Energy Systems Research

Volume 1, Number 2, 2018

Published by
Melentiev Energy Systems Institute
Siberian Branch of Russian Academy of Sciences

Available online: esrj.ru

ISSN 2618-9992

Energy Systems Research

Volume 1, Number 2, 2018

International scientific peer-reviewed journal

Available online: http://esrj.ru

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Contacts
Scientific secretary: Alexey Mikheev, Dr. of Eng.
E-mail: info@esrj.ru
Tel: +7 (3952) 950980 (English, Russian)
Fax: +7 (3952) 426796
Address: 130, Lermontov str., Irkutsk, 664033, Russia

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A method for total transfer capability estimation for generation of a trade-off solution on using available transfer capability of the controlled cutsets

A.M. Glazunova*, E.S. Aksaeva

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

***Abstract* — The paper solves the problem of calculation of available transfer capability of the controlled cutsets on the basis of the results of the methods of state estimation and total transfer capability estimation. The decentralized calculation of the total transfer capability values that are applied for generation of a trade-off solution on additional loading of the controlled cutsets is suggested. The technique of calculating the total and available transfer capabilities and the control actions intended for using the available transfer capability is described in detail. The method is illustrated by the example of calculating the total and available transfer capabilities of different controlled cutsets of a real electric power system.**

***Index Terms* — Available transfer capability, trade-off solution, total transfer capability, state estimation, electric power system.**

I. Introduction

The maximum use of the transfer capability of cutsets is important from the standpoint of the effective control of electric power system (EPS) states. The transfer capability of cutsets can be divided into two components: reserved and available. The reserved part of the transfer capability is determined by the long-term contracts on power supply. The available part is distributed on the short-term basis and is called the available transfer capability (ATC). The ATC value is a very important information for market control from the technical and economic standpoints. Overestimation of ATCs leads to overloading of cutsets and hence, to electric power system reliability loss. Underestimation of ATCs decreases effectiveness of market operation. ATC is the power that can be transmitted in the cutset above the reserved power, i.e. after the existing commitments to consumers are fulfilled [1, 2, 3]. ATC is calculated as a difference between the values of the total transfer capability (TTC) that is calculated in terms of the reliability criterion and power flow in the current system state. The correct calculation of ATC of the controlled cutsets can be obtained by determination of TTC of these cutsets.

TTC is determined by a great number of devised methods, such as: the equations of limiting conditions [4], search for the saddle point based on the generalized Newton method [5], optimal power flow (OPF) methods [6]–[10], methods of repeated power flows [11]–[16], method of analysis of power transfer distribution factors (PTDF) [17]–[20], continuous power flow (CPF) method [21], [22].

Competitive electricity market generates the need to apply a trade-off approach to determination of the maximum admissible loading of equipment [23] and to calculation of TTC and ATC of the controlled cutsets. The use of ATC of cutsets suggests a change in system states due to an extra loading of these cutsets. Obtaining the desired states is no easy task, since it is necessary to control load of several indicated cutsets and take into account the states of an adjacent network. In the case of ATC calculation of several cursets this problem gets more complicated, by that several operators take part in the process of decision making independently. The operator of each electric power system controls its own system and does not possess the data on the state of neighboring power systems. In this situation, to calculate ATC of the cutsets the operator of each system establishes, what amount of additional power should be transmitted and what state variables are suggested to be changed, i.e. the values of limits of a potential change in the state variables and a

* Corresponding author.
E-mail: glazunova@isem.irk.ru

http://dx.doi.org/10.25729/esr.2018.02.0001
Received: April 2, 2018. Revised: June 6, 2018. Accepted: June 18, 2018. Available online: October 15, 2018.

value of the desired flow in the cutset. For the actions of operators not to contradict one another it is necessary to integrate them into a single procedure, according to which the cutsets will be loaded. The single procedure is developed using the TTC estimation method and artificial neural networks.

One of the ways to harmonize the actions of commercial operators that are aimed at additional loading of the controlled cutsets is the decentralized calculation of TTC and ATC.

At present the methods of decentralized TTC calculation are being devised [21]. The key barrier for decentralized TTC calculation is the necessity of considering the correlations between the electric power system areas. Each power transmission should be analyzed from the standpoint of the entire system.

The suggested methods for TTC calculation in the decentralized system can be divided into two categories. The first category introduces a two-level structure, and a megasystem of control of all control areas is constructed. The megasystem possesses all information on the system and is responsible for all calculations on the basis of this information. The two-level system protects private information of each control area, as far as the areas do not exchange this information. However, in this case construction of communication and computer infrastructures requires high investments. The second category of the methods is applied to create multi-level areas for TTC calculation. In these methods the use can be made of the algorithm of TTC calculation in the centralized control. The problem of TTC calculation in the multi-level areas is formulated as system decomposition into several subsystems representing an area level.

The paper presents the technique, which can be referred to the first category of TTC calculation methods. The control center to be created receives all the data from all systems, the state estimation and TTC estimation are performed and then the single procedure of loading the controlled cutsets is developed.

Section 2 of the paper presents the devised method for TTC estimation. Section 3 describes the technique of generating a trade-off solution on calculation of TTC and control actions aimed at ATC application in several cutsets simultaneously. Section 4 presents the results of calculations made for a real scheme. At the end of the paper the conclusions are drawn based on the research results.

II. TTC ESTIMATION

Solution to the TTC estimation problem is based on the idea that application of the weighted least squares method of the sums of TTC estimation residuals allows the desired solution to be obtained from any point with the required accuracy by selecting the weighting coefficients. For TTC calculation the criteria of the desired state are determined by each concerned subject (for example, commercial operator) in accordance with the own interests, which leads to formation of contradictory conditions. The interests of all subjects are coordinated by satisfying the constraints of each subject. Satisfaction of the constraints for TTC estimation is guaranteed by the corresponding values of the weighting coefficients of TTC pseudomeasurements.

The initial information for input data generation that is used to calculate the estimates of measurements and TTC (parameters of the resultant load flow solution) is the on-line and calculated information. The on-line information represents the data obtained from the SCADA system [24] and WAMS [25]:

$$\bar{y} = (U_i, P_i, Q_i, P_{ij}, Q_{ij}, \delta_i), \tag{1}$$

where U_i – magnitudes of nodal voltages; P_i, Q_i – injection of active and reactive powers at the nodes; P_{ij}, Q_{ij} – power flows in transformers and lines, δ_i – voltage phases at the nodes of the scheme, in which PMUs are placed.

The calculated information is the TTC pseudomesurements (TTC PM) $P_{lk}^{TTC\ PM}$ of the controlled cutsets and their weighting coefficients.

The value of TTC pseudomeasurements is independent of the system schemes and states and is the constant calculated information that is generated in advance and stored in the database. For calculation of TTC pseudomeasurements each controlled line is represented by the simplest electric power system. The TTC pseudomeasurement for short lines is the total transfer capability of the line without violation of thermal stability. The TTC pseudomeasurement for long lines is the total transfer capability of the line without violation of steady-state stability.

The weighting coefficients of TTC pseudomeasurements can change with variation of the power system state and hence, are determined as the variable calculated information. Their values are calculated in advance by the enumeration method in terms of the system constraints and observance of the optimality criterion in selecting the weighting coefficients [26]:

$$\varphi_k = \sum_{1}^{kol} (P_{lk}^{TTC\ PM} - P_{lk}^{TTC}(x))^2 \to \min, \tag{2}$$

where kol – number of controlled lines; P_{lk}^{TTC} – estimates of flows in the controlled lines.

The vector of measurements, which is applied to TTC estimation, looks as follows:

$$\bar{y}_{\text{RES}} = (\bar{y}^{\text{n}}, \bar{y}^{a}, P_{lk}^{TTC\ PM}) = (\bar{y},\ P_{lk}^{TTC\ PM}), \tag{3}$$

where $\bar{y}^{n}$ – measurements of nonadjustable (uncontrolled) state variables. The values of these variables in the calculation process remain within the accuracy of measurements; $\bar{y}^{a}$ – measurements of adjustable (controlled) state variables. The values of these variables can vary within the specified control limits [26].

The problem of TTC calculation is to search for admissible values that are most close to the specified inadmissible value $P_{lk}^{TTC\ PM}$, and is reduced to minimization of the objective function of the weighted least squares:

$$J(x) = (\bar{y} - y(x))^T R_y^{-1} (\bar{y} - y(x)) + \left(P_{lk}^{TTC\ PM} - P_{lk}^{TTC}(x)\right)^T R_p^{-1} \left(P_{lk}^{TTC\ PM} - P_{lk}^{TTC}(x)\right), \quad (4)$$

where R^{-1} – weighting coefficients of measurements, R_P^{-1} – weighting coefficients of $P_{lk}^{TTC\ PM}$.

The estimates of the resultant state are determined by minimization of criterion (4) and the system of nonlinear equations is solved by the iterative method

$$H^T R_{RES}^{-1} \left[\bar{y}_{RES} - y_{RES}(x)\right] = 0, \quad (5)$$

where $R_{RES}^{-1} = \begin{bmatrix} R_y^{-1} & 0 \\ 0 & R_p^{-1} \end{bmatrix}$.

At each iteration the system is linearized at the solution point and the normal system of equations is solved. In the system the vector of corrections is calculated by the formula

$$\Delta x^l = \left[H^{T(l)} R_{RES}^{-1} H^l\right]^{-1} H^{T(l)} R_{RES}^{-1} \left[\bar{y}_{RES} - y_{RES}\left(x^l\right)\right] \quad (6)$$

where H^l – Jacobian matrix calculated at the l–th iteration.

The state vector is calculated by the formula

$$x^{l+1} = x^l + \Delta x^l. \quad (7)$$

The system of equations (5) is solved, until the condition

$$\Delta x^l < \xi_x \quad (8)$$

is observed. The state vector is used to calculate all state variables.

III. Technique of ATC application

The proposed technique suggests a preparatory stage, in which the universal techniques are transformed into a technique for solving the problems in concrete electric power systems. In this stage we identify a range of problems to be solved, develop scenarios and find weighting coefficients for TTC pseudomeasurements that correspond to a set scenario, current state and imposed constraints. The weighting coefficients of TTC pseudomeasurements are stored in the database.

Figure 1 illustrates a scheme of on-line control of loading the cutsets. Each EPS is represented by three blocks: data capture, creation of a single procedure for generation of instructions on additional line loading and line loading.

Capture of data on state variables of EPS is performed by the SCADA system and WAMS. The measurement vector $\bar{y}_i$ is created in each system i from the measurements. The vector is transferred to the control center.

In the block of “formation of a *single procedure*” the document is created, in which:

- the control lines are indicated;
- the values of $P_{lk}^{TTC\ PM}$ in the indicated lines are specified;
- the regulated state variables are enumerated and the ranges of their changes are determined;
- the prepared information is transmitted to the control center.

Generation of instructions. Parameters of the resultant load flow solution and data on the control actions performed to obtain this solution are sent to each system of the interconnected EPS. The case, where the operators of all EPS agree with the TTC calculation results means a trade-off solution is achieved.

The functions of the control center are:

1. To set the operational constraints of the interconnected power system y^{con}.
2. To compile on-line information
$$\bar{y} = (\bar{y}_1, \bar{y}_2, .\bar{y}_l\ ..\bar{y}_L), \quad (9)$$
where L – number of the concerned EPSs. Vector $\bar{y}$ is transferred to the state estimator and to the TTC estimator.
3. To perform the state estimation procedure.
4. To compile the calculated information
$$P_{lk}^{TTC\ PM} = (P_1^{TTC\ PM}, P_2^{TTC\ PM}, .P_j^{TTC\ PM} ..P_J^{TTC\ PM}), \quad (10)$$
where $P_j^{TTC\ PM}$ – pseudomeasurements of TTC of the controlled lines. J – number of the controlled lines.
5. To form the input vector for ANN1 based on constraints y^{con} and to form the input vector for ANN2 based on the on-line information $\bar{y} = (\bar{y}_1, \bar{y}_2, ..\bar{y}_L)$. The trained ANN selects R_P^{-1} (4) from the database. The process of ANN learning is not considered in this paper.
6. To construct the resultant vector of initial data
$$\bar{y}_{RES} = (\bar{y}, P_{lk}^{TTC\ PM}). \quad (11)$$
7. To calculate the resultant load flow solution of the interconnected EPS based on vector $\bar{y}_{RES}$ with the TTC estimation method. The vector of estimates of the resultant load flow solution has the form:
$$\hat{y}_{RES} = (\hat{y}, \hat{P}_{lk}^{TTC}). \quad (12)$$
8. To calculate the controlled actions based on the results of TTC estimation and state estimation.
9. To communicate the information about each EPS to the block of generation of instructions for the each system.

IV. Application of the Technique by the Example of a Real Calculated Scheme

A. General characteristic of the scheme and description of scenarios

The calculated scheme, shown in fig.2, includes 17 nodes, 21 (500 kV) transmission lines, and two controlled cutsets. Controlled cutset 1 is one-circuit line 1-5 and two-circuit line 2-3, controlled cutset 2 is represented by lines 11-15 and 12-15. The TTC values of two controlled cutsets are calculated on the basis of three scenarios. Scenario 1: TTC and ATC are calculated in cutset 1; Scenario 2: TTC and ATC are calculated in cutset 2; Scenario 3: TTC and ATC are calculated in cutsets 1 and 2 at their simultaneous loading.

B. TTC calculation of cutset 1 (Scenario 1)

This problem is solved by the following Scenario: calculation of TTC estimates at transmission of additional power from node 2 to node 5.

The value of the surge-impedance loading is used as a value of the TTC PMs of the lines in the controlled cutset [28].

$$P_{1-5}^{TTC\ \ PM} = 900 \quad , \tag{13}$$

$$P_{2-3}^{TTC\ \ PM} = 1800 \quad . \tag{14}$$

The constraints applied in the calculation of weighting coefficients of the TTC PMs are represented by the following inequalities:

$$\overline{P}_2 \le \hat{P}_2 \le 3431 \ , \tag{15}$$

$$0 \le \hat{Q}_2 \le 501 \quad , \tag{16}$$

$$0 \ \le \hat{Q}_4 \le 342 \quad , \tag{17}$$

$$490 \le \hat{U}_7 \le 524 \ , \tag{18}$$

$$\overline{y}_i - 3\sigma \le \overline{y}_i \le \overline{y}_i + 3\sigma \quad , \tag{19}$$

where $\overline{P}_2$, $\hat{P}_2$ – measurement and estimate of active power generated at node 2, $\hat{Q}_2$, $\hat{Q}_4$ – estimates of reactive power generated at nodes 2 and 4, $\hat{U}_7$ – estimate of voltage magnitude at node 7, σ – standard deviation.

Expression (19) means that at the nodes with nonadjustable parameters the values of measurements should remain within a range of $\pm 3\sigma$.

C. TTC calculation of cutset 2 (Scenario 2)

The stated problem is solved by the following scenario: transmission of additional power from node 15 to nodes 11 and 12.

The value of the surge-impedance loading is used as a value of the TTC PMs of the lines in the controlled cutset [28]

$$P_{11-15}^{TTC\ \ PM} = 900 \quad , \tag{20}$$

$$P_{12-15}^{TTC\ \ PM} = 900 \quad . \tag{21}$$

The constraints applied to the calculation of weighting coefficients of the TTC PMs are represented by the following inequalities

$$\overline{P}_{15} \le \hat{P}_{15} \le 1430 \quad , \tag{22}$$

$$0 \le \hat{Q}_{11} \le 50 \ , \tag{23}$$

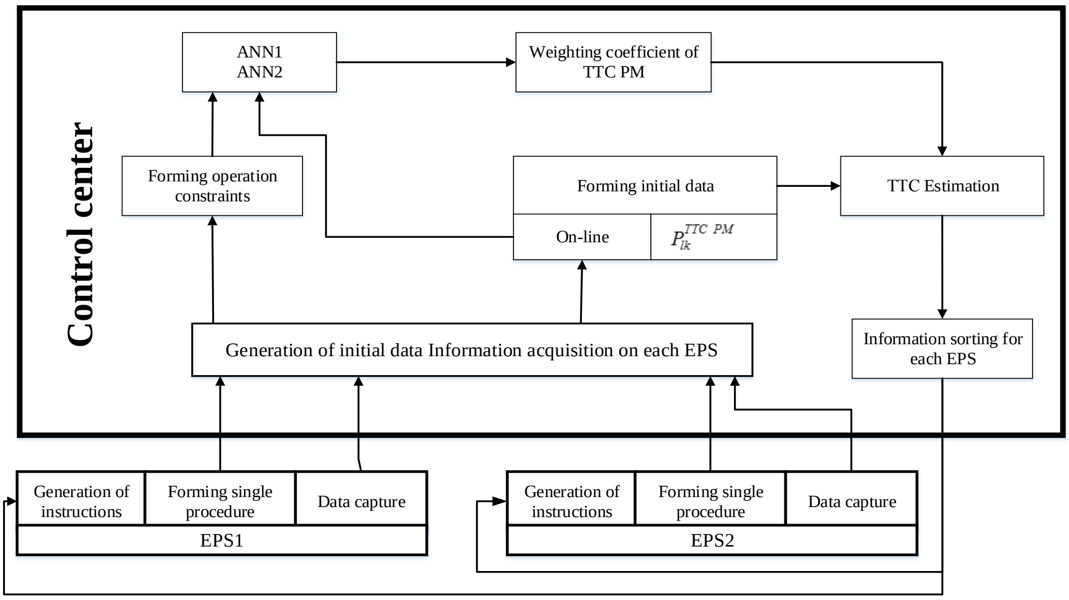

Figure 1. A scheme of online control of loading the lines on the basis of the trade-off approach.

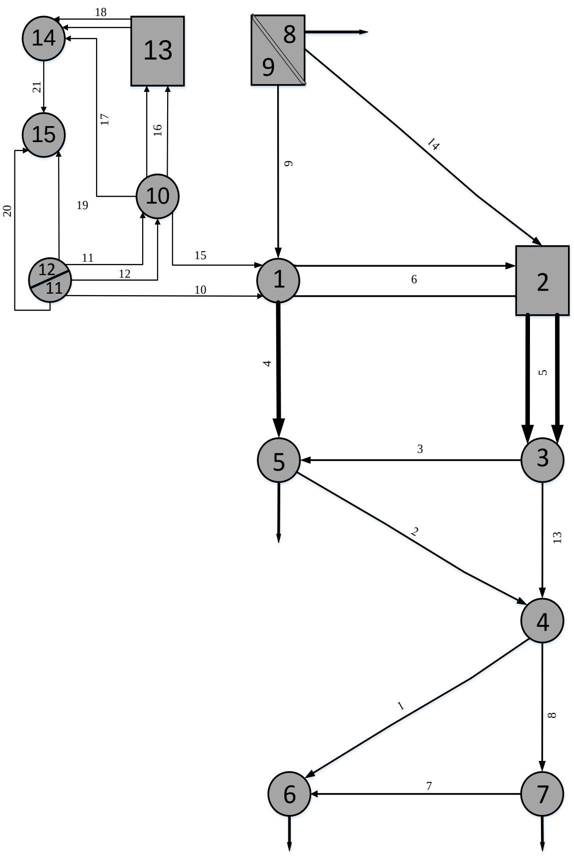

Figure 2. A scheme of a real electric power system.

$$0 \le \hat{Q}_{12} \le 50 \qquad (24)$$

and expression (19),

where $\overline{P}_{15}$, $\hat{P}_{15}$ – measurement and estimate of active power generated at node 15, $\hat{Q}_{11}$, $\hat{Q}_{12}$ – estimates of reactive power generated at nodes 11 and 12.

D. TTC calculation of cutsets 1 and 2 simultaneously (Scenario 3)

The problem is solved by the following scenario: transmission of additional power from node 15 to nodes 11 and 12, and from node 2 to node 5. The constraints applied to the calculation of weighting coefficients of the TTC pseudomeasurements $P_{1-5}^{TTC\ PM}$, $P_{2-3}^{TTC\ PM}$, $P_{11-15}^{TTC\ PM}$ are represented by inequalities (15)– (19), (22)–(24). The trade-off solution is guaranteed by satisfaction of these constraints at loading of two cutsets.

E. Calculation results

Figures 3, 5, 7 show the values of difference between the parameters of the current and resultant load flow solutions that are obtained at TTC calculation by Scenarios 1, 2 and 3, respectively. Figures 4, 6, 8 present the active power flows of the controlled lines for Scenarios 1, 2 and 3, respectively.

Figures 3, 5, 7 show that all commitments to consumers are met, as far as the state variables changed only at the controlled nodes. In Scenario 1 (Fig.3) active power changed at nodes 2 and 5 (curve P), reactive power changed at node 4 (curve Q), voltages at all nodes remained within the prescribed limits (curve U). In Scenario 2 (Fig.5) active power changed at nodes 11, 12 and 15 (curve P), reactive power changed at nodes 11, 12 (curve Q), voltages at all nodes remained within the prescribed limits (curve U). In Scenario 3 (Fig.7) active power changed at nodes 2, 5, 11, 12 and 15 (curve P), reactive power changed at nodes 4, 11, 12 (curve Q), voltages at all nodes remained within the prescribed limits (curve U).

Analysis of the graphs in Figs. 3, 4 for Scenario1 (Figs. 5, 6 for Scenario 2) allows the conclusion that the maximum power that can be transmitted in controlled cutsets 1 and 2 under the specified conditions of the EPS operation is equal to 1736,6 MW and 847,2 MW, respectively. ATC of cutset 1 is 107 MW, ATC of cutset 2 is 353 MW. Additional power equal to 104 MW (422 MW) can be transmitted owing to the following control actions: increase of reactive power generation at node 4 by 25 MVAr (at nodes 11 and 12 by 36 and 39 MVAr, respectively).

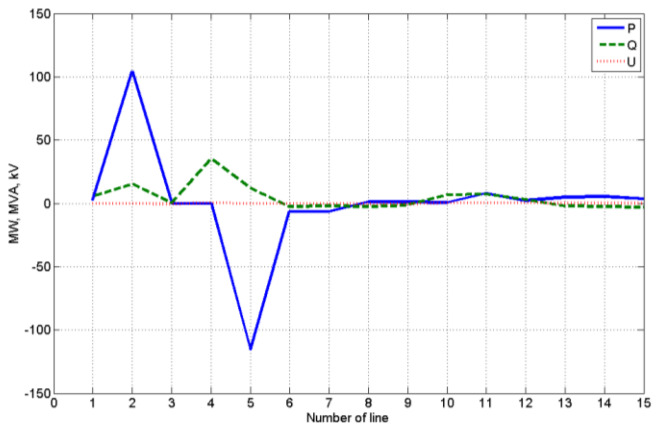

Figure 3. Deviations in active power, reactive power and voltage (Scenario1).

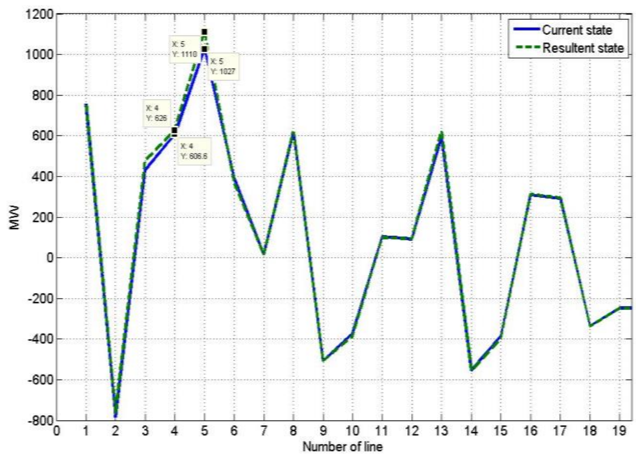

Figure 4. Active power flow in actual and resultant load flow solution (Scenario 1).

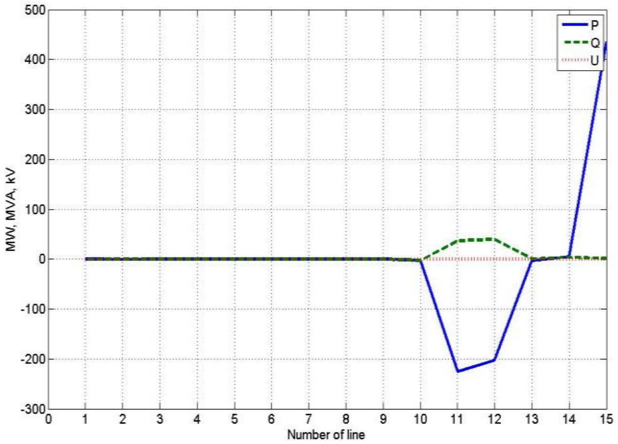

Figure 5. Deviations in active power, reactive power, voltage (Scenario2).

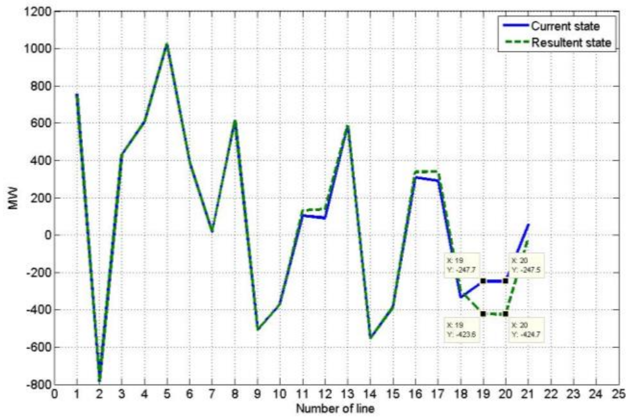

Figure 6. Deviations of active power flow in current load flow solutions (Scenario 2).

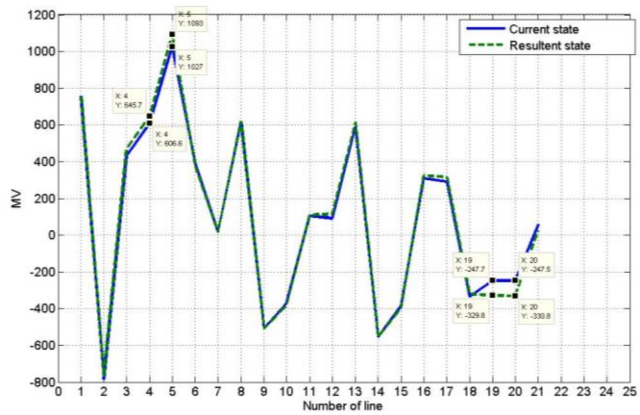

Figure 7. Deviations in active power, reactive power, voltage (Scenario 3).

Table 1 compiles the calculation results obtained for three Scenarios. Number of the cutest is given in the first line, the TTC value in the controlled cutset for each Scenario – in the second line. The ATC values of the controlled cutsets are written in the third line. The values of additional active power generation are presented in the fourth line. Controlled actions are showed in the fifth line.

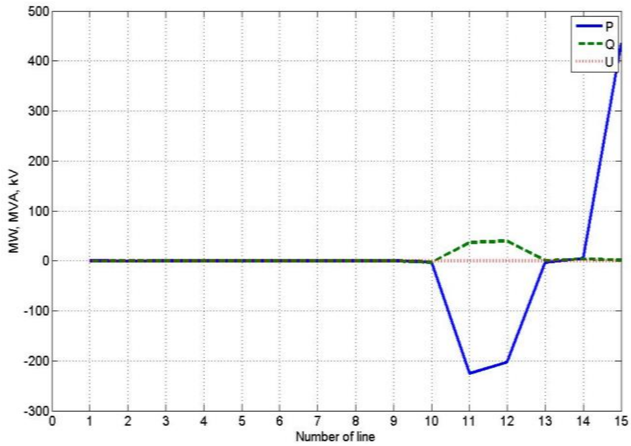

Figure 8. Active power flow in current and resultant states (Scenario 3).

Table 1. Calculation results for three Scenarios

Number of cutset	**1**	**2**	**1** (simultaneously)	**2** (simultaneously)
Flow (MW) current	1633	494	1633	494
Flow (MW) resultant	1736	847	1709	660
ATC (MW)	107	353	76	165
Additional generation (MW)	$P_2 = 104$	$P_{15} = 435$	$P_2 = 82$	$P_{15} = 202$
Control actions (MVAr)	$Q_4 = 25$	$Q_{11} = 36$ $Q_{12} = 39$	$Q_2 = 20$ $Q_{11} = 21$	$Q_4 = 23$ $Q_{12} = 22$

The last two columns present the results of the tradeoff solution. Analysis of the results in Table 1 shows that if the additional active power is transmitted simultaneously in the independent cutsets, the transmitted power values in each cutest prove to be lower than the power that can be transmitted in the same cutsets, but at different time intervals.

V. Conclusions

The paper presents a trade-off approach for calculation of the total transfer capability in two cutsets simultaneously. The TTC is calculated in a decentralized manner. The approach supposes that EPSs do not share their data among themselves. The approach supposes that EPSs do not share their data among themselves. These EPSs want to cooperate via a control center to calculate total transfer capability and available transfer capability. State estimation, estimation of total transfer capability and calculation of control actions aimed at the achievement of total transfer capability in the controlled cutsets are performed in the control center. The tradeoff solution is considered to be reached, if operators of all electric power systems agree with the control actions, and the total transfer capability values to be obtained, when these control actions are implemented.

The developed method was tested by the determination of total transfer capability and available transfer capability in two cutsets of some electric power system. The calculations were made at loading of each considered cutset alternately and at simultaneous loading of the considered cutsets. Analysis of the results confirms that:

- the TTC and ATC values depend on the current conditions of electric power system operation. With the additional power flow transmitted simultaneously in cutsets 1 and 2, the value of ATC in cutset 1 is less by 27 MW and in cutset 2 - by 187 MW than the value of ATC in the case of power transmission over cutsets 1 and 2 at different time intervals;
- the interests of all electric power systems participating in TTC and ATC calculation have been taken into consideration using the trade-off approach. The values of active and reactive generation are only changed in controlled state variables.

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Anna Glazunova is a researcher at Energy Systems Institute in the laboratory of electric power system operation control problems. She graduated from the Irkutsk Polytechnical Institute in 1982 and received the Ph.D in 2002. Her research interests are: methods of state estimation of electric power systems, methods of dynamic state estimation of electric power systems, power system real time monitoring and control. Her research interests include application of Artificial Neural Networks for on-line electric power systems control and smart grid as well.

Elena Aksaeva is a researcher at Energy Systems Institute in the laboratory of electric power system operation control problems. She graduated from the Irkutsk National Research Technical University in 2009. Her research interests are: methods of total transfer capability estimation, power system real time monitoring and control. Her research interests include application of Artificial Neural Networks for on-line electric power systems control and smart grid as well.

Dynamic investigation of congestion management methods for dynamic security assessment application

Ines Hauer[1,*], Marc Richter[2], and Chris Oliver Heyde[3]

[1] Institute of Electrical Power Systems, Otto-von-Guericke-University, Magdeburg, Germany
[2] Fraunhofer Institute for Factory Operation and Automation IFF, Magdeburg, Germany
[3] Siemens AG, Germany

***Abstract* – The large share of renewables in the generation mix and concomitant upgrading of the grid into a smart grid is making system operation more complex and highly dynamic. This necessitates swifter responsiveness to changes in system states in order to operate highly loaded grids in which dynamic security limits will likely become increasingly critical. Dynamic security assessment can be applied to detect potential hazards and to assist operators by recommending optimized countermeasures. This paper is focused on the identification of countermeasures against congestion, which can be employed in dynamic security assessments.**

These problems are generally counteracted by preventive redispatch using conventional power plants located far away. Managing the situation with technical efficiency requires factoring in distributed energy resources and loads. Based on a literature review, an extended Newton-Raphson algorithm has been chosen for this purpose. The algorithm has been modified to calculate optimal redispatch, factoring in loads, generators and slack generators. Optimal in this case denotes the most effective technical measures and solutions identified, which will return the system to its normal state with a minimum of adjustments. The suitability of the redispatch method is subsequently tested in a dynamic security assessment system. The results of the dynamic test reveal the utility of the proposed method. The redispatch amount can be reduced by factoring in generator performance after a fault.

[*] Corresponding author.
E-mail: ines.hauer@live.de

http://dx.doi.org/10.25729/esr.2018.02.0002
Received: April 13, 2018. Revised: May 31, 2018. Accepted: June 13, 2018. Available online: October 15, 2018.

***Index Terms* — dynamic security assessment, system operation, redispatch, congestion**

I. INTRODUCTION

The tremendous increase in renewable energy sources (RES) makes it necessary to upgrade the grid into a smart grid in which all system actors are coordinated smartly with communication architecture to observe system security limits. Rapid changes in the power balance caused by the volatility of renewables necessitate a system that responds more rapidly to changes in state. In 2015, the maximum quarter hourly change in wind power injected by Wind Energy Association (WEA) was 1.43 GW in eastern Germany [1]. Closure of conventional power plants is another challenge to system operation. Reducing the rotating mass and system time constants causes system states to change faster. Furthermore, high power flows through the lines and highly volatile generation lead to high utilization of the system where dynamic security limits can become more critical than static security limits. "Security of a power system refers to the degree of risk in its ability to survive imminent disturbances (contingencies) without interruption of customer service." [2]. A distinction is made between static and dynamic security analysis. The first, which is implemented in control centers at present, employs steady-state modeling to analyze whether equipment is overloaded and voltage limits are being observed after a fault. Dynamic security analysis involves different categories of system stability. A power system is considered stable "if it is able to regain a state of operating equilibrium, for a given initial operating condition, after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact" [2]. Power system stability is broken down into rotor angle stability, voltage stability, and frequency stability, specifying a variety of phenomena contingent on different time scales. [3] [4]. A dynamic security assessment (DSA) tool can assists system operators in this new operating environment [5], [6] by analyzing these stability categories. Taking the system's current operating point as the point of departure, potential threats to the system can be detected by means of an index and a contingency analysis. This data can be used to calculate the most effective countermeasures adapted to the system's operating point, the fault and the resulting stability problem [7] [8].

Methods for detecting voltage stability and eliminating voltage instability [9], [10] and automatic protection schemes [11] have been widely discussed. This paper focuses on congestion management. Given the large share of RES installed in Germany, congestion management is routine for German transmission system operators and their systems are operating close to their static security limits. Supply failures or rapid changes in weather can cause further congestion but conventional redispatch capacities are depleted. Every flexibility option has to be included to ascertain the most effective countermeasures in order to keep the system within its stability limits. This requires the capability to coordinate all actors in the system intelligently by means of a communication infrastructure. In Germany in particular, the incoming supply of renewables can be adjusted as part of system security management. Moreover, specifications are being developed at this time for controllable loads (active power and reactive power adjustment), which are operated by demand-side management systems (regulations for switchable loads).

Since congestion problems are normally not as time sensitive as short circuits, they are modeled with steady-state methods. Redispatch has to be employed technically efficiently in heavily utilized systems with a large share of volatile generating and falling system time constants. This makes dynamic security analysis factoring in generator performance increasingly more interesting for the resolution of congestion problems.

In this paper, we focus on countermeasures against congestion with the intention to implement them in an existing DSA tool. Steady-state modeling methods for ascertaining optimal redispatch are analyzed in order to keep the algorithms simple and expedite calculations. Every system component, especially loads, generators and the slack generator, have to be considered to identify the most technically efficient redispatch. Optimal in this case denotes the most effective technical measures and solutions identified, which will return the system to its normal state with a minimum of adjustments. Since stabilizing a system with optimal adjustment minimizes the probability of the other critical system states arising from the countermeasure applied, cost-effective redispatch algorithms are not applied. Finally, the algorithm was implemented in an existing DSA tool to gauge the extent to which it can be applied in dynamic security assessment programs.

II. Literature review

The literature presents different methods for determining effective generator combinations and adjusting their power to prevent congestion. A good overview is provided in [12].

One frequently discussed and applied method is based on the Power Transfer Distribution Factor (PTDF) [13] [14]. The PTDF depicts the effects of single generators or network nodes on single lines and determines the available transmission capacity (ATC) of lines [15], [16]. The PTDF's good approximations of the conventional Newton-Raphson (NR) method for calculating the ATCs are demonstrated in [17]. Most algorithms with technically effective solutions are based on the standard NR algorithm for load flow analysis or fast decoupled load flow analysis, which is a simplification of the NR [18] used to analyze load flows in high voltage grids. Numerous algorithms treat redispatch as a market measure and employ optimization algorithms to select generators based on their cost-effectiveness [19], [20], [21]. A day-ahead congestion forecast is used in [22] and [23] to incentivize to shift the load by using price signals such as demand-side response. The demand management or load scheduling can be attractive because of its current potential, particularly in the industry [24]. Cost-based redispatch using generators and loads is presented in [25] and [26]. Suitable components are selected by a sensitivity analysis, which is based on a decoupled power flow calculation and the costs of active power adjustment. Here, generators are preferable to loads. An electrical distance concept for generators [27] or intelligent technique of particle swarm optimization [28] is also used to optimize rescheduling measures factoring in market issues. The authors of [29] test the effect of three parameters on the redispatch amounts and costs: loop flows through the electricity system, an increase in renewable generation, and a remedial and preventive N-1 security criterion in a model of the Belgian power system. Additionally, [30] focuses on redispatch costs and the authors have improved LMP to incorporate the energy price, congestion revenue, financial losses and the transmission usage fee by utilizing optimal power flows based on shift factors.

The need to factor distributed generation into rescheduling measures has grown in recent years. Since congestion also occurs in distribution systems [31], the placement of distributed generation in a power system [32], its use for rescheduling, and the balance between costs social factors have to been taken into account [33].

Costs are of secondary importance when the risk of system instability is high. Then, technically efficient redispatch utilizing every available component is required to restore the system. An extension of the Newton-Raphson algorithm that ascertains technically efficient generator **r**edispatch (ENRA-R) is presented in [34]. A line sensitivity matrix is used to identify the generators that have maximum influence on the line. The power that has to be adjusted at the generators is calculated with the aid of an extended Jacobian matrix. The algorithm has been tested and verified in a European system model with 1254 nodes and 379 generators. This static method was selected and expanded for the tests in this paper since several line limits can be considered simultaneously and loads can be shed with this method, which can be applied to every voltage level. The ENRA-R method had to be extended for this study since the method in [34] did deliver the correct sensitivities when selecting the most efficient network node. The new extended method is verified by comparing the results from it with results from the standard PTDF algorithm.

This paper is organized as follows. After briefly defining redispatch, the mathematical principles of ENRA-R and its extension are presented. This method was implemented and tested in a 30-node IEEE test system to demonstrate the need for the aforementioned extension. The results were compared with the results of the PTDF method, which was also implemented. Finally, the ENRA-R was implemented in a dynamic security assessment system to calculate optimal redispatch for a sudden congestion problem. The applicability of the proposed method in DSA is demonstrated.

III. The Methodology

Network operators normally detect impending static congestion problems well before they occur and respond with the market-based countermeasure of redispatch, i.e. by adjusting production in power plants to protect lines from overloading. The principle is presented in Fig. 1. The following scenario is considered: following a single line outage in a double line, the second line is overloaded. Eliminating congestion requires reducing generation before the congestion (Fig. 1, area 1) and increasing generation after the congestion by the same amount (Fig. 1, area 2).

In a smart grid, not only conventional generation but also all system components have to be considered to solve the problem efficiently with minimum adjustment. The switch off and on of loads as well as renewable generation control are therefore taken into account in this study to identify the most effective redispatch measures.

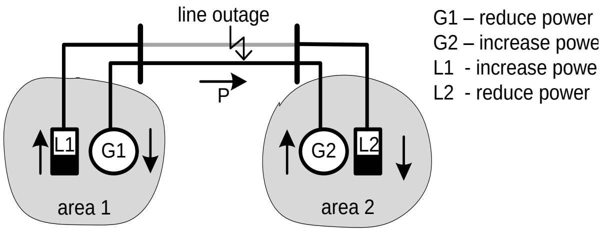

Figure 1. Principle of redispatch.

A. Determining the Optimal Redispatch Combination

1) The ENRA-R Method

The ENRA-R method introduced here is largely based on a publication by Glavich et al. [34]. The authors use the algorithm to determine the optimal adjustment of generation to solve a congestion problem. It is modified to become the ENRA-RM method, which incorporates the slack generator disregarded in [34] and loads for redispatch.

ENRA-R is based on the standard NR method [18], typically the method of choice for solving a system of nonlinear equations. Under steady-state conditions, the power flow equations are defined with Kirchoff's law as

$$\boldsymbol{f}(\boldsymbol{x}) = \begin{pmatrix} \Delta \boldsymbol{P}(\boldsymbol{x}) \\ \Delta \boldsymbol{Q}(\boldsymbol{x}) \end{pmatrix} = 0 \tag{1}$$

where x is the vector of the state variables (phase angles δ and bus voltage magnitude U). Taking an initial operating point (x_0) as the starting point, the solution is obtained iteratively.

$$\begin{bmatrix} \Delta \boldsymbol{P} \\ \Delta \boldsymbol{Q} \end{bmatrix} = \begin{bmatrix} \boldsymbol{H} & \boldsymbol{N} \\ \boldsymbol{M} & \boldsymbol{L} \end{bmatrix} \begin{bmatrix} \Delta \boldsymbol{U} \\ \Delta \delta \end{bmatrix}; \begin{bmatrix} \Delta \boldsymbol{P} \\ \Delta \boldsymbol{Q} \end{bmatrix} = \boldsymbol{J} \begin{bmatrix} \Delta \boldsymbol{U} \\ \Delta \delta \end{bmatrix} \tag{2}$$

with $\boldsymbol{H} = \frac{\partial \boldsymbol{P}}{\partial \boldsymbol{\delta}}$; $\boldsymbol{N} = \frac{\partial \boldsymbol{P}}{\partial \boldsymbol{U}}$; $\boldsymbol{M} = \frac{\partial \boldsymbol{Q}}{\partial \boldsymbol{\delta}}$; $\boldsymbol{L} = \frac{\partial \boldsymbol{Q}}{\partial \boldsymbol{U}}$

The elements of the Jacobian matrix $\boldsymbol{J}$ are the partial derivatives with respect to voltage U and voltage angle δ according to (1) [18].

The Jacobian matrix is used to identify system components suitable for efficient redispatch, in this case, generators and loads. The active power flow through the line is reduced to rectify line congestion, while the reactive power flow is disregarded [35]. Apparent power or current can also be specified as a limit, however.

