indicates that the controlled dictionary yields more stable results since index terms differ wider in bibliometrics metadata at different periods. In turn, Author Keywords, being the most subjective, better reflect the current state of the topics, and it is advisable to use them to identify emerging trends in publication topics. The IEEE Xplore platform provides both capabilities. A detailed analysis of these statements is beyond the scope of this paper and deserves a separate study.

B. Assessment of the co-occurrence of key terms based on the Apriori algorithm.

The interrelationship of key terms can describe a topic in more detail than a set of individual terms. One method of solving this problem is the Apriori algorithm designed to find associative rules.

This section used the key terms: Author KW, Index KW, IEEE Terms, and INSPEC Terms (abbreviated from INSPEC Controlled Terms).

The set of terms that occur together was reduced by

Table 5. The 25 most commonly co-occurring key terms in the IEEE Terms and INSPEC Terms fields of IEEE Xplore metadata records.

IEEE Terms	%	INSPEC Terms	%
feature_extraction*machine_learning	21.5	feature_extraction*learning-artificial_intelligence	29.36
deep_learning*feature_extraction	20	convolutional_neural_nets*learning-artificial_intelligence	22.94
training*machine_learning	9.5	neural_nets*learning-artificial_intelligence	17.43
support_vector_machines*machine_learning	9	pattern_classification*learning-artificial_intelligence	16.51
predictive_models*machine_learning	8	convolutional_neural_nets*feature_extraction	13.76
support_vector_machines*feature_extraction	8	convolutional_neural_nets*feature_extraction*learning-artificial_intelligence	13.46
data_models*machine_learning	7.5	image_classification*learning-artificial_intelligence	12.54
optimization*machine_learning	6.5	recurrent_neural_nets*learning-artificial_intelligence	10.09
machine_learning_algorithms*feature_extraction	6.5	diseases*learning-artificial_intelligence	9.17
neural_networks*machine_learning	6	image_classification*feature_extraction	8.56
task_analysis*feature_extraction	6	support_vector_machines*learning-artificial_intelligence	8.26
training*feature_extraction	6	medical_image_processing*learning-artificial_intelligence	8.26
task_analysis*deep_learning	5.5	image_classification*feature_extraction*learning-artificial_intelligence	8.26
training*deep_learning	5.5	object_detection*learning-artificial_intelligence	7.65
prediction_algorithms*machine_learning	5	internet_of_things*learning-artificial_intelligence	7.65
computational_modeling*machine_learning	5	optimisation*learning-artificial_intelligence	7.34
task_analysis*machine_learning	5	medical_image_processing*image_classification	6.73
machine_learning_algorithms*machine_learning	5	power_engineering_computing*learning-artificial_intelligence	6.42
diseases*machine_learning	4.5	medical_image_processing*image_classification*learning-artificial_intelligence	6.42
neural_networks*feature_extraction	4	neural_nets*feature_extraction	6.42
predictive_models*data_models	4	pattern_classification*feature_extraction	6.12
support_vector_machines*deep_learning	4	image_segmentation*learning-artificial_intelligence	5.81
support_vector_machines*feature_extraction*machine_learning	4	image_classification*convolutional_neural_nets*learning-artificial_intelligence	5.81
computer_architecture*machine_learning	3.5	image_classification*convolutional_neural_nets	5.81
sentiment_analysis*feature_extraction	3.5	pattern_classification*feature_extraction*learning-artificial_intelligence	5.81

imposing additional constraints, which involved sampling rows from Scopus and IEEE Xplore metadata with the word "learning." Tables 2 and 3 show the following terms with the word "learning:" deep learning, machine learning, learning systems, learning (artificial intelligence), learning algorithms, which evidences the relevance of such a restriction on sampling.

With this constraint applied to 1 250 Scopus data records will yield:

- 246 rows containing the learning string — Author Keywords;
- 324 rows containing the learning string — Index Keywords.
- And with this constraint applied to 1 250 IEEE Xplore data records will yield:
- 200 — IEEE Terms;
- 327 — INSPEC Terms.

Values in those two lists are comparable in order of magnitude.

Preparing the data for the Apriori algorithm involved standard actions: lowercasing strings, combining terms with different endings, removing unwanted characters, and combining words in a term into a single string by replacing spaces with underscores.

C. Results of applying the Apriori algorithm to the formed samples.

The 25 most frequent term groups for Scopus records for Author Keywords and Index Keywords, respectively, are listed in Table 4. The designation in Tables 4 and 5 are: % is the percentage of this key term group in the overall list of term groups that passed the 1% threshold, symbol * is used to replace the spaces between terms for more convenient viewing.

Table 4 shows that in the first 25 groups of key terms, the joint occurrence of two terms prevails. The joint occurrence of three terms is not very informative: cnn*lstm*deep_learning and artificial_intelligence*machine_learning*deep_learning. The application domain for deep_learning is most often found as feature_extraction, which corresponds to the general theme of the bibliometric metadata set used.

Table 5 presents the 25 most common groups of terms for records from the IEEE Xplore platform for IEEE Terms and INSPEC Terms, respectively.

The findings of this paper suggest that the advantage of groups of terms used in IEEE Xplore compared with the terms in Table 4 for Scopus is that they more capaciously describe the subject area due to a combination of terms describing methods and their object of application, for example:

- feature_extraction*machine_learning;
- deep_learning*feature_extraction;
- data_models*machine_learning;
- task_analysis*feature_extraction;
- training*feature_extraction;
- diseases*machine_learning;
- feature_extraction*learning-artificial_intelligence;
- image_classification*learning-artificial_intelligence;
- image_classification*feature_extraction;
- pattern_classification*feature_extraction.

Term "feature_extraction," which frequently appears on the list with different co-terms, indicates the significance of the data dimensionality reduction in pattern recognition and time-series problems, and others.

It is of interest to make an in-depth analysis of the context in which the term feature_extraction appears in publications indexed by IEEE Xplore and how this context changes over time.

D. Analysis of the context for the term "feature_extraction" in bibliometric metadata of IEEE Xplore platform in 2011-2021.

Sampling in the query ("Publication Topics:" "feature extraction") OR ("IEEE Terms:" "feature extraction"), with the filters 2011–2020, gives 136 983 results, of which:

- 113 268 – Conferences;
- 21 944 – Journals;
- 1 058 – Early Access Articles;
- 637 – Magazines;
- 73 – Books;
- 2 – Standards;
- 1 – Courses.

Main Publication Topics are:

- feature extraction (12 951);
- learning (artificial intelligence) (7 859);
- image classification (4 466);
- convolutional neural net (2 835);
- object detection (2 457);
- neural net (2 366);
- image segmentation (2 314);
- image representation (2 037);
- support vector machine (1 859);
- pattern classification (1 746);
- medical image processing (1 713);
- geophysical image processing (1 666);
- medical signal processing (1 444);
- video signal processing (1 272);
- computer vision (1 243);
- signal classification (1 149);
- image matching (1 077);
- remote sensing (1 065);
- image color analysis (1 058);
- disease (1 030);
- regression analysis (987);
- face recognition (932);
- image texture (911);
- image fusion (880);
- image resolution (877).

These topics can be summarized as follows: feature extraction by convolutional neural nets, support vector machines and regression analysis for image classification, segmentation, representation, matching, color analysis, texture and resolution for solving the problems of medical image, geophysical image, medical signal processing, remote sensing, and face recognition.

For comparison, let us show the results of the query AUTHKEY ("feature extraction") OR INDEXTERMS ("feature extraction") AND PUBYEAR > 2010 to the Scopus database, which provides metadata to 90 283 documents, of which:

- 44 846 – Conference Paper;
- 43 566 – Article;
- 854 – Review;
- 766 – Book Chapter;
- 40 – Editorial;
- 37 – Book;
- 37 – Letter;
- 17 – Short Survey;
- 16 – Note.

Thus, there is significantly more conference material on this request in IEEE Xplore than in Scopus over the same period.

E. VOSviewer for a brief analysis of research trends for the "feature extraction" topic.

VOSviewer [27, 28], a software tool for constructing and visualizing bibliometric networks, is widely used in the bibliometric analysis. For example, in the Sopus database, to the query TITLE-ABS-KEY (VOSviewer), we obtain 1 437 results, and in the WoS database, to the query VOSviewer (Topic) – 1 086 results.

In the context of this paper, it is instrumental to feature the primary possibility of using this program to identify research trends in the data of Author Keywords, IEEE Terms, and INSPEC Terms of IEEE Xplore platform. The paper does not set the objectives to provide a detailed analysis of research trends for the topic "feature detection."

The easiest way to assess the possibility of using VOSviewer to analyze trends in scientific research according to IEEE Xplore data is to break the 10-year interval into two sub-intervals and compare the occurrence of Author Keywords, IEEE Terms and INSPEC Terms in them. For a more detailed analysis, it is sensible to track changes in the composition of the key terms in individual clusters formed by VOSviewer.

A sampling of bibliometric metadata for this section was made as follows. The query ("IEEE Terms:"

Table 6. Comparison of occurrence of Author Keywords for two time intervals. N is the occurrence of the term in the sample.

Keyword 2011-2017	N	Keyword 2018-2021	N
feature extraction	480	deep learning	1 045
classification	303	convolutional neural network	942
feature selection	200	feature extraction	435
deep learning	187	machine learning	350
machine learning	185	classification	242
face recognition	130	feature selection	209
pattern recognition	128	fault diagnosis	174
support vector machine	119	object detection	148
remote sensing	116	transfer learning	147
image classification	113	cnn	132
object detection	102	feature fusion	131
segmentation	99	attention mechanism	123
sparse representation	99	image classification	113
biometrics	98	remote sensing	109
synthetic aperture radar	90	person re-identification	94
computer vision	81	computer vision	89
image segmentation	71	action recognition	87
support vector machines	66	semantic segmentation	79
dimensionality reduction	65	generative adversarial network	78
object recognition	64	deep convolutional neural network	73
action recognition	63	support vector machine	70
change detection	63	deep neural network	69
image retrieval	63	pattern recognition	69
fault diagnosis	58	face recognition	66
image processing	58	image segmentation	66

Table 7. Comparison of the occurrence of IEEE Terms for two periods.

IEEE Terms 2011-2017	N	IEEE Terms 2018-2021	N
feature extraction	5 935	feature extraction	7 050
training	1 284	training	1 665
visualization	898	task analysis	1 411
support vector machines	701	visualization	832
vectors	660	convolution	757
image segmentation	626	deep learning	698
robustness	611	semantics	696
image color analysis	606	image segmentation	679
shape	511	three-dimensional displays	664
accuracy	496	support vector machines	637
computational modeling	453	data mining	560
cameras	451	machine learning	560
kernel	448	neural networks	548
histograms	424	cameras	492
data mining	419	computational modeling	473
remote sensing	388	data models	428
detectors	372	image color analysis	416
estimation	369	kernel	414
algorithm design and analysis	356	correlation	402
hidden markov models	355	object detection	398
semantics	355	remote sensing	379
three-dimensional displays	355	convolutional neural network	374
image edge detection	347	sensors	370
correlation	336	shape	365
databases	335	robustness	329

Table 8. Comparison of the occurrence of INSPEC Terms for two time intervals.

INSPEC Terms 2011-2017	N	INSPEC Terms 2018-2021	N
feature extraction	3 991	feature extraction	7 044
image classification	1 388	learning-artificial intelligence	3 450
learning-artificial intelligence	1 309	image classification	2 024
geophysical image processing	757	convolutional neural nets	1 567
support vector machines	687	object detection	1 178
image segmentation	620	neural nets	998
object detection	589	image segmentation	994
image representation	588	image representation	972
medical image processing	586	support vector machines	754
medical signal processing	498	pattern classification	680
neural nets	457	medical image processing	625
image matching	453	geophysical image processing	602
remote sensing	442	computer vision	572
video signal processing	409	medical signal processing	543
face recognition	384	video signal processing	519
image texture	352	signal classification	498
pattern classification	348	image fusion	451
signal classification	346	image color analysis	445
regression analysis	319	remote sensing	421
statistical analysis	309	image matching	418
hyperspectral imaging	295	diseases	407
image color analysis	290	image motion analysis	394
computer vision	289	fault diagnosis	387
pattern clustering	284	recurrent neural nets	375
synthetic aperture radar	278	image texture	370

Table 9. Top 10 terms for each of the 6 clusters shown in Figure 1.

