EVALUATION OF THE STATE OF THE REGION'S ENERGY COGENERATION SYSTEMS BASED ON THE RELIABILITY OF POWER SUPPLY IN CONDITIONS OF HIGH ECONOMIC RISKS

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ABSTRACT
The reliable operation of power cogeneration systems as the most important component of large power systems is essential for national economy's successful development. The timeliness of studying the effective administrative actions to increase the economic effect for energy companies and maintain a high level of readiness of energy systems for overcoming the threats to their sustainable operation, that appear in conditions of high economic risks, is preconditioned by the presence of not only technical but also economic aspects of energy supply reliability. The structural complexity of the regional power cogeneration systems as well as availability of various interrelations between power stations and their performance characteristics lead to the development of accidents and their turning into system ones. This circumstance puts among the most urgent the requirement of a specific study of the problem of reliability analysis of the region's territories' energy supply. In the course of research, the structural systematic characteristics of power cogeneration systems and conditions contributing to appearance of system accidents leading to the loss of sustainability were taken into account. A method of indicative analysis was applied for studying the issues related to reliability and survivability of energy supply systems. Its specificity was an original methodological approach to calculation of indicators threshold values characterizing the state of energy cogeneration systems in terms of energy supply reliability based on discriminatory analysis. It allowed conducting a series of simulation calculations by indicative blocks of a situation belonging to a certain class of states and obtaining generalized assessments characterizing the reliability level of energy cogeneration systems on the territories of the regions.
Keywords: power industry, efficiency, strategy, reliability, ecology, mathematical economic models, uncertainty.

1 INTRODUCTION

Recently observed serious growth of economic risks leads to changing the operating conditions and energy cogeneration systems' management principles. This circumstance causes a substantial decrease of energy supply's reliability levels and actualizes the tasks of studying the issues of management decision making for crisis developments neutralization. It is worth mentioning that the related problems are also those of technical reliability in power cogeneration systems, where reliability means the property of performing given functions in certain amounts under certain operating conditions. At that, reliability is defined as the resultant aggregate of technical characteristics of the facility – the power plants that are a part of distributed and centralized cogeneration systems [1], [2]. Thus, the reliability of power cogeneration systems is related to the ability to avoid attaining a certain limit state (the principle of acceptable damage), after which the system may collapse and be unable to perform its functions even to the baseline minimum necessary for consumers (unacceptable operating parameters, low supply level of energy resources). The property of reliability is intrinsic to power cogeneration systems and manifests itself in abnormal situations. In the context of high economic risks, abnormality in functioning can be triggered not only by factors relating to the technical domain (equipment failure), but also by factors of economic

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(lack of investment resources, financial sustainability), environmental (environmental pollution, harmful environmental impacts) and socio-political (national and regional conflicts, strikes, etc.) nature. That is why when considering the issues of power engineering operation and development, it is not anymore sufficient to confine oneself to technical aspects of reliability analysis, but one should do a complex research of cogeneration systems reliability – reliability of operation including all above mentioned factors [3].

Although individual events related to the failure of cogeneration systems reliability appear to be random, the impact of negative factors as a whole is not random, but is the natural result of their accumulation, i.e. it has an integral character. So, when assessing the levels of energy supply reliability, first of all, along with the structural ones, it is necessary to use the integral factors of their activity, which allows obtaining more objective results of the research.

2 THE METHODOLOGICAL APPROACH TO CARRYING OUT CLASSIFICATION OF THE STATES OF POWER COGENERATION SYSTEMS BY RELIABILITY LEVELS OF ENERGY SUPPLY WITH THE HELP OF DISCRIMINATORY ANALYSIS

The classification of the states of power cogeneration systems by reliability levels of energy supply was carried out using the analysis system of multivariable data on the basis of discriminatory analysis applied in the theory of image identification. As is known, discriminant analysis is a branch of computational mathematics representing a set of statistical analysis methods for solving the tasks of pattern recognition used to decide which variables separate (i.e. “discriminate”) the emergent data sets combined into groups [4], [5].

The general idea of the developed methodological approach is as follows. If the indicator values for the different states of regional energy supply’s reliability are known, a training sample can be generated based on the statistical data, containing objects of different state classes of the region: Normal (N), Medium (M), Low (L). The classification of the current state of the regions may be carried out by the indicator values, which characterize energy supply reliability through certain decision rules – discriminator functions.