The line flow can be defined as a ''sending terminal'' or ''receiving terminal'' flow (sending and receiving terminals being the two ends of a transmission line) to ascertain the sensitivities of flows through lines of interest. Sending terminal flows are worked with here. The terminal admittance matrix $\boldsymbol{Y}_T$ is defined to simplify the power flow equations that determine "sending terminal flows". $\boldsymbol{Y}_T$ is the primary admittance matrix in which the diagonal elements are a small admittance matrix (2-port representation of branch and transformer) [36]. Each matrix's rows therefore have only two nonzero elements, one at the sending and the other at the receiving end of the branches. Multiplying $\boldsymbol{Y}_T$ by the vector of complex terminal voltages $\underline{\boldsymbol{u}}_T$ yields the vector of terminal current $\underline{\boldsymbol{i}}_T$ for all branches. Sign identification identifies the terminal nodes with positive currents $\underline{\boldsymbol{i}}_k$ for each branch k. The vector of complex sending terminal voltages is denoted by $\underline{\boldsymbol{u}}_\mathrm{k}$.

$$\underline{\boldsymbol{s}}_\mathrm{k} = 3\ \mathrm{diag}(\underline{\boldsymbol{u}}_\mathrm{k})\boldsymbol{Y}_\mathrm{T}^*\underline{\boldsymbol{u}}_\mathrm{T}^* \tag{3}$$

When U_k denotes the voltage at the sending terminal of branch k and $\delta_\mathrm{ki} = \delta_\mathrm{k} - \delta_\mathrm{i}$, then the apparent power flow s and the active power flow p on branch k can be calculated from (4) and (5) where G_ki and B_ki are the real and imaginary parts of admittance between the buses k and i.

$$\underline{\boldsymbol{s}}_\mathrm{k} = 3 \sum_{\underline{Y}_\mathrm{T}^\mathrm{ki} \neq 0} U_\mathrm{k} U_\mathrm{i} \delta_\mathrm{ki} (G_\mathrm{ki} - \mathrm{j}\, B_\mathrm{ki}) \tag{4}$$

$$\boldsymbol{p}_\mathrm{k} = 3 \sum_{\underline{Y}_\mathrm{T}^\mathrm{ki} \neq 0} (U_\mathrm{k} U_\mathrm{i} G_\mathrm{ki} \sin\delta_\mathrm{ki} + U_\mathrm{k} U_\mathrm{i} B_\mathrm{ki} \cos\delta_\mathrm{ki}) \tag{5}$$

The flow Jacobian $\boldsymbol{J_f}$ that specifies the effect of voltage and angle changes on the active power flow change through the line is determined to ascertain the sensitivity of the active power flow, which is a function of the change of the active power at the node.

$$\Delta\boldsymbol{p}_\mathbf{f} = \boldsymbol{J}_\mathrm{f} \cdot \begin{bmatrix} \Delta\boldsymbol{U} \\ \Delta\boldsymbol{\delta} \end{bmatrix} \quad \text{with} \quad \boldsymbol{J}_\mathrm{f} = [\, \boldsymbol{H}_\mathbf{f} \ \ \boldsymbol{N}_\mathbf{f} \,] \tag{6}$$

where

$$H_\mathrm{f}^\mathrm{ki} = \begin{cases} 0 & \text{if } Y_\mathrm{T}^\mathrm{ki} = 0 \\ -3U_\mathrm{k}U_\mathrm{i}G_\mathrm{ki}\sin\delta_\mathrm{ki} + 3U_\mathrm{k}U_\mathrm{i}\cos\delta_\mathrm{ki} & \text{if } \mathrm{k} \neq \mathrm{i} \\ 6U_\mathrm{k}G_\mathrm{ki} & \text{if } \mathrm{k} = \mathrm{i} \end{cases} \tag{7}$$

$$N_\mathrm{f}^\mathrm{ki} = \begin{cases} 0 & \text{if } Y_\mathrm{T}^\mathrm{ki} = 0 \\ 3U_\mathrm{k}G_\mathrm{ki}\cos\delta_\mathrm{ki} + 3U_\mathrm{k}\sin\delta_\mathrm{ki} & \text{if } \mathrm{k} \neq \mathrm{i} \\ 6U_\mathrm{k}G_\mathrm{ki} & \text{if } \mathrm{k} = \mathrm{i} \end{cases} \tag{8}$$

Equation (2) is transformed and inserted into (6) to ascertain the effect of a change in the active power injection on the active power flow through the line. The sensitivity matrix $\boldsymbol{S}$ is determined from (9) and (10).

$$\Delta\boldsymbol{P}_\mathrm{f} = \boldsymbol{J}_\mathrm{f} \cdot \boldsymbol{J}^{-1} \begin{bmatrix} \Delta\boldsymbol{P} \\ \Delta\boldsymbol{Q} \end{bmatrix} \tag{9}$$

$$\boldsymbol{S} = \boldsymbol{J}_\mathrm{f} \cdot \boldsymbol{J}^{-1} \tag{10}$$

$\boldsymbol{S}$ describes the influence of an active power change $\Delta\boldsymbol{P}$ or reactive power change $\Delta\boldsymbol{Q}$ at the system nodes on the active power flows $\Delta\boldsymbol{P}_\mathrm{f}$ of all lines. According to [34], active power can be adjusted at every node except the slack node, whereas reactive power can only be adjusted at PQ or load nodes.

2) The ENRA-RM Method

The reference generator for redispatch cannot be selected in the algorithm presented in [34] because of the singularity of the Jacobian. The active and reactive power equations of the reference node and the reactive power equations of the generator nodes at which the voltage is kept constant are removed from the Jacobian matrix in order to render it invertible. This can lead to falsification of the sensitivity matrix, which is determined from the inverted Jacobian using (10). For instance, if the sensitivity of the reference generator for the analyzed line is very large, this omission falsifies the sensitivities of other generators.

The method of power flow decomposition [37] [36] can be employed to invert the full Jacobian. The power flow equation based on (11) and (12) with the nodal admittance matrix $\boldsymbol{Y}_\mathrm{KK}$ is linearized in the current operating point with the assumption that voltages at nodes K are constant.

$$\underline{\boldsymbol{s}}_\mathrm{K} = 3\ \mathrm{diag}(\underline{\boldsymbol{u}}_\mathrm{K})\boldsymbol{Y}_\mathrm{KK}^*\underline{\boldsymbol{u}}_\mathrm{K}^* = 3\ \underline{\boldsymbol{U}}_\mathrm{K}\boldsymbol{Y}_\mathrm{KK}^*\underline{\boldsymbol{u}}_\mathrm{K}^* \tag{11}$$

$$(\underline{\boldsymbol{U}}_\mathrm{K}^{-1}\underline{\boldsymbol{s}}_\mathrm{K}/3)^* = \boldsymbol{Y}_\mathrm{KK}\underline{\boldsymbol{u}}_\mathrm{K} = \underline{\boldsymbol{i}}_\mathrm{K} \tag{12}$$

The next step will be to divide nodal currents $\underline{\boldsymbol{i}}_\mathrm{K}$ into generation currents (index G) and load currents (index L).

$$\boldsymbol{Y}_\mathrm{KK}\underline{\boldsymbol{u}}_\mathrm{K} = \underline{\boldsymbol{i}}_\mathrm{K,L} + \underline{\boldsymbol{i}}_\mathrm{K,G} = (\underline{\boldsymbol{U}}_\mathrm{K}^{-1}\underline{\boldsymbol{s}}_\mathrm{K,L}/3)^* + (\underline{\boldsymbol{U}}_\mathrm{K}^{-1}\underline{\boldsymbol{s}}_\mathrm{K,G}/3)^* \tag{13}$$

The load currents are converted into nodal admittances $\boldsymbol{Y}_\mathrm{K,L.}$ based on (14). Conversion can only be done for the particular operating point.

$$\underline{\boldsymbol{i}}_\mathrm{K,L} = \boldsymbol{Y}_\mathrm{K,L}\underline{\boldsymbol{u}}_\mathrm{K} = (\underline{\boldsymbol{U}}_\mathrm{K}^{-1}\underline{\boldsymbol{s}}_\mathrm{K,L}/3)^* \tag{14}$$

Only loads not intended for redispatch are formulated as node matrices $\boldsymbol{Y}_\mathrm{K,L1}$ to determine the sensitivity matrix $\boldsymbol{S}$. Converting one equivalent node admittance suffices in this case.

$$\boldsymbol{Y}_\mathrm{KK}\underline{\boldsymbol{u}}_\mathrm{K} = \boldsymbol{Y}_\mathrm{K,L1}\underline{\boldsymbol{u}}_\mathrm{K} + (\underline{\boldsymbol{U}}_\mathrm{K}^{-1}\underline{\boldsymbol{s}}_\mathrm{K,L2}/3)^* + (\underline{\boldsymbol{U}}_\mathrm{K}^{-1}\underline{\boldsymbol{s}}_\mathrm{K,G}/3)^* \tag{15}$$

Then, the equivalent admittances $\boldsymbol{Y}_\mathrm{K;L1}$ are integrated in the admittance matrix $\boldsymbol{Y}_\mathrm{KK}$ resulting in $\boldsymbol{Y}_\mathrm{KK}$', a different form of $\boldsymbol{Y}_\mathrm{KK}$.

$$(\boldsymbol{Y}_\mathrm{KK} - \boldsymbol{Y}_\mathrm{K,L1})\underline{\boldsymbol{u}}_\mathbf{K} = (\underline{\boldsymbol{U}}_\mathrm{K}^{-1}\underline{\boldsymbol{s}}_\mathrm{K,L2}/3)^* + (\underline{\boldsymbol{U}}_\mathrm{K}^{-1}\underline{\boldsymbol{s}}_\mathrm{K,G}/3)^* \tag{16}$$

$$\boldsymbol{Y}'_\mathrm{KK}\underline{\boldsymbol{u}}_\mathbf{K} = \underline{\boldsymbol{i}}_\mathrm{K,L2} + \underline{\boldsymbol{i}}_\mathrm{K,G} = \boldsymbol{i}'_\mathrm{K} \tag{17}$$

Employing $\boldsymbol{Y}_\mathrm{KK}$' instead of $\boldsymbol{Y}_\mathrm{KK}$ in the load flow calculation yields the same results, the important difference being that the Jacobian matrix determined from $\boldsymbol{Y}_\mathrm{KK}$' is regular and invertible. For this reason, the slack node row and slack node column in the Jacobian matrix do not have to be removed and can be factored into redispatch.

3) Determining Suitable Redispatch Combinations

The influence of all generators, including the reference generator, and the loads on the lines are determined by using the full Jacobian matrix to determine the sensitivity matrix based on (10). This method is only used to determine sensitivities. The standard Jacobian matrix is incorporated in all other algorithms.

When the intention is to perform redispatch by adjusting generation, only the sensitivities S_G of the generator nodes are considered. By contrast, all PQ elements S_{PQ} must be used when only load adjustment is being considered. This yields three possible component combinations that reduce power before the line congestion (area 1 in Fig. 1) and increase power by roughly the same amount after the congestion (in area 2 in Fig. 1).

Redispatch is presently only performed by generators so that supply is not disrupted. The flexible loads available in a future smart grid will be usable for congestion management to stabilize the system as quickly as possible.

Three different load generation combinations were analyzed (see Table 1), whereas the generator and load combination represents disconnection of load and generation (e.g. RES).

The components with the maximum impact on the affected line are selected to calculate efficient redispatch. To this end, the corresponding line of the sensitivity matrix is determined. Subsequently, the nodes of interest (e.g. the PQ nodes, generator nodes or all nodes) are filtered and sorted according to size. The generator with the highest line sensitivity and the generator with the lowest line sensitivity are selected to reduce or increase their active power output ΔP_r.

B. Determining the Required Power Adjustment

Once the appropriate components have been selected, the required power adjustment ΔP_r has to be determined. The extension of the NR algorithm is used. First, the Jacobian $\boldsymbol{J}$ is determined by the load flow calculation with its elements H, N, M and L. Second, the matrix is extended by one row and one column, which define an additional condition [34].

$$\begin{bmatrix} \Delta P \\ \Delta Q \\ \hdashline \Delta P_L \end{bmatrix} = \begin{bmatrix} H & N & \vdots & \\ M & L & \vdots & k1 \\ \hdashline & FF1 & \vdots & 0 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta U \\ \hdashline \Delta P_r \end{bmatrix} \quad (18)$$

$$\Delta P_L = P_{line} - P_{line\ limit} \quad (19)$$

In (19), ΔP_L represents the change in active power flow needed through the line so that the line is not overloaded. The limit of power flow through the lines is given by the maximal current or is defined by the system operator, who has to take into account n-1 criteria. The vector $k1$ represents the nodes selected from S at which active power should be adjusted ΔP_r. The node at which the active power should be increased by ΔP_r is specified in vector k1 by +1 and the node at which the active power should be reduced by ΔP_r is specified by -1. When loads are used, the reactive power also has to be adjusted. To do this, the relationship between active and reactive power is assumed to remain constant.

The term $FF1$ represents the active power sensitivities at the sending node of the affected line and is results from the J_{PF} elements of the line based on (9). The solution of ENRA-R includes the power to be adjusted ΔP_r in the components selected.

Table 1. Redispatch combinations.

Combination	Sensitivities	Component in area 1	Component in area 2
Generator and generator	Generator nodes $S \rightarrow S_G$	Gen. at node $\max(S_G)$: $\Delta P_r\downarrow$	Gen. at node $\min(S_G)$: $\Delta P_r\uparrow$
Generator and load	All nodes $S \rightarrow S_G$ & S_{PQ}	Gen. at node $\max(S_G)$: $\Delta P_r\downarrow$	Load at node $\max(S_{PQ})$:$\Delta P_r\downarrow$
Load and load	Only PQ nodes $S \rightarrow S_{PQ}$	Load at node $\min(S_{PQ})$:$\Delta P_r\uparrow$	Load at node $\max(S_{PQ})$:$\Delta P_r\downarrow$

Table 2. Redispatch test scenarios in the 30-node test system.

Lines	Power flow in initial state in MW	Power flow in target state in MW
Line 6	19.86	15
Line 3	13.63	10 / 12
Line 32	17.67	12

IV. Results of Implementation of ENRA-RM

A. Steady-State Test Power System

The algorithms were tested in a 30-node test system consisting of a 135 kV high voltage power system consisting of six generators, twenty loads and forty-one lines (see Fig. 2) [38], [39]. The loading of the lines selected in the initial state and the target state with a lower power flow is demonstrated in Table 2. The power limitations specified are assumed values that demonstrate the functionality of redispatch using the scenarios presented.

1) Results of the Steady-State Test

First, the redispatch algorithms are tested statically. The reduction of the power flow on the lines specified in Table II is tested with different scenarios, namely:

a. technically effective redispatch by adjusting active power to generators,

b. technically effective redispatch by adjusting load and active power to generators, and

c. technically effective redispatch by adjusting load.

a) Technically Effective Redispatch by Adjusting Active Power to Generators

The difference between the sensitivity matrix calculation based on the reduced Jacobian in [34] (principle 1) and the full Jacobian (principle 2) is presented as introduction.

The generator sensitivities of line 32 are presented in Table 3, the power flow in this line limited to 12 MW. The algorithm selects the generator with the highest sensitivity (G23) to reduce power and the generator with the lowest sensitivity (G27) to increase power. Sensitivities indicated by a positive sign are usually suited to reduce power to

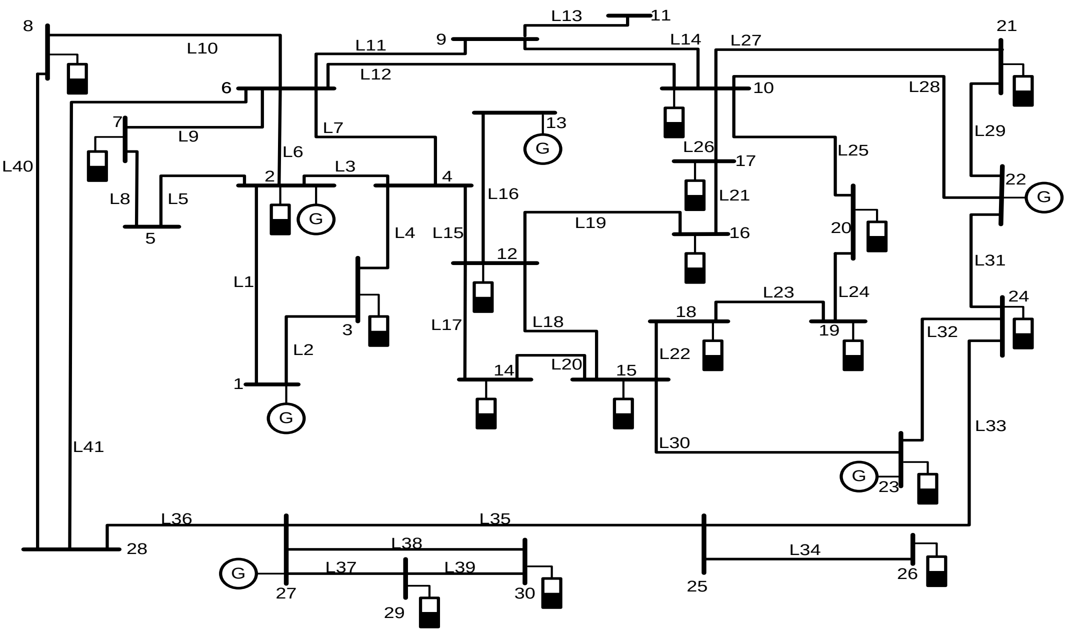

Figure 2. Test power system based on [38].

lower the power flow over the line, while sensitivities indicated by a negative sign or a small sensitivity are usually suited to increase power. The generators that increase power have little impact on the line power flow, their power input have to be adapted to balance the system.

When a generator is operated close to the limit or is unavailable for redispatch, the generator with the next lower or next higher sensitivity is selected. Reasons for generator unavailability vary. The efficiency of power plants at different operating points is not an exclusion criterion in this case since every generator has to contribute to system stability. Exclusion criteria are the necessity of the allowance of control reserve or maintenance actions.

Table 3 reveals that G23 has the largest sensitivity and G27 has the lowest sensitivity in both principles. If G27 is unavailable for redispatch, then G13 and G2 are chosen to increase power in principle 1. Following principle 2, the order is G27, G22 and, finally, G1.

Some results for principle 1 are compiled in Table 4. For test purposes, the upper limit of the generators G27 or G13 varies so that they are not always available for redispatch. Since the power output of G27 cannot be increased in case 2, G13 is chosen. Since G13 is at its upper limit in case 3, too, G2 has to be selected instead of G27 or G13. The same tests are repeated for principle 2. The results are compiled in Table 5, G22 being unavailable in case 3 and G1 being unavailable in case 4.

As evidenced by the results in Table 4, the use of G2 is considerably more efficient. Even though its sensitivity is lower than that of G13, the use of G2 requires less total power adjustment. The analysis of sensitivities in principle 2 reveals that G13 has a positive sign and is, thus, better suited for decreasing power, while G2 is the better option

Table 3. Generator sensitivities of line 32, principle 1 (P1): without slack node in G1, principle 2 (P2): with slack node in G1

	G1	G2	G13	G22	G23	G27
P1	-	-0.0008	-0.0329	0.372	0.4253	-0.0745
P2	0.0008	0.0016	0.1095	-0.0863	0.4304	-0.1039

Table 4. Influence of generators on line 32, principle 1

	Available Generators	Generators	ΔP_r [MW]
Case 1	G2, G23, G22, G13, G27	G23↓, G27↑	10.34
Case 2	G2, G23, G22, G13	G23↓, G13↑	17.93
Case 3	G2, G23, G22	G23↓, G2↑	13.30

Table 5. Influence of generators on line 32, principle 2

	Available Generators	Generators	ΔP_r [MW]
Case 1	G13, G2, G23, G1, G22, G27	G23↓, G27↑	10.34
Case 2	G13, G2, G23, G1, G22	G23↓, G22↑	11.00
Case 3	G2, G23, G13, G1	G23↓, G1↑	12.93
Case 4	G2, G23, G13	G23↓, G2↑	13.27

for increasing power.

Determination of the sensitivity matrix, including the reference generator, demonstrably results in significantly more efficiency (less power being rescheduled). Consequently, this method is employed in further research.

b) Technically Effective Redispatch by Adjustment Active Power to Loads

Demand-side management systems operate controllable loads in smart grids, thus adjusting them in critical grid situations for redispatch. A method for managing congestion by means of flexible loads is presented in [40]. Flexible electricity prices in response to line congestion can produce incentives to adjust loads to counteract congestion. In this case, loads can be adjusted in both positive and negative directions. This is easily implemented in energy storage systems that can be used as a controllable source or as a controllable sink in a smart grid. Wind power [41] and PV [42] can be combined with the storage system to coordinate balancing zones better [43] and, in this case, integrate local generation and loads in rescheduling more efficiently. Furthermore, the batteries in electric cars could be used [44] for this task, especially if the core standards for communication have been defined [45].

This makes a combination of load and generator adjustment particularly interesting. Congestion is counteracted by reducing generation in one area and a load in the other area. This constitutes a simple and practicable redispatch combination. Disconnecting loads is much easier than connecting a load. The supply from renewable energy generators, e.g. wind turbines and PV, can also be reduced or switched off in addition to power plants when reducing generation. Switching on renewables is difficult to manage, though, because of their dependence on the weather. Assuming that loads in the system are controllable, we can consider three different combinations. Redispatch incorporating controllable loads is applied in the algorithm ENRA-RM for line 32, in which the power flow should be limited to 12 MW. The results are presented in Table 6.

Adjusting loads for redispatch clearly requires less overall power adjustment. The optimal combination is contingent on the network structure and the controllable components located near the congested line. Table 7 presents an overview of the results of reducing the power flow in different lines of the 30-node test system. ΔP_r is calculated for the three component combinations to reduce the power flow through lines 1-12 by around ΔP_L.

Since more loads are distributed throughout the power system than generators, load combinations significantly lessen the adjustment of power in most cases.

A load combination or load-generator combination has to be applied whenever generator combinations cannot be employed to reduce line power flow. For instance, the active power flow through line 8 cannot be reduced to 6 MW with the existing generators. This can only be done by adjusting another 7.1 MW by selecting the load combination and adjusting an additional 1.1 MW by selecting a load-generator combination. Rapidly solving optimal rescheduling reduces the probability of further incidents caused by congestion. In terms of transient stability, an increase of the generators' active power is always accompanied by an increase in their rotor displacement angle. Since this brings the generators closer to the stability limit and synchronism can be lost earlier whenever failure or further congestion occur, adjustments have to be minimized and made using the most efficient combinations. Redispatch is normally considered as a preventive measure and thus often not time-sensitive. Notified of future congestion problems by forecasts, operators apply redispatch before congestion occurs. Given the large quantity of distributed energy sources installed, conventional and especially German power plants usually redispatch in high-wind situations. Conventional redispatch capacities are exhausted if a failure occurs, which results in another congestion problem. In such a case, other smart grid components, e.g. energy storage systems, controllable loads and distributed energy sources, are an efficient alternative to power plants for remedial redispatch. As the ever more distributed renewable energy sources are integrated, the load generator combination is the best option because power must be reduced or shut off on both sides of the bottleneck. This is usually easier than connecting a load. Loads and renewable energy sources are adjusted quickly by converter systems, which have a time advantage over conventional generators.

Table 6. Influence of component combinations on line 32.

Most efficient redispatch combination	Selected elements	ΔP_r [MW]
2 generators	G23↓, G27↑	10.4
2 loads	load 24↓, load23↑	8.4
Load and generation	G23↓, load 24↓	8.4

Table 7. Comparison of ΔP_R based on the component combinations for lines 1-12

Line	ΔP_L in MW	2 generators ΔP_r in MW	2 loads ΔP_r in MW	Load and generator ΔP_r in MW
1	3	**3.5**	9.5	**3.5**
2	3	8	12.6	**7**
3	3.6	10.6	**10**	10.6
4	4	11	**4.5**	10.9
5	2	11.9	**5.8**	**5.8**
6	2	5.3	**5.1**	**5.1**
7	2	4.6	**2.4**	7.6
8	2	12	**5.9**	**5.9**
9	2	12.4	**2.4**	**2.4**
10	2	14.1	**2.3**	**2.3**
11	2	5.2	**4.8**	7.6
12	1	**4.4**	4.7	6.7
8	**6**	**28 (maximum)**	**1.1**	**7.1**

The comparison with a method based on PTDF yields good agreement, the proposed algorithm can be applied.

B. Dynamic Testing of ENRA-RM with SIGUARD®DSA

Transmission systems are continuously analyzed with steady-state algorithms. They display only the outcome of an event or fault, though. Dynamic analyses are used to analyze system performance during the intervening period, i.e. from the beginning of an event or fault until the situation has stabilized. A dynamic security assessment tool addresses this issue. The redispatch measures presented above were calculated with steady-state algorithms. A dynamic test system including the dynamic security assessment (DSA) system simulator SIGUARD®DSA [46] has been selected to verify their applicability to this problem. SIGUARD®DSA employs the power system simulator PSS®Sincal in which the detailed power system and generator models are stored to analyze the system electro-mechanical performance. The DSA addresses voltage stability, transient stability, small-signal stability and protection. In this study, a redispatch measure is tested, which factors in generator performance.

SIGUARD®DSA determines the potential risk of different contingencies [47], [48] for an electrical power system based on a system's current state. To this end, different security indices are implemented, which indicate whether static and dynamic limits are observed or exceeded in a system and check the range to the limits. A distinction is made between global indices, which represent an entire system (e.g. small signal stability, frequency stability), and local indices, which characterize the status of individual system components (e.g. node voltages, angle stability of generators, active power flows through lines and transformers). Each index is a normalized value between 0 and 1, with 0 representing no risk (green), 0.75 denoting a critical state (red) and 1 standing for a blackout (black). A three stage Fuzzy Inference System that allows modeling of a "multivariable-reasoning system" is employed to combine the indices of the individual components into a fuzzy dynamic security index, the system index [49]. By fuzzification and defuzzification of the indices equally distributed along the interval 0 to 1, a multi-stage Fuzzy Inference System sufficiently composes an over-all dynamic performance index. In addition, an adaptive system is designed which readjusts its structure according to the number of active indices [50]. The outcome of the simulation [6] is the DSA tool's determination of an index for every contingency, which characterizes the system's state after the contingency [47]. Other methods of aggregating indices and determining system security are discussed in the literature [51]. In [52] a method is proposed to determine the maximum loading point to detect the probability for long-term voltage instability. The results are used to train a database for an artificial intelligence (AI) classifier based on the Support Vector Machines (SVM) or machine learning-based models. In online application, the SVM classifier support detecting the probability that generators operating at a high reactive power output that can announce a voltage collapse. Other DSA tools use recognition methods, such as support vector machine, artificial neural network and decision tree to reduce time-consuming simulations. These methods save results of offline time-domain simulations in a database and then train a model with decision rules. Online measurements are combined with the model and used to determine the security states of current [53]. In [54] a method is proposed that uses ensemble decision trees and is capable of predicting the security states with high accuracy and indice the confidence of the security states 1 minute ahead of real time.

The system index and the line power flow index (LPFI) are analyzed to verify the proposed method. The LPFI analyzes the power flow through each line during a dynamic simulation of 20 seconds. The limits can be parameterized individually, since the operator may have to take into account the n-1 criteria. In this test, the index becomes 1 when the power flow S reaches 130% of the rated power. The index becomes 0 when the power flow is below 70%. There is a linear relation between both extrema and the index.

The DSA test system represents a transmission system with voltage levels of 230 kV and 500 kV in which seven generators and thirteen loads or compensators are connected to twenty-five nodes. A schematic of the analyzed system is presented in Fig. 3. The system, generator and controller models were developed by Siemens AG.

1) Test Scenarios Description

Different scenarios representing different system loads and different load distributions were developed for this test system. Different contingencies, particularly short circuits at different nodes and different line outages, were implemented and tested for each scenario. Congestion primarily occurs in highly utilized systems with unbalanced load distribution. Moreover, a line outage was identified as the main cause of congestion. The effectiveness of the proposed method was verified in five scenarios, one of which is presented in detail here.

The following procedure is employed to test the redispatch measures:

1. Introduce a fault (contingency) in SIGUARD®DSA, thus causing line congestion.
2. Export steady-state operating point data after the contingency.
3. Use the ENRA-RM method to identify redispatch measures.
4. Implement the measures in the DSA test system.

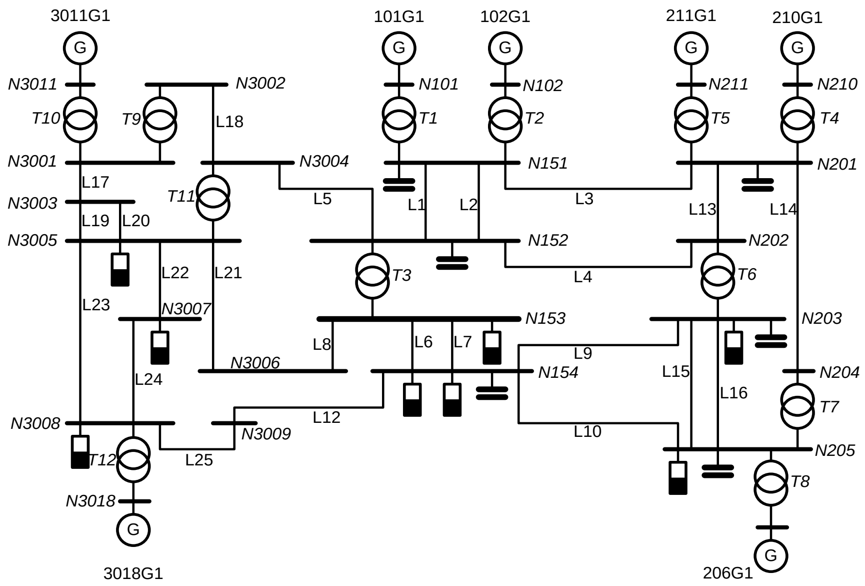

Figure 3. Dynamic test system: DSA system.

2) Test Results

One contingency entailed switching off line 14, thus causing congestion in line 13 and a static frequency deviation of 136 mHz.

The frequency and generator performance are presented in Fig. 4. In the normal state, the frequency is controlled by primary and secondary controls. In this case, generator G211 performed secondary control by reducing its power by about 115 MW. The system reaches a new steady-state operating point after 80 seconds with the active power flow on line 13 reaching 1164.8 MW (see Fig. 4,5, section 2).

The new state variables of voltage magnitude and phase angle and the new power system topology are exported and used as input data for the proposed ENRA-RM method to determine the redispatch measure for that steady-state operating point. In this case, the most efficient component combination and the power to be adjusted is calculated by an ENRA-RM algorithm to reduce the active power flow through line 13 from 1164.8 MW to 1000 MW using (18)

1. Generator combination:
G211↓, G206↑, $\Delta P_r = 275.6$ MW
2. Load-generator combination:
G211↓ L203↓, $\Delta P_r = 268.4$ MW
3. Load combination: not applicable since there are no loads on the 500 kV level

The results of the dynamic calculations for case 1 are presented in Fig. 4 that shows the changes in the active power injection of the generators G211, G206 and 101G1. The effect of this adjustment on the line power flow after 80 seconds and the line index are presented in Figure 5.

The failure (outage of line 14) initiated after 200 milliseconds of simulation time causes the line to overload, indicated by an LPFI above 0.9 and a frequency deviation of 136 mHz (Fig. 4, section 1). This deviation is compensated by primary and secondary control of generators within the next 80 seconds. Subsequently, the redispatch, calculated assuming steady-state conditions, is executed with G211 and G206.

Shifting the power injection changes the load flows and losses. They are balanced in the steady-state calculation by the slack. By contrast, a positive frequency deviation results in dynamic simulation because of the different rates of change of generators (Figure 4, section 2), which is partially balanced by the primary control. The power injected by 101G1 (Figure 4, black) is increased in order to correct this frequency deviation. The line power flow is reduced to 1016 MW by generator redispatch. The result is heavily affected by the generators, which are part of the primary control. Since the location of generators in area 1 (see Fig. 1), requiring a reduction in the power supplied, affects the line power flow adversely, the active power flow is only reduced to 1016 MW instead of 1000 MW. The primary control is replaced by the secondary control (Fig. 4). If this is performed at the generator G206, which is stepped up another 80 MW after 200 s in order to compensate for the frequency deviation, it will reduce the active power flow to the 1000 MW required. The location of the generator providing secondary control also affects the results.

The effect of the fault and the measure on the active power flow through the line and on the LPFI of line 13 is presented in Figure 5. After the fault, the LPFI increases up to 0.9, a critical overload. The line is still heavily loaded after the measure, but not critically since the value is below 0.75.

Similar results for redispatch by the load-generator combination are presented in Fig. 6 and 7. The power flow can also be reduced as required with this combination.

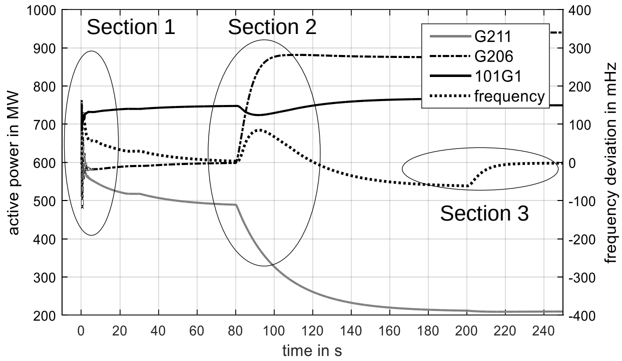

Figure 4. Redispatch by generator couple, change in active power injection.

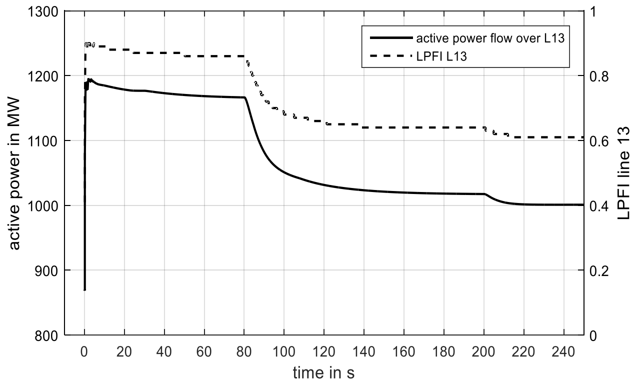

Figure 5. Redispatch with generators, dependence of the LPFI and the active power flow through the line.

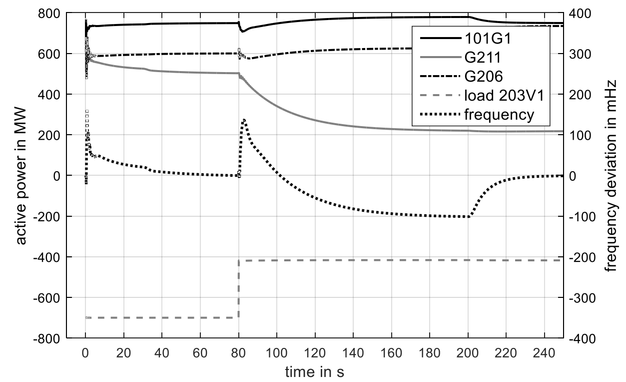

Figure 6. Redispatch by load-generator combination, change in active power injection.

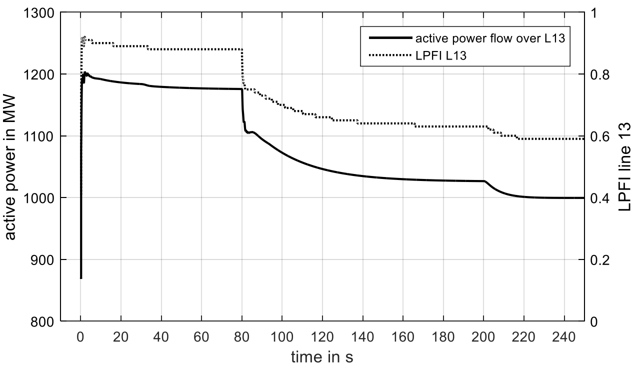

Figure 7. Redispatch with load generator combination, the dependence of the LPFI and the active power flow through the line.

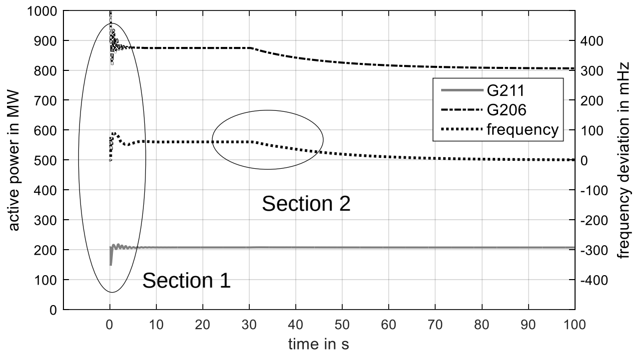

Figure 8. Preventive redispatch by generator couple, change in active power injection.

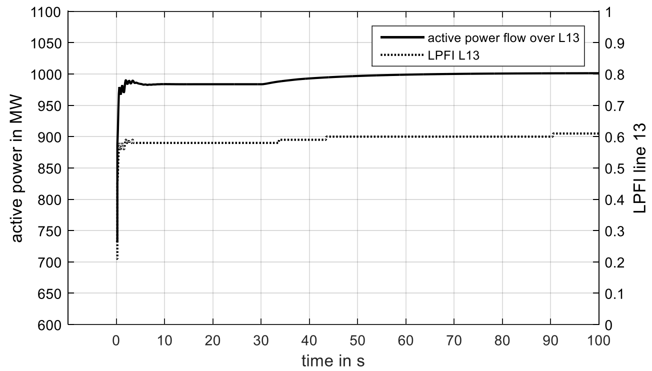

Figure 9. Preventive redispatch with generators, the dependence of the LPFI and the active power flow over the line.

Redispatch measures are usually performed preventively. For test purposes, the preventive measure is calculated based on the system initial state and the changed test system topology (switched off line 14). For this reason, the generator speed control that is active after the disturbance is disregarded. This results in a significantly larger redispatch of ΔPr = 392 MW. The results of changing generator power injection before the contingency are presented in Figure 8 and Fig. 9. The preventive measure prevents the LPFI from reaching the critical value of 0.75.

3) *Discussion*

The comparison of the total adjustment required in remedial P_{CUR} and preventive redispatch P_{PRE} including the reserve yields the following:

- $P_{\mathrm{PRE}} = \Delta P_{\mathrm{r}} + P_{\mathrm{RES}} = 971$ MW
- $P_{\mathrm{CUR}} = \Delta P_{\mathrm{r}} + P_{\mathrm{RES}} = 615$ MW

Since a preventive redispatch measure obviously requires more active power adjustment than a remedial redispatch measure, redispatch measures can be optimized when the generators' dynamic performance is factored in.

The suitability of steady-state methods for calculating optimal redispatch based on information from a dynamic security assessment system has also been demonstrated.

All of the results from the SIGURAD DSA tool are demonstrated in Fig. 10. The transient stability indices implemented are displayed on the left and the resultant

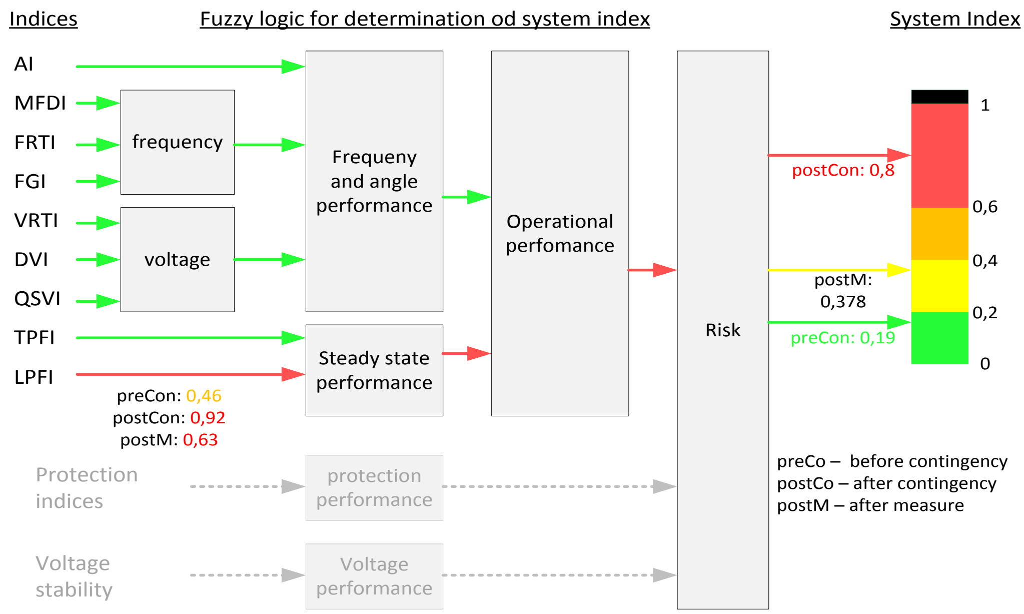

Figure 10. Results from SIGUARD®DSA tools.

system index summarizing system risk is displayed on the right. Readers are referred to [49], [6] for details of the index description. The SIGURAD®DSA also includes a voltage stability assessment as well as a wide area protection scheme based on [55] to incorporate adaptive protection schemes in the future [56].

Fig. 10 presents three different system states:

1. the system state before a contingency
2. the system state after the contingency, and
3. the system state after implementation of the proposed measure.

All indices in system state 1 are green, except LPFI, which is orange (0.46). The fuzzy logic aggregates standalone indices into a system index, which is green (lower system risk) for state 1. Line 14 is switched off in state 2. The resultant congestion problem is also evident in the system index, which rises from 0.19 to 0.8 after this contingency. This is a consequence of the higher LPFI of line 13, which increased from 0.46 to 0.92. Once the measure is implemented, the system index decreases to 0.378. Other indices are not affected.

V. Conclusion

The extension of the Newton-Raphson (NR) algorithm for optimal generator adjustment [34] has been adapted in this study to factor in the slack generator and loads for redispatch, and the effectiveness of the new algorithm with these extensions has been demonstrated. Since a comparison with a method based on PTDF yields good agreement, the proposed algorithm can be applied.

The load-generator combinations and load combinations constitute the most efficient method with the lowest power adjustment for a smart grid with controllable loads.

Furthermore, the ENRA-RM method, which determines redispatch based on a steady-state operating point, has been shown to produce excellent results in dynamic simulation. Deviations caused by the steady-state analysis are compensated by an intelligent choice of secondary control. This makes it suitable for calculating countermeasures in a system's security assessment system. Moreover, preventive redispatch measures were shown to require more active power adjustment than remedial redispatch measures. Redispatch measures can therefore be optimized when the system's dynamic performance is factored in and DSA is employed.

The ENRA method can also be adapted for voltage problems. Since voltage problems can be protracted problems, the feasibility of applying this method to adjust components during voltage problems will have to be tested in future studies.

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Ines Hauer studied mechatronics at the Otto-von-Guericke-University Magdeburg and received a diploma degree in 2010. Since 2010 she has worked as a scientific assistant at the Chair of Electric Power Networks and Renewable Energy Sources at Otto-von-Guericke-University, Germany. She received the Ph.D degree in 2014. Since 2017 she has been assistant professor for energy storage systems at the Otto-von-Guericke-University Magdeburg. Her research interests include power system stability, renewables integration, and energy storage systems.

Marc Richter worked as a graduate assistant in the Department of Electric Power Systems of Otto von Guericke University Magdeburg in Germany from 2012 to 2017. He was awarded his doctorate, summa cum laude, for his dissertation on the observability of electrical grids in 2016. At present, he is a research scientist in the Convergent Infrastructures Business Unit of the Fraunhofer Institute for Factory Operation and Automation IFF. His research interests include power system monitoring, renewables integration, and the application of industrial demand response to problems in convergent infrastructures.

Chris Oliver Heyde graduated in 2005 from Otto-von-Guericke University in Magdeburg, Germany, with the Dipl.-Ing. degree in electrical engineering. From 2005 to 2010 he worked as a scientific assistant at the Chair of Electric Power Networks and Renewable Energy Sources of the same university. He received the Ph.D degree in 2010. Since 2010 he has worked at Siemens Power Technology International as a consultant.