Label (red)	cluster	N	Label (turquoise)	cluster	N	Label (blue)	cluster	N
neural nets	1	1 455	medical signal processing	2	1 041	feature extraction	3	11 035
support vector machines	1	1 441	electroencephalography	2	510	learning-artificial intelligence	3	4 759
fault diagnosis	1	544	neurophysiology	2	437	pattern classification	3	1 028
principal component analysis	1	460	cameras	2	384	video signal processing	3	928
wavelet transforms	1	381	traffic engineering computing	2	345	face recognition	3	732
entropy	1	251	medical disorders	2	315	regression analysis	3	667
condition monitoring	1	246	pose estimation	2	307	pattern clustering	3	542
time series	1	233	image sensors	2	257	statistical analysis	3	515
mechanical engineering computing	1	230	electrocardiography	2	255	optimization	3	491
power engineering computing	1	219	stereo image processing	2	244	graph theory	3	488
Label (yellow)	cluster	N	Label (violet)	cluster	N	Label (green)	cluster	N
signal classification	4	844	image classification	5	3 412	medical image processing	6	1 211
recurrent neural nets	4	407	object detection	5	1 767	diseases	6	660
radar imaging	4	406	image segmentation	5	1 614	cancer	6	330
probability	4	399	convolutional neural nets	5	1 567	biomedical mri	6	257
gaussian processes	4	338	image representation	5	1 560	biomedical optical imaging	6	256
matrix algebra	4	323	geophysical image processing	5	1 359	brain	6	248
bayes methods	4	264	image matching	5	871	computerized tomography	6	197
gesture recognition	4	197	remote sensing	5	863	eye	6	172
speech recognition	4	191	computer vision	5	861	tumors	6	159
hidden markov models	4	184	image color analysis	5	735	patient diagnosis	6	150

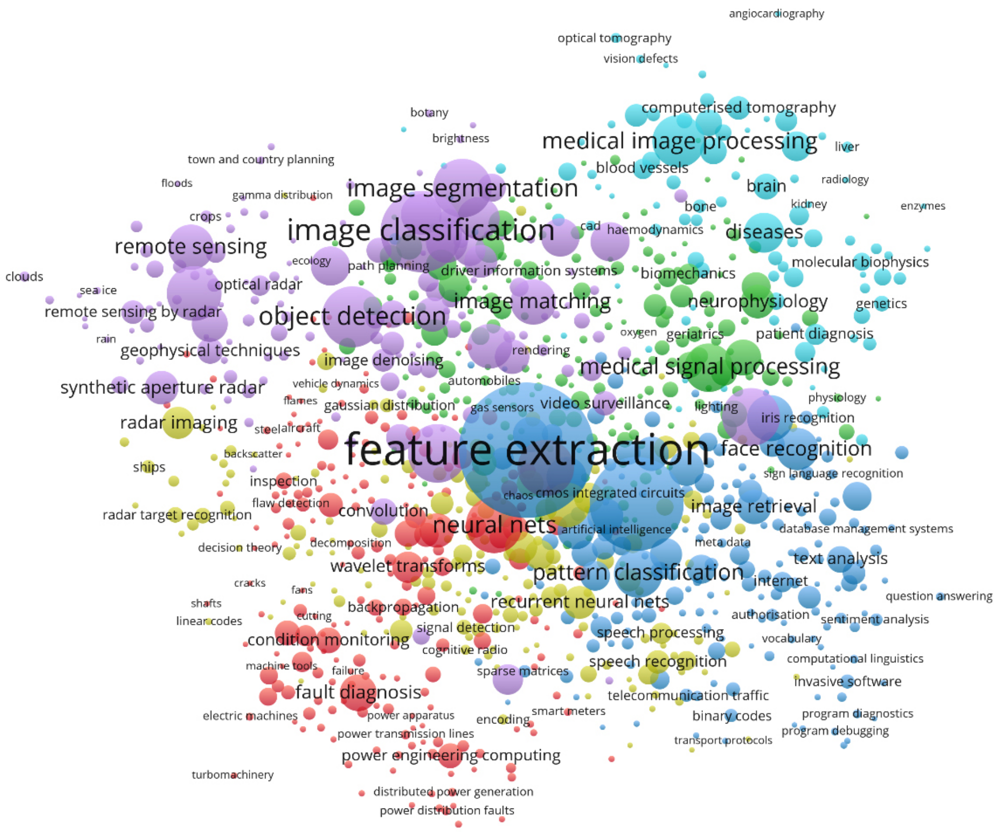

Fig. 1. Clustering of INSPEC Controlled Terms based on their co-occurrence.

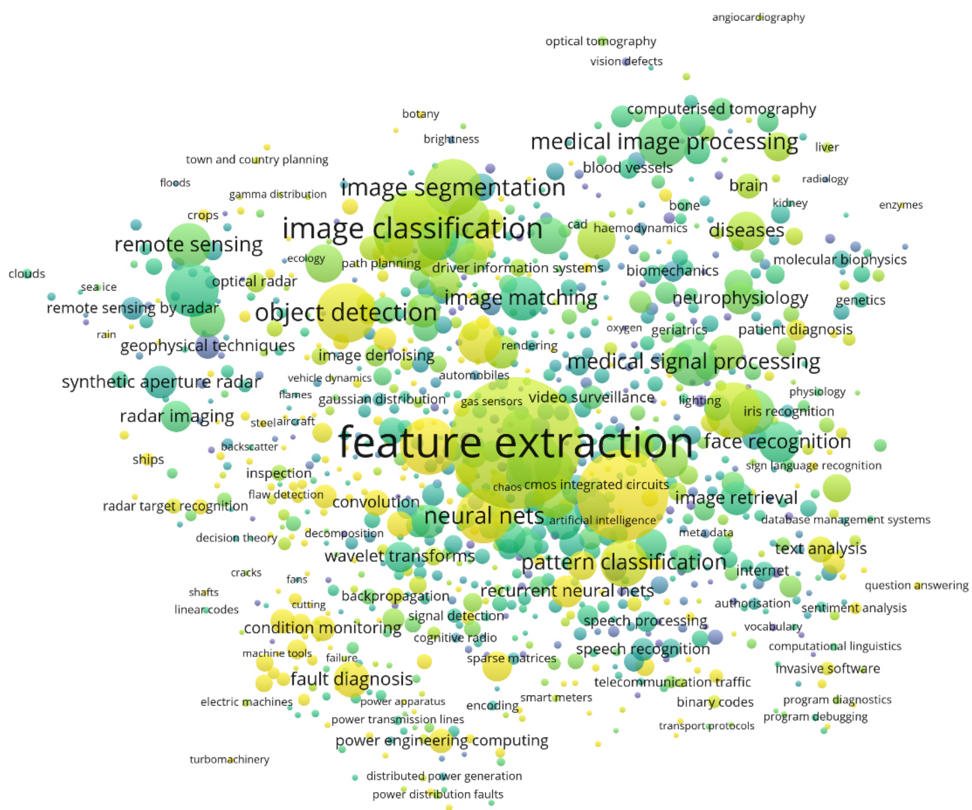

Fig.2. Trends in the term occurrence for 2011-2021.

"feature extraction") OR ("Publication Topics:" "feature extraction") is made for each year of the interval 2011-2021. If the number of publications meeting the request per year did not exceed 2 000, all metadata was downloaded, and if the number of publications exceeded 2 000, only the metadata of the first 2 000 most cited journal articles was exported (last year was not complete, data as of 15-07-2021). Metadata was summed for two intervals, 2011-2017 and 2018-2021, yielding a close number of records in each sub-sample, 7 522 and 8 000 entries, respectively.

The subject for both periods is similar – feature extraction for image analysis.

Author Keywords in 2018-2021 are more related to deep learning and neural networks, whereas, in 2011-2017, the focus is on feature selection and classification, i.e., closer to the main query (feature extraction). It can be assumed that over time, the authors' interests have shifted from feature extraction applications (face recognition, remote sensing, synthetic aperture radar, biometrics, fault diagnosis) to big data algorithms: deep learning, convolutional neural networks.

Tables 7 and 8 were built similarly to Table 6 but only for IEEE Terms and INSPEC Controlled Terms.

In IEEE Terms, the "feature extraction" themes are expressed in all periods, which is due to the request itself. However, whereas previously, the publications had emphasized classic problems, for example, visualization, support vector machines, vectors, image segmentation, image color analysis, remote sensing, hidden Markov models, and image edge detection; the subsequent periods, as in the case of Author Keywords, saw more modern, big data-related topics, including convolution, deep learning, semantics, data mining, machine learning, neural networks, and three-dimensional displays. There is a significant increase in the interest in the field of application algorithms: "three-dimensional displays."

Overall, there is a good consistency in results for Author Keywords and IEEE Terms. Therefore, it is advisable to combine them in bibliometric analysis.

INSPEC Controlled Terms are chosen from an export-controlled dictionary. Therefore, the overall set of terms for different time intervals is more stable. This factor may give an advantage in using the INSPEC Controlled Terms when considering in detail the change in dominant terms in individual years compared to Author Keywords.

The second feature of INSPEC Controlled Terms is the more frequent appearance of terms describing the applied fields of research, e.g., geophysical image processing, medical image processing, medical signal processing, video signal processing, fault diagnosis, diseases. This fact is essential, for example, when collecting materials on the specific methods of data analysis applied in a given area of research. The IEEE Xplore platform provides such a possibility.

The INSPEC Controlled Terms dictionary is periodically updated by experts and can be used to analyze emerging trends in research. This is a separate task for bibliometric analysis. However, even the simple fact that the term "recurrent neural nets" in the above data occurs only among INSPEC Controlled Terms indicates their importance for research trend analysis.

VOSviewer allows creating a general picture (landscape) of research and thematic clustering based on the co-occurrence of key terms.

In this paper, the VOSviewer is used only as applied to the INSPEC Controlled Terms for the entire 2011-2021 timeframe. The choice of INSPEC Controlled Terms is due to their control by INSPEC experts. Expert assessments are the most expensive and difficult to rank data. Thus, the export-controlled dictionaries, the level of peer review of scientific articles, the rating of journals and organizations, and the citation rate of papers are crucial in analyzing research trends because they indirectly reflect expert opinion.

Fig. 1 presents the results of term network and co-occurrence-based clustering for INSPEC Controlled Terms for all metadata by the query ("IEEE Terms:" "feature extraction") OR ("Publication Topics:" "feature extraction") for 2011-2021. By removing the records without INSPEC Controlled Terms, we get 14 840 lines to analyze.

The total number of INSPEC Controlled Terms for this sample was 3 086, of which 1 216 occurred more than five times. Out of these terms, 1 000 with the highest overall level of links were used to construct a network of terms.

If there is no limit on the number of terms in the cluster, we obtain 8 of them, which is a lot for the primary analysis. With the minimum number of terms in the cluster of 40 to 90, there are 6 clusters, with the most common ones shown in Table 9. The wide range of values (40-90) indicates the stability of the resulting clusters. This parameter is useful to adjust the number of clusters to be formed depending on the study objectives.

In VOSviewer, clusters are ordered by the number of unique terms but not by the total number of terms. Therefore, the central term of the "feature extraction" sample is included in the third cluster.

Express analysis of research trends employed VOSviewer's ability to display the change over time (Overlay in terms of VOSviewer) in the occurrence of terms used in the network. The graph of overlay over time is presented in Fig 1.

"Object detection" and "learning-artificial intelligence" are the most frequently used terms in recent times, but they are rather general in nature.

For a more detailed analysis of particular emerging research trends, it is more interesting to choose several specific terms, such as "fault diagnosis" and "condition monitoring" from the red cluster.

Note: In this paper, the terms are used as they appear on the IEEE Xplore platform. For example, "Conferences" means conference proceedings, "Publication Topics" corresponds to the dictionary of INSPEC Controlled Terms.

Next, the data meeting the query ("Publication Topics:" "fault diagnosis") AND ("Publication Topics:" "feature extraction") was used. In 2011-2021, IEEE Xplore indexed 2 042 documents that match this request, including 1 477 in Conferences and 563 in Journals. In 2011, only 65 papers were posted, including 64 in Conferences and 1 in Journals, whereas 2020 saw already 498 papers, with 296 in Conferences and 202 in Journals.

It follows from this data that in the context of the general topic of "feature extraction," in 2011, the "fault diagnosis" issue was mainly raised at conferences, and only one journal article was indexed, whereas, in 2020, there were already 202 articles and their number became commensurate with the number of conference proceedings. This situation confirms the well-known fact that it is easier to detect the emerging trends in conference proceedings than in scientific publications.

Similar dynamics are observed for the term "condition monitoring." The query ("Publication Topics:" "state monitoring") AND ("Publication Topics:" "feature extraction") for 2021-2021 found 892 documents, of which 639 in Conferences and 252 in Journals.

- 2011 → 40 in Conferences and 3 in Journals;
- 2020 → 136 in Conferences and 79 in Journals.

The terms "fault diagnosis" and "condition monitoring" are included in the same cluster, as in Fig. 1. This fact is consistent with the results of the above two queries. The distribution of publications by "Publication Topic" for them is shown in Table 10.

To show that context matters, the data from queries that include "fault diagnosis" and "condition monitoring," but without the context of "feature extraction," was used.

In 2011-2021, 23 795 documents related to the query ("Publication Topics:" "fault diagnosis") were indexed, including 19 171 in Conferences and 4 516 in Journals.

- 2011 → Conferences (1 470) and Journals (144), all of → 1 624
- 2020 → Conferences (2 311) and Journals (990), all of → 3 316

In 2011-2021, 10 942 documents related to the query ("Publication Topics:" "condition monitoring") were indexed, including 8 865 in Conferences and 1 991 in Journals.

- 2011 → Conferences (792) and Journals (63), all of →862
- 2020 → Conferences (1 099) and Journals (450), all of → 1 559

It follows from the above data that in the broader context, the decade-long increase in the interest in the terms "fault diagnosis" and "condition monitoring" in all publications is about two times, which is significantly less than in the context of "feature extraction."

The decrease in growth is due to a slight increase in the number of conference proceedings. For scientific publications, the gain is more significant.

Thus, the conclusion can be made that for the largely common problems of "fault diagnosis" and "condition monitoring," the growth of interest in them is due to the application of more advanced analytical methods for solving them, which require the procedure of "feature extraction."

III. Conclusion

Bibliometric analysis has shown that the IEEE Explore platform is an undervalued resource, despite its some advantages over well-known Scopus and WoS abstract databases, the main of which are:

- open access to the platform;
- a wide variety of key terms allowing a more detailed study of research trends;
- citation rate of publications is assessed within a specialized database, i.e., the opinion of experts in a particular subject area dominates.

The WoS system contains some inconsistencies between the Author Keywords in the database and the Author Keywords in the full texts of publications, making it difficult to use them when analyzing the topics of publications by keywords.

The comparability of the topics identified by the key terms of publications indexed in IEEE Xplore and Scopus is shown. At the same time, the controlled vocabulary, when used to identify research topics and trends from metadata of samples that satisfy queries, has the following advantages:

- the stability of the controlled vocabulary gives a better ability to compare key terms in the samples at different time intervals;
- co-occurrence of such terms better describes the topics of publications because it provides more balance between the terms defining methods of analysis and research objects.

A significant feature of IEEE Xplore is the large host of indexed conference proceedings, which helps identify emerging trends in research in an earlier stage.