Using the principle of dichotomy, the objects in the training sample belonging to a given energy supply reliability class are separated from those in the other classes. The character of the discriminator function $E(X)$ carries information about the situation class, and its value carries information about the closeness of the situation to the boundary separating objects of different classes, that is a kind of danger degree of the situation in terms of reliability [5], [6].

If $E(x_1, x_2, \dots, x_m) = 0$, then the point is on the dividing surface. A probabilistic approach, widely used in image identification theory, is used to determine the decision rules. It corresponds to a case when all the images overlap.

If images X_h of all classes $A(X_h)$ are known, then identification of the objects of unknown affiliation $a(X_0)$ must be done according to the rule:

$$X_0 \in X_h \Rightarrow a(X_0) \in A(X_h),\ h = \overline{1, m}. \tag{1}$$

Thus, the task is to build models of the K_h classes from the training sample data, on the basis of which a new object $a(X_0)$ can be identified:

$$X_0 \in K_h \Rightarrow X_0 \in X_h \Rightarrow a(X_0) \in A(X_h),\ h = \overline{1, m}. \tag{2}$$

Two types of mistakes are possible at classification: missing a target – P_1 and false alarm – P_2.

The decision rule has to enable minimizing the mathematical expectancy of losses associated with misclassification, that is:

$$F(K) = c_1 q_1 P_1(K) + c_2 q_2 P_2(K) \ \rightarrow min, \tag{3}$$

where q_1 and q_2 = a priori probabilities of occurrence of objects from the first and second classes; c_1 and c_2 = error rates for assigning objects to two classes.

As is known, the method minimizing the average loss $F(K)$ at given values q and c is called the Bayesian method [1], [7]. According to it, for populations of objects obeying the normal law of distribution, an object with parameters X should be classified as population number one if:

$$\ln(c_1 q_1) - 0.5\,((X - M_1)^T S_1^{-1}(X - M_1) - \ln|S_1|) -$$
$$- \ln(c_2 q_2) - 0.5\,((X - M_2)^T S_2^{-1}(X - M_2) - \ln|S_2|)) > 0, \tag{4}$$

where X = vector of variables in indicator space; M_1, M_2 = mathematical expectations of classes 1 and 2; S_1, S_2 = covariance matrices of classes 1 and 2; q_1, q_2 = a priori probabilities of occurrence of objects from the first and second classes; c_1 c_2 = prices of incorrect assignment of objects to classes 1 and 2.

Functionals G_i defined by equation $G_i = \ln(c_1 q_1) - 0.5\,((X - M_1)^T S_1^{-1}(X - M_1) - |S_1|)$ are called quadratic informants. In terms of informants, the classification rule looks as follows: the object should be assigned to the population for which its informant is bigger.

In the course of the research, it was found out that the most important disadvantage of using discriminant analysis method for classification of states according to regional energy supply's reliability levels is the difficulty in obtaining samples of statistically significant size.

As mentioned above, the classification of regions and their energy cogeneration systems is carried out with the help of thresholds for indicators characterizing the reliability of power supply. From this point of view, a situation existing in a certain region at a given moment may be classified for example as Normal (*N*), Medium (*M*), Low (*L*). The thresholds separating one class from another by some indicator may be marked as X_M and X_L. X_M helps to separate class *N* from *M*, and X_L, correspondingly – *M* from *L*.

According to the developed method, separation surfaces of the considered pairs of classes are built in the space of indicators. To construct them, a training sample consisting of points with known states of energy supply reliability is used [3]. Threshold points are then defined on these surfaces as intersections with the lines connecting the class centroids.

The equation of the surface separating classes 1 and 2 is written as follows:

$$\ln(c_1 q_1) - 0.5\,((X - M_1)^T S_1^{-1}(X - M_1) - \ln|S_1|) -$$
$$- \ln(c_2 q_2) - 0.5\,((X - M_2)^T S_2^{-1}(X - M_2) - \ln|S_2|)) = 0, \tag{5}$$

A line passing through the first and second class centroids with coordinates M_1 and M_2 is written as follows:

$$X = b(M_2 - M_1) + M_1, \tag{6}$$

where b is the straight line parameter.