Multi-Criteria Problems in Electric Power System Expansion Planning

N. I. Voropai, *Fellow IEEE*

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

Abstract **- The paper presents different options of the power industry structure in a market environment and the nature of electric power system expansion planning problems. Mathematical methods are proposed to solve the problems of generation expansion planning. The use of a hierarchical multi-criteria game model is demonstrated for the case of "soft" regulation of the liberalized electric power industry expansion. Methods for analysis of many preference relations in electric power system expansion planning are discussed. Two illustrative case studies are presented.**

Index Terms **- Electric Power System, Market Structure, Expansion Planning Problems, Mathematical Methods**

I. Introduction

There can be different options of the electric power industry structure in a liberalized environment. These options predetermine specific features of the problems of electric power system (EPS) expansion planning. In general, these problems are solved by a rational combination of market mechanisms and state regulation, provided there are many stakeholders (power supply companies, consumers, authorities, etc.) with a great number of non-coincident criteria. And the uncertainty of future conditions for EPS expansion is responsible for a multi-variant character of possible decisions to be made and compared [1].

Complexity and multi-dimensionality of current extended EPSs, plurality of variants and criteria, and availability of different preferences in the choice of a decision make it impossible to solve the EPS expansion problem as a general synthesis problem. In the centrally planned power industry this problem was solved by the hierarchical approach that was based primarily on the expert, but a posteriori technology for problem solving. In the liberalized power industry, the problem is drastically complicated and the technology for solving it can be represented by different options depending on specific features of the industry structure [1 – 5]. Many researchers use a game-theoretical approach [4, 7 – 10], others apply additional techniques [11 – 15]. In [16], the authors present the state of the problem as a whole.

This paper is based on generalization of [1, 3 – 6, 9, 10] and is organized as follows. Chapter II shows a general approach to the problems of decision making in different cases involving many stakeholders. Chapter III explains the sense of decision making procedures in different cases of expansion problems. In Chapter IV two case studies are discussed to demonstrate certain problems of decision making. Chapter V presents the conclusions to this paper.

II. General approach

We will analyze different options of the power industry structure [2], which affects the composition and nature of the EPS expansion planning problems. These options comprise a regulated monopoly at all levels; interacting vertically integrated electric power systems at an open access to the main grid; a single electricity buyer-seller (an electric network company) at competition between generating companies; competing generating companies under a free choice of electricity supplier by selling companies or/and consumers, when the main grid renders only transportation services; selling companies competing in electricity supply to concrete consumers; and various combinations of the above considered options [3, 6].

The general problem of EPS expansion planning can be divided into three groups of problems [3]:

- the state strategies and programs for the development of the power industry and EPS (the federal, interregional and regional levels);
- strategic plans for the expansion of power companies (vertically integrated, generating, network);
- investment projects for electric power facilities (power plants, substations, transmission lines).

Decision making on EPS expansion involves different groups of stakeholders that have their own, totally different interests that are expressed by corresponding criteria. In particular [6]:

1) Electricity producers or/and sellers (vertically integrated, generating or selling companies, electric network company as a single electricity buyer-seller) and also the entities of electric power industry that render electric power

* Corresponding author.
E-mail: voropai@isem.irk.ru

http://dx.doi.org/10.25729/esr.2018.02.0003
Received: May 22, 2018. Accepted: June 15, 2018.
Available online: October 15, 2018.

services in the wholesale electricity market (maintenance of active and reactive power reserves, provision of system reliability, etc.) are interested in profit maximization as a result of their business.

2) Electricity consumers (selling companies of different levels, concrete consumers) are interested in minimizing tariffs for electricity bought in the wholesale or/and retail markets, and providing its quality and supply reliability.

3) The authorities (federal and regional) aim to maximize revenues of budgets of the corresponding levels, minimize the environmental impact of electric power facilities, provide national and regional energy security, etc.

4) External investors (banks, juridical and natural persons) are interested in minimizing the payback period for investment in electric power facilities, maximizing dividends, etc.

We will discuss the composition and specific features of EPS expansion planning problems in terms of technology and structure.

As for the technology, electric power system is viewed as a technically single system that consists of power plants operating in parallel and connected with each other and consumers by an electric network. EPS can be modeled in different ways depending on the problem to be solved and the level of consideration. For example, the structure and allocation of generating capacities of the Unified energy system (UES) of Russia are normally chosen on the basis of aggregated representation of large subsystems (e.g. interconnected EPSs - IPSs) and transfer capabilities of tie lines among them. If the same problem is solved for IPSs, their structure is described similarly in the form of aggregated subsystems and transfer capabilities of tie lines among them. To plan the network expansion, it is necessary to represent it in detail with generation capacities and their allocation that are determined in the previous stages. The UES level usually deals with the UHV backbone network. At the IPS level the electric network is represented in greater detail considering transmission lines, and substations of lower voltage classes. This set of problems related to the EPS expansion planning is a hierarchical sequence of problems, where decisions on system expansion are adjusted (or new decisions are made) in each stage by means of its more detailed examination in the technological and territorial aspects [6].

As for the structure, in decision making on EPS expansion, the technically single EPS is a set of structural units, i.e. companies, interacting with each other. If the expansion problems are solved depending on the structure, an EPS should be represented by vertically integrated, generating and network companies which will expand based on their technological interaction within the system. When choosing decisions on generation and transmission network expansion, the vertically integrated company, for example, has to take into consideration potential decisions of neighboring companies on their expansion. The generating company has to allow for the prospects for expansion of competing similar companies and the network company as well. The network company, in turn, should have an idea on the expansion of generating companies when analyzing trends in its expansion [2, 6].

Each generating company in this case should consider both prospects for expansion of other companies and the state energy policy (at the federal, interregional and regional levels) and mechanisms of its implementation in the form of tax, credit, tariff and other policies. Working out the strategies and programs of power industry development, the state, in turn, should implement its energy policy by taking into account the incentives, possible behavior and interaction of generating companies in their expansion [6].

III. Decision making procedures

In general, the problems of EPS expansion planning as applied to many stakeholders that are guided by many non-coincident criteria are of a multi-criteria game character. Let us examine specific features of such statements for the mentioned three groups of problems: the state strategies and programs, strategic plans of power companies, and investment projects [1, 3 – 6].

A. The state strategies and programs

The state strategies and programs for the power industry development at the federal and regional levels are devised on the basis of the multi-criteria hierarchical game statements of the problems. Such problems appear, when the state is at the upper level and the power supply companies are at the lower level. These problems are solved by the formal methods for creating the incentives for stakeholder behavior at the lower level by the appropriate mechanisms foreseen at the upper level.

Here the multi-criteria hierarchical game problems may be cooperative or non-cooperative depending on conditions [4, 6].

The electric power system development coordinated by the government is considered in [4]. A hierarchical cooperative game is formulated in the normal form between the control agent (center) A_0 and the power producers B_i, $i=\overline{1,n}$, where n is the number of power producers.

The initial conditions are presented by the tuple of three sets:

$$\{I, J, K=(K_1,\dots,K_M)\}, \quad (1)$$

where I is the options of generation expansion, J is the scenarios of external conditions, K is the criteria of decision assessment, M is a number of stakeholders interested in generation expansion.

The rectangular $I\times J$-dimensional matrices are constructed:

$$X^k=\{x_{ij}^k\}, i=\overline{1,I},\ j=\overline{1,J}, k=\overline{1,K}, \quad (2)$$

where x_{ij}^k is a numerical estimate of the i-th expansion option by criterion k, provided the j-th external condition took place.

In fact, the center A_0 distributes regulation actions among the subdivisions $B_1,\ldots B_n$. The regulation actions can be budget subsidies, tax privileges, loans, etc. Thus, the center A_0 chooses the system of n vectors $\omega = (\omega_1 \ldots \omega_n)$ from the negative set $W = \sum_{l=1}^{n} w_l$ subject to [1, 4, 6]

$$\sum_{l=1}^{n} w_l \le b, \qquad (3)$$

where b is a constraint on the possibilities of the regulation center.

The possibilities of the company B_l are determined by the regulation action ω_l received from A_0. The company realizes the nonnegative decision vector $x_l(\omega_l) \in X$.

Let us suppose that the sets $x_l(\omega_l)$ at all ω_l contain a zero vector and increase monotonously by inclusion, i.e. $x_l'(\omega_l') \supset x_l(\omega_l)$ follows from $\omega_l' > \omega_l$, and $x_l(0) = 0$ is met (impossibility for the center to control the companies without regulation actions). Here ω_l' means a regulation action introduced at the next step after the regulation action ω_l [4, 6].

Let $x = (x_1,\ldots, x_n)$ be an expansion option for the companies $b_1,\ldots, b_n$. The payoff of the player B_l is supposed to be equal to $l_l(x_l) \ge 0,\ l = \overline{1, n}$. The payoff of the player A_0 is determined by the function

$$f\left(l_1(x_1),\ldots,l_l(x_l)\right) - g(\omega_1,\ldots,\omega_n) \ge 0, \qquad (4)$$

where $g(\omega_1,\ldots,\omega_n)$ is a nonnegative function that characterizes the level of actions applied by the center.

The regulation center has the right of first move and may manage the possibilities of regulated companies by controlling their activities. The main purpose of the regulation center is to minimize its regulation actions. The next Chapter presents an example illustrating the proposed hierarchical approach [4].

These problems can take place at interaction of the federal and regional levels, when the state strategies and programs are devised for the power industry development. Such problems are aimed at coordinating the national and regional interests. The state priorities in the industry development are formed at the federal level and then they are transformed into concrete trends in expansion of generation capacities and electric networks in the considered region. In general, when the principles of authority sharing are adjusted and non-contradictory, the multi-criteria hierarchical game problems of a cooperative nature can be involved. The mechanisms of inducement or persuasion are applicable here, however, with somewhat different conceptual interpretation as against the previous case [1, 4].

The indicated two problems can be studied jointly as one problem that reflects interactions among three groups of stakeholders: federal and regional levels of the country and power companies. Such problems are considered, in particular, as active systems with distributed control and are also reduced to hierarchical game models [1].

In individual cases, we can use the simpler statements of the hierarchical two-level problem as a two-stage sequence of multi-criteria problems of mathematical programming. The strategy of the national power industry development is considered in the first stage; the appropriate recommendations are adjusted at the level of strategies of regional power industry development.

The general form of optimal conditions in both stages in the multi-criteria problem is the following:

$$f\left(f_1(x), f_2(x),\ldots, f_k(x)\right) \to \max. \qquad (5)$$

The search of Pareto set is frequently used for the optimal solution to the problem under incomparable objectives.

Let $\langle X, \{f_i\}\rangle$ be a multi-objective optimization problem, where X is a set of alternatives, $f_i(i \in N = \{1,\ldots,n\})$ is an objective function. If there is no additional information about the problem, then the Pareto optimal alternatives are accepted as optimal alternatives, i.e. such $x^0 \in X$, from $f_i(x) \ge f_i(x^0)$ for all $i \in N$ and $x \in X$ results in $f(x) = f(x^0)$. In other words, the set of optimal alternatives is defined only by Pareto optimal axiom [1].

In general, the Pareto set does not provide a unique solution, thus the problem of multi-criteria decision making remains unsolved. The use of multi-criteria utility function is a feasible approach to solve this problem.

A similar two-stage sequence of problems can be analyzed in inter-sectoral terms, when the basic proportions in power industry development are determined in the first stage by the territorial-production model of the energy sector. Then, these proportions are adjusted on more detailed models for decision making on power industry development [1].

In the problems in question, the main attention is paid to the mechanisms of interaction between the federal and regional or the energy sector and energy industry levels of devising the state strategies and programs for the power industry development. Therefore, consideration of incentives for the behavior of power companies by one or another technique for representing uncertain factors becomes necessary. The key objective for power supply companies in this case is to work out effective economic, legal and institutional mechanisms. They are to stimulate the companies to take into account priorities of the state policy in electric power industry when making strategic plans of their expansion and making decisions on investment projects. The optimal proportions of such mechanisms can be improved by solving the hierarchical game problems between the above-mentioned stakeholders "state" and "power companies" [1, 4].

B. Strategic plans of power companies

Now we will analyze the next group of problems dealing with the strategic plans of power company expansion. At least three classes of such problems can be discussed here.

For the regulated monopoly without competition it may appear to be necessary to solve multi-criteria problems of mathematical programming in terms of uncertainty and different preferences [5, 6]. A rather simple way for considering uncertain factors is a scenario representation of combinations of their values. The game problems in the class of "games with nature" may be analyzed on the basis of ordinary and fuzzy payoff matrices in the other cases.

The particularity of solving the multi-criteria problems based on the utility theory under different preferences is considered in [5, 6].

Let the initial conditions be represented by a tuple of sets (1) and the solutions are considered as a set of numerical estimates of the ranks of matrices (2). In order to solve the problem of choice on the basis of multi-criteria utility function, it is necessary to determine a preference relation for the decision maker (DM). The type of the preference relation depends on the scenarios of external conditions and relative significance of each of them for DM. If the preference relation is based on the probability methodology, then according to concepts of the utility theory, recommendations for choosing an EPS expansion option are given based on the calculation of the expected utility of each option in the form

$$E_i^p = \sum_{j=1}^{J} p_j U_{ij},\ i = 1, \ldots, I, \qquad (6)$$

where p is an index indicating the probability methodology used in preference relation, U_{ij} is a generated utility function. The option with a higher numerical estimate of the expected utility is more preferable.

However, the probability methodology of the preference relation is not always acceptable. It may turn out to be more reasonable to rely on the risk methodology. The latter is especially typical of cases when some scenarios of external conditions have very low probability but their influence on decision-making should be taken into consideration. Such a situation takes place, for example, when extreme external conditions connected with large-scale events of natural, technogenic or other character are to be taken into consideration. Then, the expected utility of the EPS expansion options can be obtained from the expression

$$E_i^r = \max_i \{\min_j (U_{ij} p_j)\},\ i = \overline{1, I}, \qquad (7)$$

where r is an index indicating the risk methodology used in preference relation.

It is worth noting, that the risk methodology as a basis for the preference relation also has disadvantages because the application of (7) decreases the effect of scenarios of external conditions with a high probability on the decision choice. Both the probability and risk methodologies are limiting cases, each reflecting a real situation in formation of preference relation used by decision maker from one side only. Therefore, consideration should be given to a complex criterion on the basis of (6) and (7) [1, 5-6].

Generation of such a complex criterion involves the problem of determination of weights of its constituents. This problem can be eliminated, if the decision-making procedure is not completely formalized and the decision is chosen by decision maker on the basis of additional information characterizing dominance regions for criteria (6) and (7) to form his preferences. In this case we can ‘weigh’ decisions obtained by both criteria and determine when some option with maximum utility (6) ceases to be the most preferable and some option with the maximum utility (7) becomes the most preferable.

To this end, $I - 1$ equations of form [1, 5, 6]

$$a_{i-m} E_{i\max}^p + (1 - a_{i-m}) E_i^r = a_{i-m} E_m^p + (1 - a_{i-m}) E_m^r, i \neq m, \qquad (8)$$

are solved, where a_{i-m} is the required parameter allowing the obtained utilities to be weighed, $a_{i-m} \in [0; 1]$; $E_{i\max}^p$ is the maximum utility of the i-th option which is calculated by relation (6); E_i^r is its associated utility value calculated by relation (7); E_m^p, E_m^r are corresponding utilities of the m-th option.

The next Chapter includes some calculation results based on the above-mentioned complex criterion [5, 6].

Since in real conditions there is no single technique to comprehensively solve the problem of choice, it is desirable for decision maker to have a set of different techniques to choose the most suitable one.

Development of a strategic plan for the network company expansion, when there are vertically integrated or purely generating companies, refers to the second class of problems. Considering, in a certain sense, a subordinate role of the network company that in the most general case implies providing competition for power producers and a free choice for power consumers, we can study the problems of the network company expansion in terms of "games with nature". In this case, the uncertainty in behavior of both power producers and consumers in the wholesale market is essential and is taken into account by the appropriate payoff matrix of the game. The conceptual meaning of uncertain factors for the network company as the single electricity buyer-seller, is determined, as before, by competition, and at the power consumption level it depends only on demand uncertainty and elasticity. In this case, however, the problem can also be examined in terms of "games with nature".

The generating companies can be coordinated especially under state regulation. Then, we considered the problem of cooperative game [7].

Finally, the third class of problems is related to the development of strategic expansion plans of competing vertically integrated or purely generating companies. Without the state regulation, the problem is reduced to a multi-criteria non-cooperative game. With the state regulation, the problem takes the form of a multi-criteria cooperative game, probably of a multi-stage character, i.e. it is reduced to a positional game [8, 9].

There are several methods to obtain the cooperative game solution. The evaluation of game solution based on the Shapley value is a generally used approach. This approach calculates the fair sharing of the common utility (money, resources, etc.) among players. The Shapley value can be determined as a weighted average of limiting contributions of a participant to every coalition in which the participant may take part.

The Shapley value φ_i can be expressed for the set of players $M = \{1,\ldots,m\}$ and the set of coalitions T_i, $i=\overline{1,M}$, where *i* is the number of players in coalition T_i, as:

$$\phi_i[v] = \sum_{\substack{T\subset M\\ i\in T}} \frac{(t-1)!(m-t)!}{m!}\left[v(T)-v(T/\{i\})\right], \qquad (9)$$

where $v(T)$ is a characteristic function of coalition *T*.

To determine this function is the key objective in such problems. Traditionally the characteristic function is considered as a cost function. In a more general case, the utility function can be used [4, 6].

The maximal constituent of Shapley value is calculated using (9) for a specified coalition, if the value of utility (6) is calculated for every possible coalition. The coalition with the maximal constituent of Shapley value corresponds to the optimal option of EPS expansion. An example of using the Shapley value to solve the problem of generating company expansion is presented in [9].

C. *Investment projects*

The problems of the third group dealing with decision making on investment projects for electric power facilities (power plants, substations, transmission lines) require a business plan for the construction of the corresponding facility. Mathematically, the problem statement depends on the investor position. If the power supply company (e.g. the network company) invests in the installation, the investment project may call for the multi-criteria assessment. For an independent investor one should allow for an incentive for behavior of the other concerned stakeholders and the problem can be associated with the game statement. It can be either cooperative or non-cooperative depending on conditions [1, 6].

IV. CASE STUDIES

This Chapter presents the calculation results based on [4] and [5]. These results are purely illustrative.

A. *Case study #1*

A hierarchical system expansion is studied for two levels. At the lower level consideration is given to two independent electric power companies, each supplies power to the consumers on the served territory. The first company (system 1) sells surplus power to the second company and foresees for this purpose an additional expansion of its generating capacities. At the upper level consideration is given to the regulation body (for example, state) that can stimulate the company expansion by regulation actions.

The objective is to choose an expansion option that will enable independent companies and the regulator to generate a suitable expansion option with more profitable expansion conditions for the donor company (company 1).

Assume general expansion conditions for both companies.

The scenarios of external conditions for the first company are:

a) Maximum power consumption without power sale at minimum fuel prices.

b) Minimum power consumption without power sale at maximum fuel prices.

c) Maximum power consumption with power sale at minimum fuel prices.

d) Minimum power consumption with power sale at maximum fuel prices.

The scenarios of external conditions for the second company are similar at the exception of the fact that the company does not sell but buys electric power.

Taking into account the illustrative character of the problem, we consider the probabilities of implementing the above scenarios of external conditions to be similar and equal to 0.25 each.

The above-mentioned expansion options include the options when company 1 sells the power generated by gas-fired power plants to company 2.

Three players are to make decisions for each company: power company, authorities and consumers. All the players had equal rights, the total of weighting coefficients for all criteria was equal to unity and each criterion participated in decision making with its weight.

The options were estimated using the following criteria:

α) investment costs (million $);

τ) current costs (million $/year);

β) budget (taxes) (million $/year);

γ) tariffs ($/kWh).

The calculation results for the accepted options of solutions for companies 1 and 2 at given external conditions in terms of the estimated criteria were analysed in [4]. Gas-fired power plants were addressed as new generating capacities to be commissioned.

Table 1 presents utilities of the options for each system and ranks of the options.

Levelling of the situation (ranking of the options, Table 1) was performed by the rising price of electricity sold. We will apply option 4 from Table 1 for further analysis of the hierarchical game, because in this option the increasing electricity demand of consumers served by company 2 is met fully [4].

Thus, in the considered problem the base (first) option (Table 2) is the option of commissioning new units with a utility of 0.5117 for company 1.

The option with introduction of regulation actions will be compared to the base one only by two criteria: capital investment and current expenditures. It is precisely these criteria that underlie a decision made by the power company. The rest of the criteria were foreseen for the other participants of decision making process: the budget for authorities and tariffs for consumers.

Table 1. Initial estimates of options.

Options	Utility and ranks (in brackets)	
	System1	System 2
1	0.5284 (2)	0.2873 (4)
2	0.5154 (3)	0.6371 (2)
3	0.5302 (1)	0.5287 (3)
4	0.5117 (4)	0.7201 (1)

Table 2. Calculation results for system 1 at specified external conditions by the criteria: capital investments and current expenditures.

Criteria	Options	External conditions (for system 1)			
		A	B	C	D
α	1	170.3	170.3	1761.5	1761.5
	2'	192.3	192.3	1783.5	1783.5
	3'	182.3	182.3	1773.5	1773.5
	4'	179.3	179.3	1770.5	1770.5
τ	1	89.9	102.5	96.1	110.8
	2'	89.9	102.4	96.1	110.7
	3'	89.9	102.4	96.1	110.7
	4'	89.9	102.4	96.1	110.7

Table 3. Newly commissioned capacities.

Options	Additional capacities (MW)	Including WPP (MW)
2',3',4'	122	10

Table 4. Comparison of utilities for expansion options.

Options	Utility
	System 1
1	0.5117
2'	0.5107
3'	0.5115
4'	0.5117

The regulator encourages company 1 to construct wind power plants (WPP). These plants have high capital investments and low current expenditures. The options corresponding to WPP commissioning will be further denoted by 2', 3', 4'.

Step 1 calculates the possibility of commissioning such plants by the company itself without regulation actions from the regulator. In this case, new option 2′ (Table 2) is generated.

Table 3 shows additional capacities including capacities of WPP to be commissioned in the case of electricity sale. As is seen from Table 2, option 2′ is characterized by a rather high level of capital investments and a small decrease in current expenditures versus the base option.

Table 4 demonstrates a decrease in the utility for option 2′.

Hence, it is unprofitable for the company to construct new plants with a high level of investments.

Thus, regulation actions of the regulator are introduced at the next step. At first they may be represented by the budget subsidies, whose value is chosen arbitrarily. With the budget subsidies of $10 million, for example, the utility of option 3′ (Table 4) remains lower than the base option 1, as before. The current expenditures are low enough and their negligible increase is not indicated in Table 2.

With the regulation actions equal to the amount of $13 million, the utilities of the base option and option 4′ coincide. The capital investments for option 4′ remain higher than the capital investments for the base option. It means that if the utilities coincide, this option can be accepted by the company.

Conditions for WPP commissioning by both companies may differ slightly in the investment per power unit (for example, it is somewhat more expensive for company 1), and the current expenditures (they are on the contrary somewhat higher for company 2, for example, due to difficulties in maintaining remote WPP, at the same time in company 1 the wind power plants are located nearby). We will not illustrate this quantitatively more complicated case, as it has nothing new compared to the previous one.

Needless to say, other regulation actions of the regulator are possible for more coordinated expansion of power companies.

B. Case Study #2

B1. Problem statement

The formation of the basic structure of one of the electric power systems in Russia is considered with regard to generating equipment types for the period of some 10 years.

In this study, the external conditions of EPS expansion are:

A) Minimum power consumption without export at a minimum fuel price.

B) Minimum power consumption without export at a maximum fuel price.

C) Maximum power consumption with export at a minimum fuel price.

D) Minimum power consumption with export at a maximum fuel price.

Without dwelling on the validity of such conditions for EPS expansion by virtue of the illustrative character of the studies, in further analysis we assume the probability of each condition to be equal to 0.25.

Three options of the EPS expansion are analysed:

1) Commissioning of new coal-fired units.
2) Commissioning of new gas-fired units.
3) Partial commissioning of coal-and gas-fired units.

The above options were estimated by six criteria:

α) investment costs (million doll.);
τ) fuel costs (million doll./year);
β) budget (taxes) (million doll./year);
η) environment (ash emissions, thousand t/year);
γ) tariffs (cent./kWh);
δ) reliability (p.u.);

The options were analysed using the software package

'Soyuz' [6]. This package is designed to choose the structure of generating capacities by equipment type, their location and formation of requirements to the transfer capabilities of ties in the multi-nodal EPS taking into account seasonal and daily non-uniformities of power consumption, specific character of operation and performance of different power plants, reliability requirements, conditions for fuel supply, etc. Reliability was calculated by simulation of failures/restorations of EPS components and evaluation of a relative magnitude of power supply to consumers. The results of the studies on the considered options of the UEPS expansion at the assumed external conditions in terms of the estimation criteria are presented in Table 5.

Table 5. Estimates of options for different external conditions.

Criteria	Options	External conditions A	B	C	D
α	1	13.5	13.5	1849.5	1849.5
	2	11.7	11.7	1602.9	1602.9
	3	12.6	12.6	1726.2	1726.2
τ	1	79.1	86.1	82.1	89.3
	2	87.2	98.9	93.4	107.1
	3	83.1	92.5	87.7	98.2
β	1	3016.0	4524.0	3317.6	4825.6
	2	3317.6	5428.8	3619.2	5730.4
	3	3166.8	4976.4	3468.4	5278.0
η	1	58.1	58.1	60.4	60.4
	2	52.5	52.5	52.5	52.5
	3	55.3	55.3	56.4	56.4
γ	1	1	1.5	1.1	1.6
	2	1.1	1.8	1.2	1.9
	3	1.05	1.65	1.15	1.75
δ	1	0.9996	0.9996	0.9974	0.9974
	2	0.9997	0.9997	0.99915	0.99915
	3	0.99965	0.99965	0.99893	0.99893

B2. Calculation and analysis of utilities

We solved the multi-criteria expansion problem using the utility theory by (6), (7). The studies were performed for two sets of criteria (in Table 6 with the corresponding weighting coefficients)**:** α - 0.2, 0.3; τ - 0.2, 0.2; β - 0.15, 0,15; η- 0.1, 0,1; γ - 0.25, 0.15; δ -0.1, 0,1.

Now let us verify the stability of decisions for each system of the expert preferences at which the rank of the options changes, i.e. let us determine at which relations of the two approaches the decisions can be considered stable. Otherwise, one can rely on the decision chosen by different methods. Note that to do this we calculated parameters a_m, $m = 1,2$, by relation (8), where m means number of the first or second method for calculation of the utilities by (6) or (7) respectively. Table 7 presents the utilities of options that are calculated by (7). Table 8 presents the values of a_m for different systems of the expert preferences.

Thus, for the first set of the expert preferences, the third expansion option is the most preferable at $a_1 \in [0;0.2499]$ and the fourth expansion option - at $a_1 \in [0.2499;1]$.

For the second set, the first option is chosen at $a_1 \in [0;0.0969]$ and the fourth option - at $a_1 \in [0.0969;1]$.

Table 6. Utilities and ranks of options.

Options	Utilities and ranks (in brackets) Set 1	Set 2
1	0.4966 (3)	0.6278 (3)
2	0.6330 (1)	0.6993 (2)
3	0.5909 (2)	0.7039 (1)

Table 7. Utilities and ranks (7).

Options	Utilities and ranks (in brackets) Set 1	Set 2
1	0.1590 (3)	0.1676 (3)
2	0.1932 (2)	0.2625 (1)
3	0.2073 (1)	0.2620 (2)

Table 8. Weighting coefficients for (8).

Systems of expert's preferences	a_1	a_2
Set 1	0.2499	0.7501
Set 2	0.0969	0.9031

V. Conclusions

In a liberalized environment, we deal with a great number of decision making problems for power system expansion planning. These problems are not simple.

The mathematical programming, game-theoretical approaches or simulation assessment can be applied to solve these problems.

The development of technologies, mathematical models and techniques for power system expansion planning is of paramount importance.

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Nikolai Voropai is President of the Energy Systems Institute (Siberian Energy Institute until 1997) of the Russian Academy of Science, Irkutsk, Russia. He graduated from Leningrad (St. Petersburg) Polytechnic Institute in 1966. N.I. Voropai received his degrees of Candidate of Technical Sciences at the Leningrad Polytechnic Institute in 1974 and Doctor of Technical Sciences at the Siberian Energy Institute in 1990. His research interests include: modeling of power systems, operation and dynamics performance of large power grids; reliability and security of power systems; development of national, international and intercontinental power grids; smart grids.

Methods and Algorithms for Selecting Independent Techno-Economic Indicators

E.M. Farhadzadeh*, A.Z. Muradaliyev, Y.Z. Farzaliyev, T.K. Rafiyeva, S.A. Abdullayeva

Azerbaijan Scientific-Research and Design-Prospecting Power Engineering Institute, Baku, the Republic of Azerbaijan

***Abstract* — One of the main requirements imposed on integrated indices is the independence of their components. In actual practice, a set of reliability, cost-effectiveness and safety indices of electric power facilities is known. It is based on real opportunities for data collection. The number of such technical and economic indicators varies from units to tens. If necessary, the informational content of the integrated estimates can be enhanced by involving the data on ratings and operation conditions. The joint use of these data, however, often encounters difficulties connected with the difference in both the scale of their measurement and the extent to which they are interrelated. The methods, algorithms, and subprograms are developed to select independent technical and economic indicators that increase the reliability of comparison and ranking of the facilities and to make recommendations for the improvement of the reliability and cost-effectiveness of their operation.**

***Index Terms* — Reliability, efficiency, technical and economic indicators, ranking, boiler, distribution function**

I. Introduction

Operating experience with the equipment and devices (facilities) of electrical power systems (EPS) shows that the need for the reliability, cost-effectiveness, and safety (efficiency) of their operation has increased over time [1]. With the marked discrepancy between energy characteristics of the facilities and their technical condition, the main directions to improve the management of overall performance are to transition from intuitive comparison and ranking of the EPS facilities to the automated management. A necessary condition for the automated management is the development of methods for calculation of operational values of the integrated indices (II).

The integrated index suggests independence of the technical and economic indicators (TEI) defining it. Violation of this condition distorts the magnitude of the integrated index depending on the number of the interconnected TEI and their relationships. Technical and economic indicators of EPS facilities have, as a rule, a quantitative scale of measurement. Their relationship is established by Pearson linear correlation coefficients $\gamma_{op.}$ calculated based on the statistical data of operation and comparing $\gamma_{op.}$ with critical value γ_{α} for the set type I error [2]. At the same time, it is supposed that the distribution of F(TEI) *corresponds to the normal law* and the number of sample realizations $n_s>30$. This assumption underlies the calculation of γ, provides the correspondence of distribution of $F(\gamma)$ to the normal law and the possibility of assessing the accuracy (boundary values of a confidence interval) of the estimation of $\gamma_{op.}$.

In actuality, however, the data on all techno-economic indicators characterizing the technical condition of a facility are not always available, the number of sample realizations (for example, the number of the same-type energy units) is not always $n_s>30$, the distribution of F*(TEI) does not always correspond to the normal law, and relationships between techno-economic indicators are not always linear. This discrepancy raises doubts about the reliability of the analysis of TEI relationship, with all that it implies. *The methods to assess the relationships between real TEI samples are not developed*. The informational content of integrated indices can if necessary be enhanced by attracting, for example, some rated data characterizing overall performance of a certain facility. These data, however, have a rank-order scale of measurement, which creates certain difficulties for direct calculation of integrated indices following from the difference in the scales of measurement. However, given that data on TEI

* Corresponding author.
E-mail: elmeht@rambler.ru

http://dx.doi.org/10.25729/esr.2018.02.0004
Received: June 18, 2018. Revised: July 17, 2018. Accepted: August 8, 2018. Available online: October 15, 2018.

of the facilities measured with a numerical scale can be transformed so that it will be possible to measure them with a rank-order scale (and not vice versa), this difficulty of assessing the relationship between the considered indicators of the facility will be partially overcome [3].

The existence of a relationship between the indicators measured on a rank-order scale in practice is controlled by one of the rank tests. For the analysis, we have chosen the Spearman rank correlation coefficient, which is described in detail in [4].

1. For the automated comparison and ranking of the efficiency of the electric power system facilities, it is necessary to be able to calculate their integrated indices of operation in terms of single indicators that have different units, scales, and scale of measurement.
2. The accuracy of the integrated indices calculation depends considerably on the number of the interconnected single indicators m_p: the larger the number of m_p, the larger the calculation error.
3. The existence of relationship between techno-economic indicators is traditionally established based on the excess of the correlation coefficient calculated according to the statistical data on facility operation over a critical value with the set type I error α .
4. The selection of functionally and statistically independent TEI allows us not only to increase the reliability of the integrated index evaluation but also to reduce the volume of necessary information and bulkiness of calculations.

II. Method and algorithm for modeling independent realizations of Spearman rank correlation coefficient

Traditionally, for small n_s of TEI of ranked facilities (for example, generating units of power plants), the significance of the Spearman rank correlation coefficient $\rho_{op.}$ is determined by:

- Calculating Student's t-test by the expression

$$t_э = \frac{\rho_{op}\sqrt{n_s - 2}}{\sqrt{1-\rho_{op}^2}} \quad (1)$$

- Determining a critical value of Student's t-test t_α for a set level of significance α and the number of degrees of freedom (n_s-2) from the reference book;
- Comparing the values of t_{op} and t_α :

$$\text{if } t_{op} > t_\alpha \text{, then } H \Rightarrow H_2 \text{, else } H \Rightarrow H_1 \quad (2)$$

where H - the assumption; $\Rightarrow$ - compliance; H_1 and H_2 – assumptions (hypotheses) about the absence or existence of a significant relationship between TEI.

Compilation of a list of independent TEI is an intermediate stage for comparing and ranking the facilities, therefore the manual calculation of a set of the values ρ_{op} (for example, when the number of TEI equals 10, it is necessary to rank 90 ρ_{op} values) causes awkwardness, labor input and high risk of wrong decision.

We have developed an automated system for comparing and ranking the EPS facilities, which makes it possible both to perform faultless calculations of ρ_{op}, and to determine critical ρ_α values directly by the statistical function of distribution (SFD) of $F^*(\rho_м)$. Modeling of possible realizations of $\rho_м$ and formation of SFD $F^*(\rho_м)$ were carried out as follows:

1. The standard RAND() program models two independent samples of random variables $\{\xi_1\}_n$ and $\{\xi_2\}_n$ with a volume of n_S that are uniformly distributed on the interval [0;1].

2. A sequence of serial numbers (ranks) of sample realizations $\{\xi_1\}_n$ and $\{\xi_2\}_n$ in terms of their variation series is formed. Let them be designated by $\{r_1\}_n$ and $\{r_2\}_n$. Thus, the indicators measured with the numerical scale will be transformed into indicators with the rank-order scale of measurement.

3. The first realization of $\rho_{1,м}$ is calculated according to Spearman's formula [4]

$$\rho_{1,ì} = 1 - \frac{6 \cdot \sum_{j=1}^{n_s} (r_{1,j} - r_{2,j})^2}{n_s(n_s^2 - 1)} \quad (3)$$

4. Calculations for points 1-3 are repeated N times.

5. A variation series of a set of possible values $\rho_{1,м}$ is built in ascending order of $\rho_{1,n}$. The probability $F_1^*(\rho_{1.м}) = i/N$ is compared to each ordinal number of this series. At the same time $\alpha = 1 - F^*(\rho_{1,м}) = R^*(\rho_{1,м})$,

Table 1. The sequence of calculation of $\rho_{1,м}$.

Number of items	$\xi_{1,j}$	$\xi_{2,j}$	$r_{1,j}$	$r_{2,j}$	$\Delta r_j = r_{1,j} - r_{2,j}$	Δr_j^2	Note
1	0,287	0,249	1	1	0	0	$\rho_{1,ì} = 1 - \frac{6 \cdot \sum_{j=1}^{n_s} \Delta r_j^2}{n_s(n_s^2 - 1)} = 0.7$
2	0,337	0,776	3	4	-1	1	
3	0,806	0,265	4	2	2	4	
4	0,998	0,913	5	5	0	0	
5	0,303	0,633	2	3	-1	1	
	Total		15	15	0	6	

The sequence of $\rho_{1,м}$ calculations using formula (3) is given in Table 1 for illustrative purposes.

As one would expect, we will receive similar results with calculations based on expression (4) that represents a nonparametric analog of formula for calculation of Pearson linear correlation coefficient:

$$\rho_{1,op} = \frac{\sum_{j=1}^{n_s}(r_{1,j}-\overline{r_1})\cdot(r_{2,j}-\overline{r_2})}{\sqrt{\sum_{j=1}^{n_v}(r_{1,j}-\overline{r_1})^2}\cdot\sqrt{\sum_{j=1}^{n_v}(r_{2,j}-\overline{r_2})^2}} = 0,7 \quad (4)$$

where $\overline{r_1}$ and $\overline{r_2}$ are medians of samples $\{r_1\}_{n_s}$ and $\{r_2\}_{n_s}$, respectively.

Calculations of γ_{op} by Pearson's formula

$$\gamma_{op} = \frac{\sum_{j=1}^{n_s}(\xi_{1,j}-\overline{\xi_1})\cdot(\xi_{2,j}-\overline{\xi_2})}{\sqrt{\sum_{j=1}^{n}(\xi_{1,j}-\overline{\xi_1})^2}\cdot\sqrt{\sum_{j=1}^{n}(\xi_{2,j}-\overline{\xi_2})^2}} = 0,252, \quad (5)$$

confirms possible essential distinction between linear **(**γ_{op}**)** and rank **(**ρ_{op}**)** correlation coefficients for the same samples $\{\xi_1\}_n$ and $\{\xi_2\}_n$. It is worth reminding that random variables ξ have a uniform distribution on the interval [0,1], i.e. do not correspond to the normal law of distribution, which is the initial prerequisite for the application of Pearson's formula (5).

III. Consideration of identical realizations of indicators of attributes

The above-discussed method for transformation of a numerical scale of measurement of random variables ξ to a rank-order scale does not allow for a degree of their divergence.

At a fixed number of intervals equal to r_{max}=5 and the number of realizations of the modeled samples $n_s \geq 5$, the existence of repeated numbers of intervals (points) is inevitable. This statement is confirmed by the data of Table 2 that demonstrates the distribution of the degree of influence of six attributes on reliability and cost-effectiveness of power transformers [3]. The degree of influence is specified in points of a five-point system.

To consider this feature, we will somewhat transform points 2 and 3 of the algorithm for construction of $F^*(\rho_м)$.

A range of change in ξ [0;1] is represented by five equal intervals: (0-0,2), (0,21-0,4), (0,41-0,6), (0,61-0,8), (0,81-1,0). For realization of samples, number b of the interval (the number of points corresponding to each realization) corresponding to them is determined. Thus, the samples $\{\xi_1\}_n$ and $\{\xi_2\}_n$ are replaced with the samples of points $\{b_1\}_n$ and $\{b_2\}_n$. Unlike the samples of random variables ξ, the samples $\{b_1\}_n$ and $\{b_2\}_n$ may contain two and more identical values.

According to [4], we arrange samples $\{b_1\}_n$ and $\{b_2\}_n$ in ascending order, assign serial numbers (ranks) to realizations of the samples, identify identical realizations in samples, and calculate an average size of ranks for identical realizations.

Table 3 demonstrates the results of calculations and assessment of $\rho_{2,м}$ by (4). Samples of random variables $\{\xi_1\}_5$ and $\{\xi_2\}_5$ are the same as in Table 1.

The comparison of Tables 1 and 3 shows that the estimates $\rho_{1,op}$, and $\rho_{2,м}$ differ greatly. The value of $\rho_{2,м}$ calculated by formula (4) is less than $\rho_{1,op}$, calculated by formula (3).

The block diagram of the algorithm for the formation of ranks of realizations of discrete random variables is presented in Fig.1.

Table 2. An assessment of the rate of occurrence of points characterizing the reliability of power transformers

Number of items	**Transformer type**	**The frequency of emergence of point**				
		1	**2**	**3**	**4**	**5**
1	АТДЦТН-250000/220	-	-	-	4	2
2	ТДТН-63000/110	-	1	4	1	-
3	IEC-60076	-	-	3	1	1
4	ТДН-16000/110	1	5	-	-	-
5	ТДН-25000/110	-	-	-	3	3
6	ТДТН-25000/110	1	4	1	-	-
7	ТДТН-40000/110	4	1	1	-	-
8	ТДТН-25000/110	-	-	-	-	6
9	ТМН-10000/110	-	-	3	1	2
10	АТДЦТН-250000/330	-	1	-	2	3
11	ТДН-80000/330	-	-	-	6	-
12	ТДТН-10000/110	1	1	4	-	-
13	ТДН-25000/110	-	1	1	4	-
14	АТДЦТН-200000/220	1	2	2	-	1
15	IEC-60076	-	-	2	3	1
16	АОДЦТН-167000/500	-	-	-	2	4
17	АОДЦТН-167000/500	-	-	-	2	4
18	ТДТН-40000/110	2	1	1	1	1
19	АТДЦТН-250000/220	1	-	1	2	3

Table 3. Order of $\rho_{4,M}$ calculation by (4).

j	$b_{1,j}$	$b_{2,j}$	$r_{1,h}$	$r_{2,j}$	$\Delta r_{1,j}=r_{1,j}-\bar{r}_1$	$\Delta r_{2,j}=r_{2,j}-\bar{r}_2$	$\Delta r_{1,j}-\Delta r_{2,j}$	$\Delta r^2_{1,j}$	$\Delta r^2_{2,j}$	Note
1	2	2	2	1,5	-1	-1,5	1,5	1	2,25	$\bar{r}_1=\bar{r}_2=3$ ρ_2=0,152
2	2	4	2	3,5	-1	0,5	-0,5	1	0,25	
3	5	2	2	3,5	-1	0,5	-0,5	1	0,25	
4	5	5	4,5	1,5	1,5	-1,5	-2,25	2,25	2,25	
5	2	4	4,5	5	1,5	2	3	2,25	4	
Total			15	15	0	0	1,25	7,5	9	

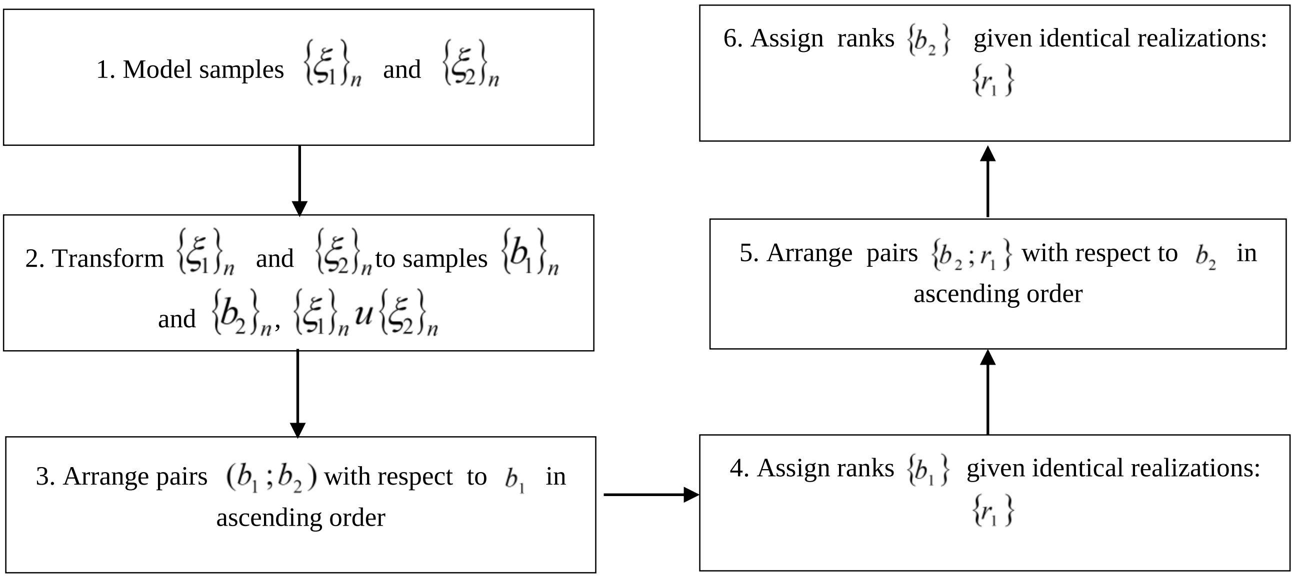

Figure 1. A block diagram of the algorithm for the formation of ranks of discrete random variables

IV. Analysis of fiducial distributions of correlation coefficients of the choice of independent values.

The above calculations and publications demonstrate that the relationship between Pearson γ and Spearman ρ correlation coefficients for the same samples is non-unique. At the same time, their critical values are assumed to be equal [6]. To analyze this feature, we propose comparing fiducial distributions of these correlation coefficients. It is worthwhile to remind that fiducial distribution means the distribution of possible realizations of integrated indices [7]. The integrated indices are taken to mean the indices whose realizations can be obtained from calculations. The integrated indices, for example, can be represented by arithmetic (geometric, harmonic) mean of random variables, indices of their spread, the coefficient of technical availability, and availability factor. The correlation coefficients also refer to them. This is a special approach to solving the inverse problem. Correlation coefficients are calculated for the samples of independent random variables providing their statistical independence.