The reasonableness of using the Apriori algorithm to identify multiple co-occurrences of terms to describe topics of indexed publications is demonstrated.

The possibility of using VOSviewer to build a landscape of scientific research and identify trends in topics is shown. Officially, VOSviewer does not support exporting data from IEEE Xplore, but it is easy to pre-process data to use this great program.

This study was not intended to explore in detail all the features of the IEEE Xplore platform for bibliometric analysis and identification of research trends, as the objective behind it was to attract the attention of specialists from the energy sector to the capabilities of this platform and encourage its wider use in their work.

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New Opportunities for the Development of Corporate Governance in Power Generating Companies for the Benefit of Investors

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***Abstract* — The paper presents an analysis of the central metrics of corporate governance in wholesale and territorial generating companies of the electric power industry that concern ownership structure and compliance of the companies with the principles of the Corporate Governance Code based on their performance results of 2018 - 2019. An increase in ownership concentration and the presence of the state in the competitive segment of the electric power industry is noted. This study has identified the least met criteria for evaluating compliance with the principles of the Corporate Governance Code. The possibilities of developing corporate governance for the benefit of investors are elucidated. These are tightening control over the observance of international "soft law" ("comply or explain"); expanding the criteria for evaluating compliance with the principles of the Corporate Governance Code that are recommended by the Bank of Russia; updating the Corporate Governance Code based on ESG (Environmental, Social, and Governance) transformation. A new form of oversight over compliance with the Corporate Code principles and criteria for evaluating the adherence to the ESG principles are proposed.**

***Index Terms*: corporate governance, development, investors, ownership, power generating companies.**

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I. Introduction

Corporate governance is aimed at creating an effective system to ensure the safety of funds provided by shareholders and their efficient use. In a stage of world development, there were defined international standards (principles) of corporate governance to protect the interests of all shareholders [1]. Domestic companies assign a central guiding role in establishing these standards to the Russian Corporate Governance Code (further referred to as the Code) [2]. The search for new opportunities for its development is due to the specificity and certain contradictions of corporate governance in Russia.

The purpose of the study was to identify new opportunities for the development of corporate governance in wholesale (WGCs) and territorial (TGCs) generating companies in the electric power industry (further referred to as generating companies) for the benefit of investors. The structure of shareholders' equity and corporate governance in 2018-2019 were considered to be the major points of corporate governance practices in these companies.

The corporate governance practices were primarily analyzed according to the criteria for evaluating the observance of the Corporate Governance Code principles (further on, evaluation criteria) by these companies. As a methodology, we used the recommendations of the Bank of Russia on the preparation of reports of domestic companies «On Compliance with the Principles and Recommendations of the Corporate Governance Code» (Letter of the Bank of Russia No. IN-06-52/8 dated February 17, 2016) and the identified evaluation criteria that were not included in the Recommendations. Generating companies that published the Corporate Governance Code Compliance Annexes (2018-2019) [3-11] in their annual reports were investigated. The companies that did not post them on their official websites (Siberian Generating Company LLC, T Plus PJSC, Fortum OJSC, TGC-14 PJSC, and generating companies of LUKOIL PJSC) were not considered.

The data used were taken from official websites of generating companies, the Unified State Register of Legal Entities, the information agency Bigpowernews [12-14], the National Council on Corporate Governance [15-16], the international companies of PricewaterhouseCoopers [17], the AFEP-MEDEF Code of Corporate Governance of listed companies (France) [18], the UK Corporate Governance Code [19], the Italian Corporate Governance Code [20], the German Corporate Governance Code [21], the Corporate Governance Code of Sberbank PJSC [22], the Russian Institute of Directors [23], the Transition Institute [24], the results of research [25-27], and other information sources [28].

The ownership structure of generating companies was analyzed as of the end of 2019, with its concentration and main shareholders determined. The observance of the evaluation criteria recommended by the Bank of Russia by generating companies in 2018-2019 was assessed. The criteria that were the least adhered to by an overwhelming number of companies were identified as well as those not included in the recommended by the Bank of Russia. New possibilities for corporate governance development in the interests of investors were elucidated. One of them is the tightening of control over compliance with international «soft law» («comply or explain») based on the French experience. Other new possibilities concerned the inclusion of additionally identified criteria of the Code into those recommended by the Bank of Russia to assess compliance with its principles; updating the Code through the ESG (Environmental, Social, and Corporate Governance) transformation with a proposed set of criteria to evaluate the observance of the ESG principles.

II. Corporate governance in generating companies

The points of corporate governance practices in power generating companies considered to be primary for the benefit of investors are

- Ownership structure.
- Compliance with the principles of the Corporate Governance Code.

These points serve as a kind of metric of corporate governance in generating companies and its further development. Ownership structure and corporate governance are closely related, but for this study, were conventionally separated.

A. *Ownership structure.*

The ownership structure is one of the characteristic features that united the models of corporate governance that emerged in developed countries into the so-called «Anglo-American» and «German» models. The representatives of the «Anglo-American» model are the USA and Great Britain. This model is characterized by a dispersed shareholding structure, i.e., with the predominance of many small (minority) shareholders. The nature of ownership and voting rights under this model is dispersed since there are no large (majority) owners. Managers are vested with substantial rights, and the main conflict is that of «a weak owner - a strong manager.» Highly developed and liquid

Table 1. The major shareholders of Russian power generating companies, 2019.

Companies	The major shareholders and their shares in shareholders' equity, %
WGC-1 OJSC	Inter RAO UES PJSC (100)
WGC-2 PJSC	Centrenergoholding LLC (73.4)
WGC-3 OJSC	Inter RAO UES PJSC (100)
Unipro (WGC-4) PJSC	Uniper SE (Germany) (83.7)
Enel Russia PJSC (WGC-5)	Enel S.p.A. (Italy) (56.4), PFR Partners Fund I Limited (Cyprus) (19.0), Prosperity Capital Management Limited (Cayman Islands)(7.7)
RusHydro PJSC	Russian Federation (Federal Agency for State Property Management) (61.2), VTB Bank PJSC (13.1), Avitrans LLC (6.0)
TGC-1 PJSC	Gazprom Energoholding LLC (51.8), Fortum Power and Heat Oy (Finland) (29.5)
TGC-2 PJSC	Litim Trading Limited (British Virgin Islands – BVI) (1.5), Cores Invest LLC (9.5), Janan Holdings Limited (BVI) (14.7), Raltaka Enterprises Limited (BVI) (7.3), Dolgovoye Agentstvo LLC (27.0)
Mosenergo PJSC (TGC-3)	Gazprom Energoholding LLC (53.5), Moscow City Government (26.5)
Quadra PJSC (TGC-4)	ONEXIM Group LLC (52.0), BusinessINFORM LLC (25.7)
T Plus PJSC (TGC-5, TGC-6, TGC-7, TGC-9)	ZAO KES – Holding (32.3), Brookweed Trading Limited (Cyprus) (20.5), Gothelia Management Limited (Cyprus) (12.2), Merol Trading Limited (Cyprus) (11.7)
Generating companies of LUKOIL PJSC (TGC-8)	LUKOIL PJSC (100)
Fortum OJSC (TGC-10)	Fortum Russia B.V. (Finland) (69.9), Fortum Holding B.V. (28.4)
TGC-11 OJSC	Inter RAO UES PJSC (100)
Kuzbassenergo JSC (TGC-12)	Siberian Energy Investment Ltd (Cyprus) (100)
Yeniseyskaya TGC (TGC-13) JSC	Siberian Energy Investment Ltd (Cyprus) (100)
TGC-14 PJSC	Energopromsbyt LLC (39.8), TRINFICO Holdings JSC (20.6), TRANSFINGROUP Asset Management JSC (20.0)

stock markets are the primary tool for external control and improvement of corporate governance in this model.

The «German» model of corporate governance is characteristic of Germany and some other countries of continental Europe, as well as Japan and Korea (sometimes the «Japanese» model is considered as an independent one). In this case, the shareholding structure is concentrated, with several major owners. Ownership is held by a small number of shareholders, voting rights are tied to ownership rights, and the position of minority owners and managers is weak. The conflict in this model of corporate governance is «weak managers, weak minority owners - strong majority owners.» The external corporate control under less developed market mechanisms is carried out through the parent bank.

The emerging Russian model of corporate governance does not fit into the global models at issue, in part because of the relative weakness of the domestic securities market and banking system, institutions of law, established practice in applying the law, non-competitive commodity markets, capital, and labor markets, and undeveloped enforcement. It has features of both corporate governance models at issue. It is partly «German» because of highly concentrated ownership and strong majority control by large owners. It is partly «Anglo-American» due to the basic principles of Anglo-Saxon law focused on the protection of small shareholders and the widespread adoption of American financial reporting standards, both embedded in Russian corporate governance [27]. According to the Institute for the Economy in Transition, the impossibility of direct adaptation of the Russian corporate governance model to the world models was justified, in particular, by the specific structure of the economy and the domestic legal environment [24].

The current ownership structure in WGCs and TGCs as of the end of 2019 (main shareholders and their shares in the share capital according to their official websites) is shown in Table 1.

According to the data presented in Table 1, the number of WGCs and TGCs decreased relative to those established after the liquidation of RAO UES of Russia (2008). This consolidation was caused, in particular, by the merger of TGC-12 OJSC and TGC-13 OJSC into the Siberian Generating Company Group, as well as the takeover of TGC-5 OJSC, TGC-6 OJSC, and TGC-9 OJSC by Volga TGC OJSC («TGC-7»), which was renamed into T Plus PJSC in 2015. WGC-6 OJSC joined Gazprom Energoholding LLC. Further consolidation of generating companies was noted to begin. The Finnish Fortum intends to buy the Russian electric power company Unipro PJSC (a German Uniper subsidiary in Russia) [3]. Gazprom Energoholding LLC is interested in purchasing the generating companies of LUKOIL PJSC and Quadra PJSC if an agreement on the evaluation of their assets is reached [13]. Negotiations are underway to merge Gazprom Energoholding LLC with T Plus PJSC. For the time being, they have been temporarily suspended due to, among other things, the unresolved price range issues for the transaction outlined by Gazprom Energoholding LLC and the role of minority shareholders in the management of T Plus PJSC [14].

There is a steady tendency for the state to increase its presence in the shareholders' equity of generating companies, with an associated general increase in the concentration of ownership. The state from the very beginning stayed in the competitive segment of power generation when the state-owned companies FGC UES OJSC, RusHydro OJSC, Gazprom OJSC, and Russian Railways OJSC partially privatized the generating assets of WGC-1 OJSC, WGC-5 OJSC, WGC-6 OJSC, TGC-1 OJSC, TGC-3 OJSC, and TGC-14 OJSC. Inter RAO UES PJSC acquired 100% of voting shares of TGC-11JSC, reorganized WGC-1 OJSC and WGC-3 OJSC in terms of its 100% ownership of shares there, and incorporated generating assets of Bashkirenergo OJSC. In this context, the permanent increase in the share of the state-owned installed electric capacity of wholesale and territorial generating companies proves telling. In 2016, the state had a little over 55%, private entrepreneurs owned 26% of the installed electric capacity of WGCs and TGCs, and foreign owners had 14% [25]. By the end of 2019, the state's share had increased to 63.9%, private entrepreneurs retained 22.5%, and foreign owners – 13.6%.

The concentration of ownership in generating companies with foreign owners increased from 78.1% (2009) to 83.7% (2019) in Unipro PJSC (former WGC-4 OJSC) and from 92.9% (2009) to 98.3% in Fortum OJSC (TGC-10 OJSC) (2019).

The concentration of ownership in generating companies owned by private Russian entrepreneurs has increased. The generating assets of Southern Generation Company - WGC-8 were transferred to LUKOIL PJSC (V. Alekperov). The merger of Kuzbassenergo JSC (former TGC-12 OJSC) and Yeniseyskaya TGC JSC (former TGC-13 OJSC) into the Siberian Generating Company increased the concentration of ownership owned by A. Melnichenko. V. Vekselberg established a new generating company T Plus PJSC, which consolidated the assets of TGC-5 OJSC, TGC-6 OJSC, TGC-9 OJSC, and TGC-7 OJSC. The majority shareholders L. Lebedev (TGC-2 OJSC) and M. Prokhorov (Quadra PJSC) increased the concentration of their ownership in these companies through their affiliated and controlled structures. Cores Invest LLC, foreign offshore companies Janan Holdings Limited, Raltaka Enterprises Limited, and Litim Trading Limited, represented among the major shareholders of TGC-2 OJSC, are affiliated with L. Lebedev. TGC-2 OJSC was also a founder of one of the main shareholders of this company, Dolgovoye Agentstvo LLC (Data from the Unified State Register of Legal Entities). M. Prokhorov controlled the main shareholders of Quadra PJSC (ONEXIM Group LLC and BusinessINFORM LLC) (see Table 1).

As a result of the permanent redistribution of ownership and the increase in the state's share in generating companies with state participation, investors are exposed to increasing risks that the state can use its influence to promote state social and strategic programs at the expense of the companies' shareholder value. This is partly a consequence of the systematic confusion of the functions of the state as regulator and shareholder, obviously contradicting the basic OECD principle of corporate governance for companies with state participation, which separates these functions. Additional investment risks are possible when the interests of certain groups of shareholders are behind the state's influence on public companies.

As the state's proportion in the ownership of generating companies increases, the number of board of directors members and CEOs from the former government employees tends to grow. There is a practice of sending directives to board members to vote on the most crucial issues (appointment/dismissal of CEO and approval of the CEO contract, approval of the strategy, amendments to some internal documents, approval of the value of dividends, and others). The number of issues on which voting directives are sent is steadily expanding. The authors of the draft resolutions included in the directives are usually not known. There is no practice of preliminary

Table 2. Compliance with the Code Criteria (the case study of WGC-2 PJSC), 2018-2019.