By substituting (6) into (5), we obtain an equation with respect to the parameter b:

$$\ln(c_1 q_1) - 0.5\,((b(M_2 - M_1) + M_1 - M_1)^T S_1^{-1}(b(M_2 - M_1) + M_1 - -M_1) - \ln|S_1|)$$
$$- \ln(c_2 q_2) - 0.5\,((b(M_2 - M_1) + M_1 - -M_2)^T S_2^{-1}(b(M_2 - M_1) + M_1$$
$$- M_2) - \ln|S_2|)) = 0.$$

(7)

After algebraic transformations, this equation is reduced to a standard form of quadratic equation:

$$b^2A_1 + bA_2 + A_3 = 0, \quad (8)$$

where

$$A_1 = 0.5(M_2 - M_1)^T(S_1^{-1} + S_2^{-1})(M_2 - M_1), \quad (9)$$

$$A_2 = (M_2 - M_1)^T S_2^{-1}(M_2 - M_1), \quad (10)$$

$$A_3 = -0.5(M_2 - M_1)^T S_2^{-1}(M_2 - M_1) - \ln\frac{c_1q_1}{c_2q_2} + 0.5\ln\frac{|S_2|}{|S_1|}. \quad (11)$$

One of two roots satisfying condition $0 \leq b_0 \leq 1$ corresponds to the intersection point of the straight line and the separating surface on the segment between the classes centroids. Using it and relation (6), the threshold values for safety indicators between classes 1 and 2 are determined.

$$X_0 = b_0(M_2 - M_1) + M_1. \quad (12)$$

3 EVALUATION OF THE STATE OF POWER ENGINEERING SYSTEMS IN THE URALS REGION IN TERMS OF ENERGY SUPPLY RELIABILITY

The Urals region is located on the Middle, the South, and partially on the North Ural, as well as on adjacent parts of the East-European and the West-Siberian plains at an area of 823.3 thousand km². It includes seven subjects of the Russian Federation: the Sverdlovsk Oblast, the Perm Krai, the Chelyabinsk Oblast, the Kurgan Oblast, the Orenburg Oblast, the Udmurt Republic and the Republic of Bashkortostan. The Urals region is exceptionally rich in various minerals. It is a highly developed heavy industry production area with a complex structure. Mineral raw materials and gas extraction, logging and timber processing are of nationwide importance. The district's industry is particularly characterized by a high level of production concentration, intra- and inter-sectoral cooperation and combination, as well as by a well-developed infrastructure, including electric power engineering. Ferrous metallurgy is the primary industry of the Urals region. Mechanical engineering (energy, transport, agriculture), forestry, chemicals, petrochemicals and mining, as well as oil and gas extraction and processing are sufficiently well developed industries.

In the framework of their research, the authors successfully apply the indicative approach for assessment of reliability levels. To assess reliability levels, this approach involves the use of some combinations of indicators – immediately assessed initial parameters [8]–[10]. Further on, these indicators are grouped in units that reflect some characteristic features in operation of power cogeneration systems. All indicators in the handled problem are divided in six units. The list of units, indicators, and threshold values is given in Table 1.

The main results of solving the set task are given in Table 2. Their analysis shows that the overall reliability of electric power supply on all territories of the Urals region is evaluated as low. It belongs to the class of insufficient reliability to a high degree only in the Sverdlovsk Oblast.

Assessments under the unit of power cogeneration systems' adequacy (unit 1) are within the range of "insufficient reliability and acceptable to some degree" (the Perm Krai) to "definitely low reliability" (the Udmurt Republic). The determining indicator under this unit is the ratio of the sum of the available power plants capacity and the throughput capacity of power links to the maximum power load of consumers (indicator 1.3).

Table 1: The indicators composition and threshold values for assessment of energy supply reliability of the Urals regions.