A large number of calculations are required to obtain possible realizations of the correlation coefficients. For this reason, the automated system for the formation of the statistical functions of fiducial distributions (SFFDs) is necessary. The SFFD of each correlation coefficient can be formed by repeatedly modeled samples, and all correlation coefficients can be calculated by one, but a repeatedly modeled pair of samples of random variables. The result of the SFFD calculation will be the same. However, the second way allows estimating the difference between the correlation coefficients. The developed algorithm and calculation program suggest the following sequence of calculations:

1. Two samples $\{\xi_1\}_{n_s}$ and $\{\xi_2\}_{n_s}$, random variables ξ with uniform distribution in the range of [0,1] with the set n_s volume are modeled [8].
2. Pearson linear correlation coefficient $\gamma_{1,M}$ is calculated by (5).
3. Samples $\{\xi_1\}_{n_s}$ and $\{\xi_2\}_{n_s}$ are transformed to the samples of points $\{b_1\}_{n_s}$ and $\{b_2\}_{n_s}$ for which Pearson linear correlation coefficients $\gamma_{2,M}$ are calculated by (5).
4. Sample ranks $\{r_1\}_{n_s}$ and $\{r_2\}_{n_s}$ for samples $\{\xi_1\}_{n_s}$ and $\{\xi_2\}_{n_s}$ are determined. The ranks are used to calculate Spearman rank correlation coefficients $\rho_{1,M}$ by (1).
5. Spearman rank correlation coefficient $\rho_{2,M}$ is calculated for samples $\{b_1\}_{n_s}$ and $\{b_2\}_{n_s}$ by (4), given identical realizations.

Table 4. Relationship between realizations of linear and rank correlation coefficients for n_s=5

Numbers of items	**Correlation coefficient at n_s=5**			
	$\gamma_{1,м}$	$\gamma_{2,м}$	$\rho_{1,м}$	$\rho_{2,м}$
1	0,404	0,319	0,2	0,306
2	0,612	0,593	0,7	0,574
3	0,213	0,321	0,1	0,162
4	0,346	0,612	-0,5	0,645
5	-0,247	-0,339	-0,4	-0,34
6	0,521	0,461	0,7	0,730
7	-0,340	-0,240	0,1	-0,278
8	-0,925	-0,955	-0,8	-0,889
9	0,217	0,036	0,2	0,263
10	-0,881	-0,785	-0,9	-0,763

Table 5. The difference in solutions related to the relationship between samples for linear and rank correlation coefficients

Numbers of items	**Samples $\{\xi\}_5$**						**Calculation results**			
							$\gamma_{1,м}$	$\gamma_{2,м}$	$\rho_{1,м}$	$\rho_{2,м}$
1	1	0,334	0,699	0,425	0,290	0,693	0,832	0,896	0,8	0,973
	2	0,076	0,910	0,618	0,544	0,984				
2	1	0,879	0,405	0,366	0,661	0,611	0,947	0,832	0,8	0,872
	2	0,965	0,136	0,265	0,563	0,709				
3	1	0,059	0,688	0,434	0,281	0,872	0,750	0,808	0,9	0,947
	2	0,533	0,129	0,800	0,670	0,836				
4	1	0,179	0,618	0,096	0,651	0,459	-0,846	-0,885	-0,9	-0,884
	2	0,486	0,396	0,674	0,204	0,256				
5	1	0,867	0,404	0,433	0,394	0,790	-0,928	-0,908	-0,7	-0,918
	2	0,300	0,942	0,909	0,846	0,635				

Table 6. Critical values $\Gamma_{1,M,\alpha}$, $\Gamma_{2,M,\alpha}$, $\rho_{1,M,\alpha}$ AND $\rho_{2,M,\alpha}$ AT N_S=5

α	$\gamma_{1,м,\alpha}$	$\gamma_{2,м,\alpha}$	$\rho_{1,м,\alpha}$	$\rho_{2,м,\alpha}$	$\gamma_{1,м,\alpha}$ [6]
0,1	0,8120	0,8077	0,8	0,8158	0,805
0,05	0,8852	0,8847	0,9	0,8922	0,878
0,01	0,9620	0,9625	1,0	0,9733	0,959
0,005	0,9761	0,9715	1,0	0,5747	-
0,001	0,9887	1,0	1,0	1,0	0,991

Table 7. Quantiles of distributions corresponding to $F^*(\ldots)$=0,5

	$\gamma_{1,м}$	$\gamma_{2,м}$	$\rho_{1,м}$	$\rho_{2,м}$
5	0,4033	0,4082	0,4	0,3947
8	0,2754	0,2790	0,2613	0,2717
10	0,2325	0,2376	0,2364	0,2357

6. Points 1-5 were repeated N=10000 times.

7. As a result:

7.1. For illustration, the relationship between realizations $\gamma_{1,м}$, $\gamma_{2,м}$, $\rho_{1,м}$ and $\rho_{2,м}$ are printed for the first ten pairs of samples $\{b_1\}_{n_s}$ and $\{b_2\}_{n_s}$ of their correlation coefficients. The results of such calculations are given in Table 4 for n_s=5. The underlined figures mean the maximum absolute values of the correlation coefficients.

7.2. Corresponding samples $\{\xi_1\}_{n_s}$ and $\{\xi_2\}_{n_s}$, and also correlation coefficients $\gamma_{1,м}$, $\gamma_{2,м}$, $\rho_{1,м}$ and $\rho_{2,м}$ were printed to illustrate the relationships between realizations of $\gamma_{1,м}$, $\gamma_{2,м}$, $\rho_{1,м}$ and $\rho_{2,м}$ provided that at least one of them exceeds the critical value given in literature data $\gamma_\alpha=\rho_\alpha$,. Some characteristic results of modeling for n_s=5 and $\gamma_{0,05}=\rho_{0,05}$=0,878 are given in Table 5. The samples allow controlling reliability of the calculations.

7.3. The corresponding values $\gamma_{1,м,\alpha}$, $\gamma_{2,м,\alpha}$, $\rho_{1,м,\alpha}$ and $\rho_{2,м,\alpha}$ were determined by $N_\alpha=(1-\alpha)N$ to compare the critical values of linear and rank correlation coefficients at α equal to: 0,05; 0,01; 0,005; 0,001 0,1 and n_s=5. The results of the calculations, and reference data about $\gamma_{1,\,м,\,\alpha}$ are given in Table 6.

7.4. Realizations of $\gamma_{1,м}$, $\gamma_{2,м}$, $\rho_{1,м}$ and $\rho_{2,м}$ were autonomously ranked and realizations corresponding to the probability of $F^*(\ldots.)=0,05\cdot i\cdot N$ at i=1,20 were printed to compare the regularities of variations in SFFDs of possible realizations of linear and rank correlation coefficients. Quantiles of these SFFDs corresponding to the probability of $F^*(\ldots)$ =0,5 and series n_s=5 are given in Table 7.

Figure 2 demonstrates the histograms of $f^*(\gamma_{1,м})$, $f^*(\gamma_{2,м})$ and statistical functions of fiducial distribution of Pearson γ_1 and Spearman ρ_2 correlation coefficients for n_s=5.

The analysis of modeling allows us to draw the following conclusions.

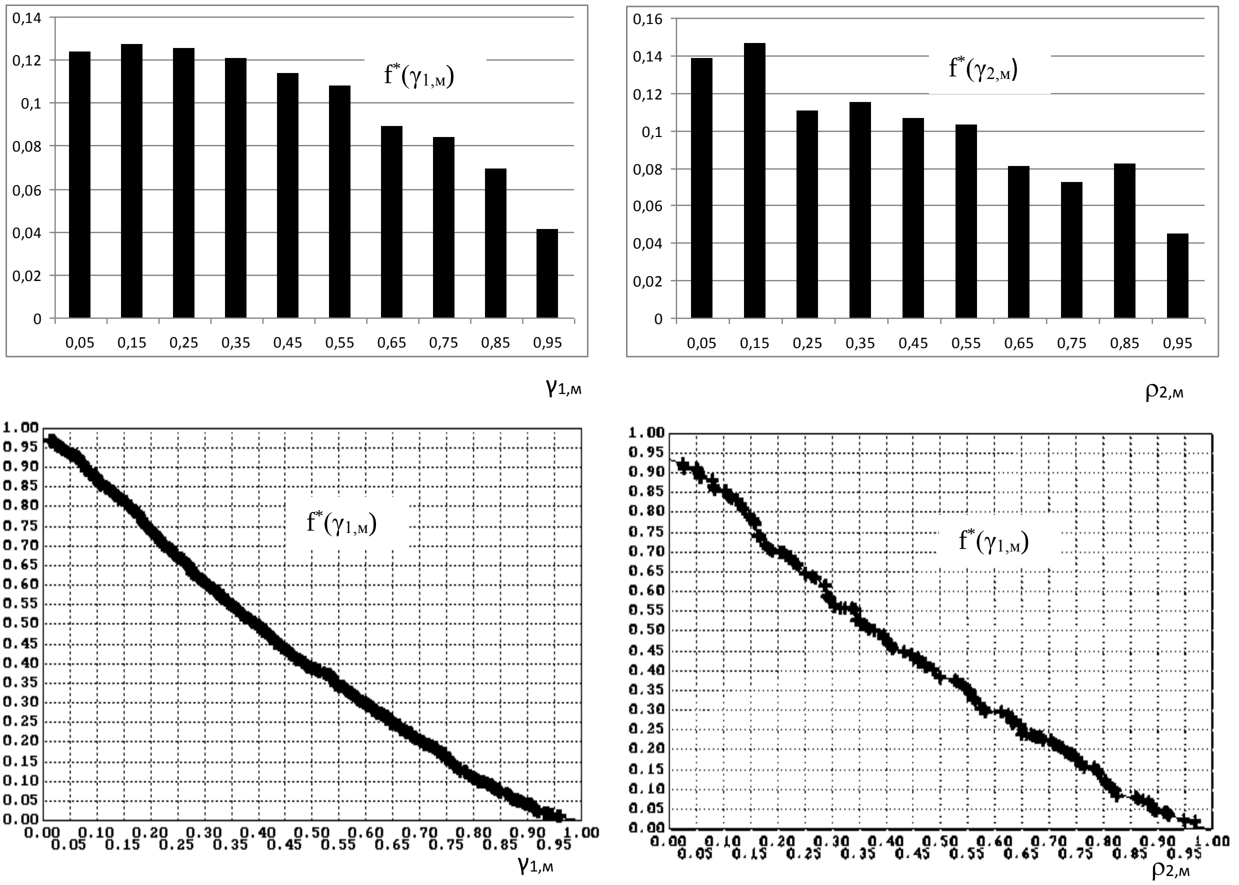

Figure 2. Histograms of distribution of correlation coefficients $f^*(\gamma_{1,м})$, $f^*(\rho_{2,м})$ and SFFDs $R^*(\gamma_{1,м})$, $R^*(\rho_{1,м})$ KK at n_s=5; $R^*(\gamma_{1,м})=1-F(\gamma_{1,м})$ $R^*(\rho_{1,м})=1-F(\rho_{1,м})$

Data from Table 4 indicate that the numerical estimates of correlation coefficients γ_1, γ_2, ρ_1 and ρ_2 for the same samples can differ greatly.

Table 5 highlights the largest values of the correlation coefficients for each of ten "tests". Pearson coefficients of linear correlation between realizations $\gamma_{1,м}$, $\gamma_{2,м}$, $\rho_{1,м}$ and $\rho_{2,м}$ exceed the critical value $\gamma_{0,01}$=0,765, which demonstrates the existence of a linear statistical relationship between them.

The data of Table 5 confirm the effectiveness of calculating no less than two correlation coefficients, in particular:

- When indicators are measured with a numerical scale, it is advisable to calculate Pearson linear correlation coefficients γ_1 and γ_2 and Spearman rank-order correlation coefficient ρ_2 [9];
- When indicators are measured in points, it is better to calculate Pearson linear correlation coefficient γ_2 and Spearman rank-order correlation coefficient ρ_2.

The recommendation is based on the difference in the extent to which these correlation coefficients take into account the properties and volume of samples (nature of distribution, the existence of identical realizations, small sample size, nonlinear nature of the relationship, etc.);

The data of Table 6 demonstrate almost insignificant divergence between the critical values of the linear correlation coefficients $\gamma_{1,м,\alpha}$, and $\gamma_{2,м,\alpha}$ obtained as a result of modeling, and theoretical data ($\gamma_{1,\alpha}$). It is worth noting that $\gamma_{м,\alpha}$ are calculated by the samples whose random realizations have uniform distribution in the range of [0,1]. Although Pearson linear correlation coefficient suggests a correspondence between random variables of samples and the normal law, in the case of small n_s, the law of distribution has insignificant influence. The insignificant divergence between $\gamma_{м,\alpha}$ and γ_α is, in fact, the indicator of faultlessness of the calculation algorithm. There is virtually an insignificant divergence between correlation coefficients $\gamma_{1,м,\alpha}$, $\gamma_{2,м,\alpha}$ and $\rho_{2,м,\alpha}$. It makes up no more than 2,5%, which experimentally confirms the existing statements about equality of $\gamma_{1,м,\alpha}$ and $\rho_{2,м,\alpha}$. However, the attempts to use these relations to state the equality between $\gamma_э$ and $\rho_{э,э}$ calculated using experimental data, can lead to incorrect conclusions as estimates can differ greatly.

An analysis of SFFD of correlation coefficients indicates that:

- at n_s=5÷10 the function of the fiducial distribution of $F^*(\rho_{1,м})$ has a pronounced discrete character;
- SFFD of $F^*(\rho_{1,м})$ is symmetric with respect to $\rho_{1,м}$=0 even at n_s=5 and, therefore, can be represented as a distribution of absolute value $\rho_{1,м}$;

Table 8. The relationship between sample size and $\Delta\rho_M$.

n_s	5	6	7	9	9	10
$\Delta\rho_M$	0,1	0,0571	0,0357	0,0238	0,0167	0,0121

- the sampling increment $\Delta\rho_M$ of an argument of distribution of $F^*(\rho_{1,M})$ depends on the value of n_s . The size of $\Delta\rho_M$ decreases nonlinearly with an increase in n_s. Table 8 presents the relationship between n_s and $\Delta\rho_M$.

It is worth noting, that decision H is traditionally made according to criterion (2) developed for continuous random variables. In fact, there are no critical values $\rho_{1,\alpha}$ corresponding to α at discrete nature of change in $F^*(\rho_{1,M})$. Therefore, we propose comparing the probabilities of $F^*(\rho_{1,M})$ and α_K rather than quintiles of distribution of $F^*(\rho_{1,M})$ (i.e. ρ_{op} and $\rho_{M,\alpha}$):

$$\text{if } \rho_{1,M,j} \le \rho_{op} < \rho_{1,M,(j+1)} \text{ and } F^*(\rho_{1,M}) < (1-\alpha_K),$$

then $H \Rightarrow H_1$ else $H \Rightarrow H_2$.

Modeling results and quantiles of correlation coefficients at α=0,5 presented for illustrative purposes testify to their equality and identity of the change pattern for the specified volume of sampling n_s, SFFDs $F^*(\gamma_1)$, $F^*(\gamma_2)$, $F^*(\rho_1)$ and $F^*(\rho_2)$. Distributions of correlation coefficients $\gamma_{1,M}$ and $\rho_{2,M}$ which are graphically presented in Fig.2, make it possible to conclude that the distribution of correlation coefficients both from ρ_1, and ρ_2 has a discrete nature and influence of discreteness declines with an increase in n_s.

Discreteness of distribution of $F^*(\rho_2)$ decreases owing to the consideration of identical values of sample realizations.

V. Conclusions

The developed method for formation of a list of independent techno-economic indicators makes it possible to transition from a full list of the indicators to individual ones, which is an indispensable condition for increasing the objectivity of integrated estimates of overall performance of electric power system facilities. The proposed method is based on the following.

1. A method for transformation of a numerical scale of measurement of the techno-economic indicators to a rank-order one. This method allows increasing both the number of the attributes characterizing overall performance of the objects and reliability of the decision by means of transition to nonparametric criteria for the assessment of the relationship between the indices (parameters) of the attributes to be considered;

2. The possibility of the automated assessment of critical values of linear and rank correlation coefficients by constructing the statistical distribution function of the modeled realizations;

3. A possible essential distinction of experimental values of linear and ranking correlation coefficients at their almost identical critical values.

4. A method intended to take into account the differences in changes in techno-economic indicators.

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Elmar M. Farhadzadeh (Professor, Dr. Sc.) was born in 1939 in the city of Baku of the Republic of Azerbaijan. He graduated from the Energy Department of the Azerbaijan Oil and Chemistry Institute in 1961. In 1982, he defended the doctoral thesis "Accuracy and reliability of characteristics of reliability of power plants" in Novosibirsk Electro-Technical Institute. Currently he is the head of the Laboratory for Reliability of the Equipment of Electric Power Systems at ASRDPPEI in Baku. His research interests are reliability and efficiency of electric power systems.
E-mail**:** elmeht@rambler.ru

Aydin Z. Muradaliyev (PhD) was born in 1960 in the city of Baku of the Republic of Azerbaijan. He graduated from Energy Department of the Azerbaijan Oil and Chemistry Institute in 1982 year. In 2013, he defended the doctoral thesis "Development of methods and algorithms for calculation of reliability indices of the electric power system equipment and devices". He is the head of the Department for Reliability of Equipment of Electric Power Systems at ASRDPPEI in Baku. His research interests include quantitative estimation of reliability of equipment and devices of electric power systems.
E-mail**:** aydin_murad@yahoo.com

Yusif Z. Farzaliyev (PhD) was born in 1958 in the city of Fizuli of the Republic of Azerbaijan. He graduated from the Azerbaijan State University in 1985, as an applied mathematician. In 2008, he defended the master's thesis "An increase in the accuracy and reliability of calculation of reliability indices of power units". He is the main expert of the Department for Reliability of Power Equipment at ASRDPPEI in Baku.
E-mail: yuszey2002@yahoo.com

Tamara K. Rafiyeva was born in 1950 in the city of Baku of the Republic of Azerbaijan. In 1973 she graduated from Energy Department of the Azerbaijan Oil and Chemistry Institute. In 2007 she defended the master's thesis "Simulation modeling of individual reliability of power units". She is a senior scientific researcher of the Department for Reliability of Power Equipment at ASRDPPEI in Baku.
Her research interests include quantitative estimation of a technical condition of the equipment and devices of electric power systems.

Samira A. Abdullayeva was born in 1968 year in the city of Baku of the Republic of Azerbaijan. She graduated from the Energy Department of the Azerbaijan Oil and Chemistry Institute in 1990. She is a leading engineer of the Department for Reliability of Equipment of Electric Power Systems at ASRDPPEI in Baku. She is a post-graduate student.

Influence of Technical Characteristics of Solid Fuels at Estimation of Emissions from Small Boiler Plants

Elena P. Maysyuk[1,2], Alexander N. Kozlov[1,*], and Irina Yu. Ivanova[1,2]

[1] Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences, Irkutsk, Russia
[2] Irkutsk Scientific Center Siberian Branch of Russia Academy of Science, Irkutsk, Russia

***Abstract*—The paper is concerned with the small-scale boiler plants, located in the coastal area of Lake Baikal. There are about 70 boilers of such kind (less than 1 Gcal/h) in the region. The fuel used by the boilers is wood and coal from various deposits. There is no data on harmful emissions into the atmosphere from the small-scale boiler plants in the Baikal natural territory. One of the indices that influence the amount of air pollutant emissions is technical characteristics of fuels. Normally, these characteristics are given in reference books and represent averaged data on coal grade and deposit. The experimentally determined technical characteristics of solid fuels from fuel storages of boiler plants differ greatly from the averaged reference ones. The calculations of the emission quantities, based on the reference and experimental data on technical characteristics show that the maximum single emission can differ by 1.5-2 times for various emission components (particulate matter, sulfur and nitrogen oxides). The research made it possible to draw a conclusion that the use of technical characteristics of fuels from reference sources distorts the results of the research. In order to receive reliable environmental estimates, technical characteristics of coals should be determined directly at energy facilities.**

***Index Terms*—Technical characteristics of fuel, coal, experimental determination, calculated emissions, particulate matter, sulfur and nitrogen oxides.**

[*] Corresponding author.
E-mail: kozlov@isem.irk.ru

http://dx.doi.org/10.25729/esr.2018.02.0005
Received: July 20, 2018. Revised: September 04, 2018.
Accepted: September 18, 2018. Available online: October 15, 2018.

I. INTRODUCTION

Numerous small-scale boiler plants in East Siberia and the Far East burn different types of fuel. There is no statistical information on the emissions of pollutants into the atmosphere from such energy sources. However, the emissions from the small-scale boiler plants are normally not cleaned and go directly to the surface layer of the atmosphere. A general characteristic of the boiler plants (capacity, load, equipment) can be found at best in the technical certificates of housing and utilities sectors of individual districts and municipal entities that can be accessed upon special request only. The assessment of emissions is a particularly urgent issue in the protected environmental zones of Russia, including coastal territories of Lake Baikal.

An object of the research is coastal territories of Lake Baikal, a unique site of world significance, protected by UNESCO. The law on the protection of Lake Baikal was adopted in 1999 [1]. It stipulates environmental zoning of the Baikal natural territory, and regulates economic activity. According to the law, some kinds of activity are either prohibited or limited. The limitations especially concern the central ecological zone of the Baikal natural territory, and particularly the operation and construction of coal-fired plants [2]. The heat sources operating in the central ecological zone are represented by the Baikalskaya CHP and above 91 boiler plants of various capacity, including 66 coal-fired boiler plants, 15 electric boiler plants, 9 wood-fired and 1 fuel oil - fired boiler plants. The small-scale boiler plants with a capacity of less than 1 Gcal/h dominate (57 plants). These boiler plants are normally socially important and provide heat to the facilities of social infrastructure [3]: schools, kindergartens, pharmacies, hospitals and residential areas.

It is worth noting that according to the current environmental regulations of the Russian Federation, it is generally accepted that the greatest contribution to the pollution of the surface layer of the atmosphere by small-scale boiler plants does not exceed 5% of the maximum permissible concentration. Thus, when the pollution of the air basin is calculated, their contribution is not taken into account. In the coastal zone of Lake Baikal, however, the sources of harmful emissions are small boiler plants, and therefore, it is sensible to keep track of these emissions.

Thus, the objective of the research is to assess the amount of air pollutant emissions from small boilers. We can either use the existing emission calculation techniques that are approved by the Government of the RF [4, 5], or measure the emissions independently using some certain experimental base. In both cases, the reliability of the initial data is important for the environmental calculations. The amount of emissionsinto the atmosphere is known to depend on the volume, technical characteristics of fuels, conditions of their combustion and degree of flue gas cleaning. In the paper, we assess the impact of technical characteristics of fuels on the amount of emissions, all other conditions being equal.

II. Review of emission calculation techniques

Various methodological approaches have been developed to assess the negative impact of energy companies on the environment.

These methods can be classified by area of research: environmental assessment (environmental impact assessment); risk assessment; damage assessment; identification of sustainable development indices; and combined methods.

Every energy facility undergoes the environmental impact assessment at the state level. The procedure of the environmental impact assessment is carried out by specialized entities that have a license to conduct it. In fact, the environmental impact assessment is a technique for assessing the influence of energy facilities on all components of the environment [6-8]. It includes:

- An estimation of the amount of pollutants emitted into the atmosphere, contaminated discharges into water bodies, production of waste, noise, electromagnetic impact, etc.;
- An analysis of the environmental measures developed for an individual power facility;
- An assessment of monitoring system for environmental safety;
- An identification of zones of the influence on the environment components, flora, fauna and humans;
- An evaluation of possible consequences of an emergency under the energy facility operation;
- A calculation of economic viability of the nature protection measures.

This method involves the collection of a large number of various technical and economic parameters, and huge statistical information. Moreover, the environmental impact assessment is a complex and time-consuming process. As a rule, the procedure of environmental impact assessment is carried out for newly introduced facilities.

The risk assessment methods [9, 10] entail determining the expected frequency of undesirable effects (on population, living organisms, vegetation, etc.) arising from the concrete negative impact of pollutants.

The environmental risk has recently become one of the management factors in the energy sector, which is applied to calculate the ratings of attractiveness. The calculation of environmental risks of energy facilities is related to the consideration of environmental pollution and damage to the environment components, including living organisms.

The world standards produced by ISO are used as criteria for assessing the environmental risks.

The environmental risk assessment provides the quantitative values of factors that affect the state of the environment and its response. In fact, the probability of an event is calculated given the value of possible damage from this event.

One of the positive aspects of the risk assessment methods is the advance consideration of possible damage and its prevention. The disadvantages of the methods include the absence of a unified formula for the calculation of environmental risk.

The damage assessment methods [11, 12] are related to the assessment of harm to the components of the environment, expressed in both monetary and physical terms. The methods of assessing the environmental damage are mainly based on probabilistic approaches and often on the expert assessments, direct and indirect calculations, and also on the market mechanism methods.

Damage is assessed for those components of the environment that are directly affected by the negative impact. Under these conditions, it is difficult to take into account the entire chain of possible consequences.

The existing methods for assessing environmental damage are based on a normative method which is described by complex mathematical relationships and requires a large number of initial data.

Currently, there is no monetary valuation of ecosystems affected by negative impacts. The existing methods for calculating environmental and economic damage are based on outdated price indicators, and their consideration through inflation factors does not correctly reflect the value of both a component of the environment and ecosystem as a whole. As a consequence, there is no universal formula for calculating the economically justified value of damage.

The methods for determining the sustainable development indicators are widely used [13-14]. One of the latest investigations in this area is based on the method of ecological and economic sustainable development indicators of the Russian regions [15]. This method entails a theoretical framework for the development of sustainability indicators and their aggregation. This method calculates the depletion of natural capital (energy resources, balance of forest resources) and damage from the pollution (emissions of CO_2 and particulate matter). All values are calculated as a percentage of gross national income.

The advantage of this method is the ability to apply it both at the regional and inter-country levels.

The methods for the development of the sustainable development indicators have as a rule aggregated indexes, which in turn is a disadvantage because important features of the territories and sources of emissions located on them, including energy facilities, are not taken into account. These methods can serve as some benchmark for making management decisions.

The combination of different methods for assessing the impact of energy facilities on the environment makes it possible to use different mathematical tools and apply the available information for calculations, and also to take into account the regional features to the greatest extent.

An ecological and economic assessment of the energy development options in the region is important when developing regional energy programs. The assessment makes it possible to search for a correspondence between the anthropogenic load and the ability of the environment to bear it without irreversible negative consequences [16].

The main methods for assessing the impact of energy facilities on the environment include the methods for calculating pollutant emissions into the atmosphere by power plants and boilers with different capacities, that are officially approved in Russia [17-18]. This research is based on these particular methods for environmental assessment of technical characteristics of fuels.

Each of the presented methods has its advantages and disadvantages and can be applied depending on the objectives to be achieved.

III. FORMULATION OF THE PROBLEM OF TECHNICAL CHARACTERISTIC OF SOLID FUEL

A technique for the calculation of an amount of emissions of different substances (fly ash, oxides of nitrogen (NOx) and sulfur (SO_2), carbon monoxide), that are formed as a result of fuel combustion, suggests the use of data on technical characteristics of the fuel burnt. The technical characteristics of solid fuel include the following indices: moisture content, ash content, volatile yield, ultimate composition, heating value, and sizes of lumps. Normally, technical characteristics of solid fuels are given in special information and reference editions that contain averaged values and limits for variations in the indices for grade and deposit. The reference values of technical characteristics are available for many fuels. At the same time, the natural variability of coal properties within an individual deposit, and development of new deposits make the list of reference values suitable only for rough engineering calculations [19]. The reference books, as a rule, do not have the data on technical characteristics of low-grade coal from small open pit mines, for example Tarasovsky lignite coal, Tugnuisky lignite coal and Kharanutsky lignite coal, that are used locally.

Currently, the determination of technical characteristics of fuel is regulated by a great number of standards: State standards of Russia and National standardization organizations, for example ISO, ASTM.

Different methods are used to determine technical characteristics of coal. For example:

- volatile matter is determined according to State Standard 6382-2001 “Mineral solid fuel” (ASTM D3175-17 Standard Test Method for Volatile Matter in the Analysis Sample of Coal and Coke) [20];
- fuel moisture content is determined by mass loss due to sample drying in a drying chamber at a temperature of 105°C according to State Standard R 52911-2013 “Mineral solid fuel, methods of total moisture content determination” (ASTM D3173 / D3173M - 17a Standard Test Method for Moisture in the Analysis Sample of Coal and Coke) [21];
- fuel ash content is found by mineral residue after a complete combustion of a sample in the muffle furnace according to State Standard 55661-2013 “Mineral solid fuel. Determination of ash content” (ASTM D3174-04 Standard Test Method for Ash in the Analysis Sample of Coal and Coke from Coal). [22];
- the lowest heating value of fuel is determined by the classical method of burning a sample in oxygen in bomb calorimeter according to State Standard 147-2013. “Mineral solid fuel” (ASTM D5865-13 Standard Test Method for Gross Calorific Value of Coal and Coke) [23].

Thus, in order to determine technical characteristics of fuels, laboratory needs to be equipped with a great amount of equipment. Therefore, a common practice in Russia is the determination of fuel characteristics on site of production or in laboratories of energy companies. In doing so, however, we obtain characteristics of the entire coal basin or large batches ready for delivery to a consumption site.

In the territory at issue, the consumers use the coals from six various deposits: Pereyaslovsky, Azeisky, Tarasovsky, Tugnuisky, Kharanutsky (lignite coals) and Cheremkhovsky (hard coal). The indicated coals except for the Pereyaslovsky coal belong to the local coals produced in the Irkutsk region and Republic of Buryatia. Fuel oil and Pereyaslovsky coal are used in larger boiler plants with a capacity from 6 Gcal/h, and are not considered in this research.

Table I presents the comparison of various reference data on qualitative composition of fuels burnt in small boiler plants of coastal zone of Lake Baikal (using the coefficients for conversion from one state to another [24]) [25-32].

Comparison of the same fuel characteristics from different reference sources shows that for some indices the difference is insignificant, for example, the moisture content of the Azeisky lignite. At the same time, the other indices of this coal differ greatly, for example, ash content varies from 16.5 to 28 %.

Table 1. Technical characteristics of fuel burnt in coastal zone of Lake Baikal.

Fuel	W^r,%	A^d,%	C^{daf},%	S^{daf},%	N^{daf},%	Q^{daf}, MJ/kg	Source
Hard coal							
Tugnuisky coal	11-15	19-27	n/d	0.2-0.5	n/d	29-35.7	[25]
Kharanutsky coal	7-8	11-13	77.0	0.8	n/d	27.7-28.3	[26]
Tarasovsky coal	12-14	16-19	n/d	0.7	n/d	24.7-26.8	[25]
Cheremkhovsky coal	14-16	29-35	n/d	2.2-3.7	n/d	28.8-34.0	[27]
	15.0	29.8	77.0	1.6	1.1	32.4	[28]
	12.0	15.0	77.0	1.6	n/d	n/d	[29]
	13.0	27.0	77.0	n/d	1.6	31.7	[30]
	15.0	34.0	77.0	1.6	n/d	29.9	[31]
	12.0	25.0	n/d	1.0	n/d	30.1	[32]
Lignite							
Azeisky coal	26-30	24-28	n/d	0.5-0.8	n/d	27.9-28.1	[25]
	25.0	17.0	81.0	0.7	1.6	30.4	[32]
	25.0	16.5	73.0	1.6	1.1	30.4	[30]
Biomass							
Fuel wood (pine, birch)	40.0	1.0	51.0	0	0.7	17.21	[25]

Note: W – moisture content, A – ash content, Q – heating value of fuel, r – as received, d – dry, daf – dry ash free fuel mass; n/d – no data.

The observed disagreement between the reference data is explained by a number of circumstances. Firstly, variability of coal properties within one deposit, which is confirmed by a great number of studies conducted by different companies. This fact can be seen on the example of Cheremkhovsky hard coal. Secondly, the reference values were obtained for the coal produced more than 15 years ago and consequently were published in the 15-year old literature at minimum [30-31].

IV. A METHODOLOGY FOR EXPERIMENTAL DETERMINATION OF TECHNICAL CHARACTERISTICS OF SOLID FUEL

Experimentally, the technical characteristics of solid fuels were determined using a simultaneous thermal analyzer manufactured by the firm NETZSCH Geratebau. The analyzer includes the block for thermal analysis STA 449 F1, the quadrupole mass spectrometer QMS 403 Aeolos, and the block of pulse thermal analysis PulseTA.

The application of the simultaneous thermal analyzer proved suitable since it simultaneously determines different parameters for one sample, which provides high reliability of measurements. Moreover, the thermal analyzer gets increasingly wider application in the energy studies [33].

The technique for the determination of technical characteristics of solid fuel suggests preparing a representative sample by the standard method of quartering. The representative sample of fuel with a mass of 20-30 mg is burnt in the air flow. The resulting combustion products are recorded by the quadrupole mass spectrometer.

The choice of sample mass is caused by both the bulk density of fuel and the possibility of its complete combustion in specified conditions. The complete combustion is provided by a sufficient quantity of oxidizer passing through the furnace. The oxidizer quantity is calculated based on theoretically possible amount of air necessary for complete combustion of the fuel sample according to [34].

V. RESULTS OF THE EXPERIMENTS

Special experiments were performed in this research to compare and analyze the data on technical characteristics of the fuels.

Figure 1 presents a standard thermo-analytical curve and mass peak intensity curves of gas phase macrocomponents produced during the Azeisky lignite combustion.

An analysis of Figure 1 shows that in a temperature range from the room temperature to 150°C, the surface water is produced. In a temperature range of 280 – 660°C the process of coal sample combustion occurs and the ultimate oxides (H_2O, CO_2, SO_2, NO_2) are produced. The ash content is determined by the coal sample combustion residue.

Using the technique for a quantitative analysis of thermo-analytical and mass-spectrometric data [35], we determined the experimental values of technical characteristics of the investigated coals.

An error of the component determination makes up ±3% for C, ±0.3% for H, ±1% for O, ±0.05% for S, and ±0.02% for N. The experimentally determined characteristics of fuels burnt in the boiler plants of central ecological zone are presented in Table II.

Comparison of the data from Tables 1 and 2 indicates that the reference values and the experimentally determined values have discrepancies. These discrepancies are explained by a number of circumstances. Firstly, the properties of coals vary within the field. Secondly, the

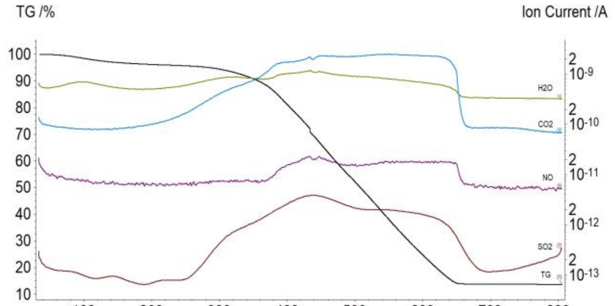

Figure 1. Thermo-analytical curve (% mass) and curves of intensity of peaks of burning masses of Azeisky coal.

Table 2. Technical characteristics of solid fuels determined by experiment.

Solid fuel	W^r,%	A^d,%	C^{daf},%	H^{daf},%	O^{daf},%	S^{daf},%	N^{daf},%	Q^{daf}, MJ/kg
Cheremkhovsky hard coal	3.3	16.8	70.2	4.5	23.2	1.0	1.3	26.9
Azeisky lignite	12.2	7.6	77.6	4.5	17.0	0.1	0.7	30.2
Kharanutsky hard coal	2.7	26.5	75.0	8.3	14.7	1.1	1.0	34.3
Tarasovsky hard coal	12.8	10.3	66.9	4.4	27.9	0.4	0.4	24.2
Fuel wood (pine)	47	1.3	53.9	5.8	40.3	0	0.4	19.9
Fuel wood (birch)	23	0.3	44.8	4.5	50.1	0	0.5	14.4

technical characteristics of coal change when it is stored and transported to the place of consumption. This is especially true if the fuel transportation is long and during this period coal undergoes several freeze-thaw cycles. The authors of [36] indicate that if the fuel quality control is not performed appropriately, the total losses in the energy value of fuel can be up to 20-30%. Thirdly, the coal samples studied in this research were taken not in the place of its extraction, but in the fuel storage of the boiler plants of the required level of power.

However, the difference in W^r cannot characterize the quality of measurement, since the experiments involved dried coal. Moreover, ordinary coals at deposits are known to have rather high moisture content reaching 40%.

We can also state that the reference value of ash content Ad is apparently overstated. It is probably assumed according to the upper value of a range of possible values [32], which is proved in [37] where the value of ash content is lower and close to an experimentally determined value. Thus, based on an analysis of the obtained results we can conclude that the reference value should be considered to be less accurate. In the case of biomass, the difference between the experimentally determined technical characteristics and reference values is explained by different structure and ultimate composition of pine and birch.

VI. Discussion and calculation of the pollutants

In the coastal areas of Lake Baikal most of the small boiler plants have hand-fired furnaces. Therefore, the calculations of emissions from combustion of various fuels in small boiler plants assume the hand-fed hot water boiler KVr-0.5. The main technical characteristics of such boilers can be found on websites of different companies [38].

The emissions of harmful substances into the atmosphere are calculated according to the technique approved by the State Committee of the Russian Federation for the Protection of Environment in 1999.

Table 3. Technical Characteristics of the boiler KVR-0.5, depending on the fuel type.

Index	Fuel type		
	Hard coal	**Brown coal**	**Fuel wood**
Carbon loss (q_4),%	6	7	1
Fly ash share (a_{fa})	0.22	0.19	0.25

The technique is intended for the determination of air pollutant emissions from fuel combustion in boilers with a capacity below 30 t of steam per hour or less than 20 Gcal/h [4, 5]. The calculation was done for four main components: particulate matter (M_S), SO_2 (M_{SO_2}), NOx (M_{NOx}), and CO (M_{CO}). The initial data on qualitative characteristics of fuels were reference data (Table 1) and experimentally obtained data (Table 2). Thereby, the reference data for Tugnuisky hard coal, Azeisky lignite and Cheremkhovsky hard coal are the data taken from the information and reference edition published by Rosinformugol in 2006 [25] that were assumed for raw steaming coal on average for a deposit.

Consumption of coal equivalent is assumed according to the technical data for boiler KVr-0.5 and equals 88 kg c.e./h [37]. Incomplete combustion (q_3) is assumed to equal 2% for all considered types of fuel. Data on carbon loss and ash content in the flue gas are presented in Table III [4, 25], there is no flue gas cleaning.

The calculated fuel characteristics by reference and experimentally determined values are presented in Table IV. The calculation is characterized as a maximum emission at a rated load of the boiler.

The qualitative characteristics of Tugnuisky hard coal were not measured. This is why this coal is not considered in the comparison of calculation results.

The comparison of the obtained results shows that the emission values calculated by the fuel characteristics taken from the reference literature in most cases exceed the calculation results based on experimentally determined characteristics by 1.5-2 times for different emission components (Table V).

In the case of Azeisky lignite and Cheremkhovsky hard coal, the overall difference for all pollutants makes up more than 2 g/s (or by 1.5-1.6 times). The close results are obtained for the emissions from biomass combustion. Moreover, the calculation results do not virtually differ for the quantities of nitrogen oxides and carbon oxide for all considered fuel types, whereas the divergence in the amount of particulate matter and sulfur dioxide is great. Nevertheless, the obtained results made it possible to compare the environmental indices of the fuel.

The highest emissions of SO_2 are observed at combustion of Cheremkhovsky hard coal - 1.35 g/s, and the lowest – at combustion of Tugnuisky hard coal - 0.18 g/s. The emissions of nitrogen oxides for all the studied fuels lie in a range of 0.55 – 0.63 g/s.

As for the amount of carbon monoxide emissions, they

Table 4. Calculated emission for reference and experimentally determined technical characteristics of fuel, g/s.

Fuel	Emission by component				Total
	Ms	Mso_2	M_{NOx}	Mco	
Reference technical characteristics					
Azeisky lignite coal	4.07	0.40	0.57	1.33	6.38
Cheremkhovsky hard coal	3.64	1.35	0.59	1.35	6.94
Tugnuisky hard coal	2.80	0.18	0.62	1.36	4.94
Tarasovsky hard coal	2.23	0.29	0.62	1.35	4.49
Kharanutsky hard coal	2.02	0.33	0.63	1.35	4.33
Fuel wood (pine, birch)	0.32	0	0.55	1.42	2.29
Experimentally determined technical characteristics					
Azeisky lignite coal	1.97	0.04	0.63	1.33	3.97
Cheremhovsky hard coal	2.33	0.48	0.62	1.35	4.78
Tarasovsky hard coal	1.96	0.21	0.60	1.35	4.12
Kharanutsky hard coal	2.75	0.42	0.64	1.35	5.15
Fuel wood (pine)	0.34	0	0.55	1.42	2.31
Fuel wood (birch)	0.26	0	0.56	1.42	2.23

Table 5. Comparison of calculation results of emission for reference and experimentally determined fuel characteristics (difference).

Fuel	Components of emissions				Total
	Ms	Mso_2	M_{NOx}	Mco	
Difference (between the calculations based on reference data and calculations based on measured data)					
Azeisky lignite	2.10	0.36	-0.06	0	2.41
Cheremkhovsky hard coal	1.31	0.87	-0.03	-0.02	2.16
Tarasovsky hard coal	0.27	0.08	0.02	0	0.37
Kharanutsky hard coal	-0.73	-0.09	-0.01	0	-0.82
Fuel wood (pine, birch)	-0.02	-	0	0	-0.02
Multiplicity factor (between the calculations based on reference data and calculations based on measured data)					
Azeisky lignite	2.1	10.0	0.9	1.0	1.6
Cheremkhovsky hard coal	1.6	2.8	0.95	1.0	1.5
Tarasovsky hard coal	1.1	1.4	1.03	1.0	1.1
Kharanutsky hard coal	0.7	0.8	0.98	1.0	0.8
Fuel wood (pine)	0.9	-	1.0	1.0	0.99

appeared to be almost the same for the considered coals (1.33 – 1.36 g/s), and the emission from fuel wood combustion is a bit higher – about 1.42 g/s.