Subsections	The number of principles recommended by the Code	Number of criteria for assessing compliance with the principle	Status of compliance with the evaluation criteria					
			2018			2019		
			Complied with	Not complied with	Partially complied with	Complied with	Not complied with	Partially complied with
I. Rights of shareholders and equal conditions for shareholders in exercising their rights								
1.1.	6	14	12	-	2	12	-	2
1.2.	4	5	3	1	1	3	1	1
1.3.	2	2	2	-	-	2	-	-
1.4.	1	1	1	-	-	1	-	-
II. Board of directors								
2.1.	7	12	9	1	2	10	-	2
2.2.	2	3	2	1	-	2	1	1
2.3.	4	5	-	2	3	-	3	2
2.4.	4	6	3	2	1	4	2	-
2.5.	3	4	2	2	-	2	2	-
2.6.	4	8	4	2	2	3	1	4
2.7.	4	4	3	1	-	2	-	2
2.8.	6	13	4	2	7	4	1	8
2.9.	2	3	2	1	-	-	3	-
III. Corporate Secretary								
3.1.	2	3	3	-	-	3	-	-
IV. Remuneration system for members of the board of directors, executive bodies, and other key executives								
4.1.	4	4	3	1	-	3	1	-
4.2.	3	3	1	1	1	2	-	1
4.3.	3	6	3	3	-	3	3	-
V. Risk management and internal control system								
5.1.	4	5	4	1	-	3	1	1
5.2.	2	3	2	-	1	3	-	-
VI. Information disclosure, information policy								
6.1	2	5	4	1	-	3	1	1
6.2	3	7	7	-	-	7	-	-
6.3	2	3	3	-	-	3	-	-
VII. Material corporate actions								
7.1.	3	5	4	1	-	4	-	1
7.2.	2	4	3	1	-	3	1	-
Total	79	128	84	24	20	81	21	26

discussion of these projects by board members. There is virtually no voting against draft resolutions proposed in the directives since board members who do not vote «for» can, among other things, be excluded from candidates at the next nomination. This practice of voting by directives negatively affects the decision-making of independent directors, ultimately distorting the entire institution of independent directors and harming other shareholders. Former officials as independent directors are no longer responsible for the company's standing but serve only the interests of the state [23, 25, 28].

In foreign practice, companies with state participation restrict and even prohibit the election of ministers, secretaries of state, and other high-ranking government officials to the boards of directors. This practice helps prevent conflicts of interests among politicians, regulators, and other shareholders. Such restrictions are necessary for generating companies with state participation to avoid lobbying (through state officials on boards of directors with regulatory powers) of management interests and giving state companies preferential treatment over private companies [23].

In the emerging environment, measures are needed to strengthen generating companies' observance of the corporate governance principles for the benefit of investors. Such principles are meant to ensure the safety of funds provided by the investors and their efficient use, thus reducing the risks that investors cannot assess.

B. Compliance with the principles of the Corporate Governance Code.

Corporate practice in any of the world models follows international principles. These principles are recognized worldwide, including in developing countries and countries in transition that are interested in attracting investment. They emerged from the generalization of data on corporate governance of the states of the Organization for Economic Cooperation and Development («Principles of Corporate Governance of the OECD») [1]. In this paper, they are given below in an updated (after their revision in 2014-2015) and slightly aggregated form:

- The corporate governance structure shall encourage transparent and fair markets and efficient resource allocation, comply with the rule by law, and support effective oversight and enforcement.
- The corporate governance structure shall protect the rights and ensure fair and equal treatment of all shareholders. All shareholders shall have the opportunity to be compensated for the violation of their rights.
- The corporate governance infrastructure shall provide thorough incentives and prescribe that securities markets function in a way that promotes good corporate governance development.
- The corporate governance structure shall recognize the rights of stakeholders, as provided by law or in multilateral agreements and encourage active cooperation between corporations and stakeholders.
- The corporate governance infrastructure shall ensure timely and accurate disclosure of information on all material matters related to the corporation, including the financial standing, results of operations, ownership, and management of a company.
- The corporate governance structure shall provide for the strategic guidance of the company, effective control over management by the boards of directors, and accountability of the boards of directors to the company and shareholders.
- These international principles of corporate governance, given domestic specifics, formed the basis of the Russian Corporate Governance Code developed in 2014. After some generalization consistent with the Bank of Russia's recommendations for reporting on «Compliance with the Principles and Recommendations of the Corporate Governance Code» in the annual reports of Russian companies, the principles of the Russian Code are listed below [2].
- Observance of shareholders' rights to participate in the management and profits of companies, ensuring equal conditions for their exercise, reliability, and efficiency of accounting for shareholders' rights to their shares.
- Effectiveness and professional competence of the

Table 3. Generating companies' compliance with Code criteria, 2018-2019.

Companies (PJSC)	Complied with				Partially complied with				Not complied with			
	2019		2018		2019		2018		2019		2018	
	Number	%	Number	%	Number	%	Number	%	Number	%	Number	%
Inter RAO	124	96.8	125	97.6	2	1.6	2	1.6	2	1.6	1	0.8
Enel Russia	120	93.8	120	93.8	5	3.9	5	3.9	3	2.3	3	2.3
TGC-1	81	63.3	89	69.4	27	21.1	37	28.0	20	15.6	2	1.6
RusHydro	123	96.1	123	96.1	3	2.3	2	1.6	2	1.6	3	2.3
Unipro	102	79.7	98	76.5	16	12.5	18	14.1	10	7.8	12	9.4
WGC-2	81	63.3	84	65.6	26	20.3	20	15.6	21	16.4	24	18.8
Mosenergo	78	61.0	62	48.4	30	23.4	56	43.8	20	15.6	10	7.8
Quadra	76	59.4	75	58.6	22	17.2	22	17.2	30	23.4	31	24.2
TGC-2	80	62.5	58	45.3	36	28.1	37	28.9	12	19.4	33	25.8

Table 3. Generating companies' compliance with Code criteria, 2018-2019.

Companies (PJSC)	Complied with				Partially complied with				Not complied with			
	2019		2018		2019		2018		2019		2018	
	Number	%	Number	%	Number	%	Number	%	Number	%	Number	%
Inter RAO	124	96.8	125	97.6	2	1.6	2	1.6	2	1.6	1	0.8
Enel Russia	120	93.8	120	93.8	5	3.9	5	3.9	3	2.3	3	2.3
TGC-1	81	63.3	89	69.4	27	21.1	37	28.0	20	15.6	2	1.6
RusHydro	123	96.1	123	96.1	3	2.3	2	1.6	2	1.6	3	2.3
Unipro	102	79.7	98	76.5	16	12.5	18	14.1	10	7.8	12	9.4
WGC-2	81	63.3	84	65.6	26	20.3	20	15.6	21	16.4	24	18.8
Mosenergo	78	61.0	62	48.4	30	23.4	56	43.8	20	15.6	10	7.8
Quadra	76	59.4	75	58.6	22	17.2	22	17.2	30	23.4	31	24.2
TGC-2	80	62.5	58	45.3	36	28.1	37	28.9	12	19.4	33	25.8

board of directors in making decisions in the interests of companies and their shareholders.

- Performance of the Corporate Secretary in protecting the rights and interests of shareholders.
- Availability of a policy for the remuneration of members of the board of directors, members of executive bodies, and other key executives, ensuring their recruitment, motivation, and retention in the company, convergence of financial interests of members of the board of directors with the interests of shareholders.
- The efficiency of the risk management and internal control system.
- Completeness, relevance, and reliability of disclosed information for shareholders and investors to make informed decisions. Equal and easy access to this information.
- Observance of the rights and interests of shareholders in carrying out material corporate actions.
- The principles of the Code are presented in its seven sections. The sections contain 24 additional subsections with 79 principles of the Code under three-digit numbers («1.1.1.» or «1.2.3.», and others) and 128 evaluation criteria recommended by the Bank of Russia. Each evaluation criterion is assigned the compliance status: «complied with,» «partially complied with,» and «not complied with.» The case study of WGC-2 PJSC shows how the results of compliance with the Code criteria in 2018-2019 were obtained for each generating company (see Table 2).

Table 3 shows only the totals for the number of criteria of the Code that are «complied with,» «partially complied with,» and «not complied with» by generating company in 2018-2019 (including percentage points).

According to this Table, generating companies varied significantly in their compliance with Code principles. In 2019, the leaders in compliance were state-owned companies – Inter RAO PJSC, RusHydro PJSC, and Enel Russia PJSC (Italy). Of the 128 evaluation criteria, they met 96.8%, 96.1%, and 93.8%, respectively. At the bottom of this list were privately-owned companies – TGC-2 PJSC and Quadra PJSC – that adhered to 62.5% and 59.4% of evaluation criteria and were among the worst scoring companies. Comparative analysis of the values of leaders and the worst scoring companies in terms of the «not complied with» status of adherence to the evaluation criteria indicates that Quadra PJSC was a downright worst scoring company, with the largest gap in values. It lagged 10 to 15 times behind the leaders in compliance with the principles of the Code.

Equally significant differences were also noted in the status of individual companies' compliance with the principles of the Code. The generating companies leading in observance of these principles had the following proportions of «partially complied with» and «not complied with» criteria of those 128 ones assessed in 2019: Inter RAO PJSC – 1.6%, 1.6%; Enel Russia PJSC – 3.9%, 2.3%; and RusHydro PJSC – 2.3%, 1.6%. The undeniably worst scoring company (Quadra PJSC) had a relative shift toward an increase in the criteria that were «not complied with» – 17.2%, 23.4%. In other companies, the opposite changes were observed, i.e., towards a rise in the number of the criteria that were «partially complied with.» The most indicative companies in this regard were WGC-2 PJSC – 28.1%, 9.4% and Mosenergo PJSC – 23.4%, 15.6% (see Table 3).

The oppositely directed changes among generating companies were observed when comparing 2018–2019 Code compliance results. Almost nothing changed in the leading companies. Unipro PJSC, Mosenergo PJSC, and TGC-2 PJSC increased the number of criteria they comply with by 3.2%, 12.6%, and 17.2%, respectively. In the rest of the companies, the number of these criteria went down. There was an increase in the number of unmet criteria, which was mainly observed at TGC-1 PJSC and Mosenergo PJSC. This increase was largely due to a shift from criteria that were «partially complied with» to those «not complied with.» The number of criteria that were «partially complied with» decreased in these companies by 6.9% and 20.4%, respectively (see Table 3).

Based on the analysis of the ownership structure of generating companies and their compliance with the principles of corporate governance, new opportunities for its development were formulated.

Table 4. The evaluation criteria least complied with for sections i-ii of the code, 2019.

Principles	Criteria for evaluating compliance with the Code principles
1.2.1.	2. Dividend policy provisions take into account consolidated financial statements.
1.2.2.	1. The dividend policy contains clear indications of the circumstances for non-payment of dividends.
1.2.4.	The Company strives to exclude the use by shareholders of other ways of obtaining profit (income) at its expense, in addition to dividends and liquidation value.
2.3.1.	1. The adopted procedure for evaluating the performance of the board of directors (BoD) includes an evaluation of the professional qualifications of its members.
2.3.3.	As part of the BoD's performance evaluation process during the reporting period, the board analyzes its needs with a focus on professional qualifications, experience, and business skills.
2.3.4.	As part of the procedure for evaluating the BoD in the reporting period, the board considers whether the number of its members corresponds to the needs of the company and the interests of its shareholders.
2.4.2.	1. The BoD forms an opinion on the independence of each candidate and submits the relevant conclusion to the shareholders. 2. The BoD reviews the independence of its current members, who are listed as independent directors in the annual report, at least once during the reporting period.
2.4.3.	1. Independent directors constitute at least one-third of the BoD.
2.4.4.	Independent directors make a preliminary evaluation of material corporate actions related to a possible conflict of interests, and results of such evaluation are provided to the BoD.
2.5.1.	1. The BoD Chairman is independent, or a senior independent director is selected from the independent directors.
2.5.2.	As part of the procedure for evaluating the BoD performance in the reporting period, its Chairman performance is evaluated.
2.5.3.	1. The internal documents stipulate the obligation of the BoD Chairman to take measures to timely provide materials on the issues on the agenda of the meetings to its members.
2.6.1.	3. A procedure is established to enable the BoD to obtain professional advice on matters within its competence at the Company's expense.
2.6.3.	1. Individual attendance of meetings of the BoD and its committees, and time to prepare for participation in them, are considered part of the procedure for evaluating the BoD performance in the reporting period.
2.8.1.	1. The BoD forms an audit committee comprised solely of independent directors.
2.8.2.	1. The BoD establishes a remuneration committee consisting only of independent directors. 2. The remuneration committee is chaired by an independent director, who is not the BoD chairman.
2.8.4.	1. In the reporting period, the BoD reviews the correspondence of members of its committees with the objectives of the board of directors and the Company's business goals.
2.8.5.	1. BoD committees are chaired by independent directors. 2. Internal documents contain provisions according to which non-members of committees may attend their meetings only when invited by the Chairman of a relevant committee.
2.8.6.	1. During the reporting period, the chairmen of the committees regularly report on their work to the BoD.
2.9.1.	1. Self-evaluation or external evaluation of the BoD performance in the reporting period involves evaluating the BoD, its members, and committees. 2. The results of the self-evaluation or external evaluation of the BoD are reviewed at its face-to-face meeting.
2.9.2.	An external organization is engaged at least once to conduct an independent evaluation of the quality of the BoD's performance during the last three reporting periods.

III. New opportunities for the development of corporate governance

The study focused on three strands of new opportunities for the development of corporate governance in power generating companies for the benefit of investors in the foreseeable future:

Strengthening compliance with international «soft law.»

Expanding the criteria for evaluating the compliance with the Code principles

Updating the Code.

A. Strengthening compliance with international «soft law.»

Adherence of generating companies to the evaluation criteria recommended by the Bank of Russia was considered one of the possible directions of corporate governance development for the benefit of investors.