The emissions of particulate matter (fly ash) depend largely on ash content in the fuel. Therefore, they were the highest for the most high-ash (Cheremkhovsky and Kharanutsky) hard coals.

VII. Conclusion

The data on technical characteristics of solid fuels, particularly coal, from reference books considerably distort the findings of the research, i.e. the amount of pollutant emissions coming to the atmosphere from small boiler plants burning them. The final result for the maximum single emission for one and the same type of coal can differ by 1.5-2 times for various emission components (particulate matter, sulfur and nitrogen oxides).

In order to calculate more accurately the amount of emissions, we recommend the use of characteristics experimentally determined directly at energy facilities rather than reference data.

Large-scale energy companies determine technical characteristics of coal on a mandatory basis. However, small boiler plants do not make such measurements. Moreover, the quality of coals gets considerably worse at storage, which increases carbon loss and unburnt fuel as well as the share of fly ash. Consequently, the amount of emissions into the atmosphere rises. Therefore, it is especially important to measure moisture, ash and sulfur content of the fuel, because the calculated values of particulate matter and sulfur oxides emissions diverge greatly depending on the initial characteristics of solid fuels.

Thus, the conducted studies allow us to draw the following conclusion. The emissions of pollutants from combustion of Azeisky lignite are lower by 1.6-2.2 times compared to the other considered types of coal. Table VI demonstrates the specific emission into the atmosphere per ton of burnt fuel for the considered types of coal and fuel wood. Specific emission is calculated as a sum of three main components: particulate matter, sulfur and nitrogen oxides when burning 1 ton of fuel.

However, as the calculations show, from an environmental perspective, fuel wood can become the best alternative to coals, as the specific emission from fuel wood combustion is much lower.

Table 6. Specific emission into the atmosphere from combustion of 1 ton of fuel (or 1 m^3 of firewood), T of emission/t of fuel.

Coal			**Fuel wood**
Azeisky lignite coal	**Cheremkhovsky hard coal**	**Tugnuisky hard coal**	
0,11	0,24	0,18	0,005

Acknowledgments

The study was carried out under the Integration Program of ISC SB RAS, No. AAAA-A17-17041250054-8, in the framework of the scientific project III.17.1.2 of the Program for Fundamental Research of SB RAS, No. AAAA-A17-117030310448-0 with the equipment of the "High-temperature circuit" (ESI SB RAS).

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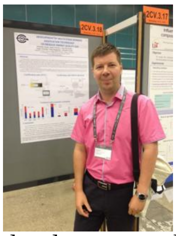
Elena P. Maysuyk PhD in economics (2002), Senior Researcher of the Laboratory for Energy Supply to Off-grid Consumers, Melentiev Energy Systems Institute SB RAS, Irkutsk. Education: Energy Department of Irkutsk Polytechnic Institute with specialization on Heat power plants (1989). The research interests are: environmental issues of energy systems development in Eastern Siberia and the Far East.



Alexander N. Kozlov, PhD, Senior Researcher at Melentiev Energy Systems Institute SB RAS, Irkutsk, Russia, and researcher at Kutateladze Institute of Thermophysics, SB RAS, Novosibirsk, Russia. Currently, A.N. Kozlov is Head of the Experimental Group engaged in the development, design and construction of plants for thermochemical conversion of solid fuels. The research interests are heterogeneous solid fuel (biomass, coal) combustion, and design of simple engineering techniques for calculation of gasification process. (e-mail: kozlov@isem.irk.ru)

Irina Yu. Ivanova PhD in economics, Head of the Laboratory of Energy Supply to Off-grid Consumers, Melentiev Energy Systems Institute (ESI) SB RAS, Irkutsk. The winner of the regional competition in the field of science and technology. Education: Department of Cybernetics at Irkutsk Polytechnic Institute with two specializations: in Computer-aided Management and Large Energy Systems (1981). The research interests are: small-scale energy, the policy of energy supply to consumers in the northern and remote areas, modeling of financial and economic activities of autonomous energy sources. (e-mail: nord@isem.irk.ru)

Forecasted Trends of Green Energy Development in Vietnam

Pham Trung Son*

Electrification Department, Faculty of Electromechanics, Hanoi University of Mining and Geology, Hanoi, Vietnam.

Abstract **- The paper focuses on the assessment of the current situation in production and consumption of different kinds of energy in Vietnam, including the potential of green energy sources, and the current situation in the development of green energy sources in Vietnam. Based on the above-mentioned assessment, the paper proposes targets for the development of green energy to ensure energy security and environmental protection. To ensure the feasibility of developing green energy, the paper presents the detailed assessment of green energy policies and mechanisms, which determine the future direction for green energy development in Vietnam.**

Index Terms **- environment; energy security; green energy sources; green energy policy; Vietnam.**

I. Introduction

Energy security today and in the next two decades is a concern and a real problem of many nations. Vietnam is a developing country, so energy supply and demand are very urgent issues. Many rich countries are also suffering from the problem of providing the economy with different kinds of energy to meet sustainable development goals in the context of rising energy prices.

According to the US Energy Information Administration (EIA) forecast, world energy demand could probably increase by 48% to 2040 [1-6, etc.]. However, fossil fuel energy is limited, are enough to satisfy the current energy consumption rate for 51 years. Today 84% of energy comes from fossil fuels [7]. Coal still provides about 40% of the world's electricity [8].

* Corresponding author.
E-mail: phamtrungson_istu_ru@mail.ru

http://dx.doi.org/10.25729/esr.2018.02.0006
Received: July 25, 2018. Revised: August 13, 2018. Accepted: August 22, 2018. Available online: October 15, 2018.

As stated by experts, Vietnam has a diversified source of fuel energy (coal, gas), but this source is not abundant. The National Assembly of Vietnam has voted to stop the project of building nuclear power plants in Ninh Thuan province, but this leads to a severe energy shortage in the future. In the context of the 4.0 technology revolution, energy plays an increasingly important role in the economic development, in the industrialization and modernization of the country. Without serious and effective decisions, energy security in Vietnam will not be guaranteed. Parallel to the urgent need to ensure energy security is a matter of ensuring safety for the environment. It has been estimated that greenhouse gas emissions have increased tenfold in the past 100 years [9]. Therefore, average surface temperatures could rise between 2°C and 6°C by the end of the 21st century [2,10,11].

Global warming leads to a significant global climate change, which has serious consequences for human life and the environment. The consequences of global warming are closely related to the energy production and consumption [12,13]. Vietnam is a country with a long coastline and should be one of the many countries most affected by climate change. Considering this situation, the paper assesses the potential of green energy sources and the current situation in the development of green energy sources in Vietnam, proposes targets for energy development to ensure energy security and environmental protection towards accomplishing the goals of sustainable development and response to climate change. The detailed assessment of green energy policies that will determine the future direction for green energy in Vietnam will be important and of great practical value.

The contents of this paper are as follows. Chapter II includes an overview of energy supply and demand in Vietnam. The need to develop clean, renewable energy is discussed in Chapter III. Chapter IV presents the development potential of the renewable energy industry in Vietnam. Chapter V explains the proposed goals for green energy development to ensure the national energy security and environmental protection. Chapter VI discusses acceptable policies and decisions for renewable energy development in Vietnam. The conclusions of this paper are presented in Chapter VII.

II. OVERVIEW OF ENERGY SUPPLY AND DEMAND IN VIETNAM

Vietnam is a country with a developing economy. The country has reached the level of middle income. Such positive factors as the strength of the country, the desire for development, a golden population ratio, smart and creation people, the constructive and actionable government, indicate that Vietnam will continue to grow rapidly in the next decade. As the analysis shows, energy demand and supply in the world in general and energy demand and supply in Vietnam are pressing issues. The results of this research will clarify the problem of energy supply and demand in Vietnam in recent years:

Primary energy supply, converted to kilotons of oil equivalent (ktoe), in the period of 2000-2015 is demonstrated in Fig.1 [3].

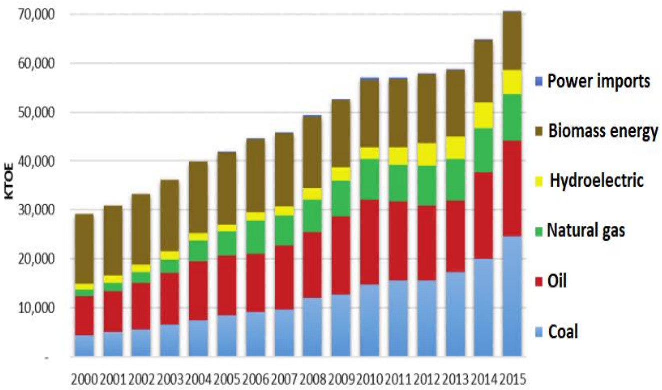


Figure 1. Primary energy supply in the period of 2000 - 2015.

A per year increase is 13.4% for gas; 12.2% for coal; and 6.2% for oil.

Energy consumption trend is presented in Fig. 2 [3].

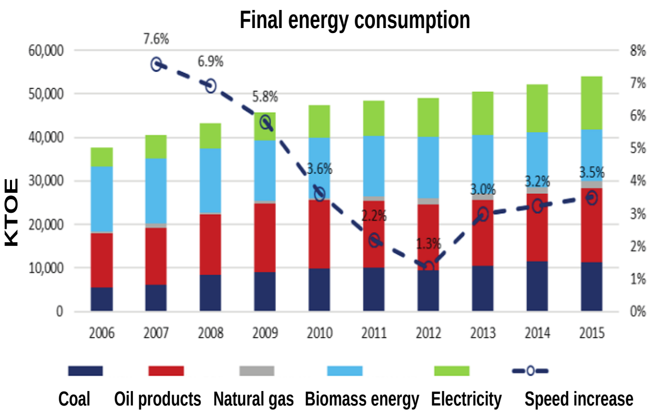


Figure 2. Energy consumption in the period of 2006-2015.

The chart shows that the types of fossil fuel energy used are increasing so rapidly that they meet the energy needs of the present. However, this leads to a completely negative environmental situation in the country.

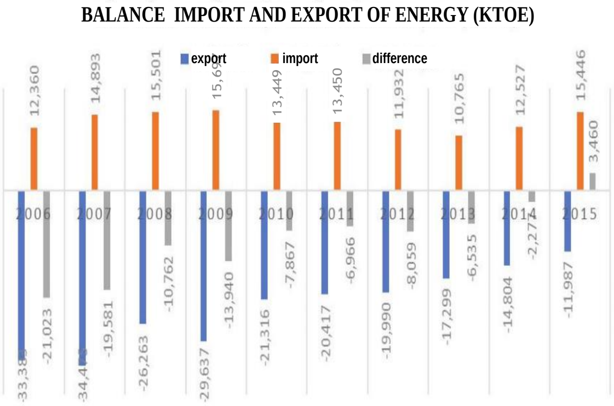


Figure 3. Energy import and export in the period of 2006-2015.

To ensure energy security, balance power sources between regions, provide power supply continuity, stability, and power quality, Vietnam had to import and export energy, which is illustrated for the period of 2006-2015 in Fig. 3 [3].

Previously, Vietnam was an energy exporter, but now the country imports energy from neighboring countries to ensure sufficient energy for consumption.

The comparison of different kinds of energy consumption in 2006 and 2015 by different sectors (million toe) is summarized in Fig. 4 [3].

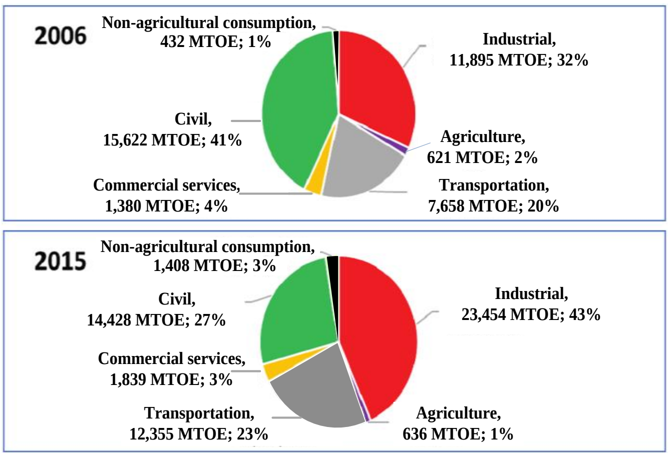


Figure 4. Energy consumption structure in the period of 2006-2015.

The structure of energy use has shifted sharply, from a backward agricultural country with the main source of energy used for living, to a developed industrialized country with a high rate of energy use.

The changes are particularly great in the installed capacity portfolio at the end of 2016, as is shown in Fig. 5 [4].

Power source	Capacity MW	%
Hydropower	15,857	37.6
Coal fired power	14,448	34.3
Oil fired power	1,370	3.3
Gas fired power	7,502	17.8
Diesel, Small Hydropower and Renewables	2,418	5.8
Import	540	1.2
Total	42,135	100

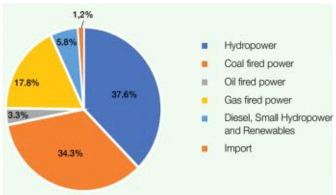


Figure 5. Installed capacity portfolio by the end of 2016.

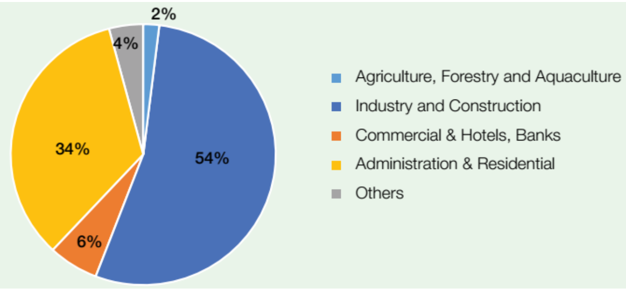


Figure 6. Power consumption in different sectors by the end of 2016.

Year	2011	2012	2013	2014	2015	2016
Power sales growth (%)	10.49	11.43	9.30	11.58	11.70	11.21

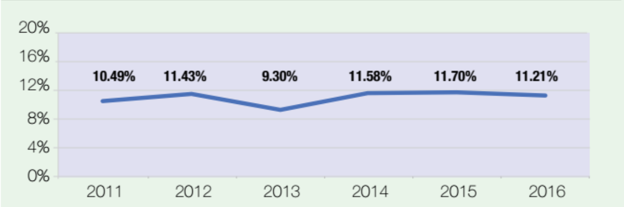


Figure 7. An annual growth rate of electricity consumption.

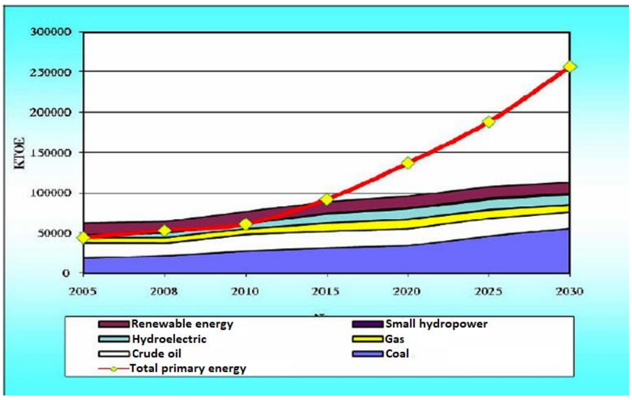


Figure 8. Overall demand and availability of primary energy in the long term.

Power consumption in different sectors by the end of 2016 [4] is shown in Fig. 6.

An annual growth rate of electricity consumption [4] is demonstrated in Fig. 7.

Nowadays, the situation of energy supply and demand is as follows. According to the expert estimations, Vietnam is a country with diversified, but not plentiful energy sources. The economic and technical potential of Vietnam's hydroelectricity is forecasted to produce 65÷70 billion kWh annually [5].

Under the mining plan of the coal industry, coal output will only be sufficient to supply about 12,000 MW, which means that no more than 72 billion kWh per year can only be produced, even by the years 2025-2030 [5].

In the light of the forecast of the offshore gas resources, they are only enough for the development of gas power plants to produce over 100 billion kWh per year and about 3-5% of the gas needed to supply the other industrial facilities [5].

The potential for crude oil production will soon reach the

Table 1. Overall demand and availability of primary energy in the long term

Energy Type	2010		2015		2020	
	Natural unit	KTOE	Natural unit	KTOE	Natural unit	KTOE
Primary energy demand		**61123**		**91675**		**148786**
Ability to locally supply		**76889**		**89402**		**96172**
Inside:						
Coal	49.8 m. tons	27888	60 m. tons	31680	70 m. tons	34562
Crude oil	19.86 m. tons	20217	20 m. tons	20360	20.7 m. tons	21073
Gas	7.98 b. tons	7183	11.43 b. tons	10288	12.68 b. tons	11413
Hydroelectric	30.13TWh	6478	54.4TWh	11695	60.4TWh	12994
Small hydropower	1.99TWh	428	4.2TWh	905	6.46TWh	1391
Renewable energy	44.5 m. tons	14695	43.8 m. tons	14474	44.6 m. tons	14740
Redundency(+); Shortage (-)		**+15766**		**-2273**		**-52614**

ceiling level (around 17 ÷ 18 million tons per year) and gradually decline in the period after 2015. Based on the assessment of the increase in energy demand and the ability to exploit domestic energy resources, experts have estimated the balance of overall demand and the ability to meet the demand for primary energy types in the long term, as is shown in Table 1 and Fig. 8 [5].

Indeed, Vietnam is facing challenges such as rising energy demand, while environmental bindings are becoming increasingly tighter and heavier. On the one hand, this situation puts pressure on ensuring the national energy security, and on the other hand, creates the problems for the economy to mobilize sufficient investment capital for the energy sector. To ensure energy security, Vietnam is transforming from an energy exporter to an energy importer.

To solve the energy problem for the country's economic development, the Ministry of Industry and Trade (MOIT) suggested a policy mechanism with two approaches, one is using energy efficiently and cost-effectively, and the other is using environmentally friendly technologies to produce energy.

Vietnam is shifting from an inefficient use of fossil fuels to the use of clean, renewable energy sources, by changing production patterns and promoting sustainable energy consumption, aiming to achieve a low-carbon economy.

III. THE NEED TO DEVELOP CLEAN, RENEWABLE ENERGY

The following arguments will indicate the need to develop renewable energy in Vietnam [6, 14, 15]:

- Contribution to energy security: the investment in energy efficiency and saving, consumption, and production with cleaner technologies; the development of renewable energy sources will contribute significantly to ensuring the national energy security.
- Contribution to sustainable economic growth: renewable energy can make a significant contribution to the sustainable economic growth, especially at the national level.
- Contribution to environmental sustainability.
- Contribution to health care for the people.
- Contribution to the energy supply to rural, mountainous and island areas; remote areas, areas with special difficulties.
- Contribution to the efficient development of the energy sector: at present, the investment costs for some renewable energy technologies are declining rapidly, especially in the electricity sector.

- Maximization of the value of resources in the country and each locality.

IV. THE DEVELOPMENT POTENTIAL OF THE RENEWABLE ENERGY INDUSTRY IN VIETNAM

The Ministry of Industry and Trade of Vietnam has approved the master development plan for wind power in some localities. According to this plan, by 2030: Ca Mau can develop 3,607 MW; Binh Thuan - 2,500 MW; Ninh Thuan - 1,409 MW; Tra Vinh - 1,608 MW; and Soc Trang - 1,470 MW [6].

The prospects for solar energy are as follows. For the countries with the tropical climate like Vietnam, solar energy is used almost all year round. According to the survey on the amount of solar radiation in the country:

- Northern provinces (from Thua Thien Hue province to the North) have an average of 1800 to 2100 sunshine hours per year. In particular, the sunny areas are in the Northwest (Lai Chau, Son La, Lao Cai) and the North Central Region (Thanh Hoa, Nghe An, Ha Tinh).

- The provinces in the South (from Da Nang to the South), have about 2000÷2600 sunshine hours. The amount of solar radiation is estimated at about 20% higher than in the northern provinces. In this area, the sun shines almost all year round, even in the rainy season. Therefore, for the South-Central and Southern provinces, solar radiation is a great resource for exploitation and use.

- An average annual solar energy intensity in Vietnam is 4.6 kWh/ m2 / per day in the whole country (in comparison with the average level of the whole world). The northern area has an average radiation intensity of 3.69 kWh / m2 / per day and an average radiation intensity in the southern area is 5.9 kWh / m2 / per day.

In recent years, many localities, companies, and businesses have studied and promoted the development of solar power projects: Electricity of Vietnam (EVN) and its member units are planning and preparing 3 projects with a total capacity of about 3,100 MW, mainly on the surface of the lake. More than 20 investors have registered to invest in solar power projects in Binh Dinh province.

Biomass energy has the following prospects. Biomass energy is the form of energy derived from organic substances, such as wood, agricultural products, organic waste, urban solid waste, algae, and other plants. The potential biomass resources are:

- Firewood is fuels derived from wood, extracted from forests, perennial industrial plants, fruit trees and scattered trees, wood waste from wood processing factories. The total amount of firewood in Vietnam is about 32 million tons equivalent to 11.6 million TOE.

- Agricultural waste includes post-harvest agricultural waste such as rice straw, tops and leaves, branches and stalks, cassava stalks, etc., agricultural and industrial waste, rice husk, peanut husk, peanut pulp, etc. The total amount of agricultural waste in Vietnam is about 80 million tons equivalent to 17.6 million TOE.

- Livestock waste (cattle dung) can be used to produce biogas. The amount of biogas that can be recovered from livestock is about 11.3 billion m3 / year.

- Waste, including organic waste, waste from urban and rural life; waste from production facilities, businesses, agencies can be used for energy purposes, etc. The capacity to recover energy from organic waste is about 0.82 million TOE.

- Organic waste sources (molasses, used cooking oils and fatty acids) can be used as the main raw material for biofuel production. The capacity to recover energy from these organic substances is currently about 0.8 million TOE.

- Totally, the potential of biomass energy in Vietnam is about 60 million TOE.

The other forms of renewable energy in Vietnam are the following.

- Hydropower: According to the hydropower ladder planning on major rivers and small and medium hydropower planning in localities approved by some competent authorities, Vietnam could develop 1279 hydropower projects with a total capacity of 26,500 MW. There are 1164 small hydropower projects (capacity ≤ 30MW) with the total installed capacity of 7745 MW. There are 72 medium hydropower projects (with a capacity of over 30 MW to 100 MW) and 43 rather large hydropower projects (with a capacity of more than 100 MW) with the total installed capacity of 14,583 MW. There is also the potential to develop more than 200 projects, mainly small hydropower ones, with a total capacity of over 400 MW. When fully exploited, Vietnam's hydropower plants can annually produce about 95-100 billion kWh including about 35÷40 billion kWh to be produced by small and medium hydropower plants.

- Geothermal: According to the preliminary estimation, the total capacity of geothermal plants in Vietnam, could reach over 400 MW. Areas with great geothermal potential are North West and North East of North, and especially Central Vietnam such as Le Thuy (Quang Binh), Mo Duc, Nghia Thang (Quang Ngai), Hoi Van (Binh Dinh), Tu-pho, Danh Thanh (Khanh Hoa) provinces, and the others. These sites are highly feasible for the projects on construction of geothermal plants.

- Ocean energy: Tidal power energy of Vietnam is estimated to be 1.5 billion kWh per year and is concentrated in Quang Ninh Coast (about 1.3 billion kWh per year). Additional 0.2 billion kWh / per year can be exploited with a small capacity in the lower river of Mekong.

V. PROPOSED GOALS FOR GREEN ENERGY DEVELOPMENT TO ENSURE ENERGY SECURITY AND ENVIRONMENTAL PROTECTION

The strategic objectives are the following:

- To increase step by step the rate of access to clean energy and electricity for people in rural, mountainous, remote, border and island areas.

- To strive to provide most households with electricity and modern, sustainable and reliable energy services at reasonable prices.

- To develop and to use green, renewable energy sources to meet the sustainable environmental objectives and to develop a green economy:
- To reduce greenhouse gas emissions from energy activities to compare with a normal development plan.
- To reduce imported fuel for energy purposes.
- To increase the total amount of renewable energy.
- To increase the amount of electricity produced from renewable energy.
- To increase the absorption area of the solar water heater.
- To increase households with solar-powered appliances (hot water boilers, cooking stoves, heating and cooling space, water distillation use solar energy).
- To increase the use of biogas technology.

According to the scenario of renewable energy development, Vietnam can exploit a 3,000-5,000MW capacity with an output of more than 10 billion kWh from renewable energy by 2025. If there is a reasonable support policy, this will be a big contribution to the National demand for electricity output. According to a preliminary study and assessment of the renewable energy development potential up to 2050, the potential of the wind, solar, geothermal and biomass energy development could be even greater.

VI. Policies and solutions for renewable energy development in Vietnam

Despite the high renewable energy potential, the investment in renewable energy development in Vietnam has not yet met the potential and strengths available in the country. This situation is mainly because the economy of renewable energy sources is not really attractive, along with barriers related to mechanisms, policies, implementation organization, and technology application. This limits the implementation of renewable energy projects. To develop renewable energy in Vietnam, it is necessary to concentrate resources, use the maximum potential of renewable energy in the country with advanced technologies suitable for the practical conditions of each region, and enhance economic, social and environmental efficiency. It is necessary to expand the market for renewable energy technologies, to develop the machinery-manufacturing industry and provide the renewable energy services in the country. It is also required to strengthen the potential for research, development, transfer, and application of new forms of renewable energy.

At the same time, it is also imperative to have a strategy for hydropower, biomass, wind, and solar energy development and create mechanisms and policies for its implementation.

- It is necessary to encourage organizations and individuals with different forms of ownership to participate in the development and use of renewable energy and persuade the Government to protect the legitimate rights and interests of organizations, companies and individuals that develop and use renewable energy.
- The electricity companies should have to buy all electricity produced from renewable energy sources when these power plants are connected to the grid in their localities under their respective management. The electricity purchase and sale are made through the power purchase agreement. Electricity projects using renewable energy sources for electricity production should be given a priority in the national electrical system.
- Organizations and individuals operating in the electricity sector have to be responsible for contributing to the development of the national renewable energy sector.
- Electricity end-users buying electricity from the national grid have to develop renewable energy sources with the main purpose of meeting their electricity needs and provide clearing mechanism.
- Projects on the development and use of renewable energy sources have to be entitled to investment credit preferences, which obey the current law provisions on investment credits and export credits of the Government.
- Projects on the development and use of renewable energy sources should be exempted from import tax for imported goods in order to create fixed assets for the projects. Imported goods, including raw materials, supplies, and semi-finished products which cannot be produced in the country are imported to serve the production of the projects in accordance with current regulations on export tax and import tax.
- The income tax exemption and discount for the enterprises involved in the projects on the development and use of renewable energy sources should be implemented for projects in the areas eligible for investment preferences under the current tax law.
- The land use levy or land rent for the projects on the development and use of renewable energy sources should be exempted or reduced, which complies with the current provisions of law applicable to projects in the areas entitled to investment preferences.
- Priority should be given to the studies related to the development and use of renewable energy resources in the field of science and technology and high-technology industries; it is also necessary to allocate funds to support scientific and technological research in pilot projects, industrialization projects for the development and use of renewable energy, promote technological innovations related to the development and use of renewable energy, reduction of production costs of renewable energy products and improvement of product quality, etc.

Some solutions to implement the Strategy are:

+ Real estate developers are responsible for fulfilling the requirements of using solar energy in the design and construction of buildings in accordance with technical standards issued by the Government agencies.

+ Petroleum trading enterprises must combine the sale of bio-liquid fuels to meet the national standards in the local fuel sale system.

+ The Ministry of Industry and Trade should annually promulgate specific regulations on the minimum proportion of biofuel liquid fuels to be sold in localities to petrol and oil trading enterprises.

+ It is necessary to set up a sustainable energy development fund using national budget funds, environmental fee revenues for fossil fuels, financial support and contributions from organizations and individuals outside the country and other legal capital to support the financing of activities promoting the development of energy industry nationwide.

+ It is necessary to encourage and support the development of services and consulting organizations in the field of renewable energy use.

+ It is necessary to encourage and support universities, vocational training, design and scientific institutions to develop curricula, syllabus and teach new subjects related to renewable energy.

+ It is necessary to develop the renewable energy industry, encourage the research, transfer, reception and effective application of technical and environmental advances and technologies aimed at producing and using renewable energy.

+ It is necessary to establish and develop a renewable energy technology market, create equality based on healthy competition among enterprises of all sectors, promote the development of production projects, sales and service of renewable energy production and use, etc.

Companies should sign grid connection agreements with the enterprises using renewable energy sources for electricity generation, already licensed or included in the list of renewable energy source projects, approved by the competent authority, to purchase all electricity generated from renewable energy projects which meet the technical standards of connection to the grid in the area within the grid system managed by power companies.

VII. CONCLUSION

Vietnam is undertaking industrialization in the direction of sustainable development, stepping into the 4.0 technology revolution, accelerating economic development, implementing the modernization of the country. Therefore, the sustainable development of the industries related to the exploitation and processing of fossil fuel is indispensable. The use of fossil fuels for energy production is one of the causes of global climate change. It also produces large quantities of ash, harmful gases and pollutants to the soil, water and air.

The paper analyzes in detail the environmental impact of energy production and consumption, the overview of energy demand, the relationship between the energy security and environment safety issues. Based on the assessment, the targets for the green energy development are proposed to ensure energy security and environmental protection. To ensure the feasibility of green energy development, an emphasis is made on the detailed assessment of green energy policies aimed at defining the future direction for green energy in Vietnam, toward accomplishing the goals of sustainable development responding to climate change.

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Pham Trung Son, Ass. Prof., Dr., Lecturer of the Department of Electrification of Industrial Enterprises, Electromechanical Faculty, Hanoi University of Mining and Geology, Hanoi, Vietnam. His research interests are reliability and security of power systems, energy security, renewable energy sources.

Ensuring Russia's Energy Security at the Regional Level: Methodology of Evaluation, Results and Main Trends

Sergey M. Senderov, Elena M. Smirnova, and Sergey V. Vorobev*

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

***Abstract* – The paper is devoted to an assessment of the state of regional energy security, and an analysis of the main trends and scale of changes in the state of energy security in the regions of Russia. The approaches to obtaining an integrated assessment of energy security at the regional level are presented. The expert opinions on the relative importance of key indicators are given. Specific regions of Russia are examined on the example of the Siberian Federal District. Regions of Russia with an unsatisfactory state of energy security are identified, and the dynamics of changes in the state of energy security in all of Russia's regions during the period from 2012 to 2016 are shown. Factors and reasons for the formation of negative and positive energy security trends are analyzed. The main directions of activities to improve the level of energy security in most regions of Russia are presented.**

***Index Terms*—Energy security, Integral assessment, Indicators, Regional level.**

I. Introduction

One of the most important activities to achieve and maintain the required level of energy security in Russia is monitoring and indicative analysis of the energy security status. This is an essential component for the formation of control, analytical and coordination functions of the State regulation in the field of energy security. The aims of monitoring the energy security of the Russian Federation and its regions are to identify the observed and expected processes, phenomena and parameters that determine the level and threats to energy security. At the same time, the identification process is based on a system of indicators that adequately describe the situation in this or that aspect of energy security. Thus, the meaning and essence of monitoring and indicative analysis lie in displaying information on the degree of implementation of energy security threats, using an indicator system, when comparing the numerical values of these indicators with their threshold values. In accordance with this, Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences (ESI SB RAS) has developed a database for the justification and decision-making on ensuring the energy security of the Russian Federation and its regions. It is also important to analyze the dynamic range of indicators values and their qualitative assessments in order to understand the direction of emerging energy security trends.

The angles of considering the issue of energy security in Russia and other countries slightly differ. For many countries, this is, first of all, the independence from external energy supplies and diversification of energy supply sources. This understanding of energy security is found in the materials of the International Energy Agency [1], European Parliament [2] and others. In Russia, energy security is understood as a state of protection of citizens, society, the State and the economy from the threat of a failure to meet their energy needs with economically accessible energy resources of acceptable quality, and from threats of energy supply interruption [3, 4]. In fact, we are talking about balancing the supply and demand of energy or eliminating energy shortage in different conditions.

There are different approaches to monitoring energy security. They are implemented at the country level and affect primarily the issues of fuel supply, economy, and environment. In [5], the authors pay special attention to the following indicators: resource estimates, reserves to production ratios, diversity indices, import dependence, political stability, energy price, a share of zero-carbon fuels, market liquidity. The authors of [6] focus on problems of fuel and energy supply of consumers in dependence on primary energy production, external primary energy supplies, and functioning of external

* Corresponding author.
E-mail: seregavorobev@isem.irk.ru

http://dx.doi.org/10.25729/esr.2018.02.0007
Received: July 13, 2018. Revised: September 24, 2018. Accepted: October 08, 2018. Available online: October 15, 2018.

primary energy suppliers.

Many researchers pay much attention to the issues of sustainable development of the national economy [7].

The authors of [8] present various opinions about the nature and methods of research into energy security issues. All methods described in this paper reveal comprehensively the features of the energy security study in terms of a country or a region of the world. These methods take into account the political and economic nature of the relationships between players in the energy market and can be undoubtedly applied to the research at the country level. Considerable attention is paid to the diversification of energy suppliers. At the same time, at the level of countries and regions of the world, technical issues of energy supply sustainability of a territory within countries are usually not considered. Research [9] is also devoted to the geopolitical problems of ensuring the energy security of individual countries. It shows that the opportunities to ensure demand for energy are the main driving force for economic growth and social welfare improvement of any country. The issues of energy security at the level of countries and regions of the world are described in [10]. The study presented in [11] deals with energy security indicators also at the country level. The study presented in [12] conceptualizes energy security as consisting of the interrelated factors of availability, affordability, efficiency, sustainability, and governance. It then matches these factors with 20 metrics constituting an energy security index measuring international energy security performance across 18 countries. Comprehensive studies have been carried out but again they focus on the level of countries and regions of the world. Almost the same questions and at the same level are presented in [13, 14].

The authors of [15] analyze the trends in energy security across the three Baltic countries. The aggregate measures of energy security are devised by means of multi-criteria decision-making techniques. The choice of energy security indicators was based on the priorities set out in the European Union energy policy.

In general, the investigation into the energy security problems of individual territories within a particular country should address other issues. First of all, these are the issues of technical availability of final types of energy for consumers under different operation conditions of energy systems, and only after the technical availability is achieved, all the other components of regional energy security can be discussed.

In other sources, for example, in [16], the authors pay more attention to the issues of meeting the environmental requirements. Speaking about the national level, some researchers, for example [17], focus on the role of renewable energy resources in ensuring energy security. This can certainly help but largely depends on the climatic and geographic features of the country or region.

There are virtually no studies on the assessment of the energy security of individual regions. Apparently, this is due to the fact that in some countries some regions have a much smaller area of the territory than in Russia. At the same time, they are connected with each other by energy relations much more closely and intensively.

To assess the state of energy security in Russia's regions and, to identify emerging trends in this regard, appropriate monitoring and analysis of the state of domestic energy are needed. Such an assessment can be performed in accordance with the methodology for monitoring the state of Russia's energy security at the regional level, i.e. based on the monitoring of the most important indicators of the energy sector operation at a given point in time.

This paper presents materials characterizing the state of energy security in the regions of Russia for all Federal Districts. Such estimates were obtained using the methodology for energy security monitoring [18]. All regions are ranked according to the state of their energy security. The studies conducted in different time frames (2012, 2016) allowed assessing the direction of changes in the energy security situation in the regions of Russia and the dynamics of these changes over the past five years.

A detailed analysis of how the energy security requirements are met for each indicator is examined in this paper on the example of the Siberian Federal District.

II. A METHOD OF ENERGY SECURITY MONITORING AT THE REGIONAL LEVEL IN RUSSIA

At present, the assessment of the state of regional energy security in the country [18, 19] is based on the use of a system of indicators conventionally distributed across three interrelated blocks, Table. 1.

The values of the indicators characterize the energy security situation in the region in terms of an analyzed aspect. Separation of individual blocks is necessary to obtain an idea of the most important aspects of regional energy security. Each of the indicators presented in Table 1 has its own, previously expertly generated and justified, threshold value. It is the threshold values that determine the boundary of the assignment of the actual value of the indicator to a particular area of qualitative states.

In most cases, these indicators can be taken from official statistics, some of them are calculated specifically. Indicator 2.3 “The ability to meet fuel demand in the conditions of a sharp cooling (10% increase in consumption) in the region” is calculated using a set of mathematical models specially developed by the Melentiev Energy Systems Institute SB RAS [20]. These models allow determining the possibilities of supplying the necessary volumes of all energy types to end consumers under different conditions, including peak demand for energy resources in case of a sharp cooling.

The method in [18] uses two threshold values for each indicator. The pre-crisis threshold value of the indicator means a boundary value between the normal and pre-crisis state of the energy sector in the aspect described by this indicator. The crisis threshold means the boundary between the pre-crisis and crisis states. These threshold values are determined in [18] expertly and indicate the boundaries of the transition of a particular indicator from one qualitative state to another. If the indicator is in a negative state, it is necessary to apply the measures that will help improve the energy security situation in terms of an analyzed aspect.

Table 1. The Most Important indicators of regional energy security

1. Block of energy resource production and availability for the fuel and energy supply system of a region
1.1. The ratio of the total available capacity of the region's power plants to the maximum electric load of consumers in the region. 1.2. The ratio of the available capacity of power plants and the capacity of inter-system ties between regions to the maximum electric load in the region. 1.3. Possibilities of meeting the demand for primary energy from the region's sources.
2. The block of fuel and energy supply reliability in the region
2.1. The share of the dominant resource in the total primary energy consumption in the region. 2.2. The share of the largest power plant in the installed electric capacity in the region. 2.3. The ability to meet fuel demand in the conditions of a sharp cooling (10% increase in consumption) in the region.
3. Block of the state of the basic production assets of energy systems in the region
3.1. The degree of depreciation of the basic production assets of the energy sector in the region. 3.2. The ratio of the average installed capacity commissioned annually and the power plant capacities reconstructed over the last 5-year period to the installed capacity in the region.

Based on the comparison of actual values of specific indicators with their thresholds, the level of crisis indicators is estimated. In this case, however, it is impossible to assess the state of the energy security as a crisis one in the entire region. Some indicators may have the values acceptable from the energy security standpoint, the values of others may be in a crisis or pre-crisis state. The picture can vary from region to region and from year to year. Accordingly, in order to form a final qualitative assessment of the energy security state in the region, it is necessary to convolve the qualitative assessments of the status of individual indicators in a single integrated assessment of energy security of the analyzed territory.

The state of an indicator, depending on the location of its values on the state scale, is estimated as follows:

$$f(S_i)=\begin{cases} N,\ S_i < S_i^{PC} \\ PC,\ S_i^{PC} \le S_i < S_i^{C} \quad i=1,n \\ C,\ S_i \ge S_i^{C} \end{cases} \tag{1}$$

where n –the number of indicators being evaluated; S_i – actual (expected) value of the i-th indicator; S_i^{PC}, S_i^{C} - pre-crisis and crisis threshold values of the i-th indicator; N, PC, C - a qualitative assessment of the state of the energy sector in terms of the aspect indicated by the i-th indicator: normal, pre-crisis and crisis, respectively.

Due to the fact that the indicators chosen for the assessment are not equally important, an integral assessment takes into account the significance of each specific indicator in their common set or "specific weights" of all indicators in the overall system of their value. Each indicator is compared in pairs with other indicators within 1. The expert group determines the weighted average expert value of conventional significance of the i-th indicator in comparison with the j-th indicator. The specific weight of the indicator in the total sum of weights is determined by the equation:

$$V_i = \sum_{j=1}^{n} \upsilon_{ij} \Big/ \sum_{i=1}^{n}\sum_{j=1}^{n} \upsilon_{ij} \tag{2}$$

where V_i - is the specific weight of the i-th indicator in the system of indicators being evaluated; υ_{ij} - conventional significance of the i-th indicator in comparison with the j-th indicator.

Based on the above-described comparison, we qualitatively assess the energy security status of specific regions of Russia:

$$Q = \begin{cases} N,\ \sum_{i=1}^{n} V_i^N \ge \delta_N \\ PC,\ \sum_{i=1}^{n} V_i^C \prec \delta_C \ \text{è}\ \sum_{i=1}^{n} V_i^N \prec \delta_N \ , \quad i=1,n \\ C,\ \sum_{i=1}^{n} V_i^C \ge \delta_C \end{cases} \tag{3}$$

where Q – an integral assessment of the qualitative state of the region's energy security; V_i^N, V_i^C - a specific weight of the i-th indicator, which is in the range of normal and crisis values, respectively; δ_N, δ_C - coefficients that characterize a normal or a crisis state, respectively.

Based on the monitoring of the dynamic range of the integral indicator values, such an assessment indicates in which direction the energy security level of a particular region is changing and which region the Federal District or the country should pay attention to, first of all.

III. An Analysis of the Energy Security State in the Regions of Russia

In order to demonstrate the efficiency of the methodological approach, to identify and assess the trends in changes in the most important energy security factors of the subjects of Russia, the following steps were taken:

- based on statistical information, a database was created for all regions of Russia [21-23];

– the values of all the indicators indicated in Table 1 are estimated over a time span from 2012 to 2016;
– the values of energy security indicators were quantitatively correlated with their threshold values corresponding to specially designated groups of territories;
- using the expression (3) we obtained integral assessments of the energy security state in each of the analyzed regions.

The analysis of the obtained data on all subjects of Russia demonstrates the trends in the energy security situation.

Based on the analysis conducted for the time span of 2012-2016, the energy security situation has not changed radically in 80% of the regions. In general, information on the attribution of these regions to the areas of crisis, normal or pre-crisis state is presented in Figure 1. As evidenced by an analysis of Figure 1, most of the regions of the Russian Federation are located in the area of the crisis and pre-crisis state of energy security.

Let us consider the regions where the energy security situation has changed qualitatively for the analyzed period.

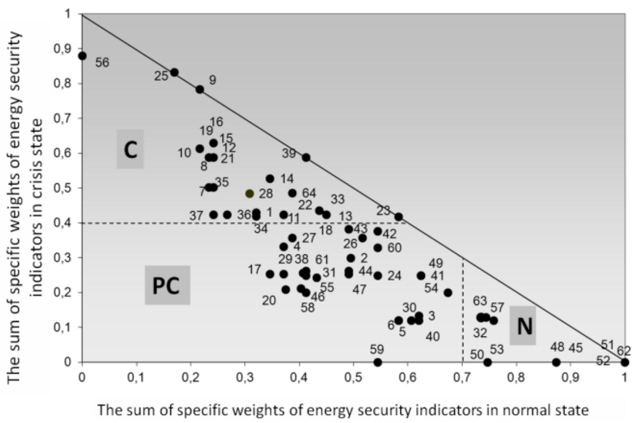

Figure1. The final state of energy security of the subjects of Russia, 2016.

1 - The Republic of Karelia; 2 - the Republic of Komi; 3 - Vologda Region; 4 - Kaliningrad Region; 5 - Leningrad Region; 6 - Murmansk Region; 7 - Novgorod Region; 8 - Pskov Region; 9 - Belgorod Region; 10 - Bryansk Region; 11 - Vladimir Region; 12 - Voronezh Region; 13 - Ivanovo Region; 14 - Kaluga Region; 15 - Kostroma Region; 16 - Kursk Region; 17 - Lipetsk Region; 18 - Moscow Region; 19 - Orel Region; 20 - Ryazan Region; 21 - Smolensk Region; 22 - Tver Region; 23 - Yaroslavl Region; 24 - The Republic of Dagestan; 25 - Kabardino-Balkaria Republic; 26 - Republic of North Ossetia-Alania; 28 - the Chechen Republic; 29 - Stavropol Territory; 30 - Krasnodar Territory; 31 - Volgograd Region; 32 - Rostov Region; 33 - Republic of Kalmykia; 34 - Republic of Bashkortostan; 35 - Republic of Mordovia; 36 - Republic of Udmurtia; 37 - Chuvash Republic; 38 - Orenburg Region; 39 - Penza Region; 40 - Perm Territory; 41 - Samara Region; 42 - Saratov Region; 43 - Ulyanovsk Region; 44 - Sverdlovsk Region; 45 - Tyumen Region; 46 - Chelyabinsk Region; 47 - Altai Territory; 48 - Kemerovo Region; 49 - Novosibirsk Region; 50 - Omsk Region; 51 - Tomsk Region; 52 - Krasnoyarsk Territory; 53-Irkutsk Region; 54 - Republic of Buryatia; 55 - Republic of Tyva; 56 - The Altai Republic; 57 - the Republic of Sakha (Yakutia); 58 - Primorsky Territory; 59 - Khabarovsk Territory; 60 - Amur Region; 61 - Kamchatka Territory; 62 - Sakhalin Region; 63 - Chukotka Autonomous District; 64 - Jewish Autonomous Region.

These regions are presented in Table 2. In this Table *N*, *PC* and *C* mean qualitative assessment of the state of the energy sector in the aspect indicated by the i-th indicator: normal, pre-crisis and crisis, respectively.

In 2016, the crisis situation was noted in all the regions of the Central District, with the exception of the Lipetsk, Ryazan and Tula regions. In the Tula region (Table 2), the crisis situation shifted to the pre-crisis one due to the commissioning of capacities in 2013-2015 (at the 190 MW Novomoskovskaya thermal power plant and the start-up of two 225 MW hydroelectric generators at Cherepetskaya thermal power plant).

During the analyzed period, the situation improved in such regions as the Republic of Mari El, the Republic of Tatarstan, the Kirov region, Kurgan region, Magadan region and the Republic of Crimea. The improvement in the situation was due to the active policy of renewal of fixed production assets, and the implementation of planned capital repairs in electric and heat power industries, which made it possible for the regions to reach the pre-crisis values, thus moving from the range of the crisis values. For example, the Republic of Tatarstan has commissioned 590 MW of new generating capacities in the last three years of the analyzed period (2014-2016). Gas production in the Republic increased almost threefold, which enhanced the capability to meet the needs for primary energy from the region's sources and allowed the Republic to shift to the range of normal values of the corresponding indicator (1.3) (Table 2).

In the Republic of Crimea, the situation improves every year, due to the implementation of projects for the construction of generation facilities in the Republic and the provision of a reliable and uninterrupted power supply. The region has significant potential for the development of alternative energy sources, such as solar and wind. In 2014, the Republic of Crimea put into operation a 25 MW wind farm, and in 2015-2016, it commissioned four lines of Energy Bridge to connect the power system of Crimea to the UES of Russia (UES South), with a total capacity of 800 MW. However, at the same time, deterioration of power equipment on the peninsula is about 70%, which requires appropriate attention and measures to reduce it.

It is worth paying attention to the regions where the energy security situation stabilized in six years, and by 2016 had moved to the region of acceptable values. There are only four such subjects (5% of the total number of those analyzed): the Astrakhan Region, the Nizhny Novgorod Region, the Republic of Khakassia and the Transbaikal Territory. The conditions for improving the situation were: modernization of electric power equipment, annual commissioning of new generating capacities and, as a consequence, a decrease in the share of the largest source in the installed electric capacity in the region (indicator 2.2), and an increase in the ability to meet the demand for primary energy from the region's own sources.

Table 2. Assessment of the qualitative state of energy security in selected regions of Russia.

Year	The order numbers of the energy security indicators								The sum of the specific weights by state			The qualitative state of energy security
	1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	Boundaries of states			
	Specific weights of indicators								C[1]	PC	N[2]	
	0,104	0,138	0,133	0,120	0,079	0,170	0,127	0,129				
1	2	3	4	5	6	7	8	9	10	11	12	13
Arkhangelsk Region												
2012	N	N	C	PC	N	C	PC	N	0,303	0,247	0,450	**PC**
2016	N	N	C	PC	N	C	H	K	0,432	0,120	0,448	**C**
Tambov Region												
2012	N	N	C	C	PC	PC	C	PC	0,380	0,378	0,242	**PC**
2016	N	N	C	C	PC	PC	C	C	0,509	0,249	0,242	**C**
Tula Region												
2012	N	N	C	C	PC	PC	C	C	0,509	0,249	0,242	**C**
2016	N	N	C	C	N	PC	PC	N	0,253	0,297	0,450	**PC**
Karachay-Cherkess Republic												
2012	N	N	C	C	N	N	N	N	0,253	0	0,747	**N**
2016	N	N	C	C	N	N	N	PC	0,253	0,129	0,618	**PC**
Astrakhan Region												
2012	N	N	N	N	PC	N	PC	C	0,129	0,206	0,665	**PC**
2016	N	N	N	N	PC	N	PC	N	0	0,206	0,794	**N**
Mari El Republic												
2012	N	N	PC	C	N	C	PC	C	0,419	0,26	0,321	**C**
2016	N	N	N	C	N	C	PC	N	0,29	0,127	0,583	**PC**
Republic of Tatarstan												
2012	N	N	PC	C	N	C	PC	C	0,419	0,26	0,321	**C**
2016	N	N	N	C	N	C	PC	PC	0,29	0,256	0,454	**PC**
Kirov Region												
2012	N	N	C	C	N	N	C	C	0,509	0	0,491	**C**
2016	N	N	C	C	N	N	C	N	0,38	0	0,62	**PC**
Nizhny Novgorod Region												
2012	N	N	N	C	N	N	PC	C	0,249	0,127	0,624	**PC**
2016	N	N	N	C	N	N	PC	N	0,12	0	0,88	**N**
Kurgan Region												
2012	N	N	C	C	C	N	C	C	0,588	0	0,412	**C**
2016	N	N	C	C	PC	N	PC	N	0,253	0,206	0,541	**PC**
The Republic of Khakassia												
2012	N	N	N	PC	C	N	PC	N	0,079	0,247	0,674	**PC**
2016	N	N	N	PC	C	N	N	N	0,079	0,12	0,801	**N**
Transbaikal Territory												
2012	PC	PC	N	PC	PC	N	PC	C	0,129	0,568	0,303	**PC**
2016	N	N	N	PC	N	N	PC	N	0	0,247	0,753	**N**
Magadan Region												
2012	N	N	C	C	C	N	PC	C	0,461	0,127	0,412	**C**
2016	N	N	PC	C	C	N	PC	C	0,328	0,26	0,412	**PC**
Republic of Crimea												
2012	C	N	C	C	N	N	PC	C	0,486	0,127	0,387	**C**
2016	C	N	C	C	N	N	PC	N	0,357	0,127	0,516	**PC**

[1] The state of energy security in the region is considered as a crisis if the sum of the specific weights of indicators in state "C" exceeds 0.4.

[2] The state of energy security in the region is considered as normal if the sum of the specific weights of indicators in the state "N" exceeds 0.7.

IV. An analysis of energy security situation in the selected federal district

The results of the energy security analysis for the years 2012 and 2016 are presented below for illustration.

Along with the qualitative assessment of the energy security level in the regions in 2016, in order to show some trends, we provide the information on the qualitative assessment of the relevant indicators in 2012. An analysis of the data from the corresponding Tables for the subjects of the Siberian Federal District makes it possible to briefly characterize the trends inherent in the energy sector in the light of energy security requirements.

The information on the first block of indicators is shown in Table 3.

Table 3. Characteristics of the status of indicators in the subjects of the Siberian Federal District for the block of energy resource production and availability for the fuel and energy supply system for 2012, 2016.

Region	Indicator	Unit of measurement	The threshold values of the indicator[3]		Value and status of indicator			
			N	C	2012		2016	
1	2	3	4	5	6	7	8	9
Altai Territory	1.1	unit	0,5	0,3	0,74	N	0,72	N
	1.2	unit	1,5	1,2	3,03	N	3,1	N
	1.3	%	60	40	1,55	C	1,75	C
Kemerovo Region	1.1	unit	0,5	0,3	0,85	N	1,01	N
	1.2	unit	1,5	1,2	2,27	N	2,55	N
	1.3	%	40	20	5,88	N	1052	N
Novosibirsk Region	1.1	unit	0,5	0,3	1,03	N	1,03	N
	1.2	unit	1,5	1,2	2,18	N	2,18	N
	1.3	%	40	20	33,7	N	40,4	N
Omsk Region	1.1	unit	0,5	0,3	0,84	N	0,86	N
	1.2	unit	1,5	1,2	2,44	N	2,46	N
	1.3	%	40	20	48,3	N	36,9	PC
Tomsk Region	1.1	unit	0,5	0,3	0,81	N	0,77	N
	1.2	unit	1,5	1,2	2,76	N	2,77	N
	1.3	%	60	40	121	N	294	N
Krasnoyarsk Region	1.1	unit	0,7	0,5	1,65	N	2	N
	1.2	unit	1,5	1,2	2,39	N	2,74	N
	1.3	%	60	40	140	N	142	N
Irkutsk Region	1.1	unit	0,7	0,5	1,58	N	1,6	N
	1.2	unit	1,5	1,2	2,11	N	2,13	N
	1.3	%	60	40	122	N	122	N
The Republic of Khakassia	1.1	unit	0,7	0,5	2,85	N	2,42	N
	1.2	unit	1,5	1,2	4,67	N	4,28	N
	1.3	%	60	40	557	N	740	N
Transbaikal Territory	1.1	unit	1,0	0,8	1,22	N	1,19	N
	1.2	unit	1,5	1,2	1,6	N	1,57	N
	1.3	%	60	40	266	N	233	N
The Republic of Buryatia	1.1	unit	0,5	0,3	1,31	N	1,28	N
	1.2	unit	1,5	1,2	3,35	N	3,19	N
	1.3	%	60	40	49,6	PC	76,1	N
Tyva Republic	*1.1*	*unit*	*0,5*	*0,3*	*0,38*	*PC*	*0,22*	*C*
	1.2	unit	1,5	1,2	1,18	C	1,78	N
	1.3	%	60	40	199	N	240	N
Altai Republic	1.1	unit	0,5	0,3	0	C	0,13	C
	1.2	unit	1,5	1,2	0	C	0,13	C
	1.3	%	60	40	7,69	C	12,2	C

[3]The boundaries of the state areas ("N" - acceptable (normal) state of energy security for this indicator, "C" - a crisis state).

According to the first set of indicators, most subjects of the Siberian Federal District have an acceptable situation from the energy security standpoint. The exception is the Republic of Altai, where the values of the indicators are in a crisis state (Table 3). Here we can note a low level of the maximum electrical load of consumers. The situation, however, started slowly to improve in 2014-2016. Three solar power plants with a total capacity of 15 MW were commissioned (Kosh-Agach solar power plants -1, 2, and Ust-Kansk solar power plant), and new capacities are planned to be put in operation in the future.

Compared to 2012, in 2016, the values of indicator 1.2 for the Republic of Tyva lie in the range of acceptable values. In 2014, owing to the modernization of the Kyzylskaya and Chadan substations the transfer capability of the intersystem ties was increased to 280 MW of which up to 100 MW can be transferred to Western Mongolia. However, in general, the problem of energy shortage in the Republic is not solved.

As for the first block of indicators, in particular, indicator 1.3 ("Possibilities of meeting the demand for primary energy from the region's own sources"), as we can see, the

Altai Territory and the Republic of Altai have crisis values. In the Omsk Region by 2016 the situation worsened due to a 20% decrease in the fuel oil production over the past five years. In the Republic of Buryatia, the values of the indicators have moved into the region of acceptable ones, as a result of the development of a number of small coal deposits for local needs and an increase in the level of coal production by 30% over the past five years.

The satisfactory situation in terms of the first block of indicators is in the Republic of Khakassia. The maximum electrical load is ensured by a sufficient margin. Extraction of significant volumes of coal provides positive values of the indicator of supply with its own primary energy.

According to the second set of indicators, the situation in a large part of the regions is aggravated by an excessively high share of the dominance of one of the imported resources (indicator 2.1, Table 4)

Table 4. Characteristic of the status of indicators in the subjects of the Siberian Federal District for the fuel and energy supply reliability block

Region	Indicator	Unit of measurement	Threshold values of the indicator			Value and status of indicator			
			N	PC	C	2012		2016	
1	2	3	4	5	6	7	8	9	10
Altai Territory	2.1	%	40		70	92,4	C	88,5	C
	2.2	%	50		70	22,8	N	24,2	N
Kemerovo Region	2.1	%	90	>90		83,5	N	96,0	N
	2.2	%	50		70	25,8	N	23,7	N
Novosibirsk Region	2.1	%	40		70	72,6	C	68,9	PC
	2.2	%	50		70	39,4	N	39,4	N
Omsk Region	2.1	%	40		70	50,6	PC	54,3	PC
	2.2	%	50		70	43,4	N	42,8	N
Tomsk Region	2.1	%	90	>90		68,7	N	62,9	N
	2.2	%	50		70	24,3	N	27,7	N
Krasnoyarsk Region	2.1	%	90	>90		73,5	N	75,4	N
	2.2	%	40		50	39,2	N	32,8	N
Irkutsk Region	2.1	%	90	>90		76,5	N	70,6	N
	2.2	%	40		50	34,12	N	33,9	N
The Republic of Khakassia	2.1	%	90	>90		96,5	PC	96,5	PC
	2.2	%	40		50	90,9	C	89,5	C
Transbaikal Territory	2.1	%	90	>90		96,4	PC	98,1	PC
	2.2	%	30		40	29,3	N	28,3	N
The Republic of Buryatia	2.1	%	40		70	95,1	C	94,2	C
	2.2	%	50		70	83,3	C	79,1	C
Tyva Republic	2.1	%	90	>90		97,2	PC	100	PC
	2.2	%	50		70	36,3	N	59,5	PC
Altai Republic	2.1	%	40		70	53,8	PC	43,8	PC
	2.2	%	50		70	100	C	64,1	PC

[4] Indicator 2.3 is estimated based on the results of studies on the model of the energy sector as the extent to which the consumer is provided with primary energy in case of possible cooling, increasing consumption by 10%. For all subjects of the Siberian Federal District, increased consumption is fully met, which corresponds to the zone of acceptable (normal) states.

In 2012-2016, the coal share in the Republic of Buryatia and the Altai Territory exceeded 90%. The pre-crisis situation, with a share of the dominant resource, is observed in the Novosibirsk, Omsk regions, the Republic of Khakassia, Tyva, as well as in the Transbaikal Territory and the Altai Republic.

In the Irkutsk region, Kemerovo region and the Krasnoyarsk Territory, the situation for this indicator can be considered acceptable, due to the dominance of their own energy resources in these regions. At the same time, the qualitative assessment of the "pre-crisis" state in the self-reliant regions (belonging to group 1) indicates the advisability of greater diversification of the fuel and energy supply in order to increase the systems readiness for potential changes in the structure of the fuel and energy balance in the country and its regions for various reasons, including the prices for primary energy resources.

According to indicator 2.2 (the share of the largest power plant in the installed electric capacity of the territory), the most acute situation is observed in the Republic of Buryatia (Gusinoozerskaya thermal power plant - 79% of the total installed capacity) and Khakassia (Sayano-Shushenskaya hydropower plant - 89% of the total installed capacity). Since in the event of an accident, such a high share of a single source is very dangerous due to possible problems in the electricity supply to consumers.

According to this indicator, the situation in the Altai Republic has improved in recent years, moving from crisis to pre-crisis state by commissioning new capacities and redistributing the load.

The Republic of Tyva is in the pre-crisis state where, from the energy security standpoint, it is desirable to develop the trend of generating capacity growth to cover the increasing demand for electricity (mobile gas turbinepower plant - 59% of the installed capacity in the region).

Another important aspect affecting the energy security in the regions is the state of the main production assets of the energy sector. The averaged data on the wear and tear of the main production assets in the energy industries in the regions, correlated with the book value of these industries in these regions, allow us to approximately estimate the average wear and tear in the energy sector of the regions.

As is evidenced by Table 5, the energy equipment in the Novosibirsk Region, Altai Republic, and the Altai Territory has deteriorated in recent years (and, most importantly, continues to deteriorate at a fairly rapid pace).

Table 5. Characteristics of the status of indicators in the subjects of the Siberian Federal District for the block of state of the main production assets of energy systems

Region	Indicator	Unit of measurement	The threshold values of the indicator		Value and status of indicator			
			N	C	2012		2016	
1	2	3	4	5	6	7	8	9
Altai Territory	3.1	%	40	60	58,5	PC	60	C
	3.2	%	2	1	1,6	PC	1,7	PC
Kemerovo Region	3.1	%	40	60	47,5	PC	43,7	PC
	3.2	%	2	1	3,7	N	1,9	N
Novosibirsk Region	3.1	%	40	60	55	PC	61	C
	3.2	%	2	1	1	C	0,7	C
Omsk Region	3.1	%	40	60	38,3	N	36,7	N
	3.2	%	2	1	9	N	7,3	N
Tomsk Region	3.1	%	40	60	33,6	N	39,7	N
	3.2	%	2	1	12,2	N	0,9	C
Krasnoyarsk Region	3.1	%	40	60	44	PC	38	N
	3.2	%	2	1	2,9	N	4,9	N
Irkutsk Region	3.1	%	40	60	54,2	PC	53,7	PC
	3.2	%	2	1	1,8	PC	0,6	C
The Republic of Khakassia	3.1	%	40	60	39,5	N	38,7	N
	3.2	%	2	1	7,7	N	4,4	N
Transbaikal Territory	3.1	%	40	60	48,3	PC	47,7	PC
	3.2	%	2	1	2,9	N	3,9	N
The Republic of Buryatia	3.1	%	40	60	45,9	PC	43,4	PC
	3.2	%	2	1	2	PC	5	N
Tyva Republic	3.1	%	40	60	50,1	PC	58,4	PC
	3.2	%	2	1	29,2	N	7,3	N
Altai Republic	3.1	%	40	60	62	C	70	C
	3.2	%	2	1	0	C	33,7	N

The situation in the energy industries in most of the other regions of the District continues to deteriorate, remaining in the middle of the pre-crisis range in such regions as Irkutsk Region, Republic of Tyva, Republic of Buryatia, and Kemerovo Region. With the renewal and modernization of the basic production assets of the energy sector, in 2016 positive trends were observed in Khakassia, due to the active restoration and modernization of the Sayano-Shushenskaya hydropower plant, modernization at the Abakanskaya thermal power plant and the commissioning of two power units with a total capacity of 256 MW. In the Kemerovo Region, Kuzbassenergo carried out a major overhaul of 11 turbine units, and power units were put into operation at Novokuznetskaya gas turbine power plant. In the Omsk Region and the Republic of Buryatia, acceptable values of the indicator are also associated with an active policy for capital repairs and reconstruction of power generating capacities. To a large extent, the value of this indicator is due to the commissioning of new capacities, major repairs and technical re-equipment of existing power generating sources.

The crisis situation in the aspect reflected by indicator 3.2 is observed in Novosibirsk region, Tomsk region, Irkutsk region and the Republic of Altai, where the commissioning of new capacities during the analyzed 5-year period was insufficient, and practically no serious work was done to modernize the installed equipment, which in turn led to a decrease in the level of energy security in the regions. Smaller capacities were put into operation and some equipment upgrades were carried out in the Altai Republic and the Altai Territory (130 MW was commissioned at Barnaulskaya thermal power plant -2 in 2016), but in insufficient (in terms of energy security) volumes to reverse the negative trends towards the aging of the basic production assets. According to the indicator of the renewal of power generating equipment in the Irkutsk Region and the Transbaikal Territory, the number of new capacities put in operation was insufficient. In the Irkutsk Region in 2012, a turbine unit with a capacity of 50 MW was launched at the Novo-Irkutsk thermal power plant. In the Transbaikal Territory, a hydroelectric unit with a capacity of 225 MW was commissioned at Kharanorskaya hydropower plant in the same year. In addition, major repairs of equipment and reconstruction were carried out. These actions brought the situation in terms of this indicator into an acceptable state from the energy security standpoint in the Transbaikal Territory but they were insufficient for the Irkutsk Region to cope with the crisis.

Table 6. Qualitative assessment of the energy security state in the subjects of the Siberian Federal District

Year	Numbers of energy security indicator								The sum of the specific weights by state			The qualitative state of energy security
	1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	Boundaries of states			
	Specific weights of indicators											
	0,104	0,138	0,133	0,120	0,079	0,170	0,127	0,129	C[5]	PC	N[6]	
1	2	3	4	5	6	7	8	9	10	11	12	13
Altai Territory												
2012	N	N	C	C	N	N	PC	PC	0,253	0,256	0,491	PC
2016	N	N	C	C	N	N	PC	PC	0,253	0,256	0,491	PC
Kemerovo Region												
2012	N	N	N	N	N	N	PC	N	0	0,127	0,873	N
2016	N	N	N	N	N	N	PC	N	0	0,127	0,873	N
Novosibirsk Region												
2012	N	N	PC	C	N	N	PC	C	0,249	0,260	0,491	PC
2016	N	N	N	C	N	N	К	C	0,376	0	0,624	PC
Omsk Region												
2012	N	N	N	PC	N	N	N	N	0	0,120	0,880	N
2016	N	N	PC	PC	N	N	N	N	0	0,253	0,747	N
Tomsk Region												
2012	N	N	N	N	N	N	N	N	0	0	1	N
2016	N	N	N	N	N	N	N	C	0,129	0	0,871	N
Krasnoyarsk Region												
2012	N	N	N	N	N	N	PC	N	0	0,127	0,873	N
2016	N	N	N	N	N	N	N	N	0	0	1	N
Irkutsk Region												
2012	N	N	N	N	N	N	PC	PC	0	0,256	0,744	N
2016	N	N	N	N	N	N	PC	C	0,129	0,127	0,744	N
The Republic of Khakassia												
2012	N	N	N	PC	C	N	N	N	0,079	0,120	0,801	N
2016	N	N	N	PC	C	N	N	N	0,079	0,120	0,801	N
Transbaikal Territory												
2012	N	N	N	PC	N	N	PC	N	0	0,247	0,753	N
2016	N	N	N	PC	N	N	PC	N	0	0,247	0,753	N
The Republic of Buryatia												
2012	N	N	PC	C	C	N	PC	PC	0,199	0,389	0,412	PC
2016	N	N	N	C	C	N	PC	N	0,199	0,129	0,674	PC
Tyva Republic												
2012	PC	C	N	PC	N	N	PC	N	0,138	0,351	0,511	PC
2016	N	C	N	PC	PC	N	PC	N	0,242	0,326	0,432	PC
Altai Republic												
2012	C	C	C	PC	C	C	C	C	0,880	0,120	0	C
2016	C	C	C	PC	PC	C	C	N	0,672	0,199	0,129	C

[5] The state of energy security in the region is considered as a crisis if the sum of the specific weights of indicators in state "C" exceeds 0.4

[6] The state of energy security in the region is considered as normal if the sum of the specific weights of indicators in the state "N" exceeds 0.7

The above-presented and analyzed values of the main indicators form the basis for an integrated assessment of the energy security level in the subjects of the Siberian Federal District. To obtain such an assessment, an approach based on the convolution of indicator values was used, taking into account their specific weights. Qualitative characteristics of the state of all the indicators discussed in Table 3-5, were collected according to the respective territories and processed according to a special method. As a result, a qualitative final assessment of the energy security status of the territories of the subjects of the Siberian Federal District was presented in Table 6.

As is evidenced by the data in Table 6, the best condition for energy security is observed in the Tomsk Region and the Krasnoyarsk Territory. The level of energy security in the Kemerovo region, Omsk region, Irkutsk region, and the Transbaikal Territory can be considered close to acceptable. It is necessary to pay serious attention to indicators, whose values in these territories lie in the zones of "crisis" and "pre-crisis" values. This signals serious fuel and energy supply problems in the territories in the part described by the values of the respective indicators. In addition, the negative state of the indicators characterizing the state of the basic production assets and the renewal of the energy sector in these regions hinders the improvement in energy security.

The most acute energy security situation is in the Republic of Altai. Here, the crisis situation of most of the monitored indicators is evident. This concerns both the degree of the maximum electrical load and the share of the largest power generating source in the installed capacity in the Republic and the wear and tear of the main production assets of the energy sector.

An analysis of the dynamics of qualitative assessments of energy security in the regions and quantitative values of the weights of indicators in different states from 2012 to 2016 allows drawing a conclusion that the energy security situation during this period on average had positive trends: for all subjects of the Siberian Federal District, with the exception of the Republic of Altai.

V. The main energy security trends in the regions of Russia

In order to identify the trends in the changes in the regional energy security in terms of individual indicators, we will analyze the change in their state from 2012 to 2016. In Table 7 as a percentage, the qualitative conditions of various indicators are presented for the years 2012 and 2016.

Based on the comparative analysis and data presented in Table 7, the following results were obtained. The situation in the regions has changed slightly over the six-year period in terms of the indicators: 1.1 (The ratio of the total available capacity of the region's power plants to the maximum electric load of consumers in the region), 1.2 (The ratio of the amount of available capacity of power plants and the intersystem ties between regions to the maximum electric load in the region), 1.3 (Possibilities of meeting the demand for primary energy from the region's sources) and 2.3 (the ability to meet fuel demand under in case of a sharp cooling (10% increase in consumption) in the region).

Table 7. The indicators of energy security in the regions and the assessment of the energy security state in the Russian regions (2012, 2016), %

Indicator	Status of the indicator by region			
	Year	N	PC	C
1.1	2012	79	5	16
	2016	79	4	17
1.2	2012	90	5	5
	2016	92	4	4
1.3	2012	34	9	57
	2016	36	9	55
2.1	2012	18	17	65
	2016	13	18	69
2.2	2012	49	25	26
	2016	53	20	27
2.3	2012	57	16	27
	2016	56	17	27
3.1	2012	6	72	22
	2016	10	70	20
3.2	2012	35	17	48
	2016	46	13	41

The situation with the share of the dominant resource in the total consumption of primary energy in the region worsened by 5% (indicator 2.1). This situation is observed in all the regions of the Central, North Caucasian, Volga Federal Districts, as well as the Kaliningrad, Leningrad, Murmansk, Novgorod and Pskov regions of the North-West Federal Districts that do not have sufficient sources of their own for primary energy production, and where gas is the dominant type of fuel.

According to indicator 2.2 (The share of the largest power plant in the installed electric capacity of the region), the situation as a whole, across the country, has improved by 5% due to the commissioning of new capacities. The commissioning of new capacities along with repairs led to a certain improvement in the situation in terms of indicator 3.1 (Degree of depreciation of the basic production assets of the regional energy sector) - by 4% and indicator 3.2 (The ratio of the average annual commissioning of installed capacity and reconstruction of power plants in the region over the last 5-year period to the installed capacity in the region) - by 11%. Although at the same time, in all the regions of Russia the current values of the degree of equipment wear and tear are 50-60% and the situation requires close attention.

VI. Conclusion

In general, the energy security situation in the subjects of Russia is unsatisfactory. Most of the regions are characterized by crisis and pre-crisis values of the indicator weights.

It is worth noting that a relatively high percentage of regions have an acceptable energy security situation in terms of indicator 1.2 (The ratio of the available capacity of power plants and the transfer capability of intersystem ties between regions to the maximum electric load of consumers in the region) - 92% and indicator 1.1 (The ratio of the total available capacity of the region's power plants to the maximum electric load of consumers in the region) - 79% of the regions.

As evidenced by Table 7, the pre-crisis situation in 70% of the regions is affected by the unsatisfactory state of indicator 3.1, i.e. the degree of depreciation of the basic production assets in the energy sector in the region. As in the majority of the subjects of the Russian Federation, the current values of the equipment wear are 50-60%.

Acknowledgment

The research was carried out within the framework of the scientific project III.17.5.1 of the Program for Fundamental Research of the SB RAS, reg. number AAAA-A17-117030310451-0.

The research was supported in part by RFBR (project No. 18-58-06001)

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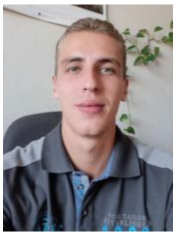
Sergey M. Senderov was born in 1964. He graduated from Irkutsk Technical University in 1986. He is a Doctor of Engineering, Head of Energy Security Department and Deputy Director of Melentiev Energy System Institute SB RAS. His research interests are energy security, threats and indicators of energy security, the reliability of energy systems, and fuel-energy supply

Elena M. Smirnova graduated from Irkutsk Technical University in 2008. She is a senior engineer of Melentiev Energy Systems Institute SB RAS, Irkutsk, Russia. Her research interests are energy security, threats, and indicators of energy security.



Sergey V. Vorobev was born in 1990. He graduated from Irkutsk Technical University in 2012. He is Ph.D. in engineering and researcher at Melentiev Energy System Institute SB RAS. His research interests are the reliability of energy systems, the reliability of gas supply, and energy security.

Research into the loss of synchronism in power systems due to disturbances based on an analysis of electromechanical waves

N.N. Lizalek, V.V. Vasiliev*

Novosibirsk State Technical University, Novosibirsk, Russia

Abstract **– In this paper, we suggest studying the stability of power systems under disturbances by analyzing the processes of synchronism loss, given electromechanical waves in power system that form an oscillatory structure of motion. In contrast to the classical formulation of the stability problem, an indispensable part of the study on the loss of synchronism is the location of an out-of-step cutset in the system (the spatial structure of instability). The problem of synchronism loss analysis has two statements: the prediction of possible instability structures and the determination of the instability structures in specific emergencies. The prediction of instability structures is made based on the equal areas method applied to the motion of excited oscillators in the system. In this case, possible instability structures are selected by comparing the energy and time characteristics of the unstable motion. The analysis of the processes of synchronism loss in power systems for a given emergency involves the calculation of the kinetic energy of mutual oscillations of an unstable pair of an oscillatory structure. The identification of the unstable pair of subsystems enables the out-of-step cutset to be located. The excess kinetic energy of the mutual motion of the unstable pair subsystems becomes an energy characteristic of the loss of synchronism.**

Index Terms **– Power systems, electromechanical waves, oscillatory structures, oscillators of the system, possible and actual trajectories of motion, energy-time diagrams, unstable pair**

* Corresponding author.
E-mail: v_v_vasiliev@mail.ru

http://dx.doi.org/10.25729/esr.2018.02.0008
Received: July 06, 2018. Revised: August 27, 2018.
Accepted: October 02, 2018, Available online: October 15, 2018.

I. Introduction

The complexity of electromechanical transients in power systems manifests itself in the complexity and diversity of the processes related to upsetting the stability of parallel operation of synchronous machines (angle stability).

One of the important goals of the practical study on the loss of stability is to determine the position of the out-of-step cutsets under various emergency disturbances. Identification of the *spatial structure of instability* becomes particularly relevant when building automatic emergency control systems to ensure the stability of complex power systems under emergencies that occur far from generating sources.

Classical methods of studying the stability of complex power systems (the method of "small" oscillations, transient stability analysis using the Lyapunov function) do not determine the position of an out-of-step cutset [1-4]. The studies are completed as soon as the *fact of stability or instability* of the considered system is established. The out-of-step cutset is detected beyond the stability study procedures, after the numerical calculation of the unsteady transient process on the basis of an analysis of changes in the angular coordinates at different nodes of the system over time.

Practical analysis of stability requires an answer not only to the question – 'Will there be a stability loss in case of a particular disturbance (finite or "infinitesimal")?', but also to the questions: 'In what cutset will this loss of stability occur and how does its spatial position depend on the properties of the system and disturbance?' Within the framework of such an extended formulation of stability problems, the issue of the spatial position of the cutset where the out-of-step conditions develop (the structure of unstable motion) becomes an integral part of the methods and algorithms of the study. Such a statement can be called the problem of analysis of disintegration processes of synchronous operation (synchronism) of power systems under disturbances (the structural stability analysis).

The issue of a structure of unstable motion is part of the more general issue of the spatial structure of electromechanical motion in a complex system. The spatial structure of motion (hereinafter referred to as the structure of motion) can be understood as the division of a system into regions (subsystems), within which the motion of components included in them at the time under consideration have some common qualitative feature. It is worth noting that this common feature should be determined not only for the rotors of synchronous machines but also for the voltage vectors at the nodes of the system. This makes it possible:

- to cover the entire space of the power system;
- to determine which pairs of connected nodes belong to different subsystems, i.e. to distinguish the ties between them, by determining the boundaries of the subsystems and their connectivity with others and, consequently, to build a topology of motion in the system.

Such a feature can be represented, for example, by the *sign of angle change* (between the voltage vector or the longitudinal axis of the synchronous machine rotor and the vector rotating at a speed of the center of the system inertia), which occurred from the emergency disturbance to the considered time.

The idea of the center of inertia of the power system was introduced in [5] and repeatedly used [6,7, etc.]. The velocity and motion of the center of inertia of the power system describe its general motion under the influence of disturbances. The characteristics of the motion of the inertia centers of the subsystems determined in one way or another were not used in the studies of transients and stability. A remarkable property of non-inertial systems of coordinates associated with the centers of inertia of the system and subsystems (zero total momentum of motions relative to the centers of inertia [8]), makes it possible to significantly simplify the calculations of kinetic and potential energy, determine their spatial distribution and qualitative composition (regional and local components) and, on this basis, analyze the processes of loss of synchronism.

The structure of motion is determined by many factors: the network structure of the system and the "rigidity" of connections, the distribution of inertial masses, the action of control systems, the location of the disturbance and its severity. It is an important characteristic of the transient process, whose development in time and space results (under stability loss) in the spatial structure of instability.

The processes of stability loss are closely related to the physical effects observed during electromechanical oscillations in the power system. These effects manifest themselves in *the spatial patterns* of the network (in the nodal space) of the power system. Computational studies allow us to establish five qualitative effects because power systems belong to the class of distributed oscillatory systems (in the format: effect - to the left, its cause – to the right):

1. A small number of free oscillations observed under any specific disturbances.

A small number of observed oscillations under disturbances in an extended system.	=	The resonance nature of the system response determined by the place of disturbance.

2. The phenomenon of oscillation dispersion caused by the concentration of rotating masses.

The farther the observation area from the emergency center, the later and slower the oscillations begin in it.	=	Low-frequency electromechanical oscillations propagate faster than high-frequency oscillations.

3. The wider spread of low-frequency oscillations.

The lower the frequency of oscillations, the greater part of the system experience them.	=	Low-frequency oscillations have longer wavelengths and greater penetration than high-frequency oscillations.

4. The oscillations in the system near its center of inertia occur in the form of motions of areas (subsystems), any adjacent of which move in opposite directions, i.e. the oscillatory motion is *wavelike distributed* throughout the system. As the transient process develops, the number and composition of subsystems, as well as the method of their integration by inter-regional ties, i.e. the structure (topology) of the observed oscillatory motion (its oscillatory structure), in general, change. This effect can be represented by the ratio:

Oscillations occur in the form of oppositely directed motions of adjacent areas (regions) of the system.	=	The topology of oscillatory motions is determined by their wave character.

5. The fifth qualitative effect is associated with a *possible change in the spatial position of the cutset with* primarily developing out-of-step conditions under a further increase in the disturbance severity, which leads to stability loss. This effect is naturally associated with the changes in the relationships between the conditions of the motion development along the limit (in terms of stability) paths in the extended power system, which contains a lot of *weak links* that appear in different places. These weak links manifest themselves through the development of instability under different values of the limit disturbance in the considered place of the system at different times. It appears that the observed structure of the primarily developing out-of-step condition is determined by the location of the weak link, which reaches the critical stability state first. This consideration can be represented as follows:

A change in the instability structure with a change in the disturbance severity.	=	A change in the location of the weak link that reaches the critical state first.

The basic idea of the structural stability analysis is the assumption that the instability is always associated with "weak" cutsets in the system, whose overload at dynamic or static variations in the conditions leads to instability. The manifestations of these weak links in the processes of stability loss can be associated with energy characteristics of the electromechanical transient process: its kinetic and potential energy and *the spatial distribution of these components* in the system.

Changes in the kinetic and potential energy of the system and its parts are determined by the trajectory of motion. When choosing the trajectories of the system motion, studied for stability, it is advisable to use trajectories, obviously dangerous for stability. Due to the fourth of the above-mentioned properties of electromechanical oscillations, it can be assumed that these trajectories should be chosen on the basis of studies of the structure of the oscillatory motion developing in the system under emergency.

The method used to study electromechanical processes and stability of power systems is based on an analysis of spatial-temporal characteristics of the system response to disturbing effects caused by wave processes in a distributed oscillatory system with lumped masses [9, 20]. The wave approach has been recently widely used to describe the motion of energy systems and to state the stability problems. However, despite the development of microprocessors and technologies for obtaining phasor measurements [10-12], the algorithms for emergency control to prevent stability loss in power systems [13] do not use the wave approach yet.

In the known studies devoted to the development of the wave approach [14-18], there are features that do not enable them to be fully used in the analysis of the processes related to the loss of synchronism. Firstly, the models with distributed mass are often used, which, generates an unlimited spectrum of frequencies and destroys dispersion when considering wave processes. Secondly, the concept of the structure of motion is not used, which significantly complicates the formulation of stability problems of complex power systems and solving them.

Thus, the kinetic energy and potential energy of the electromechanical transient process, defined in [17,18], are not associated with the structure of oscillatory motion, their distribution in the space of the power system and the effect of this distribution on stability are not considered. At the same time, the concept of the structure of motion is quite natural within the wave approach, which has the ability to operate positive and negative half-wave areas of the system. Thirdly, electromechanical waves are considered to analyze the propagation of disturbances in the running version, which makes it difficult to study the weak links of the system. Weak links of the system are easier to identify on the basis of standing waves. In addition, in general, these studies are intended for a mathematical description of electromechanical motion and instability processes, their physical content recedes into the background.

The application of the wave approach used in conjunction with the analysis of the structure of motion for the study of the processes of synchronism loss is the main content of this paper. The wave approach used to identify the structure of motion allows us to consider the processes from a physical point of view: namely, the loss of synchronism of the power system as a combination of the wave process of the oscillatory structure formation and the development of unstable motion between the arising objects of this oscillatory structure.

In [19-25], the authors present the main content of the approach used to study the processes of loss of synchronism in complex power systems. These studies are focused on:

-the structures of "small" standing electromechanical self-oscillations of extended power systems of different scale (hereinafter referred to as wave structures) [20];

- the algorithms for estimation of transient stability with the use of wave and oscillatory structures, based on energy relations (the equal areas method for the oscillatory structures of motion) [19,21,23,24];
- the statements and proposals for solving the problems of predicting the out-of-step conditions due to disturbances in the power system and identifying the out-of-step conditions of generators (the center of the swing is inside the synchronous machine) [22];
- the algorithms for identification of instability and location of an out-of-step cutset using the results of the integration of the equations of the mathematical model of the power system [25];
- the algorithms for selecting control actions of emergency control systems to ensure stability, using dynamic models of the control object [25].

The equal areas method is the most well-known and long-used method of dynamic stability analysis [1,2,26, etc.]. This method, used in this paper for oscillatory motion structures, is designed to search for limit transient disturbances that lead to the loss of transient stability between the subsystems of the oscillatory structure in the first and second cycles of swings. It is implemented by calculating [23, 24]:

- the relative velocities of motion of regional subsystems of the oscillatory structure after any disturbance (emergency scheme);
- the ascending branches of trajectories of regional displacement of subsystems of the oscillatory structure (with increasing mutual angles between the centers of inertia of the adjacent subsystems) in the pre-emergency scheme (coinciding with the post-emergency one) in the first and second cycles of swings (conditions on the ascending branch of the first cycle are determined by a staged change in the generator angles proportional to the relative velocities of their regional motion, the conditions of the second cycle of swings are calculated similarly for the opposite signs of relative velocities);
- the full (for zero duration of emergency) braking margins for the subsystems in the first and second cycles of swings until they reach the maximum displacement identified by the appearance of a positive time derivative of the total kinetic energy of regional motion;

- the acceleration work of subsystems in the emergency scheme by calculating a series of conditions under changes in the generator angles proportional to their regional relative velocities;
- the conditions (full kinetic energy of oscillations, acquired by the system in emergency conditions, the maximum duration of the emergency, structure of instability) under which the acceleration work of the subsystems can be compensated by the remaining braking work in the first cycle or braking margin in the second cycle of swings.

As in the classical equal areas method, modeling of the power system is simplified (synchronous machines are represented by constant EMF behind transient reactance, the differential equations of rotor motion do not allow for the damping torque). The load can be represented by shunts and static voltage characteristics. All calculations are carried out for the complete scheme of the power system.

Below we consider two statements for the nonlinear problem of studying the processes of the loss of synchronism in an electric power system:

1. *Forecast of possible options of the synchronism loss* for some set of disturbances to make a general overview of the stability problems.

2. *Identification of the synchronism loss* during the transient process and determination of its characteristics under specific topology and operating conditions.

The first of them is based on the method of equal areas for oscillatory motion structures, does not require calculations of electromechanical transients and is designed to:
- estimate the conditions for the development of unstable motion (determination of limit disturbances);
- determine instability structures at disturbances in different places of the power system;
- identify actual cases of changes in the instability structure with an increase in the emergency severity;
- estimate time characteristics of unstable processes to formulate the requirements for emergency control systems;
- determine the requirements for the speed of relay protection and switching devices.

The second solution can be used to:
- construct automatic emergency control systems that employ a *dynamic mathematical model of the system of any complexity* when selecting control actions to ensure the stability of complex power systems;
- visualize the power system modeling results (to display the motion of the emerging subsystems) by computer software for the calculation of electromechanical transients;
- identify the structure of the power system (or its part) motion based on the phasor measurements used to control it.

The results of the research are presented in Sections 2, 3 and 4 of the paper. In Section 2, we propose a hierarchical structure of coordinate systems for describing the motion of synchronous machines. The power and energy characteristics of the motion of the power system divided into subsystems in the coordinate systems associated with the center of inertia of the system and the centers of inertia of the subsystems are determined. The idea of system-wide, regional and local processes is introduced. An emphasis is placed on the independence of the system-wide energy characteristics of motion and the total energy of oscillations from the assumed subdivision into subsystems.

Section 3 presents the basic concepts and algorithms to identify the instability structures in the case of transient disturbances of the considered steady-state conditions in a power system give an overview of the composition of the stability problems. Since the calculations are of an assessment nature (carried out without integration of the equations of the mathematical model of the system), the structures of the motion coincide with the wave (oscillating) structures of "small" oscillations excited in case of an emergency in the considered place of the system. In this case, it is assumed that the "weak" ties of the system are sufficiently fully represented by the intersystem cutsets of wave structures describing "small" standing electromechanical waves of different frequencies in the power system with "off" damping.