This direction is due to a significant number of the identified evaluation criteria recommended by the Bank of Russia (2019) that are least observed by the vast majority of generating companies. They were grouped into individual sections of the Code. The evaluation criteria that are least complied with for Sections I-II of the Code are shown in Table 4.

The evaluation criteria least complied with for Sections III-VII of the Code are shown in Table 5.

According to Tables 4 and 5, the vast majority of the least observed evaluation criteria at generating companies are related to the performance of their boards of directors within their delegated authority. This situation is most likely because the board lacks a decisive role in corporate governance as a body of strategic guidance and management control. After all, from a legal point of view,

Table 5. The evaluation criteria least complied with for Sections III-VII of the Code, 2019.

Principles	CRITERIA FOR EVALUATING COMPLIANCE WITH THE CODE PRINCIPLES
4.1.2.	During the reporting period, the remuneration committee reviews the remuneration policy and the practice of its implementation and provides appropriate recommendations to the BoD, if necessary.
4.1.3.	The remuneration policy contains transparent mechanisms for determining the size of remuneration for members of the BoD, executive bodies, and other key executives and regulates all types of payments, benefits, and privileges provided to them.
4.2.1.	Fixed annual remuneration is the only monetary form of remuneration to the members of the BoD in the reporting period.
4.2.2.	Provision and disclosure of clear rules for share ownership by the BoD members aimed to encourage long-term ownership of such shares if the internal document (policy) on remuneration suggests granting them the Company's shares.
4.3.1.	2. The appropriate relationship between the fixed and variable parts of remuneration to the members of executive bodies and other key executives of the Company based on the results of the evaluation of the BoD is adopted. 3. A procedure is established to ensure the return of the performance pay, unduly received by the members of the Company's executive bodies and other key executives, to the Company.
4.3.2.	1. A Long-Term Incentive Program using the Company's shares (financial instruments with such shares as the underlying asset) is implemented. 2. The right to sell shares and other financial instruments in the Program does not arise earlier than three years from the moment of its granting.
6.1.1.	2. The BoD (or its Committee) reviews the issues pertinent to compliance with the information policy at least once during the reporting period.
6.1.2.	3. If there is a person that performs control of the Company, their memorandum regarding their plans for corporate governance in the Company is published.
7.1.2.	1. There is a procedure for independent directors to state their opinions on material corporate actions before their approval.
7.2.2.	3. Internal documents provide an expanded list of grounds on which members of the BoD, and other persons referred to in respective laws, are considered to be interested in transactions.

every shareholder is the owner of generating company, the real power, however, belongs to the controlling shareholders.

In this regard, it is difficult not to agree with the authoritative opinion of I. Belikov (I. Belikov is the founder and head of the Russian Institute of Directors), who has considerable professional experience in this area, including membership on the boards of directors of more than 20 Russian and foreign companies of various capital structures and statuses (private, state-owned, public, non-public). In his opinion, only controlling shareholders seek to retain complete control over their companies. Given the high concentration of equity capital, significant non-market risks of doing business, and relatively weak legal and judicial protection, they can influence strategy development and decision-making by making the practice of current close interaction with the top executives of companies the basis of management. The top management directly and officially depends on the controlling shareholders and is more understandable to them as a partner than the board of directors. Controlling shareholders with more power than the board of directors can themselves influence the top executives, independently decide on the appointment and dismissal of CEOs and, often, top managers; set main objectives for them; and determine the size and forms of their remuneration. boards of directors are assigned the role of a formal participant in this relationship (often a mere observer) [23]. An indirect confirmation of this is the formal approach of generating companies to ensuring good corporate governance practices as identified in previous studies [26].

In this case, it seems necessary to tighten oversight of companies' compliance with international «soft law,» i.e., the «comply or explain» principle (this provision is recommended by the OECD for countries with relatively weak legal and regulatory structures). In this regard, the experience of France, also with its predominantly concentrated shareholding structure, is attractive and would probably be instrumental. This country established the HCGE (Haut Comité de Gouvernement d'Entreprise/ High Committee of Corporate Governance) to tighten oversight of compliance with international «soft law.» The Committee aims to oversee the application of the Code's recommendations, including reviewing companies' compliance reports. The HCGE has neither punitive nor judicial powers, but its very existence and the constant control it performs are powerful means of preventing violations of corporate governance best practices.

At the same time, generating companies require some revision and expansion of the evaluation criteria recommended by the Bank of Russia.

B. Expansion of the criteria for evaluating the compliance with the Code principles.

In the context of the introduction of information technologies, the criteria of the Code, not included in the recommendations of the Bank of Russia for reports «On Compliance with the Principles and Recommendations of the Corporate Governance Code,» are relevant. They are identified by further analysis and are listed under three-digit numbers below under the corresponding principles of the Code. Additional criteria are in italics.

1.1.5. Each shareholder shall be able to freely exercise the right to vote most easily and conveniently for them.

• *Systems are created to enable shareholders to vote electronically on the Internet by filling out a voting ballot electronically, for example, through a personal account on the Company's website.*

2.3.2. The members of the board of directors shall be elected through a transparent procedure allowing shareholders to obtain information about candidates sufficient to form an idea of their personal and professional qualities.

• *A preliminary discussion by shareholders of the candidates proposed for nomination to the board of directors is arranged.*

• *Information on the person (group of persons) who nominated this candidate, on the nature of their relations with the Company, on their membership in the boards of directors in other legal entities, as well as the nomination of this candidate to the boards of directors or for election (appointment) to other legal entities, is disclosed. Information on the person's relations with affiliated persons and principal counterparties of the Company is given.*

• *Information about candidates' compliance with the requirements for independent directors is indicated.*

• *An Internet forum on the agenda of the General Meeting of Shareholders is organized to collect shareholders' opinions on the candidates' compliance with the independence criteria.*

2.9.1. The evaluation of the board of directors' performance shall be aimed at determining the degree of efficiency of the board, its committees, and members of the board, compliance of their work with the Company's development needs; promoting active involvement of the board in performing its duties, and identifying areas where its performance can be improved.

• *A formalized procedure is developed to evaluate the performance of the board of directors as a whole, the performance of its committees, each member of the board of directors, and its Chairman.*

6.1.1. The Company shall develop and adopt an information policy that ensures effective information interaction among the Company, shareholders, investors, and other stakeholders.

• *A dedicated page is organized on the Company's official website, where it posts answers to frequently asked questions from shareholders and investors, a regularly updated calendar of corporate events, and other information useful to shareholders and investors.*

6.2.2. Company is advised to avoid a formalistic approach to information disclosure and to disclose material information about its activities, even if such information is not required to be disclosed by law.

• *Information on legal entities controlled by the Company, which is material to the Company, including information on their role, their primary activities, the functional relationships among the key companies in the group, and the mechanisms for ensuring accountability and control within the group, is disclosed.*

• *Information about related party transactions following the criteria established by International Financial Reporting Standards (date; description of the terms of the transaction; names of counterparties and how they are related; grounds on which the transaction is classified as a related party transaction; reasonableness of the transaction; the transaction amount and its percentage of assets) is disclosed.*

The development of corporate governance in generating companies in the interests of investors also requires certain adjustments to the Code itself, which has not been updated since its publication.

C. Updating the Code.

Codes of corporate governance in global practice are regularly updated. Their new revisions were adopted in the United Kingdom [19], Austria, Denmark, and Mexico (2018), Germany [21], Belgium, and Saudi Arabia (2019), Italy [20], and France [18] (2020). The central emphasis in these revisions was mainly on improving the mechanisms of interaction between boards of directors and shareholders; achieving gender equality in the boards; strengthening oversight of the applied policy of accrual of remuneration of top management and individual remuneration of senior executives; environmental and social aspects [16]. The primary purpose of the amendments is to supplement the previously developed recommendations and more clearly define the objectives of corporate governance in the modern socio-economic context.

The Russian Code, in our opinion, needs an ESG transformation to be brought up to date. Environment, social development, and corporate governance are today's unquestionable trends that involve environmental protection, fair treatment of employees and customers, and strong corporate governance. The ESG metrics are viewed by socially conscious investors as an effective tool for managing non-financial risks to achieve long-term competitive advantages of companies and are used by them to test potential investments.

Few generating companies consider the interests of their stakeholders and combine long-term economic, environmental, and social aspects in a single development strategy, factoring in social responsibility as a direct responsibility of the state. On PwC's (PricewaterhouseCoopers is an international network of companies offering consulting and audit services) maturity scale for evaluating ESG disclosure, these companies can be categorized as «laggards» [17]. The analysis of general corporate governance practices has indicated that the information they disclose about social programs and environmental policies is not detailed or systematic. They show only selected provisions on environmental policy, occupational safety and health, social programs for employees, sponsorship, and charity. Some companies have developed vision statements to implement environmental policies, but the current expenditures for environmental protection, as well as construction and reconstruction of environmental protection facilities, are very low.

The following criteria are proposed to assess whether companies comply with ESG principles:

The ESG system is built into the architecture of corporate governance systems of companies.

An ESG policy is developed based on the views of a wide range of stakeholders and formulates the goals, objectives, and basic principles of the company's ESG activities.

An ESG committee or supervisor from the board of directors on these issues is established.

The authority of the ESG committee is defined, including review and coordination of issues related to ESG initiatives (preparation of development strategy, internal processes, portfolio of core projects, and others), interaction with management and external stakeholders on ESG agenda issues, control over the company's ESG work.

The qualifications and experience of ESG committee members in this area are disclosed.

ESG issues are reviewed by the board of directors regularly.

Generally accepted GRI standards and principles of international reporting are used in disclosing the ESG information (GRI stands for Global Reporting Initiative, the standards of which are recognized by the UN as the main universal tool of corporate reporting, reflecting the economic, environmental and social performance of the company).

An independent auditor is engaged to verify the accuracy of ESG disclosures.

ESG metrics are developed.

ESG issues are included in the overall risk management system.

Remuneration of top management of companies is formed following the objectives set with respect to ESG and the timing of their accomplishment.

Non-financial metrics tied to the remuneration of senior executives of companies are defined.

Internal documents of companies are updated in connection with the ESG application.

It is worth noting that the legislation cannot timely and promptly respond to changes in corporate governance practices since it takes a considerable amount of time to introduce such changes. In this regard, the updates proposed for the Code can be made by generating companies in their internal documents, primarily in their Corporate Governance Codes. Advanced Russian companies are an example of this. In particular, Sberbank PJSC implements ESG principles in its corporate practice [22].

IV. Conclusion

The study has revealed a high concentration of ownership and the growing presence of the state in it. There is a significant number of criteria for evaluating compliance with the Code principles, which are not observed by an overwhelming majority of generating companies. New opportunities for the development of corporate governance in the interests of investors have been elucidated. They are related to strengthening compliance with international «soft law,» expanding the criteria for evaluating compliance with the principles of the Code, as well as its ESG transformation. These opportunities will allow a fresh look at the prospects for improving corporate governance in generating companies: for owners – when meeting the criteria for evaluating compliance with its principles and updating internal documents; for investors – when making more informed decisions to form a portfolio of effective assets.

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Effect of Grid Faults on Dominant Wind Generators for Electric Power System Integration: A Comparison and Assessment

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***Abstract* — In recent times, various types of wind generators have been linked to the power grids globally and the focus has been to control them to be more efficient and reliable. This study concisely discusses performance analysis, modeling, and assessment of different wind generators (permanent magnet synchronous generator, doubly-fed induction generator, squirrel cage induction generator), covering their benefits, drawbacks, and impact on the electric power systems. This comparison aims to guarantee that their technical and economic evaluations are comparable, allowing engineers to make a more informed decision about which generator is best suitable for their installation. Findings for the investigated wind generators lead to significant observations about their application fields, such as permanent magnet synchronous generator outperforms doubly-fed induction generator and squirrel cage induction generator, especially during grid disruptions; on the other hand, squirrel cage induction generator is simple and inexpensive.**

***Index Terms*: doubly-fed induction generator (DFIG), modeling, power system disturbance, permanent magnet synchronous generator (PMSG), squirrel cage induction generator (SCIG), wind generators.**

Abbreviations

WG - wind generator
PMSG - permanent magnet synchronous generator
DFIG - doubly-fed induction generator
SCIG - squirrel cage induction generator
RES - renewable energy sources
WT - wind turbine
NN - neural network
EST- energy storage tools
FACTS - flexible alternating current transmission system
FLC - fuzzy logic controller
WECS - wind energy conversion system
VSWG - variable-speed wind generator
FSWT - fixed-speed wind turbine
GSC - grid-side converter
VSC - voltage-source converter
IGBT - insulated-gate bipolar transistor
MSC - machine-side converter
MPPT - maximum power point tracking

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I. Introduction

Renewable energy use has risen dramatically in current years all around the universe. The large-scale integration of renewable energy sources (RESs) into electrical grids has resulted in significant changes in power production technologies. This progress has been made possible by more effective management and enhancement of the electrical components, both of which have contributed to the improvement of the quality of the power delivered [1]. RESs offer a great potential to help certain regions grow sustainably while also giving a lot of socioeconomic advantages. Diversity of electricity supply, environmental sustainability, and the establishment of new industry and business possibilities are among the RES advantages [2, 3].

Due to the international agreements achieved, we might be witnessing the rupture of the link between electricity generation and CO2 emissions nowadays [4]. As seen in Fig. 1, more than a 50% increase in the global electricity demand is expected by 2030, while the amount of CO2 released by this sector remains stable. This can be a turning point since increments in electricity consumption have always been coupled with proportional rises in CO2 emissions. This switching is a consequence of the expected and necessary transformation in the electrical energy sector. Around 70% of the new electricity generation units are projected to be low-carbon technologies raising the total share of these sources to nearly 45% of overall generation by 2030 [4]. Inevitably, RESs have a central

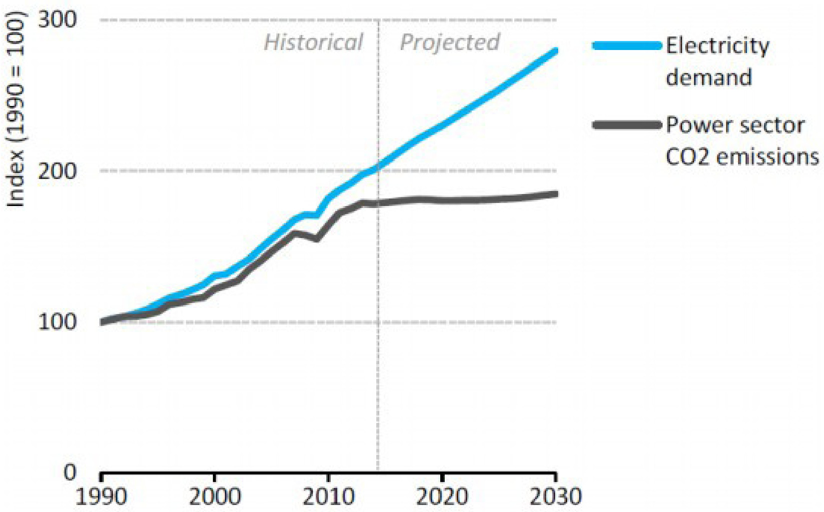


Fig. 1. Growth in world electricity demand and related CO2 emissions since 1990 [4].

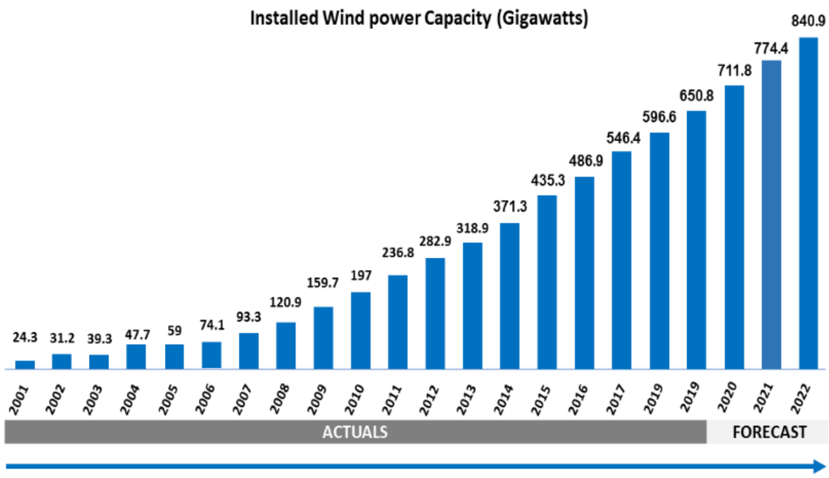


Fig. 2. Global installed wind power capacity.

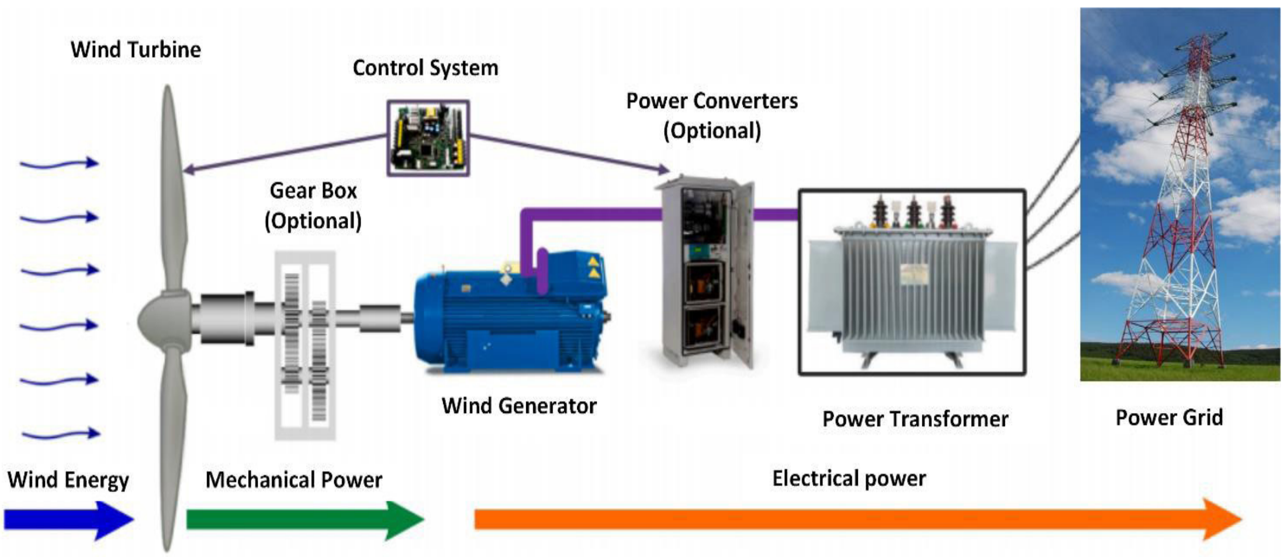


Fig. 3. General working principle of the WECS operation

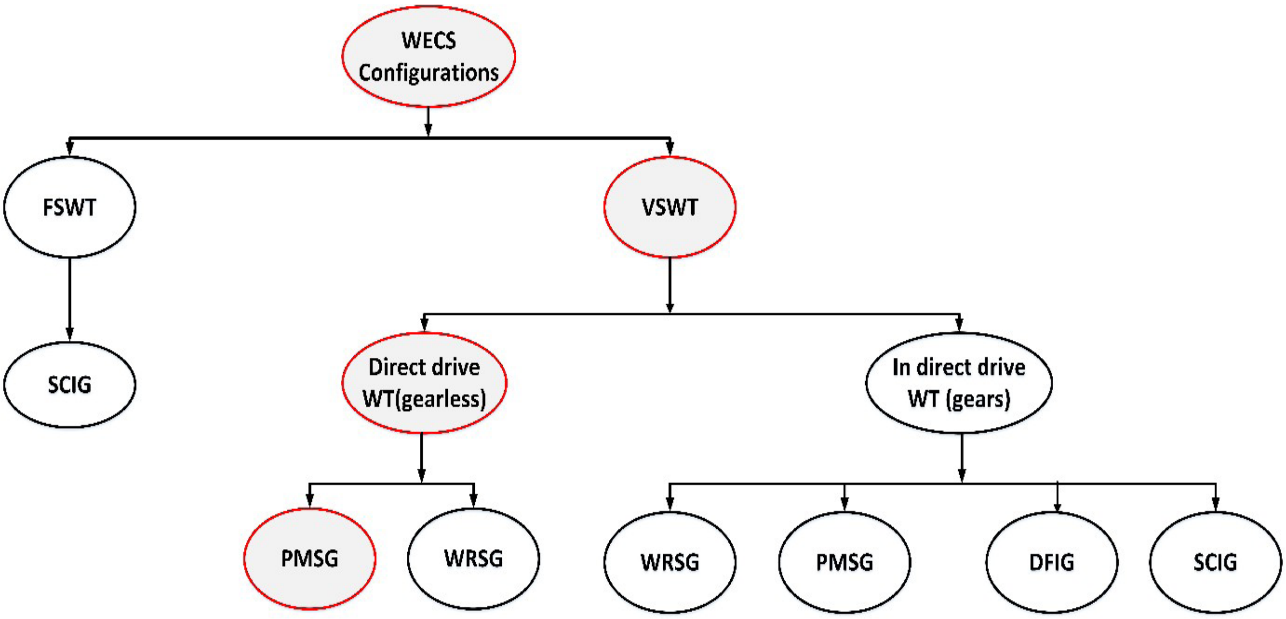


Fig. 4. Classification of WECS.

role to play here. For instance, estimations of 4 000 % and 1 000% growth in the total final energy consumption share of solar PV and wind generators (WGs), respectively, were reported in the literature [5]. Compared with other RESs, wind energy is inexpensive, produces energy with negligible environmental impacts, and is more dependable. The wind power capacity installed globally from 2001 to 2022 is shown in Fig. 2 [6].

The study of wind speed and other wind characteristics in a given location is critical for building wind turbines (WTs) on land or in the water. The Weibull is particularly useful for analyzing the data of wind velocity probability density in WT systems. In addition, data from the fluctuation of average wind speed can be obtained by applying Prandtl's law. Nevertheless, different technologies and existing WT designs should be considered to select the one that performs well in a specific application. Wind energy is a plentiful resource given by mother nature [7, 8]. Furthermore, the worldwide availability of this sort of RES makes it suitable for autonomous energy production. Old WGs operate at a fixed speed, while modern WGs can operate at variable speeds and meet the new grid requirements [6].

Various software and hardware solutions have been used for improved and efficient operation of the grid-connected WGs. The software schemes include PI-optimization methods, FLC and its modifications, and neural networks (NNs) [9, 10]. Complex nonlinear troubles can be solved using some heuristic methods with minimal computational time but with poor accuracy solutions [11, 12]. Hardware approaches are based on energy storage tools (ESTs), FACTS tools, or a hybrid of both to improve the grid integration capabilities [13].

The purpose of the study provided in this paper is to compare and evaluate the most popular WGs currently existing in the market. In addition, the influence of grid faults on various WGs has been studied, and their benefits and drawbacks are provided to aid researchers to more deeply understand their actions during grid fail. The assessment of WGs carried out in this study is to assist the researchers in selecting the most appropriate WG for their specific use.

This paper can be outlined as follows. Section 2 presents the characteristics of SCIG, DFIG, and PMSG with the operating concept of WECSs. Section 3 focuses on the mathematical model of the WT system and the aforementioned WGs. The advantages and disadvantages of WGs under investigation are discussed in Section 4, while the local grid implications on the three major WGs are summarized in Section 5. Section 6 assesses the studied WGs. The major concluding remarks are presented in Section 7.

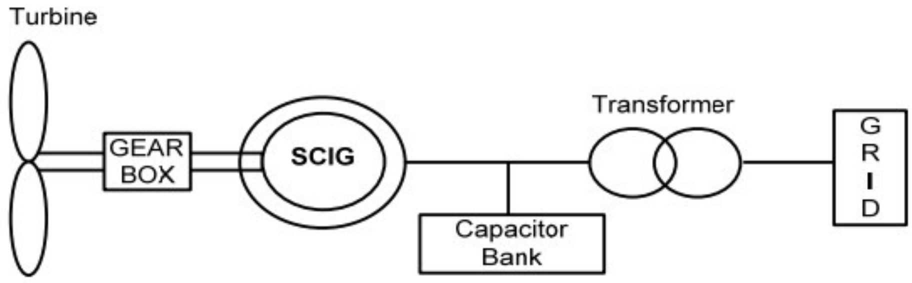
II. Configurations of dominant wind generators

Advanced technologies are being applied to WECSs to make them more effective and achieve the grid necessities. This study concerns the three most common WGs, which are SCIG, DFIG, and PMSG.

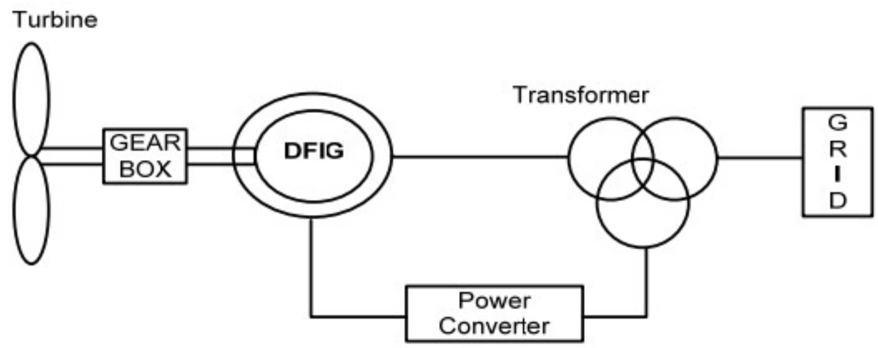
1) *Working principle of WECS*

The working principle of the WECS involves two stages. In the first stage, the kinetic energy in the wind is being captured and converted into mechanical energy through the blades of the aerodynamic WT rotor. The second stage is electromechanical power conversion, which employs an electrical generator that converts mechanical energy into electrical energy to be transmitted to an electrical power grid [14]. This is the general principle of operation, and it is shown schematically in Fig. 3.

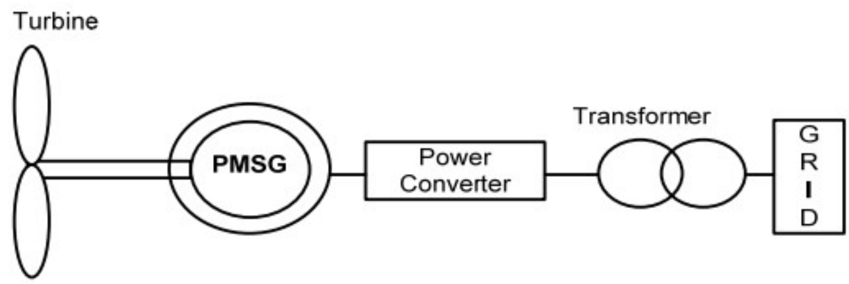
2) *Classification of WECS*



(a)



(b)



(c)

Fig. 5. Generating systems used in WECSs: (a) SCIG, (b) DFIG, and (c) PMSG.