Section 4 presents algorithms for tracking the development of the oscillatory structure of motion when integrating the equations of the mathematical model of the system used, a method for locating the cutset with out-of-step conditions and the energy characteristic of instability, i.e. the excess kinetic energy of an unstable pair of subsystems.

II. The structure of the motion and its power and energy characteristics

We introduce a formal representation of the *structurally organized motion* of power systems. Let us divide a set of nodes of the power system into a number of subsets. The nodes included in one of these subsets will be assigned to some subsystem. We will divide the system into subsystems so that each node of the system is included in only one subsystem, and, in addition, let all nodes of the subsystem form a simply-connected region on a network graph of the system. The system links that connect the subsystem nodes with each other will be called the internal ties of the subsystem. The links connecting the nodes from different subsystems will be referred to as intersystem ties. The resulting partition of the system into subsystems and intersystem ties connecting them represents a structural presentation (**structural model**) of the system.

To simplify, the structural model will be called the "structure" of the system S (which must be distinguished from the usual network structure). The number of subsystems included in the structure gives its dimension *R(S)*. It is clear that one and the same system can be represented by a set of its structural presentations (structures).

Let the motion of the system be known, i.e. all coordinates of the system are known as functions of time.

Let the rotation speed of the i-th synchronous machine be represented by a sum of constant component (rotation frequency in the initial conditions) and *three relative processes*:

$$\Omega_{gi}(t) = \Omega_0 + \Delta\Omega_{gis}(t) + \Delta\Omega_{s0}(t) + \Delta\Omega_0(t), \quad (1)$$

where:

$$\Omega_0 = \Omega_0(0),$$

$$\Delta\Omega_0(t) = \Omega_0(t) - \Omega_0,$$

$$\Delta\Omega_{s0}(t) = \Omega_{s0}(t) - \Omega_0(t),$$

$$\Delta\Omega_{gis}(t) = \Omega_{gi}(t) - \Omega_{s0}(t),$$

$$\Omega_0(t) = \frac{\sum_i J_i \Omega_{gi}(t)}{\sum_i J_i}, \quad \Omega_{s0}(t) = \frac{\sum_{i_s} J_i \Omega_{gi}(t)}{\sum_{i_s} J_i}.$$

The following symbols are introduced here: $\Omega_0(t)$ - the velocity of the center of inertia of the system, $\Omega_{s0}(t)$ - the velocity of the center of inertia of the subsystem to which this synchronous machine is assigned, i, i_s - the set of active (generator) nodes in the whole system and in the s-th subsystem, J_i - moment of inertia of the i-th synchronous machine, $\Delta\Omega_0(t)$ - the deviation of the velocity of the center of inertia of the system at time t from the initial one in the steady state Ω_0 (the highest level of the motion hierarchy), $\Delta\Omega_{s0}(t)$ - synchronous motion of the subsystem - *regional process*, determined by the deviation of the velocity of the center of inertia of the subsystem relative to the velocity of the center of inertia of the system (the average level of the hierarchy of motion), $\Delta\Omega_{gis}(t)$ – individual motion - *the local process* of motion of a synchronous machine in the s-th subsystem relative to its center of inertia (the lowest level of the motion hierarchy).

The motion of the system, described by the introduced three-stage hierarchical system of relative processes, will be called *structurally organized*. The structural organization of the system leads to the allocation of objects at different levels: the system as a whole, subsystems and individual synchronous machines. Depending on the system structure, the same motion of the system will be structurally organized in different ways (will have different forms of structural organization). As can be seen from the above relations, the component of the motion of the center of inertia of the system remains unchanged with the variation in the system structure.

It is possible to represent the absolute motion of rotor of the synchronous machine $\delta_{gi}(t)$ at time t as a sum of components

$$\delta_{gi}(t) = \delta_{gi}(0) + \Omega_0 t + \int_0^t \Delta\Omega_0(t)dt + \int_0^t \Delta\Omega_{s0}(t)dt + \int_0^t \Delta\Omega_{gis}(t)dt =$$
$$= \delta_{gi}(0) + \delta_0(t) + \Delta\delta_0(t) + \Delta\delta_{s0}(t) + \Delta\delta_{gis}(t), \quad (2)$$

where $\delta_{gi}(0)$ - initial value, $\delta_0(t)$ - the displacement of the center of inertia of the system at a constant velocity of its motion, $\Delta\delta_0(t)$ - the relative motion of the center of inertia of the system due to changes in the velocity of its motion in the interval (*0-t*), $\Delta\delta_{s0}(t)$ - the angular displacement of the center of inertia of the subsystem relative to the center of inertia of the system, $\Delta\delta_{gis}(t)$ - the angular displacement of the synchronous machine in the s-th subsystem relative to the center of inertia of the same subsystem.

It follows from the introduced definitions that if each generator of the system is assigned to a particular (but only one) subsystem, then, regardless of the method of splitting the system into subsystems, the total momentums of relative (near the centers of mass) motions of subsystems in the system and synchronous machines in subsystems are zero:

$$\sum_s J_s \Delta\Omega_{s0}(t) = 0, \sum_{i_s} J_i \Delta\Omega_{gis}(t) = 0 \quad \text{for all } s. \quad (3)$$

where $J_s = \sum_{i_s} J_i$ - total moment of inertia of the subsystem.

Differentiation and integration of (3) give the corresponding relations for relative accelerations and relative angular displacements

$$\sum_s J_s \frac{d(\Delta\Omega_{s0})}{dt} = 0, \ \sum_{i_s} J_i \frac{d(\Delta\Omega_{gis})}{dt} = 0, \quad (4)$$

$$\sum_s \int_0^t J_s \Delta\Omega_{s0}(t)dt = \sum_s J_s \Delta\delta_{s0}(t) = 0,$$
$$\sum_{i_s} \int_0^t J_i \Delta\Omega_{gis}(t)dt = \sum_{i_s} J_i \Delta\delta_{gis}(t) = 0. \quad (5)$$

Taking into account the relations for the total momentums in the coordinate systems of the centers of inertia of systems and subsystems allows us to obtain the equations of motion of individual objects of the structure. The motion of the center of inertia of the system satisfies the equation

$$J_E \frac{d(\Delta\Omega_0)}{dt} = \Delta M_E, \quad (6)$$

where ΔM_E is the total excess torque on the shafts of machines in the system.

The equation of relative motion of the center of inertia of the s-th subsystem in a non-inertial system associated with the center of inertia of the system can be written as follows

$$J_s \frac{d(\Delta\Omega_{s0})}{dt} = \Delta M_s - \frac{J_s}{J_E} \Delta M_E \quad (7)$$

The value $\Delta M_{s0} = \Delta M_s - \frac{J_s}{J_E}\Delta M_E$ is an excess torque acting on the subsystem at its relative motion near the center of inertia of the system. It follows from the definition of ΔM_{s0} that $\sum_s \Delta M_{s0} = 0$. The torques ΔM_s act on subsystems in their absolute motion.

The equation of motion of the synchronous machine relative to the center of inertia of the subsystem, in which it is included, is

$$J_i \frac{d\left(\Delta\Omega_{gis}\right)}{dt} = \Delta M_i - \frac{J_i}{J_s}\Delta M_s \qquad (8)$$

The value $\Delta M_{is} = \Delta M_i - \frac{J_i}{J_s}\Delta M_s$ is an excess torque acting on the synchronous machine at its relative motion near the center of inertia of the subsystem the machine belongs to. For the sums ΔM_{is} and ΔM_i for all machines in the subsystem, the ratios are performed $\sum_{i_s}\Delta M_{is} = 0, \sum_{i_s}\Delta M_i = \Delta M_s$.

The excess torques ΔM_i affect the synchronous machine in their absolute motion.

The total kinetic energy of the system $K(t)$ at time t is the kinetic energy in the steady state K_0 plus additional kinetic energy $\Delta K(t)$ gained during the transient period (*0 - t*), i.e. $K(t) = K_0 + \Delta K(t)$. The additional kinetic energy of the system $\Delta K(t)$ consists of the contributions of individual synchronous machines $\Delta K_i(t)$: $\Delta K(t) = \sum_i \Delta K_i(t)$.

When summing (given the relations (3)), we obtain the kinetic energy of the system in a transient process, expressed through the variables that define the structurally organized motion (9):

$$K(t) = K_0 + \sum_s\sum_{i_s} J_i \frac{\Delta\Omega_{gis}^2(t)}{2} + \sum_s J_s \frac{\Delta\Omega_{s0}^2(t)}{2} + J_E \frac{\Delta\Omega_0^2(t)}{2} + \Omega_0 J_E \Delta\Omega_0(t)$$

The additional total kinetic energy $\Delta K(t)$ is divided into components (10):

$$\Delta K(t) = \sum_s K_{locs}(t) + \sum_s K_{regs}(t) + K_{sys}(t) = K_{loc}(t) + K_{reg}(t) + K_{sys}(t),$$

where K_{loc}, K_{reg}, K_{sys} - kinetic energies of *local* oscillatory processes in subsystems, *regional* oscillatory processes in the system and general motion in the *translational degree of freedom*. The last component is represented by the expression

$$K_{sys}(t) = \Omega_0 J_E \Delta\Omega_0(t) + J_E \frac{\Delta\Omega_0^2(t)}{2}. \qquad (11)$$

The component K_{locs} characterizes the intensity of internal motions in subsystems, their "heating”. The component K_{regs} determines the proportion of the kinetic energy of oscillations sent to the oscillatory motion of a region, considered as a whole.

The components K_{loc}, K_{reg} characterize the processes due to the *oscillatory degrees of freedom*, they equal zero at synchronous motion in the entire system. The sum of the components

$$K_{osc} = K_{reg} + K_{loc} = \sum_s J_s \frac{\Delta\Omega_{s0}^2(t)}{2} + \sum_s\sum_{i_s} J_i \frac{\Delta\Omega_{gis}^2(t)}{2} \qquad (12)$$

determines the total *kinetic energy* of the system oscillations. The latter relationship can be interpreted as a *spatial decomposition* of the kinetic energy of oscillations.

Since the total kinetic energy of the system in a transient process and its component determined by translational motion, do not depend on the structure of the system, the sum $K_{osc} = K_{loc} + K_{reg}$ does not depend on the partition of the system into subsystems either. In the event of variation in the structure of the system, only the relationship between the kinetic energy of local and regional processes K_{loc} K_{reg} will change.

Based on the equations for relative motion, we write the following relationships between the work and the changes in kinetic energy for the objects (system -subsystem- synchronous machine)

$$\int_{t_0}^{t} d\left(J_E \frac{\Delta\Omega_0^2}{2}\right) = \int_{\Delta\delta_0(t_0)}^{\Delta\delta_0(t)} \Delta M_E d\left(\Delta\delta_0\right), \qquad (13)$$

$$\int_{t_0}^{t} d\left(J_s \frac{\Delta\Omega_{s0}^2}{2}\right) = \int_{\Delta\delta_{s0}(t_0)}^{\Delta\delta_{s0}(t)} \Delta M_{s0} d\left(\Delta\delta_{s0}\right), \qquad (14)$$

$$\int_{t_0}^{t} d\left(J_i \frac{\Delta\Omega_{gis}^2}{2}\right) = \int_{\Delta\delta_{gis}(t_0)}^{\Delta\delta_{gis}(t)} \Delta M_{is} d\left(\Delta\delta_{gis}\right). \qquad (15)$$

The right-hand parts of relationships (13 – 15) determine the work performed during the motion of the system objects. It can be associated with changes in the potential energy on their trajectories.

Similar relationships can be obtained with the introduction of a four-step hierarchy of motions with the selection of objects: system-platforms (zones) - subsystems-synchronous machines.

III. THE FORECAST OF THE SYNCHRONISM LOSS OPTIONS UNDER SHORT-TERM TRANSIENT DISTURBANCES

Possible instability development in different cutsets of a power system even with the unchanged location of the emergency center determines the necessity of introducing a concept of a spectrum *of limit disturbances of dynamic stability*. This is an energy spectrum. To determine the spectrum of limit disturbances means to estimate the minimum energy characteristic of the transient process accompanied by stability loss, in which case each structure of the excited instability will correspond to its energy index.

The processes of stability loss of the mutual motion on small time intervals (in the first and second cycles of swings) are essentially connected with the first, fourth and fifth of the above-mentioned properties of the power system as a distributed oscillatory system. The second and third properties on these time intervals do not have time to manifest themselves. They will begin to play a significant role in the processes of stability loss at more distant time instants (in the third, fourth, etc. cycles of swings).

The first property determines *the composition of the excited oscillators of the system* [19, 21] under considered disturbance, while the fourth and fifth properties jointly identify a system object winning the "race" to the loss of synchronism. A comparison of the instability options involves the determination and comparison of the following indices:

- the magnitude of the limit disturbance in terms of stability (the energy characteristics of limit disturbances);
- the time of the unstable motion development;
- the spatial configuration of instability (locations of out-of-step cutsets).

Figure 1 shows typical *small-size oscillating structures* taken from low-, medium - and high-frequency parts of the spectrum of "small" electromechanical self-oscillations of power systems [20] (they were obtained considering power systems of various sizes with the number of synchronous machines varying from units to hundreds). The numbered circles denote inphase moving groups of synchronous machines-subsystems, the straight lines stand for dynamic cutsets. For the oscillating structures, the inertia of subsystems is demonstrated by the change in the radius of a circle symbolizing the subsystem, proportionally to the cubic root of its total rotating mass.

The small-size oscillators of the system are its "weak" links represented by intersystem cutsets. Their manifestations through the processes of loss of stability under specific disturbances are determined by modeling the oscillatory structures of the motion (models of motion) developing in each of them. The identification of subsystems of model oscillatory structures on a particular oscillator under a specific disturbance in the system [19, 21] has a simple physical meaning: a subsystem is a connected region of the system in which all the subsystems of the oscillating structure move in one direction relative to the center of inertia of the system.

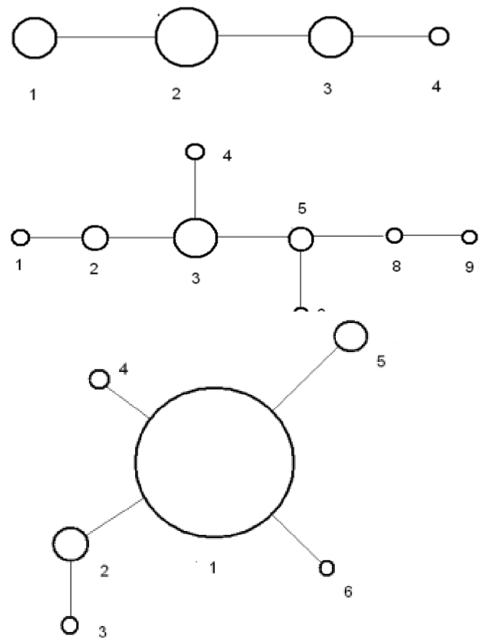


Figure 1. Examples of oscillating structures of power interconnections.

During its motion, the system is divided into subsystems maximum possible in terms of size within which the maximum attainable synchronism is provided. Opposite displacement of adjustment subsystems of the oscillatory structure is a precondition for instability of their mutual oscillations as whole structural entities. The maximum sizes of the subsystems mean that the study on the processes of loss of the intersystem stability of mutual motion in a given model oscillatory structure does not need a more detailed structural representation of the system by a larger number of subsystems.

Model oscillatory structures are distinguished on oscillating structures of power systems coinciding with the wave structures of "small" oscillations of different frequencies [20]. The oscillation frequency can be used as the "name" of the oscillator [19, 21]. The consideration of the first of the power system properties as a distributed oscillatory system is reduced to the use of oscillators associated with the regional spectra of small oscillations. This is achieved by specifying the support nodes of the application of the forcing harmonic action in the part of the system where the considered emergencies occur [20-22]. The model oscillatory structures constructed on the system oscillators characterizing the structures of “small” oscillations near the equilibrium point in the pre-emergency conditions can be used to describe the free motion of the system after the elimination of the disturbing effect.

The determination of the stability limit disturbances requires the calculation of the work under mutual oscillations in the system. The equations of energy balance at oscillations of objects of various hierarchical levels on time interval (t_0 – t) have the form (13 – 15). Integrals of (13-15) must be calculated on the trajectories of the system, i.e. at angular coordinates, velocities, and voltages that satisfy the equations of transient process of the system. Let all coordinates and corresponding velocities of relative motion of all objects of the system (subsystems and individual synchronous machines within the subsystems), and, consequently, all unbalances of moments, be known at some time t_0. The differentials of the system variables at any time are determined by the equations of motion.

$$d\left(\Delta\delta_{s0}\right) = dt \cdot \Delta\Omega_{s0}(t), \qquad d\left(\Delta\delta_{gis}\right) = dt \cdot \Delta\Omega_{gis}(t), \tag{16}$$

$$d\left(\Delta\Omega_{s0}\right) = \frac{dt}{J_s}\Delta M_{s0}(t), \qquad d\left(\Delta\Omega_{gis}\right) = \frac{dt}{J_i}\Delta M_{is}(t). \tag{17}$$

The procedure of integration of the equations of motion and calculation of the work is reduced to the summation of the differentials of variables and elementary work (products of unbalances of moments and the differentials of displacements).

The observer of the system motion, being in the situation that has developed by the time t_0, is not able to determine what margin of change in the potential energy of the system remains until the loss of stability. The reason for this is that the calculation of the work requires knowledge of the system trajectory, i.e. the integration of the equations of motion at $t > t_0$. However, some estimation of this margin can be made on the basis of the assumption about the smallness of the change in the object velocities (i.e. object velocities can be considered constant). Fixation of the object velocities at the time t_0 allows us to predict the change in system angles in the simplest way, i.e. to determine their differentials without integration of the equations of motion [19].

In fact, this procedure is reduced to stopping the integration process at time t_0 and calculating the work under the predicted uniform motion of objects (i.e. along the trajectory that continues the actual trajectory after the time instant t_0). It is clear, that to correctly determine the moments acting in the system at each point of such a trajectory, the balance equations of active and reactive power at the nodes of the system must be satisfied. Such trajectories, satisfying only the laws of conservation of momentum of relative motions near the centers of inertia (3) and the equations of power balance, will be called possible [19, 23, 24]. On a possible trajectory, the equation of motion may not be satisfied. It appears that the invariability of the objects velocities along a possible trajectory is not necessary. It is enough to ensure their proportionality on this trajectory (not constant speed of the objects, but the relationship between them).

The appearance of the extremum of the function that determines the dependence of the potential energy change in the displacement of the object in question $\Delta W_{ob}(\Delta\delta_{ob})$ gives an estimate of its limit value and critical angle. If the kinetic energy of the object at time t_0 exceeds the estimated margin of the potential energy variation, then we can expect stability loss at an angular displacement close to the critical one, in a time interval [8, 21-24]

$$\Delta T = \int_{\Delta\delta_{ob}(t_0)}^{\Delta\delta_{crit}} \frac{d\Delta\delta_{ob}}{\sqrt{\frac{2}{J_{ob}}}\sqrt{K_{ob}(t_0) - \Delta W_{ob}(\Delta\delta_{ob})}}, \tag{18}$$

where $K_{ob}(t_0)$ – kinetic energy of the object at the time t_0, $\Delta W_{ob}(\Delta\delta_{ob})$ – change in the potential energy of the object as a function of its deviation from its position at time t_0. If $K_{oб}(t_0)$ is selected equal to the change in potential energy that occurs from the initial position to its extreme value, at which $K_{ob}(t) = 0$, the motion on the interval (t_0 – t) will be along the limiting trajectory, where the stopping point coincides with the time when the potential energy extremum is reached. These estimates can be used to make control decisions to ensure stability at time t_0.

These considerations can form the basis of the algorithms designed to estimate the parameters of limit shock disturbances. A momentum disturbance is characterized by the values of velocity deviations at the time of disturbance elimination Δt, which determine the distribution of changes in the momentum and kinetic energy of objects in the system.

The distribution of momentum across the system (i.e. the relationships between the momentums of different objects) depends mainly on the place of application of the disturbance. If we focus on a specific distribution of the momentum at some severity of the test disturbance that does not lead to a stability loss, the increase in its severity can be modeled by a proportional increase in the amplitude of the momentums of objects due to an increase in the duration of the emergency. The severity of the test disturbance is characterized by the kinetic energy of oscillations, which is acquired by the system during the interval of the momentum action

$$K_{first}^{test}\left(\Delta t\right) = K_{reg}^{test}\left(\Delta t\right) + \sum_{s} K_{loc}^{test}\left(\Delta t\right). \tag{19}$$

Let us consider a possible trajectory of motion that begins at the moment t_{+0} (characterized by the momentums of objects at this time) and continues until the stability loss. The object, whose potential function of displacement reaches the extremum first, is the culprit of the stability loss. The extreme value of the potential function of an unstable object shows the value of the maximum kinetic energy of oscillations to be transferred to this object by the disturbance at the initial time to cause its instability. Knowing the kinetic energy of the object that leads to stability loss, we can determine the corresponding momentum of this object. The ratio between the object momentum limiting in terms of stability at the initial time and the object momentum calculated with a test disturbance $\beta_{ob}^{\lim}$

$$\beta_{ob}^{\lim} = \frac{J_{ob}\Delta\Omega_{ob}^{\lim}}{J_{ob}\Delta\Omega_{ob}^{test}} = \frac{\Delta\Omega_{ob}^{\lim}}{\Delta\Omega_{ob}^{test}}, \quad (20)$$

shows the relationship in which the momentums of all objects should change when the severity of the test disturbance changes to the level necessary for the loss of stability of the object in question. Then the value of the limit disturbance (the maximum kinetic energy of oscillations) can be determined based on the information about the test disturbance

$$K_{first}^{\lim}(\Delta t) = \left(\beta_{ob}^{\lim}\right)^2 K_{reg}^{test}(\Delta t) + \left(\beta_{ob}^{\lim}\right)^2 \sum_s K_{loc}^{test}(\Delta t). \quad (21)$$

We will first dwell on the estimation of maximum momentum disturbances in the first cycle of swings. This means that the consideration is given to the processes of the first quarter of the oscillation period, during which the maximum angular displacement of objects relative to the initial position occurs. The result of the momentum action is the formation of a momentum distributed across the system $J_i\Delta\Omega_{gi} = \Delta M_i \Delta t$ by the time of the restoring switching Δt. With the known distribution $J_i\Delta\Omega_{гi}$, we determine $\Delta\Omega_O(\Delta t)$ – variation in the velocity of the center of inertia of the system and the magnitude $\Delta\Omega_{iO}(\Delta t) = \Delta\Omega_{гi} - \Delta\Omega_O(\Delta t)$ – deviations of the machine rotational velocities from the center of the inertia of the system. These deviations determine free motions in translational ($\Delta\Omega_O(\Delta t)$) and in oscillatory ($\Delta\Omega_{iO}(\Delta t)$) degrees of freedom of the system, respectively.

Since only the relationships between the momentums are important for the calculations, the magnitude Δt, unknown in advance, can take any value (when it changes, the relationships between the momentums of objects do not change). In practical calculations, it is convenient to choose it equal to unit. Emphasizing this circumstance, we denote this value as Δt_{calc}.

Let us choose one, for example, the *k*-th oscillatory degree of freedom and corresponding oscillator. Oscillatory impulses $J_i\Delta\Omega_{iO}$ split between its synchronous and local motions. This means that each of the subsystems of the corresponding oscillator acquires a certain impulse with its sign and amplitude. Since we consider a certain disturbance, in the general case, the adjacent subsystems acquire the momentums that are not necessarily of an opposite sign. The oscillatory structure of motion for this emergency, characterized by antiphase motions of the adjacent subsystems, is obtained from the oscillating structure after the merger of its adjacent subsystems with the same momentum signs. The kinetic energy of the oscillatory motion under this disturbance will be divided into regional and local components

$$\Delta K_{osc}(\Delta t_{calc}) = \Delta K_{reg}(\Delta t_{calc}) + \sum_s \Delta K_{locs}(\Delta t_{calc}), \quad (22)$$

what is characterized by the ratio N_k: $N_k = \frac{\Delta K_{reg}(\Delta t_{calc})}{\Delta K_{osc}(\Delta t_{calc})}$, that determines the proportion of regional (synchronous) motions of the considered structure in the kinetic energy of oscillations. The distribution of the oscillation energy between synchronous machines of the system can be considered in terms of various oscillators of the system, in each of which the weight coefficient of the energy of synchronous motions is determined. We can assume that the oscillators in which the weight of synchronous motions has the maximum value, will belong to the dominant part of the excited oscillators. In this case, it means that these oscillators maximally resonate with the disturbance distributed in the form of a momentum.

In the event that the assessment reveals an instability structure, the value Δt_{emerg} of the duration of the considered emergency leading to a loss of stability is determined with the revealed structure of motion. The relationship $\beta = \frac{\Delta t_{emerg}}{\Delta t_{calc}}$ shows in what ratio the momentums of the objects of the oscillatory structure must change at the initial time in order to cause a loss of stability with this structure of unstable motion. This allows us to estimate the maximum kinetic energy of oscillations in terms of stability $\Delta K_{osc}^{\lim}$, which the disturbance should give to the oscillatory degrees of freedom of the system for the stability loss to occur with the revealed structure of motion

$$\Delta K_{osc}^{\lim}(\Delta t_{emerg}) = \beta^2 \left[\Delta K_{reg}(\Delta t_{calc}) + \sum_s \Delta K_{locs}(\Delta t_{calc})\right]. \quad (23)$$

In the described algorithm the emergency is represented as a short-term impulse action, during which the moment imbalances remain unchanged.

The assumption about the constancy of the moment imbalances makes it possible to approximately determine the kinetic energy of the oscillations $\Delta K_{osc}(\Delta t)$, input to the system in case of an emergency (independent of the system structure) as a quadratic function of its duration Δt

$$\Delta K_{osc}(\Delta t) = 0.5\sum_i J_i \Delta\Omega_{i0}^2(\Delta t) = 0.5\left(\sum_i \frac{\Delta M_i^2}{J_i} - \frac{\Delta M_E^2}{J_E}\right)\Delta t^2. \quad (24)$$

The coefficient at the squared time interval Δt^2 in (24) characterizes the susceptibility of the oscillatory degrees of freedom of the system to the emergency and determines the processes of kinetic energy accumulation in them.

An important characteristic of an unstable motion is the time necessary to achieve critical displacements after elimination of limit disturbance in terms of stability. This value can be determined with the help of relationship (18), in which the kinetic energy is equal to a certain maximum kinetic energy of the subsystems of the instability structure, and the potential energy is equal to the braking work (taken win an opposite sign) performed on the way of these subsystems after elimination of the emergency before they reach the limiting displacements. In addition, we can similarly calculate the time to reach the limiting displacement for the disturbances beyond limits.

Having carried out similar calculations for other oscillators of the system, we obtain an estimate of the spectrum of limit disturbances in the considered place of the system that lead to stability loss in various cutsets s_i of the power system in oscillators named *«f_i»*. It is convenient to display the calculation results for multiple oscillators on an energy-time diagram. An example of such a diagram is shown in Figure 2 for three dominant oscillations of a certain power system (115 nodes, 33 synchronous machines) at a short circuit in a selected node.

The spectrum of "small" self-oscillations of this system contains 32 components. The oscillations of the first ten of them have non-star-like structures. The horizontal line segments show the energy levels of the kinetic energy of the oscillations, which the system must have after switching off the short circuit for the development of instability of various oscillators (energy levels of excitation of the instability structures of oscillators). The length of these segments shows the time that will pass after the short circuit is switched off until the moment of stability loss under the limit disturbance. With the disturbances beyond the limit, the time to reach the critical point decreases (energy-time "tails" of the beyond–limit disturbances that are directed upwards and to the left appear in each horizontal line). The cutsets of instability structures are given in the form of numbers of subsystems of oscillating structures between which this cutset is located. The parabola going from zero shows the dependence of the acquired kinetic energy of oscillations on the duration of the emergency.

An analysis of the cutsets of the three obtained instability structures in the electrical network of the system shows that for the considered emergency all of them coincide (this is the same cross section). As is seen from the Figure, with a short circuit lasting less than ~0.2 seconds, the stability loss will not occur. With an increase in the short circuit duration above 0.2 sec, the stability loss associated with the oscillations of the oscillating structure of 1,6884 Hz, will manifest itself in the first place. The Figure also demonstrates that with a short-circuit duration of ~0.2 seconds, the stability will be lost in ~1.5 seconds after the short-circuit clearing, i.e. there is a time resource for emergency control to maintain stability, equal to 1.5 seconds. Accordingly, with the growth of the short circuit duration, this time resource is reduced. Testing the obtained results by direct calculation of the transient process shows their good match, both in terms of the short-circuit duration limit, and the location of the out-of-step cutset.

If we assume that the oscillatory structures of the spatial oscillators in the second cycle of oscillations coincide with the oscillatory structures of the first cycle, and the momentums of the subsystems only change sign, then it is also possible to estimate the stability loss conditions in the second cycle. The algorithm for this calculation does not differ much. The differences are only in calculating the time when the subsystems of the instability structure reach the limiting displacements, since in this case it is necessary to take into account the time spent on the first cycle.

Figure 3 shows the energy-time diagram of instability in the first and second swing cycles, calculated at a short circuit at another node of the same power system. Two dominant oscillating structures were considered, and it appeared for one of them (1.5521 Hz) that the stability could be lost in the second cycle. The corresponding curve is shown as a dotted line. It is seen that the instability in the second cycle of the cutset 1 – 4 of this structure develops over a long period of time.

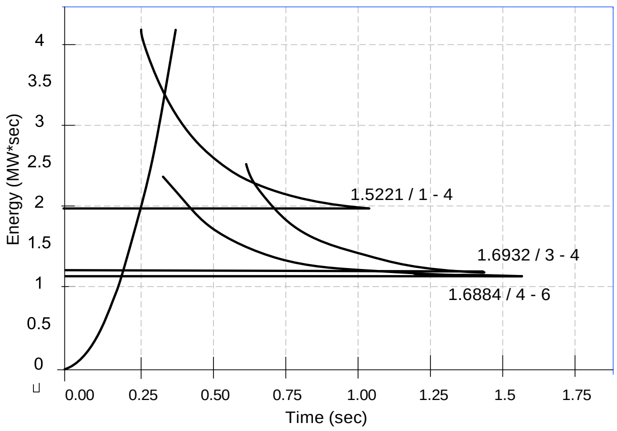


Figure 2. Time-energy diagram of instability.

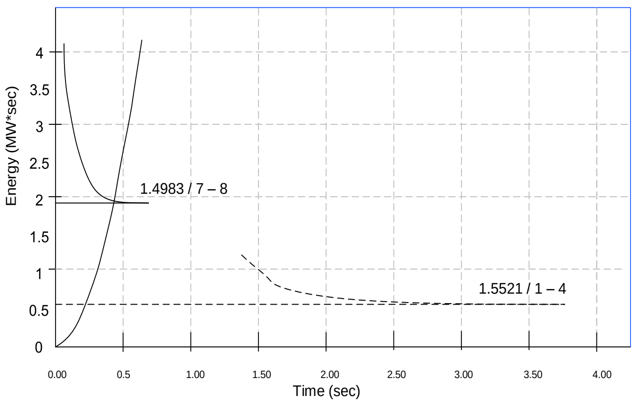


Figure 3. Time-energy diagram of instability in the first and second swing cycles.

With a larger magnitude of disturbance sufficient for the instability development in the first cycle, the instability will be observed in the form of a rapid development of the out-of-step conditions in the cutset 7 – 8 of the spatial oscillator 1,4983 Hz that does not coincide in the network with the previous cutset.

The instability characteristics shown in Figure 3 can be confirmed by the calculation of transient processes in a sufficiently complete simulation of the power system (taking into account speed controllers, power system stabilizers and excitation systems, damping rotor circuits). In Figure 4, the results of calculation of the transient process in the power system is represented by hodographs of voltage vectors at different nodes of the system (only a fragment of its scheme is shown). The transient process is caused by the 0.2 s connection of a short circuit shunt at node 5220 (the short circuits at this node are represented by the energy-time diagram in Figure 3). The hodographs show that the out-of-step conditions in the system are developing in the cutset formed by lines 2200-4202 and 4201-4203. Since nodes 4202 and 4203 are located practically in the centers of oscillation, lines 4205-4202 and 4205-4203 can also be considered to be the out of step cutset (adjacent cutset). The state shown in the Figure is reached in 3.3 second after connecting the short-circuit shunt.

Figure 5 demonstrates the calculation results for the transient process in the same scheme (the initial conditions) in case of a short circuit at the same node when it lasts 0.35 s. In the system, the out-of-step conditions are developing in the cutset constructed from the lines 5128-5122 and 5128-5126 (or 5122-5124 and 5126-5124). The state fixed in the Figure occurred in 1.1 s after connection of the short- circuit shunt.

In both examples, the voltage vectors in the out of step part of the system rotated a little more than one complete revolution with respect to the reference axis of the angles (which is represented by the longitudinal axis of rotor of the most powerful synchronous machine in the system). Considering the motion of the voltage vectors to the loss of stability, it can be established that in the first case this disturbance occurs in the second cycle of swings, and in the second – in the first cycle. With an intermediate value of the short circuit duration (between 0.2 and 0.35 sec.), the out-of-step cutset does not change its position and coincides with the first of the above cases. When the short circuit lasts less than 0.2 s no loss of stability is observed.

Out-of-step cutsets obtained by constructing energy-time diagrams coincide with one of the cutsets identified in the calculation of the transient process in the considered emergencies. The situation presented in Figure 3 determines the change in the position of the out-of-step cutset with an increase in the severity of the disturbance at some place of its location. It refers to the cases in which this change is associated with instability at different swing cycles. Such effects, however, can sometimes be observed within one swing cycle (usually, not the first). In this case, a more energy-intensive instability case outpaces the development of a less energy-intensive one, and the out-of-step cutset is usually situated closer to the emergency site.

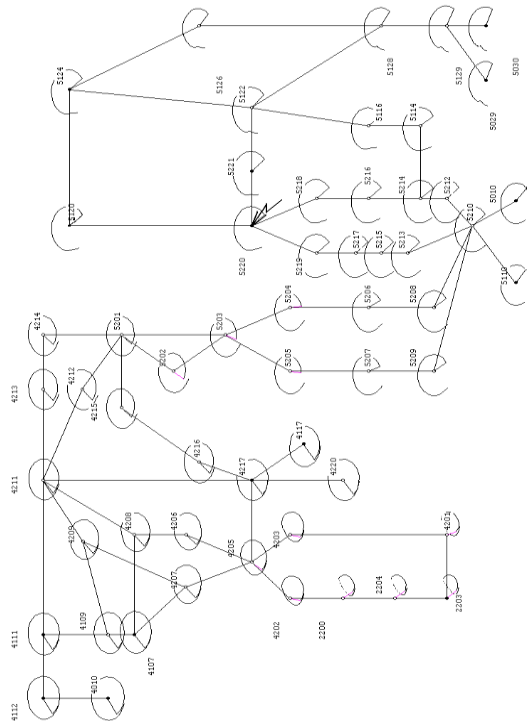


Figure 4. Stability loss in the system under a short circuit at node 5220 with a duration of 0,2 second.

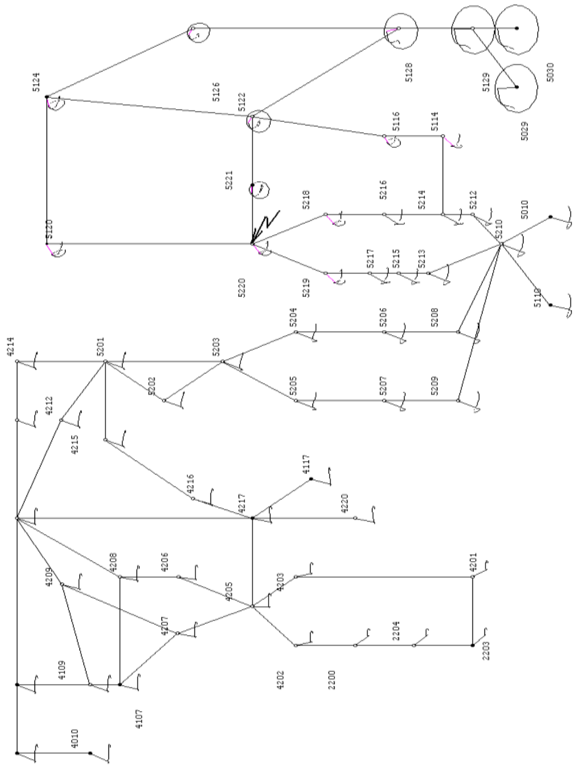


Figure 5. Stability loss in the system under a short circuit at node 5220 with a duration of 0,35 second.

The described algorithm for estimation of limiting impulse disturbances is, in fact, an extension of the known equal areas method to the oscillatory structures, which can contain more than two subsystems. The use of a possible trajectory of motion allows us to calculate the kinetic energy stored in the stage of emergency condition in the objects of the oscillatory structure suitable for describing the motion after the emergency elimination (after restoring switching), based on the calculation of the work on the motion of these objects in emergency conditions. In this case, for the impulsive transients, the oscillatory structure of the post-emergency condition is based on the oscillatory structures of the pre-emergency scheme. The damping of the acquired kinetic energy is determined by the calculation of braking work of these objects in the post-emergency conditions [23, 24]. These publications describe in more detail the method of calculations and their results for a particular system, up to the construction of power characteristics in the power-angle coordinates for the cutset with developing out-of-step conditions.

IV. The Research on the Process of Synchronism Loss in a Power System Based on Integration of Its Equations of Motion

In addition to survey studies on stability, it is necessary to analyze the conditions of development and characteristics of unstable motion in terms of specific network structure, operating conditions, and emergency situations. This can be done in detail in the simulation of electromechanical transients in the power system based on the calculation of its equations of motion [25]. The resulting trajectories of the system satisfy the equations of the mathematical model and they can be attributed, on this basis, to the actual trajectories of motion. In this case, it is assumed that the mathematical model is adequate to the described object.

Loss of stability is linked to the attainment of critical conditions under the mutual motion of objects in an inhomogeneous system. The detection of the oscillatory structure changing in time in the transient process is based on the basic topological property of wave motion, namely, that its crests and troughs coexist in space. The boundaries between the crests and troughs can most likely be included in the out-of-step cutsets where loss of stability and loss of synchronism occur. Subsystems of oscillatory structure represent positive and negative half-waves. In general, these half-waves can represent the spatial distribution of accelerations, velocities, or displacements.

The structural organization of motion is based on the formation of groups of synchronous machines moving relative to the center of inertia of the system in a similar way. Such groups (the cores of subsystems) form the areas of the system around themselves, and the voltage vectors at the nodes of these areas adopt the nature of the group motion [25]. Let us choose, for example, a sign of deviation of their rotation speed from the rotation speed of the center of inertia of the system $\Delta\Omega_{gi0}(t)$ as a group feature for synchronous machines lying inside the selected area. This means that the sign of all variables

$$\Delta\Omega_{gi0}(t) = \Omega_{gi}(t) - \Omega_0(t) \tag{25}$$

at time t must be the same for all machines in the group forming the core of the subsystem. The system nodes that fall under the influence of the group will be determined on the basis of a similar requirement for the signs of deviations $\Delta\Omega_{i0}(t)$ of their individual frequencies $\Omega_i(t) = \dfrac{d\theta_i(t)}{dt}$ from the rotational speed of the center of inertia of the system $\Omega_0(t)$ (the relative individual frequencies)

$$\Delta\Omega_{i0}(t) = \frac{d\theta_i(t)}{dt} - \Omega_0(t), \tag{26}$$

where $\theta_i(t)$ the angle of the voltage vector at the node relative to the fixed axis. When calculating electromechanical transients, the angles of the voltage vectors and the rotors of synchronous machines are measured relative to a somehow selected common reference axis, usually a rotating one. The time derivatives for the angles measured in such a way are calculated using the following relations:

$$\frac{d\delta_i(t)}{dt} = \Omega_i(t) - \Omega_{ref}(t) \tag{27}$$

where $\Omega_{ref}(t)$ - the angular velocity of the reference axis, $\delta_i(t)$ - angle relative to it. Then, with this measurement of angles, we obtain:

$$\Delta\Omega_{i0}(t) = \Omega_i(t) - \Omega_0(t) = \frac{d\delta_i(t)}{dt} + \Omega_{ref}(t) - \Omega_0(t). \tag{28}$$

One subsystem will include all the nodes of the system, at which the individual frequencies are either higher or lower than the angular velocity of the center of inertia of the system.

To identify subsystems, we determine the boundaries between them. In this case, the attribute of the boundary tie connecting two adjacent subsystems becomes a different sign of deviations of the individual frequency at the nodes at its ends. If we assume all such ties of the system at time t to be disabled and make a topological analysis of the system to identify disconnected subsystems, the common feature for the resulting subsystems will be the same sign of deviations of individual frequencies within the subsystem, and any adjacent subsystems will be characterized by different signs of these deviations.

The described algorithm allows determining the oscillatory structure of motion in the system as a function of time $S(t)$. This oscillatory structure defines the spatial distribution of the relative velocities of the system as an electromechanical wave, and highlights alternating areas that outrun or fall behind the center of inertia of the system.

Relative displacements can also be used to determine the structure of motion. Since the stability of electromechanical oscillations is determined by the work carried out on the trajectory of motion, the studies usually consider the displacement wave, which determines the work done by redundant moments in the transient process [25].

Displacement of the voltage vector of the node relative to the center of inertia of the system, accumulated on the interval (t_0-t) $\Delta\delta_{i0}(t,t_0)$ given (28) will be determined as follows:

$$\Delta\delta_{i0}(t,t_0)=\int_{t_0}^{t}\Delta\Omega_{i0}dt=\delta_i(t)-\delta_i(t_0)-\int_{t_0}^{t}(\Omega_0-\Omega_{ref})dt. \qquad (29)$$

The calculation of the integral on the right-hand side gives:

$$\Delta\delta_{i0}(t,t_0)=\delta_i(t)-\delta_i(t_0)-\frac{\sum_k J_k\left[\delta_{gk}(t)-\delta_{gk}(t_0)\right]}{J_E}, \qquad (30)$$

where $\delta_{gk}(t)-\delta_{gk}(t_0)$ - change in the angle of the k–th synchronous machine on the interval (t_0-t), and the summation is performed for all synchronous machines of the system. The angles of voltage vectors and angles of rotors of synchronous machines measured relative to the reference axis used in the calculation are used in the right-hand part of (30).

After $\Delta\delta_{i0}$ is calculated for all nodes of the system, and the ties connecting the nodes with different signs of these deviations are marked, we can similarly identify the oscillatory structure of the system motion. Here, we employ the relative displacements accumulated over a finite time interval, and represent the result of the motion of the system distributed in the nodal space by an electromechanical displacement wave. The alternating areas of the system are shifted with respect to the vector rigidly connected with the center of inertia of the system to the positive or negative sides (half-waves of integral relative displacements).

Since the oscillatory structures are associated with the motion of large masses, they evolve rather slowly and it is possible to determine the time intervals during which the oscillatory structure is unchanged. The process of the oscillatory structure evolution in time and space is associated with an unsteady wave process in a significantly inhomogeneous system. Of greatest interest are the structures that form in the system by the time when the development of the out-of-step conditions starts. It is these structures that must be considered to determine emergency control.