Based on their operational speed, WECSs can be classified into two main categories: fixed speed WTs and variable speed WTs. Moreover, they can also be subdivided into many different types based on their ability, reliability, efficiency, performance, and minimal cost [14]. Fig. 4 shows the classifications of WECSs. As regards the construction of their generating system, almost all of the currently mounted WTs use one of the configurations shown in Fig. 5.

a) SCIG technology

SCIG is the first electrical generator used to generate electrical power by capturing the power of the wind. The output of SCIG is used to be directly connected to the power grid through a power transformer, which results in its rotor speed varying slightly according to the amount of power needed by the grid. However, these variations are as small as 1 to 2% of its rated speed. Accordingly, it is often called a constant speed or FSWT. Impressively by altering the number of pole pairs of its stator winding, the SCIGs, equipped with WTs, can run at two completely different (but constant) speeds. SCIG needs a continuous supply of reactive power for its operation, which is undesirable, especially when it connects large WTs to weakened grids. Thus, capacitors play a significant part for SCIG by supplying fully or partially the amount of reactive power needed for the generator to achieve unity or near-unity power factor. There are considerable hazards related to this generator, i.e., the power captured from the wind is

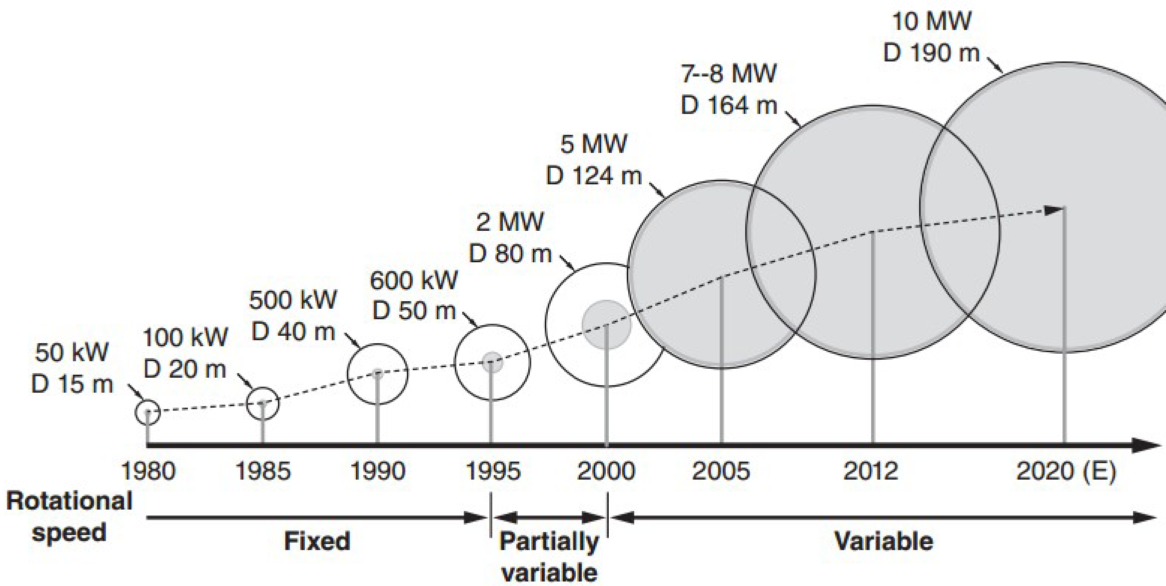


Fig. 6. State-of-the-art development – wind generators.

sub-optimal, it is exposed to danger due to self-excitation for the period of the power grid interruption, and reactive power compensation is required [15].

b) DFIG technology

DFIG is viewed as a starting point for the VSWG because its mechanical rotor speed can be easily decoupled from the power frequency of the electrical power grid. This can be achieved by using a power electronic converter to feed 3-phase power to the DFIG rotor windings, as shown in Fig.5. In this way, the mechanical and electrical frequencies of the rotor can be decoupled, and consequently, the electrical frequency of the rotor could be aligned to its stator counterpart and independently of the rotor's mechanical speed. Change in the DFIG's rotor resistance can result in a shift of the torque/speed characteristics of the generator and an increase in transient rotor speed of about 10% of the nominal rotor speed [15].

c) PMSG technology

PMSG is the first generator to make a complete benefit of the power electronic converters to be decoupled from the power grid. The used GSC is a VSC, i.e., IGBT bridge. The MSC can be either a VSC for a large scale, in MW, or a diode rectifier for a small scale, in kW. It is characterized by self-excitation, simple structure, high power density, low maintenance, absence of gears, good controllability, and full-scale power electronics interface. It is one of the most attractive and promising WGs due to its reported merits [12, 16].

SCIG, DFIG, and PMSG represent about 97% of generators in the market these days. It is clear from Fig. 6 that before 1995, WGs had been based on FSWTs due to their simplicity and low cost, but their main drawback is the need for reactive power to assist voltage support. In 1995–2000, DFIG became the dominant sector due to its merits like reduced cost and the presence of power electronic converter. Due to the problems with the earlier two WGs, PMSG is currently the major WG that can meet MPPT and new grid code requirements. The main cause of the rapid growth of VSWTs is the advance in power converters technology [17, 18].

III. Modeling of dominant wind generators

1) WT model

The WT model can be articulated as follows [12, 13]:

$$Cp\left(\lambda,\beta\right)=0.5176\left(\frac{116}{\lambda_i}-0.4\beta-5\right)\exp^{-\frac{21}{\lambda_i}}+0.0068\lambda\,,$$

$$\lambda=\frac{\omega_r R}{V_W},$$

$$T_m=\frac{P_m}{\omega_r},$$

$$T_m=J_{eq}\frac{d\omega_r}{dt}+B_{eq}\omega_r+T_e\,,$$

where, Cp, λ, ω_r, J_{eq}, B_{eq}, T_e, T_m are the studied WT parameters defined in [12].

2) PMSG model

The PMSG's concept is fully defined in [12] and can be represented as follows:

$$V_{ds}=R_sI_d+\lambda_d-\omega_e\psi_q,$$
$$V_{qs}=R_sI_q+\lambda_q-\omega_e\psi_d.$$

The stator flux connection components can be written as:

$$\psi_d=L_dI_d+\psi_{pm},$$
$$\psi_q=L_qI_q,$$
$$\lambda_d=L_dI_d+\psi_{pm}.$$

The T_e can really be defined in the following way:

$$T_e = \frac{3}{2} n_p \left(\lambda_d I_q - \psi_q I_d\right) = \frac{3}{2} n_p \left(\psi_{pm} I_q + I_d I_q \left(L_d - L_q\right)\right).$$

For the surface-mounted PMs sort, ($L_q = L_d$). So, T_e can be written as tracks:

$$T_e = \frac{3}{2} n_p \left(\psi_{pm} I_q\right).$$

3) DFIG model

The DFIG concept is discussed and defined in [19] and can be exemplified as follows:

$$V_{ds} = R_s I_{ds} - \frac{d\psi_{ds}}{dt} - \omega_s \psi_{qs},$$

$$V_{qs} = R_s I_{qs} + \frac{d\psi_{qs}}{dt} + \omega_s \psi_{ds},$$

$$V_{dr} = R_r I_{dr} + \frac{d\psi_{dr}}{dt} - \left(\omega_s - \omega_r\right) \psi_{qr},$$

$$V_{qr} = R_r I_{qr} + \frac{d\psi_{qr}}{dt} + \left(\omega_s - \omega_r\right) \psi_{dr},$$

$$\psi_{ds} = L_s I_{ds} + L_m I_{dr},$$
$$\psi_{qs} = L_s I_{qs} + L_m I_{qs},$$
$$\psi_{dr} = L_r I_{dr} + L_m I_{dr},$$
$$\psi_{qr} = L_r I_{qr} + L_m I_{qs},$$

$$T_e = \frac{3}{2} P\left(\psi_{ds} I_{qs} - \psi_{qs} I_{ds}\right).$$

4) SCIG model

The dynamic behavior of the SCIG-WG is given as follows [20]:

$$V_{qs} = R_s I_{qs} + P\lambda_{qs} + \omega\lambda_{ds},$$
$$V_{ds} = R_s I_{ds} + P\lambda_{ds} - \omega\lambda_{qs},$$
$$V_{qr} = R_r I_{qr} + P\lambda_{qr} + (\omega - \omega_r)\lambda_{dr} = 0,$$
$$V_{dr} = R_r I_{dr} + P\lambda_{dr} - (\omega - \omega_r)\lambda_{qr} = 0,$$

$$\begin{bmatrix} I_{ds} \\ I_{qs} \\ I_{dr} \\ I_{qr} \end{bmatrix} = \frac{1}{D_1} \begin{bmatrix} L_r & 0 & -L_m & 0 \\ 0 & L_r & 0 & -L_m \\ -L_m & 0 & L_s & 0 \\ 0 & -L_m & 0 & L_s \end{bmatrix} \begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix},$$

$$\lambda_{ds} = (V_{ds} - R_s I_{ds} + \omega\lambda_{qs})/S,$$
$$\lambda_{qs} = (V_{qs} - R_s I_{qs} - \omega\lambda_{ds})/S,$$
$$\lambda_{dr} = (V_{dr} - R_r I_{dr} + (\omega - \omega_r)\lambda_{qr})/S,$$
$$\lambda_{qr} = (V_{qr} - R_r I_{qr} - (\omega - \omega_r)\lambda_{dr})/S,$$
$$D_1 = L_s L_r - (L_m)^2,$$
$$T_e = 1.5P(I_{qs}\lambda_{ds} - I_{ds}\lambda_{qs}).$$

IV. Benefits and drawbacks of the compared wind generators

Table 1 shows a comparative analysis of the three types of generators discussed in this study. The benefits and drawbacks of these generating systems are compared against each other and listed concisely in the Table.

V. Local grid impacts on the common wind generators

High wind power penetration has resulted in some noticeable local impacts on the power system, including changes in node voltage, fault currents, harmonics, and flicker [21, 22]. A comparison of these impacts and their effects on the three WGs are stated briefly in Table 2.

VI. Assessment of wind generators

Both technological and economic considerations should be addressed while selecting the kind of WG for specific conditions and applications. According to previous research, the SCIG voltage decreases most after a three-phase failure, requiring more time to recover while also using reactive power. Stator voltage and rotor speed instability may occur as a result of this. On the other hand, when a PMSG is subjected to a 3-phase fault, the

Table 1. Benefits and drawbacks of the more used generating systems.

Generator	SCIG	DFIG	PMSG
Advantages	Simple and robust	Less mechanical stress	Negligible mechanical stress
	Less expensive	Small converter	Absence of gearbox
	Electrically efficient	Aerodynamically Efficient	Aerodynamically Efficient
	Standard WG	Standard WG	Standard WG
	————	MPPT operation	MPPT operation
	————	Variable speed	Variable speed (0–100%)
Disadvantages	Achieves grid codes using costly hardware solutions only	Achieves grid codes using hardware solutions only	Achieves grid codes using either hardware or software solutions
	Aerodynamically less efficient	Electrically less efficient and affected by the grid disturbances	Heavy and large
	Gearbox is essential	Gearbox is essential	Power converter is a must
	Mechanical stresses	High cost	————
	Noise and vibration	Complex control	————
	Necessity of large and expensive compensation units	Speed varies about 30% of rated speed only	————

Table 2. Effects of grid's local impacts on the three dominant wind generators.

Local impact	SCIG	DFIG	PMSG
Changes in grid voltage	Compensation is a must, using FACTS tools or storage systems	Compensation is feasible, however, it is contingent on the converter's rating	Compensation is possible, however, it is conditional on the converter's rating
Harmonics	Hot point of research and interest, and a major issue	Less interest, and is not a major issue	Least interest, and is not a major issue
Flicker	Important, due to absence of power converters	Important, due to partial scaling of power converters	Unimportant, due to high system inertia and full scaling of power converters
Fault current sharing	Large share, due to direct connection to power grid	Small share, due to partial existence of power converters	No share, due to power converter's fault current blocking capability

grid voltage is higher than that with DFIG used. The employment of power converter units allows the regulation of reactive power during breakdowns, which helps to reduce voltage fluctuations.

Previously, if severe difficulties arose, WGs linked to the grid were typically just unplugged. Nowadays, many nations have mandated that WGs should not only stay attached but also help in the event of a severe grid outage. PMSG and DFIG are superior to SCIG in terms of meeting this criterion. PMSG can supply more reactive power to the grid during or after a failure than DFIG, and PMSG meets the additional standards better than DFIG.

Existing WGs are meant to operate for 120 000 hours through the course of their 20-year life span. The expenditures of operation and maintenance can make up 10-20% of the overall cost of a WG system. The cost of operations is determined by the number of jobs given and the size of the wind project, not by the kind of WG [23].

Since direct drive (PMSG) systems do not include a gearbox, their maintenance costs are different from those of other systems. The repair cost is higher for WGs that employ gearboxes because they have more rotating components (gearboxes) and wearing points necessitating more repair. As a result, the cost of maintaining WGs incorporating gearboxes is often 1% greater than that of PMSG systems.

As the size of WGs has grown, it becomes challenging to develop dependable gearboxes that can resist the massive pressures they must endure. As per a current survey, some WGs in a five-year-old wind farm are now on their second or third gearbox retrofit. In regions with high wind instability, such as mountainous terrain, a gearbox is more prone to wearout. For example, if a 1.5 MW WG gearbox is rebuilt at a local repair shop in the United States, it will cost between \$150 000 and \$200 000, accounting for 10% to 15% of the entire project capital cost. However, with the gearbox to be delivered and repaired outside of the United States, an additional 80% of the cost must be paid [24].

PMSG systems do not have a gearbox, therefore, this problem never arises. In this example, the overall project cost of employing these technologies is less than that of using a gearbox system. Nevertheless, if the PMSG-WG systems fail, their repair costs will also be appreciable because their primary shaft, bearings, and rotor are usually incorporated into one framework, and their scale is large.

VII. Conclusions

Wind energy is becoming more widely used globally, and several technological advances are being used to design new WGs. The three major WGs have been modeled, with grid implications studied and assessed herein in this paper. In addition, their benefits and drawbacks have been discussed. Since SCIG-WGs lack reactive power management, they are utilized only by tiny wind farms. Although DFIGs require smaller initial capital and have been deployed more widely than PMSGs, PMSGs can maintain grid voltage better than DFIGs during failures. When maintenance is factored in, all turbine models have equal long-term costs.

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Achievements and Challenges of Systems Studies on Energy Development in Russia, Their Possibilities in the "Digital" Society

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***Abstract* — The paper addresses major achievements, current trends, and challenges in systems studies on energy development. Further evolution of the methodology for these studies in the context of "digitalization" will depend on the development of artificial intelligence tools. The scope of planned work and possible means for its implementation in the systems studies on the energy development in the future information society are investigated for various forms of its organization.**

***Index Terms*: energy development, strategic planning, artificial intelligence, neural network, agent model, Russia.**

I. Introduction

The methodology and tools for systems studies on energy development, which originated in the USSR 50 years ago, were updated and modified 20-25 years later to fit the market conditions of the Russian economy. Until the mid-2010s, they had been effectively employed to formulate strategic planning documents for the national energy sector, including its sectoral and territorial systems. Paradoxically, but with the adoption of the Federal Law on strategic planning and on the threshold of a new energy transition in the world, the state uses the scientific justification of the country's energy development prospects increasingly less.

The digital revolution requires the transition of systems studies of energy (and economic) development to a new level. Some countries may build a **digital mobilization** economy when centralized planning furnished with artificial intelligence or a mega-set of production-territorial mathematical models will spread to households. An alternative concept of **liberal** «digitalization» of society focuses on the self-organization of market participants when foreseeing the future (they use agent models to iteratively develop mutually agreed scenarios for the evolution of the economy and energy). Based on these scenarios, the Market Council builds a preferred corridor of economic development, and each participant controls these processes using blockchain technologies, thereby identifying their opportunities and risks. The liberal digital economy will require traditional operations research methods to be supplemented with new tools, including a) neural networks, image recognition methods, and other artificial intelligence tools, b) agent-based models and methods for their interaction, c) distributed ledger technologies. To do that, however, one should find ways to overcome the theorem «On the impossibility of democracy» proved by K. Arrow.

II. Systems research overview

As shown in the review [1], the USSR embarked on working out the methods for systems studies of energy development as tools for centralized planning [2] in the early 1960s. Theoretically, they were comprehended [3, 4] and normatively fixed in planning [5, 6] in the early 1970s, and by the end of this decade, their original versions appeared in the USA and Europe [7-9].

The systems methodology was used in formulating the USSR Energy Program for the long term [10] and the section of Fuel and Energy Complex in the Comprehensive Program of Scientific and Technological Progress of the USSR. In the practice of annual and five-year planning, however, the energy subsystem of the automated system of planned calculations of the USSR State Planning Committee worked before the country collapsed only as an experiment. Although, the methods and models were widely used to optimize and justify decisions when designing the development of the fuel industries, the electric power industry (including nuclear power), and heating systems [1].

Russia's transition to market relations expanded its participation in the world energy markets and, despite the drop in domestic demand for energy, strengthened the

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energy sector as a donor to the economy. This circumstance required the formulation of the country's energy policy as a locomotive of the economy [11, 12], understanding its role in world energy [13], and the development of Russia's Energy Strategy [14]. The previous tools for systems studies of energy development in the country [15] and regions [16] and the relationship between energy and the economy [17] were radically updated and expanded.

Forecasts of the demand for various fuel and energy types across the country, along with the projections of financial, material, and labor resources that can be allocated by the economy for energy needs, are essential instruments for energy development. In the USSR, this information was provided by the State Planning Committee. In a market Russia, a system of economic development models (including agent-based ones) and the methods of their interaction with the energy development models were originated to obtain this information in a required amount [18, 19].

To work out the strategic planning documents for the energy development of the country and regions, the largest exporter must forecast the situation in the world energy markets. The information-model system [20] designed for this purpose became a part of the model and information complex SCANER (Super Complex for Active Navigation in Energy Research) [21].

The global economic crisis of 2008 brought down the size of Russia's GDP by almost 8% and the production of energy resources by 5%, completing the «golden decade» of the country's economic and energy development. In 2014, the previous goals of accelerating economic growth were replaced by the liberal paradigm of «sustainable» development with practically no GDP growth and an increase in the share of the poor, with the planning of energy development carried out increasingly more formally.

After many years of discussions, federal law on strategic planning [22] was adopted. It regulates the structure and scope of the planning process in the country. Formally, satisfactory compliance with the range and terms of development of the top-level strategic documents stipulated by the law is offset by the weakness of the planning process in the economy and its sectors, especially the energy sector. The adjustment of the Energy Strategy until 2035, which began in 2013, was not provided with up-to-date forecasts of the country's socio-economic development. As a result, after the approval of the document in 2020, the Government is now forced to make a decision to update it, along with related general schemes for the development of the energy sector industries. The state's requests for research to improve energy markets and enhance the energy security of the country and regions have also decreased in number.

As a result, since the mid-2010s, specialists in systems analysis have switched from practical applications of the developed tools to academic research on the issues of energy development in the world and Russia. In contrast to the United States and European Union, Russia does not have its vision of how world energy should evolve. Meanwhile, since 2012, Energy Research Institute (ERI) has been regularly updating the forecasts of the situation in the world energy markets and energy development scenarios in the world and Russia with its systems methods and tools [23] considering the expected technological breakthroughs, changes in the composition and behavior of the major players, and other uncertainties [24, 25]. These results, however, are not used in the strategic planning of the energy and economic development of the country.

According to the law [22], the Russian economic and energy development management was reorganized from *normative planning* used in the USSR to *indicative planning* of development goals, main objectives, and tools of achieving them with a limited range of quantitative indices of successful performance of economic agents with state participation. This is how forecasting has been organized in the United States since the 1990s. Socialist China switched to a similar concept of strategic planning of the economy (and energy as its constituent) at the beginning of the 21st century [26]. In Russia, however, indicative planning of the economy and energy, given the noted irregularity of the process, is hampered by control of the process by large businesses and low validity of documents developed. Indeed, in the United States (and to a lesser extent in China), the entire hierarchy of indicative planning is equipped with publicly discussed model calculations performed *on a competitive basis* by well-funded powerful research entities [26]. In Russia, the substantiation of strategies and programs for economic development is fragmented, their discussion is selective and formal, and the results are mostly ignored in the adopted documents.

The development of concepts and programs for the digitalization of industries and companies in Russia for the period until 2024, which has begun in recent years, is almost exclusively aimed at collecting and identifying available information and using it only in the operational management of enterprises and partially - in sectors of the economy. However, the fourth (digital) technological revolution, which is rapidly going on in the world [27], will not avoid managing the development of the economy in general and energy in particular. Whereas the access of researchers to computers in the 1960s gave impetus to the creation of a methodology and tools for systems studies of energy development, a considerable transformation of human society with its total «digitalization» will require (and will allow) the transfer of these studies to a qualitatively new level.

III. Trends, challenges, scenarios

Today we are witnessing a challenging environment in the field of systems research in the energy sector.

1. In the world, there are conflicting processes of absorption, specialization, and dispersal of systems

research in the energy sector (SRE): their methods and means are increasingly absorbed by the instruments of systems studies of the development of the economy and society at all levels of the hierarchy while specializing in the issues of climate, technological progress, and security, and being scattered to solve a number particular problems.

2. In contrast to the global trend toward expansion and «legitimization» of the use of systems research instruments, in Russia, with the adoption of the Federal Law «On Strategic Planning,» they, as noted above, are not used to substantiate forecasts and plans for the energy development.
3. The program «Digital Economy of the Russian Federation» until 2024 involves collecting, identifying, and using the information for the operational management of enterprises and, in part, sectors of the economy, ignoring management of their development.
4. The immanent systems research tools for control over the functioning and development of large-scale energy systems (mathematical modeling and optimization) are beginning to be threatened by artificial intelligence tools. In combination with total video and digital control, artificial intelligence can either replace or become a crucial tool for the development of systems energy research in a «digitalized» society.

Let us consider this alternative in more detail. Artificial intelligence is rapidly expanding its sphere of dominance:

- in the early 2000s, it beat champions in competitive games (checkers, chess, Chinese go);
- in 2017, artificial intelligence won the world poker tournament (already a much more difficult competitive game);
- in 2021, Facebook created an artificial intelligence algorithm (bot), which, as an anonymous participant, entered the 2 percent of winners in the competitive-cooperative game «Diplomacy.» This game suggests that you need to compete and cooperate with other players, deceive them and simulate their assessment of your strategy. Artificial intelligence is already ready to participate in the operational activities of the business.

The achievements of artificial intelligence make its victory in solving problems of managing the functioning of energy systems and problems of operational and short-term planning of their expansion a reality. A relatively stable set of objects to be managed and consumers require only periodic «retraining» of bots, which is not easy but can be done.

To discuss the **possible evolution of systems studies of energy development in the course of «digitalization,»** we will rely on recent publications concerned with the view of the coming information society [28-31]. Their generalization in the form of ***scenarios*** is given in the Table, which indicates the scope of planned works and possible tools for their implementation in the future (2030-2050) information society with various ways of its organization.

In an unfavorable geopolitical situation, some countries can build a **mobilization** digital economy, which suggests that centralized planning extends to a household level (column 3 in Table 1).

In ***the first version*** of this scenario, the economic (and energy) development plans are built by *artificial intelligence.* Its use in *the medium* and, especially, *long-term* planning, however, requires «self-tuning» of neural networks to various development scenarios of a planning object and its external environment. The centennial experience of the USSR and Russia's development [32] shows that the socio-economic conditions in the country

TABLE 1. A scope of planned works and tools for systems studies of energy development depending on the type of information society (2030-2050).

Scope of work		Required tools by type of society	
		Mobilization	Liberal
Planning of stages and tools	Depth of plan development	Planning down to the household level	No plan
	Planning tools	Version 1. Artificial intelligence Version 2. A system of economic and energy development models	Agent-based models of economic and energy entities
	Means of communication	Super-Internet	Super-Internet
	Coordination of decisions in the energy sector and economy	From the federal level to the enterprises	Model simulation of market operation
	Decision making	Top level of management	Decentralized
Information sources	Input data	Integral databases on energy and economy	Data are formed in the course of market operation simulation
Planning of results	Development plans, taxes, prices, investment programs	Optimal plans for the development of production and standardization of energy consumption	Market entities make their planned decisions and take risks of development
	Management rules	State	Market Council
	Improvement in planning	State	Market Council

changed dramatically every 10-15 years with non-recurring causes, nature, and frequency of crises. This factor does not provide sufficient historical data for artificial intelligence learning in strategic planning tasks. Therefore, the first version of a mobilization society until 2050 seems problematic. The efforts in this area are made by China and planned by Russia and other countries.

According to ***the second version*** *of the mobilization scenario*, plans for the economy (and energy as its subsystem) development are calculated on computer networks using a *mega-set* of production-territorial *mathematical models*. Input information for the models is generated by neural networks (time-tested artificial intelligence tools) using available *reported databases* and estimating their error. Based on optimization calculations, other neural network types generate representative *scenarios for the development of systems* and the corresponding *matrix* of established *indicative indices*. On this basis, the planning authority makes decisions, which are then automatically detailed into production and investment plans, prices and taxes for enterprises, and consumption rates for the population.

Here, the concept, which was developed in the USSR back in the 1970s and suggested using computers for planning the development of the economy and managing it, is outlined in terms of modern information technologies [33].

An alternative concept of **liberal** «digitalization» of the society reflects how futurologists from information science [34] see the trends in the development and use of information technologies to manage the development of the economy and energy (column 4 in Table 1). In the absence of even indicative plans, market participants are expected to *be self-organized* in a complex future foreseeing process. Neural networks generate input information for them. According to it, mutually agreed scenarios of the economy and energy evolution are iteratively developed with the *agent models* of participants in computer networks. Based on these scenarios, the Market Council forms (according to the criteria of the maximum rate and quality of growth at minimum systems risks) a *preferred corridor* of economic development (including energy). Each participant as a *decentralized autonomous organization* (DAO) [35] can use blockchain technologies [36] to control the decision-coordination processes and determine their *future opportunities and risks.* Meanwhile, the Market Council adjusts the rules of the community and improves the requirements for the tools.

Thus, the liberal digital economy will require that traditional methods for operations research be equipped with such new tools as a) neural networks, image recognition methods, and other artificial intelligence tools; b) agent models and methods of their interaction; c) distributed ledger technologies. It is unclear when and to what extent this concept will be implemented, but mastering these tools and technologies will significantly advance the methodology of systems studies of energy development.

In addition to these (basically technical) difficulties, the liberal concept of a «digital» society comes across the theorem "On the impossibility of democracy" proved by K. Arrow (1972 Nobel-prize winner) [37]. This theorem blocks the self-organization of agent models, i.e., the possibility of coordinating their decisions without a decision-maker. Apparently, for this reason, agent models are still used only in the tasks of operational control of the systems, where the involvement of dispatcher, as sole master, is mandatory.

The history of the market economy has confirmed the validity of Arrow's theorem. Indeed, the 18th century saw ten economic crises causing growing damage in 70 years. In the 19th century, their regularity was disrupted by the 2nd World War, but it seems that it will recover in the 21st century. Our history also confirms the validity of the theorem. The transition of the USSR in the 1950s to «collective management» increasingly more hampered its development and in 1991 destroyed it, and in the 1990s, «democratic» Russia did not get out of crises. After a short boom at the beginning of the century, the *global collapse* of 2008 threw the country into long-term stagnation.

The opportunity to overcome the effect of Arrow's theorem is seen in replacing the decision maker's functions with adequate and «digitized» ***legislation*** with *blockchain algorithms* for monitoring its execution. The success of work in this strand will affect whether or not the next generation of people will turn into gears of *a mobilization society*, and systems energy studies can and should contribute to overcoming this threat.

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