The relations for the determination of kinetic energy of regional motion and its total time derivative for the variable oscillatory structure have the form:

$$K_{reg}(S(t))=\sum_{s(t)}J_s\frac{\Delta\Omega_{s0}^2(t)}{2}, \qquad (31)$$

$$\frac{dK_{reg}}{dt}(S(t))=\sum_{s(t)}\Delta M_{s0}(t)\Delta\Omega_{s0}(t). \qquad (32)$$

It can be seen that the determination of the regional characteristics of the transient process in a variable oscillatory structure is reduced to a simple recalculation of the relative velocities and moments for the newly identified subsystems. These relations can be interpreted as a way of understanding the speed, power and energy characteristics of the transient process over its entire time period in the context of the structure $S(t)$ that has developed by a certain time t.

The kinetic energy of an object on the interval *(t_0-t)* may increase or decrease. In the first case, the work is positive, in the second - negative. Since work A can be linked to a change in potential energy ΔU (according to the definition of the latter as $\Delta U=-A$), then the positive work corresponds to a descent into a potential well. Negative work corresponds to an ascent from the potential well. It is worthwhile to note that the idea of a potential well due to the presence of non-potential forces in the power system is not strict, but it makes it possible to increase the visibility of the physical picture of oscillations and instability. The study of the structural organization of oscillations, that involves the identification of regional objects (subsystems), allows determining the spatial and temporal characteristics of transmutation of kinetic and potential energy of the system in the transient process.

The physical cause of the instability in the transient process is the insufficient resources for braking divergent objects (subsystems). In the case of structurally organized motion, this means that the kinetic energy of regional motion is too large and the synchronizing torques are unable to stop the diverging subsystems. Using the idea of an object moving in a potential well, we can say that the instability is associated with the fact that this object has attained the maximum of a potential function, behind which there is another potential well, with a different equilibrium position (if it exists) [25].

Let us consider pairs of coupled subsystems of the oscillatory structure. These pairs can contain both subsystems of oscillatory structure and subsystems formed as a result of complete or partial merging of subsystems located on different sides of the considered cutset. Thus, the pair can cover part of the system or the whole system. For simplicity, we assume that the subsystems included in it have numbers 1 and 2.

Determine a relative velocity of the center of inertia of the subsystem that *contains both subsystems* of the pair relative to the center of inertia of the system $\Delta\Omega_{(1+2)0}$ on the basis of the relation:

$$J_1\Delta\Omega_{10}+J_2\Delta\Omega_{20}=(J_1+J_2)\Delta\Omega_{(1+2)0},$$

where $\Delta\Omega_{10}(t)$ and $\Delta\Omega_{20}(t)$ are the deviations of the velocities of the first and second subsystems of the pair relative to the center of inertia of the system; J_1 and J_2 are the moments of inertia of the subsystems. Deviations of the velocities of the subsystems from the velocity of the center of inertia of the pair $\Delta\Omega_{1(1+2)}$ and $\Delta\Omega_{2(1+2)}$ are equal to:

$$\Delta\Omega_{1(1+2)} = \Delta\Omega_{10} - \Delta\Omega_{(1+2)0},$$
$$\Delta\Omega_{2(1+2)} = \Delta\Omega_{20} - \Delta\Omega_{(1+2)0}. \quad (33)$$

For these velocity deviations, the ratio will always be satisfied:

$$J_1\Delta\Omega_{1(1+2)} + J_2\Delta\Omega_{2(1+2)} = 0. \quad (34)$$

Two equations of motion of the subsystems of the pair relative to its own center of inertia will have the form:

$$J_1 \frac{d\left(\Delta\Omega_{1(1+2)}\right)}{dt} = \frac{\Delta M_1 J_2 - \Delta M_2 J_1}{J_1 + J_2} = \Delta M_{1(1+2)}, \quad (35)$$

$$J_2 \frac{d\left(\Delta\Omega_{2(1+2)}\right)}{dt} = \frac{\Delta M_2 J_1 - \Delta M_1 J_2}{J_1 + J_2} = \Delta M_{2(1+2)}, \quad (36)$$

where $\Delta M_{1(1+2)}$ and $\Delta M_{2(1+2)}$ - the relative excess moments of subsystems 1 and 2 determining their motion near the center of inertia of the pair, and $\Delta M_{2(1+2)} = -\Delta M_{1(1+2)}$.

The kinetic energy of the regional oscillations $K_{reg(1+2)}$ of the pair is determined as a sum of the kinetic energy of the two subsystems:

$$K_{reg(1+2)} = 0.5J_1\Delta\Omega_{10}^2 + 0.5J_2\Delta\Omega_{20}^2 = \quad (37)$$
$$= 0.5(J_1 + J_2)\Delta\Omega_{(1+2)0}^2 + 0.5J_1\Delta\Omega_{1(1+2)}^2 + 0.5J_2\Delta\Omega_{2(1+2)}^2$$

As is seen from (37), part of the kinetic energy is associated with the general motion of the pair, and there is a component determined by the internal regional oscillations of the subsystems of the pair near its center of inertia $K_{\text{int}(1+2)}$

$$K_{\text{int}(1+2)} = 0.5J_1\Delta\Omega_{1(1+2)}^2 + 0.5J_2\Delta\Omega_{2(1+2)}^2 \quad (38)$$

It follows from (35) and (36) that the change $K_{\text{int}(1+2)}$ is equal to the integral of work of the relative moment on the mutual displacement of subsystems $\Delta\delta_{12}$:

$$\int_{t_0}^{t} dK_{int(1+2)} = \int_{\Delta\delta_{12}(t_0)}^{\Delta\delta_{12}(t)} \Delta M_{1(1+2)} d\left(\Delta\delta_{12}\right), \quad (39)$$

where $d\left(\Delta\delta_{12}\right) = \Delta\Omega_{12}dt$ and $\Delta\Omega_{12} = \Delta\Omega_{1(1+2)} - \Delta\Omega_{2(1+2)} = \Delta\Omega_{10} - \Delta\Omega_{20}$.

The known method of transformation of differential equations of motion applied to the pair leads to a similar relation. The first of them is multiplied by J_2, the second - by J_1, then, the second is subtracted from the first one. As a result, we obtain one differential equation of mutual motion of subsystems:

$$J_{red} \frac{d\left(\Delta\Omega_{12}\right)}{dt} = \Delta M_{1(1+2)} \quad (40)$$

The excess moment in the right-hand side of (40), which determines *the mutual motion* of the subsystems, coincides with the excess moment acting on the first subsystem in its relative motion near the pair's center of inertia. The value $J_{red} = \frac{J_1 J_2}{J_1 + J_2}$ is the reduced moment of inertia. *Kinetic energy of mutual motion* is described by equation (40): $0.5J_{red}\Delta\Omega_{12}^2$.

If (40) is converted into an integral relation of type (39), it can be established that the kinetic energy of mutual motion of the subsystems of the pair is equal to the total kinetic energy of oscillations of the subsystems of the pair relative to its own center of inertia [25].

The possibility of calculating the work for pairs of adjacent subsystems of the oscillatory structure depending on their relative displacement $\Delta\delta_{12}$ (i. e. on one coordinate), allows a schematic presentation of the potential well bounded on both sides by potential barriers that determine a margin for negative work on the ascending sections of the trajectories of the first and second cycle (Figure 6).

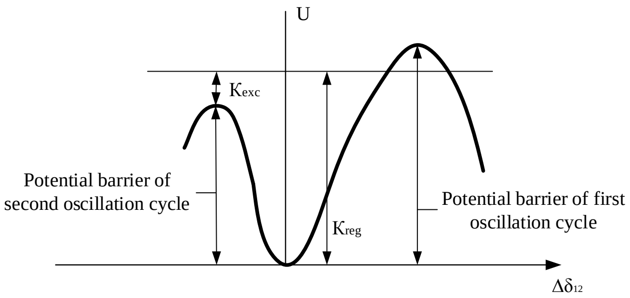


Figure 6. Determination of the excess kinetic energy leading to the loss of synchronism between the subsystems of instability structure in the second oscillation cycle.

If in this Figure we display the kinetic energy acquired by the subsystems, its comparison with the heights of the potential barriers will allow us to judge about the loss of synchronism in the system in the first or second oscillatory cycles (Figure 6 shows a case of instability in the second oscillatory cycle). The value of the kinetic energy, that was not converted into potential energy (in negative work), K_{exc} acts as excess kinetic energy, which is the cause of the instability.

The identification of the loss of dynamic stability with subsequent development of out-of step conditions and location of the out-of-step cutset should be performed automatically. Algorithms for such an analysis should be built into the program for calculation of transient processes. Note that these algorithms can be applied to any mathematical model used for numerical analysis of electromechanical transients. These algorithms should determine the main characteristics of the loss of synchronism in a power system for a given disturbance (if the loss of stability occurs). The characteristics of the loss process can be: the time after which the out-of-step conditions start to develop in the system, the out-of-step cutset (or the cutsets under a multi-frequency out-of-step conditions), the excess kinetic energy that caused the development of the out-of-step conditions in this cutset. If stability is maintained, the algorithm should allow this to be established automatically.

Identification of a subsequent loss of stability based on an analysis of the extreme values of work done during the motion of an object is very difficult algorithmically. Therefore, the fact of a loss of stability is easier to establish based on the calculation of mutual displacements of the subsystems of a variable oscillatory structure. In the event that the mutual displacement of subsystems in the transient process reaches a certain limiting value, the development of an unstable motion is identified.

To identify the instability and determine an out-of-step cutset, it is necessary to identify the inter-system tie (inter-system ties) of the oscillatory structure, along which the out-of-step conditions develop. Such a tie can be determined by the calculations of changes in mutual angles between adjacent subsystems of the oscillatory structure. For the adjacent *s-th* and *m-th* subsystems, the change in the mutual angle $\Delta\delta_{sm}(t,t_0)$ on interval (t_0-t) is determined as follows:

$$\Delta\delta_{sm}(t,t_0)=\Delta\delta_{s0}(t,t_0)-\Delta\delta_{m0}(t,t_0)= \\ =\frac{\sum_{k_s} J_k\left[\delta_{gk}(t)-\delta_{gk}(t_0)\right]}{J_s}-\frac{\sum_{k_m} J_k\left[\delta_{gk}(t)-\delta_{gk}(t_0)\right]}{J_m}, \quad (41)$$

where k_s and k_m - sets of generator nodes of the *s-th* and *m-th* subsystems. In this case, the intersystem tie in which the out-of-step conditions occur can be identified on the basis of:

$$\left|\Delta\delta_{sm}(t,t_0)\right|\geq 180^\circ. \quad (42)$$

If the disconnection of the detected intersystem tie leads to the division of the system into two separate parts, the determination of the out-of-step cutset is completed. Practical calculations show that the oscillatory structures with respect to displacements, which emerge in the system immediately before the out-of-step condition and at the initial stage of its development get extremely simplified. They often consist of two subsystems, and rarely of three and four subsystems. The cases of ring structures have not been observed in computational practice yet.

With instability between two adjacent subsystems of the oscillatory structure formed in the system, the development of the out-of-step conditions begins, and it is accompanied by an increase in their mutual angular displacement. We call such a pair of subsystems unstable [25]. Figure 7 shows an unstable pair. Depending on the number of subsystems of the oscillatory structure, the unstable pair can cover a part of the system or the whole system.

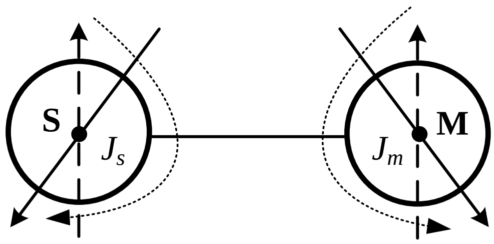


Figure 7. Unstable pair.

The oscillations of the subsystems of an unstable pair (with the numbers of subsystems 1 and 2) relative to its center of inertia are described by relationships that are similar to the analogous relationships for a simple two-machine scheme. The difference is that the excess moment determining the mutual motion of the subsystems depends on the total trajectories of the motion (regional plus local) of synchronous machines of the entire system (both outside and inside the unstable pair), and not only on the regional mutual displacement $\Delta\delta_{12}(t,t_0)$, as it would be for a real two-machine scheme [25].

A potential well can be constructed on the basis of the calculation of the transient process by plotting the kinetic energy of mutual oscillations at a certain time taken with a negative sign along the ordinate axis, and the mutual angle $\Delta\delta_{12}(t,t_0)$ observed at the same time along the abscissa axis [25].

It is clear that the calculated potential wells reflect, in a different form, the same energy relationships that underlie the equal areas method, different from the latter by using actual trajectories. At the same time, the changes in potential energy on these trajectories are calculated not by calculating the work (which is difficult), but by determining the kinetic energy changes (which is much easier in algorithmic terms). The equal areas method is used to estimate the limit disturbances. The study of potential wells for the unstable pair is focused on the search for emergency control preventing the loss of stability.

Due to the presence of non-potential forces in the power system, the notion of a potential well is not strict. It is illustrative and in good agreement with everyday experience. The Figures below for the calculated potential wells are simplified. They, for example, do not show the discrepancy between the ascending and descending branches of the same swing cycle associated with damping, and the manifestations of local motion. Figure 8 shows the calculated potential well for the loss of synchronism in the first swing cycle. The area 1-2 is the downward slope of the potential well in the case of emergency conditions, 2-3 is the ascending branch of the first swing cycle in the post-emergency conditions. The sequence of positions in the potential well is 1-2-3.

Figure 9 shows the calculated potential well under loss of synchronism in the second oscillation cycle. The area 1-2 is a slope of the potential well in the case of emergency conditions, 3-2-4 - potential well in disaster mode.

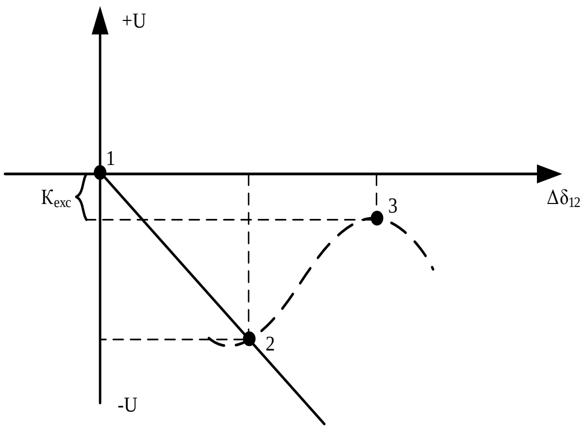


Figure 8. The calculated potential well under loss of synchronism in the unstable pair cutset in the first oscillation cycle.

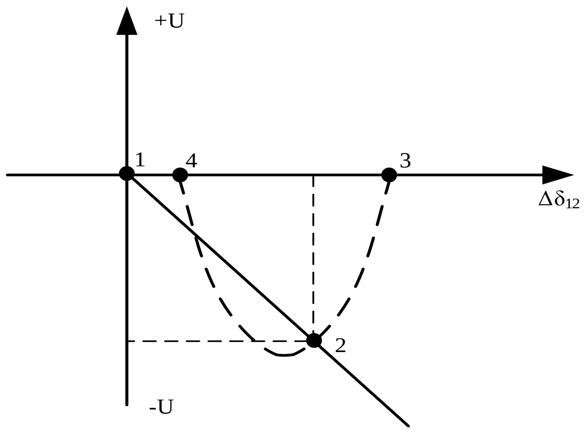


Figure 10. The calculated potential well of the pair of subsystems under steady motion in the first and second oscillation cycles.

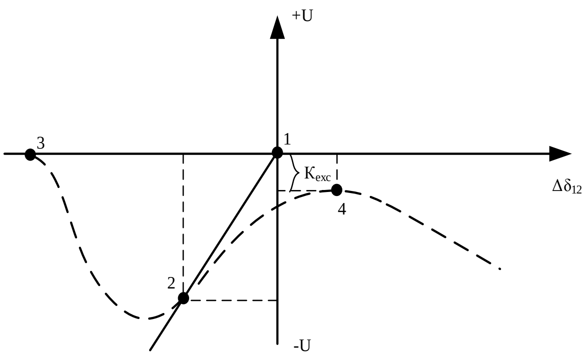


Figure 9. The calculated potential well under loss of synchronism in the unstable pair cutset in the second oscillation cycle.

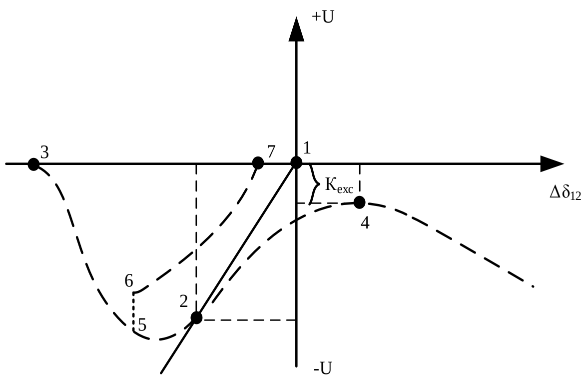


Fig. 11. Change in the calculated potential well under successful emergency control action preventing loss of synchronism in the second oscillation cycle.

Subsystem 1 running out at the loss of synchronism in the first cycle of swings is lagging behind. The sequence of positions is 1-2-3-2-4.

Figure 10 shows the steady mutual motion in the first and second swing cycles. The sequence of positions is: 1-2-3-2-4-2. These Figures are qualitatively identical for any pairs of adjacent subsystems of oscillatory structure (there is no unstable pair). If the stability is maintained in the subsequent cycles of swings, then, in the presence of damping, we can talk about reduction in the size of the potential wells of these pairs in the subsequent stages of motion in the vertical and horizontal directions (they are pulled into the point of stable equilibrium of the pairs in the post-emergency conditions). With negative damping (self-oscillation), the sizes of some potential wells increase, and their shape is distorted until an unstable pair appears.

At a fixed oscillatory structure (detected, for example, at the beginning of the out-of-step condition development), which is used to analyze the motion throughout the entire transient process, starting from a disturbance, and at the moments of switching that are not accompanied by a change in the inertial mass, the velocities of the inertia centers of the system and subsystems, as well as their kinetic energy are unchanged. With changes in the rotating masses, these characteristics of motion also change.

The possible impact of emergency control on the type of the calculated potential well is shown in Figure 11. It demonstrates the case where the uncontrolled system falls out of synchronism in the second cycle of the oscillation shown in Figure 9. At the moment represented by position 5, located at the end of the descending branch of the first swing cycle, the generators are switched off. The change in kinetic energy between positions 5-6 is associated with a decrease in the inertial mass of the run-out subsystem. The area 6-7 represents an ascending stable branch of the second swing cycle. The sequence of positions inside the potential well in the first and second cycles of swings is 1-2-3-5-6-7-6.

V. Conclusion

The wave nature of electromechanical oscillations determines the priority of the system motion structure in the formation of the transient process and its stability. In a complex system, it is the structure of the motion (what oscillates with respect to what), which is the main goal of the study. It determines all the essential aspects of the process, starting with its specific features and stability and ending with the location of the out-of-step cutset. The wave approach to identifying the spatial structure of electromechanical oscillations allows us to study the processes of loss of synchronism in power systems under the influence of disturbances.

The study of these processes is based on the energy relations for structurally organized motion. The main method is to replace the problem of stability analysis in its classical formulation, which does not use the concept of "the structure of motion", with a set of small problems of stability analysis of structurally organized forms of the studied motion.

The description of structurally organized motion is based on the use of hierarchically built systems of coordinates. In the simplest case, we focus on the following: the translational motion of the center of inertia of the system, the oscillatory motion of the centers of inertia of subsystems relative to the center of inertia of the system, and synchronous machines relative to the centers of inertia of subsystems.

Using this hierarchical structure, we can analyze the processes of loss of synchronism in complex power systems on possible (without integration of equations of motion) and actual (with integration of equations of motion) trajectories by determining kinetic and potential energy of oscillations with identification of their regional and local components.

The loss of synchronism entails two physical processes:

- the process of formation and development of the oscillatory structure of motion as a consequence of the wave electromechanical process that determines the interactions within the system;

- the process of loss of stability of parallel operation (angle stability) between the arising adjacent subsystems of the oscillatory structure of motion developing in space and time.

The study of the processes of loss of synchronism is carried out on the basis of interrelated algorithms designed to determine:

- the energy characteristics of stability limit disturbances for survey studies using energy-time diagrams;

- the excess kinetic energy resulting in an unstable pair of subsystems for the analysis of stability in specific emergencies and the choice of emergency control;

- the time of the unstable motion development;

- the location of the out-of-step cutset.

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Nikolay N. Lizalek is currently a Professor of the Department of automated electric power systems of Novosibirsk State Technical University, Doctor of Technical Sciences, Professor. He graduated from the Department of Electric Power of Novosibirsk Electrotechnical Institute in 1969. In 1976, he defended his thesis «The study of electromagnetic transients of synchronous machine operating in a circuit with complex operator resistance», and in 1994 he defended his doctoral thesis «Analysis of the dynamic properties of power connections based on the wave approach».

Vladimir V. Vasilev graduated from Novosibirsk State Technical University with a degree in relay protection and automation of electric power systems in 2007. In 2011, he defended his thesis «Development of automation of complex emergency load shedding». Currently, he works as a Chief Expert in the Department of Emergency Control of Relay Protection and Automation Service in the Branch of JSC «System Operator of the Unified Power System» - «United dispatching control of the South power system» and is an associate Professor of the Department of Power Plants of the Novosibirsk State Technical University.

"Floating" threshold values for energy security indicators describing the tariffs of energy resources

Elena V. Bykova*

Institute of Power Engineering of Academy of Sciences of Moldova, Republic of Moldova

***Abstract* — The paper briefly presents the methodological approaches to analyzing the energy security and the system of indicators used in Moldova. One of the tasks is to determine the threshold values of indicators, which, when exceeded, indicate a state of crisis.**

The threshold values are determined for the entire time series of values and for each indicator individually. Different approaches can be used. However, for the indicators describing energy tariffs, the attempts to use fixed thresholds for the entire time series were unsuccessful.

Tariffs for energy resources and GDP are interrelated. Tariffs are involved in the calculations of Intermediate Consumption - one of the GDP components. The growth of tariffs is one of the reasons for the decline in GDP.

In this regard, there was a need for a special new approach to the development of threshold values of tariff indicators that would be related to annual changes in GDP.

The idea that the growth of tariffs should not exceed the GDP growth was used to determine the threshold values.

The annual values of the maximum possible growth of tariffs are obtained based on the dynamics of the GDP growth. They gave the ("floating") thresholds for tariff indicators for each year of the time series.

***Index Terms* — indicator, tariff, GDP, energy security, threshold values**

I. Introduction

Energy security is considered comprehensively, given the diversity of aspects of the power system and energy sector operation (a multidisciplinary approach) [1-2].

* Corresponding author.
E-mail: elena-bicova@rambler.ru

http://dx.doi.org/10.25729/esr.2018.02.0009
Received: July 23, 2018. Revised: September 6, 2018. Accepted: September 14, 2018. Available online: October 15, 2018.

The authors of [3] place an emphasis on the need for an analysis of energy supply in terms of 4 aspects: the availability, accessibility, economic feasibility and environmental compatibility. The study of energy security is necessary for the development of energy policy and and reduction in energy dependence [4-5].

Modeling of energy security taking into account the economic, technical and environmental aspects is carried out in [6].

Modeling can include an analysis of various scenarios of balancing energy flows and take into account the involvement of renewable energy sources in order to reduce emissions, analysis of economic advantages [7-8].

The indicative analysis is a method of research on the energy security of the power system and energy sector [9]. The methodology makes it possible to form a system of indicators, determine the crisis threshold values of indicators, compare current and thresholds values, determine the degree of criticality of each indicator, define a general final index of energy security, and form a list of measures to ensure and improve the level of energy security [10-15].

The system of indicators reflects the state of the energy in Moldova and includes more than 50 indicators [11]. They are structured in 10 blocks:

Block № 1 - provision of fuel;
Block № 2- production of electricity and heat;
Block № 3 - transport and distribution of electricity;
Block № 4 - import of electricity;
Block № 5 - the ecological block (CO2 emissions);
Block № 6 - consumption of electricity and heat;
Block № 7 - the economic block (tariffs for electricity and heat, debts in the energy sector, energy and electricity intensity);
Block № 8 - investments;
Block № 9- own fuel and energy resources;
Block № 10 - social and personnel aspects of the energy sector;

An analysis of time series and a comparison of current and crisis values on the scales of crisis are performed for each indicator. The scales of crisis have normal, pre-crisis and crisis intervals, which are further divided into ranges in the ratio of 1,2; 1.4; 1.6; 1.8 and >1.8 from the normal state [10].

Threshold values can be provided by the expert or obtained analytically. The expert method is simple and convenient but its downside is subjectivity. Attempts were made to obtain analytic expressions for threshold values (by the method of principal components, discriminant analysis, and some others). The resulting crisis and pre-crisis values were close to each other, [10].

A method of functional interrelations is proposed in [11]. The essence of the method is that the threshold values of indicators are calculated analytically and only one indicator - GDP growth - is provided by expert. The method shows more stringent thresholds compared to expert ones, on average, by 10%.

For each indicator, the threshold values are determined individually, depending on the nature of the indicator. For some indicators, the threshold value is calculated with respect to the base level, for some – based on a range of values, and for some – based on an average multi-year value.

For some indicators, the determination of threshold values is a complex task. In particular, the threshold values have not been established for most of the environmental indicators. For some economic indicators, it is also difficult to determine the threshold values by calculation or to justify expert values.

There are threshold values for all indicators of energy security. They are the same for the entire time series.

There are several indicators, however, for which this approach is unsatisfactory. These are the indicators of tariffs for electricity, heat, and gas. The attempts to determine a fixed boundary for the crisis state were unsuccessful. It is difficult to substantiate a value that can be considered as critical for the tariffs. Tariffs constantly vary. They are linked with the overall economic situation. Moreover, tariffs affect GDP, as they are involved in the formation of "Intermediate Consumption", i.e. one of the GDP components. The higher the tariffs, the greater the value of "Intermediate Consumption" and, correspondingly, the lower the GDP.

This is analyzed in detail in [16-18], where the authors derive a formula that relates tariffs to GDP:

$$\Delta T\ (\%)=\alpha\ \Delta GDP\ (\%) \quad (1)$$

This formula can be expressed in words as follows: if the GDP increases by Δ% in comparison with the previous year, the tariffs can be increased by no more than Δ%. The α is a binding coefficient. In order for the economy to develop, the tariff growth should be less than the GDP growth, i.e. $\alpha < 1$.

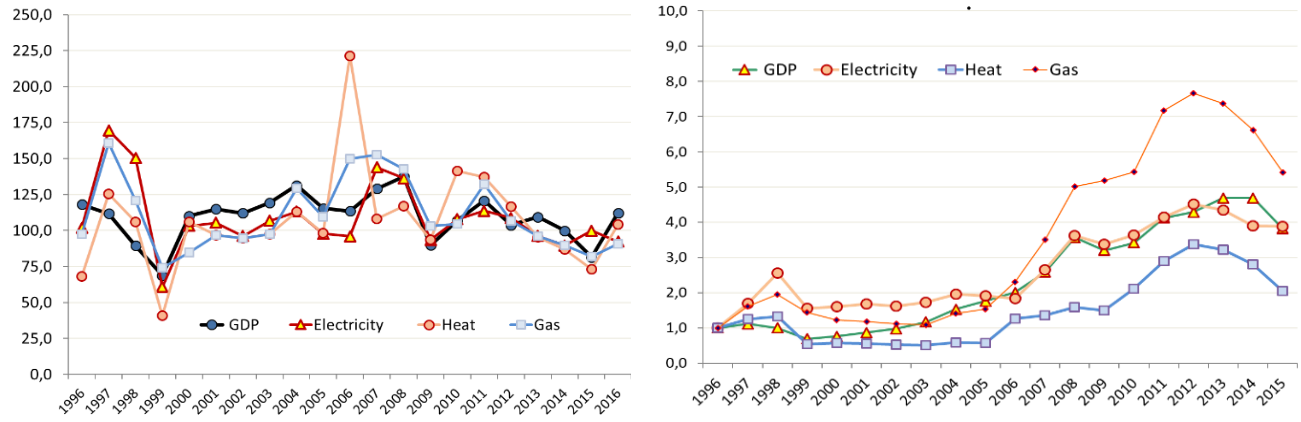
This formula shows the dynamic relationship between tariff growth and GDP growth. The fact of their influence, however, remains unobtrusive.

Energy security, by definition [9], is aimed at providing the necessary fuel and energy resources not only to the country, territory, region but also to a specific person. Tariff values have a direct impact on the standard of living of the population and on their incomes, which remain after deducting the costs paid for energy from the average per capita income.

In this regard, the attempts to introduce the boundary tariff values in the form of a percentage of the base level, a percentage of the average multi-year level, and other approaches proved unsuccessful.

Table 1. GDP growth and Tariffs changes for Previous and Base Year.

Year	Exchange rate, Lei/$	GDP		Tariffs			Tariffs, Previous year = 100			Tariffs, Base year=100 (1997)		
		Billions USD	Ratio to previous year	Electricity, $/MWh	Heat, $/Gcal	Gas, $/1000 m^3	Electricity, %	Heat, %	Gas, %	Electricity, per unit	Heat, per unit	Gas, per unit
1996	4,6	1,7	1,18	0,03	32,6	61,1	102	68	98	1	1	1
1997	4,62	1,9	1,12	0,05	40,9	98,3	170	125	161	1,70	1,25	1,61
1998	5,37	1,7	0,89	0,08	43,4	118,8	151	106	121	2,55	1,33	1,94
1999	10,52	1,17	0,69	0,05	17,7	88,0	61	41	74	1,55	0,54	1,44
2000	12,43	1,29	1,10	0,05	18,7	74,5	103	106	85	1,60	0,57	1,22
2001	12,87	1,48	1,15	0,05	18,1	72,0	105	97	97	1,69	0,56	1,18
2002	13,57	1,66	1,12	0,05	17,2	68,2	96	95	95	1,62	0,53	1,12
2003	13,94	1,98	1,19	0,05	16,7	66,4	107	97	97	1,73	0,51	1,09
2004	12,33	2,6	1,31	0,06	18,9	85,8	113	113	129	1,96	0,58	1,40
2005	12,60	3	1,15	0,06	18,6	93,9	98	98	109	1,92	0,57	1,54
2006	13,13	3,41	1,14	0,06	41,1	140,6	96	221	150	1,84	1,26	2,30
2007	12,14	4,4	1,29	0,08	44,5	214,6	144	108	153	2,65	1,36	3,51
2008	10,39	6,06	1,38	0,11	52,0	306,8	136	117	143	3,61	1,59	5,02
2009	11,11	5,44	0,90	0,10	48,6	316,5	93	93	103	3,38	1,49	5,18
2010	12,37	5,81	1,07	0,11	68,7	331,4	108	141	105	3,64	2,11	5,42
2011	11,74	7,02	1,21	0,13	94,3	437,9	114	137	132	4,14	2,89	7,17
2012	12,11	7,28	1,04	0,14	110,1	467,8	109	117	107	4,51	3,38	7,66
2013	12,59	7,97	1,09	0,13	105,1	450,0	96	96	96	4,34	3,22	7,37
2014	14,04	7,96	1,00	0,12	91,3	403,7	90	87	90	3,89	2,80	6,61
2015	18,82	6,49	0,82	0,12	66,7	330,6	100	73	82	3,89	2,04	5,41



a) b)

Figure 1. GDP growth and tariffs changes for the previous year (a) and base year (b) in current prices.

The formulas linking GDP growth and tariff growth, in fact, determine the allowable critical limits for tariffs for each year, i.e. "floating" for the time series. They determine the threshold values for tariffs. This approach allows us to solve the problem of threshold values for indicators of tariffs for fuel and energy resources.

The values of GDP growth (current prices) are shown in Table 1 and Figure 1. Table 1 includes the data on an increase in the tariffs for natural gas (for the population), electricity and heat. The data of Tables 1-2 are given for 1997-2015, which enables an analysis for a long period.

According to formula (1), the tariff growth should not exceed the GDP growth. We accept this thesis as a general rule to determine thresholds for each year. If the percentage of GDP growth in the previous year, for example, for 1997/1996, is 112%, then 12% is the limiting value for the tariff increase in 1997. In reality, they were raised:

- by 70% - for electricity;
- by 25% - for heat;
- by 61% - for gas.

Thus, the increase in tariffs in 1997 for all three types of energy resources was excessively high. This caused a decline in GDP from 1.9 to 1.7 billion dollars or up to 89% of GDP in 1998 (1998/1997). Thus, the decline in GDP was 11% (current prices).

Despite this fact, in 1998, the tariffs were raised again:

- by 51% - for electricity;
- by 6% - for heat;
- by 21% - for gas.

Later, in 1999, GDP declined, even more, amounting to 1.17 billion dollars or 69% (1999/1998). In 1998, the tariffs did not increase.

Next year, in 2000, GDP could grow a little and reach $ 1.29 billion or 10% (1999/1998). The tariffs were increased:

- by 3% - for electricity;
- by 6% - for heat.

There was no increase in the tariffs for gas.

Continuing this analysis, one can see similar trends for other years.

The percentage of the GDP growth is not positive for all years. There are years when there was a decline in GDP and the percentage of growth was negative. For such cases, the crisis threshold value can be left at the level of the last GDP growth. In general, in such years, the tariffs should not be raised but should be reduced by an amount equal to the percentage of GDP decline.

Table 2 demonstrates the GDP growth for the previous year and crisis and pre-crisis threshold values for the above data.

Table 2. Crisis and Pre-Crisis Threshold Values.

Year	GDP growth by the previous year, %	Crisis threshold values, %	Pre-crisis threshold values (half of the crisis), %
1997	12	12	6
1998	-11	0	0
1999	-31	0	0
2000	10	10	5
2001	15	15	7,5
2002	12	12	6
2003	19	19	9,5
2004	31	31	155
2005	15	15	75
2006	14	14	7
2007	29	29	14,5
2008	38	38	19
2009	-10	0	0
2010	7	7	3,5
2011	21	21	10,5
2012	4	4	2
2013	9	9	4,5
2014	0	0	0
2015	-18	0	0

A. Principles of determining the crisis threshold values

1) For the years when GDP increases by Δ (%), the tariffs can be raised by no more than Δ (%). The crisis

threshold for the tariff indicators is equal to Δ, the pre-crisis threshold is equal to ½ Δ;

2) For the years when the GDP growth is 0%, there should be no tariff growth at all. The crisis threshold for tariff indicators is 0 (%);

2) For the years when there is a decline in GDP, the tariffs should be reduced by a similar amount. In extreme cases, the tariffs should be kept at the previous level, so that GDP could have a positive increase, but there should not be any rise in the tariffs. The crisis threshold will also be 0%. Accordingly, the pre-crisis threshold is also 0%.

Intermediate intervals of the crisis scale are calculated using the general principle:

For the crisis interval (C):

C (cth) = C • 1.2 (**C**risis **TH**reat);

C (cc) = C • 1.4 (**C**risis **C**ritical);

C (ce) = C • 1.6 (**C**risis **E**mergency).

For the pre-crisis (PC) interval, the values are divided into 3 equal groups:

PC (i) = PC (Pre-Crisis **I**nitial);

PC (d) = PC + (K-PC) • 1/3 (Pre-Crisis **D**eveloping);

PC (c) = PC + (K-PC) • 2/3 (Pre-Crisis **C**ritical);

B. *Example*

For example, in 1997, the GDP growth rate is 12%. Consequently, the crisis threshold is also 12%. The scale ranges are calculated using the above formulas:

C = 12%; PC = 6%; C (cth) = 14.4%; C (cc) = 16.8%; C (ce) = 19.2%.

PC (i) = 6%; PC (d) = 8%; PC (c) = 10%.

The scale of crisis is constructed based on the calculated values. The 1997 tariffs were marked on it. In 1997, the gas tariff increased by 62%, the electricity tariff by 79%, and the heat tariff - by 26%. These values immediately fall within the interval of a crisis emergency state.

Similar calculations were performed for other years. The results obtained using a qualitative analysis of the tariff growth values are as follows:

- 1997 The GDP (1997/1996) increased by 11.76%, therefore, the tariffs could not be increased. In actuality, however, the tariffs were increased by 70.33% - for electricity, by 26% - for heat and by 61.57% - for gas. Therefore, this situation is a crisis for all tariffs. Electricity - "C", Heat - "C", and Gas -"C";

- 1998 There was no increase in GDP (1998/ 1997), hence, the tariffs should not have been raised at all. The increase in tariffs had to be equal to 0. In fact, all three types of the tariffs grew. Therefore, this situation is a crisis with respect to tariffs. Electricity - "C", Heat - "C", and Gas-"C";

- 1999 There was no increase in GDP (1999 /1998), therefore, the tariffs should not have been raised at all. In actuality, however, the tariffs for electricity and gas increased. Therefore, this situation is a crisis for these two tariffs. Electricity - "C", and Gas-"C";

- 2000 There was an increase in the value of GDP (2000/1999), hence, the tariffs could be raised by the value of the GDP growth (10.09%). In fact, the tariffs for electricity and heat grew by 22% and 25%, respectively. Thus, this situation is a crisis for these two tariffs. Electricity - "C", and Heat - "C";

- 2001 There was an increase in the value of GDP (2001/ 2000), consequently, the tariffs could be raised by the value of the GDP growth (by 14.91%). In fact, the tariffs grew only by 9.02% for electricity, and did not change for heat and gas. Therefore, the situation for all tariffs is normal;

- 2002 There was an increase in GDP (2002/ 2001), hence, the tariffs could be raised by the value of the GDP growth (by 12.161%). In fact, the tariffs grew only by 1.5% for electricity, and did not change for heat and gas. Therefore, the situation for all tariffs is normal;

- 2003 There was an increase in GDP (2003/2002), consequently, the tariffs could be raised by the value of the GDP growth (by 19.28%). In fact, the tariffs rose only for electricity - by 9.63%, and did not change for heat and gas. Therefore, the situation for all tariffs is normal;

- 2004 There was an increase in GDP (2004/ 2003), hence, the tariffs could be raised by the value of the GDP growth (by 31.31%). In fact, the tariffs rose only for gas - by 14.25%, and did not change for heat and electricity. Therefore, the situation for all tariffs is normal;

-2005 There was an increase in GDP (2005/2004), therefore, the tariffs could be raised by the value of the GDP growth (by 15.38%). In fact, the tariffs rose only for

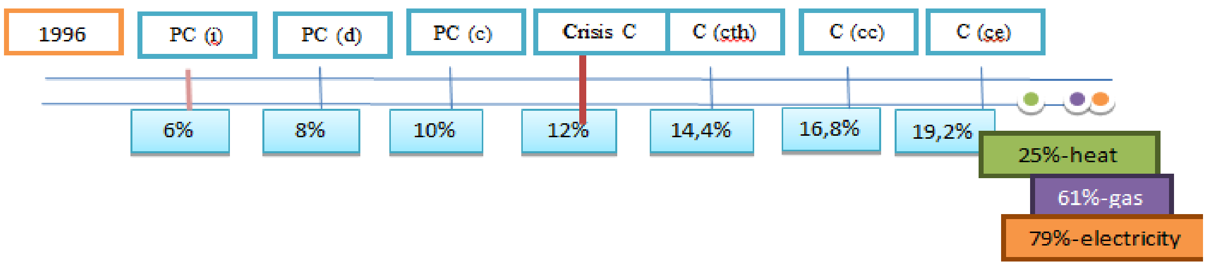


Figure 2. The scale of the crisis for the indicators of 3 tariffs: for electricity, heat and natural gas. The scale depicts the actual values for 1997 in the form of 3 color points.

gas - by 11.81%, and did not change for heat and electricity. Thus, the situation for all tariffs is normal;

- 2006 There was an increase in GDP (2006/2005), consequently, the tariffs could be raised by the value of the GDP growth (by 13.60%). In fact, the tariffs rose only for heat - by 130.77% and for gas - by 56.04%, and did not change for electricity. Therefore, this situation is a crisis for these two tariffs (heat and gas) Heat - "C", and Gas-"C";

- 2007 There was an increase in GDP (2007/2006), therefore, the tariffs could be raised by the value of the GDP growth (by 29.11%). In fact, the tariffs for electricity grew by 33.11%, for gas - by 41.06%, and did not change for heat. Thus, this situation is a crisis for these two tariffs. Heat - "C", and Gas-"C";

- 2008 There was an increase in GDP (2008/ 2007), thus, the tariffs could be raised by the value of the GDP growth (by 37.64%). In fact, the tariffs increased by 16.75% - for electricity, by 22.39% - for gas, and did not change for heat. Therefore, this situation is a crisis for electricity tariff. Electricity - "C";

- 2009 There was no growth of GDP (2009/2008), consequently, the tariffs should not have been raised at all. In fact, the tariff for gas increased by 11.81%, and the tariffs for electricity and heat did not change. Therefore, this situation is a crisis only for the gas tariff. Gas-"C";

- 2010 In 2010, GDP increased to the 2009 level, i.e. by 6.9%, consequently, the tariffs could be increased by no more than 6.9%. In actuality, however, the tariff for electricity increased by 20%, for heat - by 57.37%, and for gas - by 16.52%. Therefore, this situation is a crisis for all tariffs. Electricity - "C", Heat - "C", and Gas-"C";

- 2011 In 2010, the increase in GDP compared to 2009 was 20.7%, hence, the tariffs could be raised by no more than this amount. In reality, the tariff for electricity increased by 7.97%, for heat – by 30.23%, and for gas – by 25.43%. Therefore, this situation is a crisis for two tariffs (heat and gas). Heat - "C", and Gas-"C"

- 2012 In 2012, GDP increased to the level of 2011, i.e. by 3.32%, thus, the tariffs could be increased by no more than this amount. In fact, the tariff for electricity was increased by 12.3%, for heat - by 20.43%, and for gas - by 10.23%. Therefore, this situation is a crisis for all tariffs. Electricity - "C", Heat - "C", and Gas-"C";

- 2013 In 2013, the increase in GDP compared to the 2012 level was 9.38%, therefore, the tariffs could be raised by no more than this amount. In actuality, they changed a little: the electricity tariff remained the same, the heat tariff decreased by 0.71%, and gas tariff did not change. Therefore, the situation is normal for all tariffs;

- 2014 In 2014, there was no increase in GDP compared to 2013. The tariffs should not have been raised. They did not rise. The situation is normal.

- 2015 There was no GDP growth in 2015/2014, but there was a decline (-18.47%). The actual increase in electricity tariff was 33.86%, the tariff for heat decreased, and the tariff for natural gas grew by 9.81%. The tariffs had to be lowered instead of the increase or at least they had to be maintained at the level of the previous year. Electricity - "C", and Gas-"C".

The further study is aimed at including new threshold values for these indicators (tariffs of natural gas, electricity, and heat) in the software for the analysis and monitoring of energy security and for calculations during annual monitoring.

II. Conclusion

A new methodological approach is proposed to determine the threshold values for three indicators of energy security, reflecting tariffs for natural gas, electricity, and heat.

The new methodological approach implements the idea that the tariff growth should not exceed the GDP growth.

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Elena Bykova is a researcher of the Institute of Power Engineering of the Academy of Sciences of Moldova, received the Ph.D. degree in 2003. Professional interests are: systems analysis in the energy sector, development of energy systems, process modeling in the energy sector, the methodology of calculating and monitoring indicators for the energy security of the country (region), modern technologies for electricity and heat production, new transmission and distribution of electric energy, monitoring greenhouse gas emissions, studies of energy balance and the prospective development of energy sector. compensation system for the provision of ancillary services in medium voltage distribution networks.