Name of blocks and indicators	Symbol	Threshold values		
		N	*M*	*L*
1. Unit of power cogeneration systems adequacy				
1.1. Share of own sources of electric energy in the energy balance of the territory.	1.1	75	65	55
1.2. Ratio of available power plants capacity to the maximum consumers power load (%)	1.2	100	85%	70
1.3. Ratio of the sum of the available power plants capacity and the throughput capacity of power links to the maximum power load of consumers (%)	1.3	220	190	160
2. Unit of fuel supply systems adequacy				
2.1. Share of own sources in the balance of boiler and furnace fuels (%)	2.1	70	50	30
2.2. Share of own sources in the balance of motor fuel (%)	2.2	75	55	35
2.3. Share of completion of the target on coal accumulation,%	2.3	100	90	80
2.4. Share of completion of the target on black oil fuel accumulation (%)	2.4	90	75	60
3. Unit of power cogeneration systems structural and performance reliability				
3.1. Ratio of the reserved capacity of power plants to consumers' maximum electrical load (%)	3.1	14	10	6
3.2. Availability factor of the electric power plants generating equipment.	3.2	86	78	70
4. Unit of power cogeneration systems survivability				
4.1. Share of predominant heat resource in the consumption of boiler and furnace fuels (%)	4.1	35	50	65
4.2. Installed capacity share of the largest power plant (%)	4.2	25	35	45
4.3. The level of securing the demand for heat sources capacity in context of a sharply increased demand	4.3	105	95	85
5. Unit of power companies main production assets reliability and efficiency				
5.1. Wear-out rate of electric power companies main production assets (%)	5.1	30	45	60
5.2. Depreciation degree of the fuel industry enterprises basic production assets,%	5.2	30	45	60
5.3. Share of commissioning the installed capacity and technical re-equipment of electric power plants in the territory over a five-year period (%)	5.3	8	5	2
6. Unit of assessment of financial and economic performance of electric power companies				
6.1. Ratio of the excess of overdue accounts payable of the electric power industry enterprises of the territory over the overdue accounts receivable to their annual production volume (%)	6.1	5	10	15
6.2. Ratio of the excess of overdue accounts payable of enterprises in the fuel industry of the territory over the overdue accounts receivable to their annual output (%)	6.2	4	8	12
6.3. Ratio of overdue accounts payable of electric power enterprises to their annual output (%)	6.3	20	35	50
6.4. Ratio of overdue accounts payable of fuel industry enterprises to their annual output (%)	6.4	20	35	50

Table 2: The results of assessment of the status of power cogeneration systems of the Urals region by power supply reliability.

Region name	*RC*	Indicator block number												Overall rating	
		1		2		3		4		5		6			
		DS	*DI*	*DS*	*DI*	*DS*	*DI*	*DS*	*DI*	*DS*	*DI*	*DS*	*DI*	*DS*	*DI*
Perm Krai	*N*	0.865	1.3	0.958	2.1	1.000	3.2	0.002	4.1	0.002	5.1	0.109	6.2	0.002	4.1,
	M	1.000	1.3	0.989	2.1	0.841	3.1	0.230	4.1	0.995	5.1	0.193	6.2	0.193	6.2
	L	2.293	1.3	1.000	2.1	0.445	3.1	1.000	4.1	1.000	5.3	1.000	6.2	1.000	2.1, 4.1, 5.3, 6.2
Sverdlovsk Oblast	*N*	0.088	1.3	0.989	2.1	0.473	3.2	0.502	4.1	0.079	5.1	0.971	6.3	0.079	5.1
	M	0.995	1.3	1.000	2.1	0.971	3.2	1.000	4.1	1.000	5.1	1.000	6.2	0.971	3.2
	L	1.000	1.3	0.999	2.1	1.000	3.2	0.791	4.1	0.908	5.3	0.999	6.2	1.000	1.3, 3.2
Orenburg Oblast	*N*	0.003	1.3	1.000	2.1	0.531	3.2	0.003	4.1	0.002	5.1	0.763	6.3	0.001	1.3, 4.1
	M	0.035	1.3	0.958	2.1	0.989	3.2	0.109	4.1	1.000	5.1	0.907	6.2	0.035	1.3
	L	1.000	1.3	0.908	2.1	1.000	3.2	1.000	4.1	0.981	5.1	1.000	6.1	1.000	1.3, 3.2, 4.1, 6.1
Republic of Bashkortostan	*N*	0.365	1.3	1.000	2.1	0.908	3.2	0.003	4.1	0.005	5.2	0.908	6.3	0.003	4.1
	M	1.000	1.3	0.999	2.1	1.000	3.2	0.316	4.1	0.817	5.2	1.000	6.3	0.316	4.1
	L	0.791	1.3	0.981	2.1	0.865	3.2	1.000	4.1	1.000	5.3	0.865	6.3	1.000	4.1, 5.3
Udmurt Republic	*N*	0.088	1.3	0.943	2.2	0.943	3.2	0.009	4.1	0.098	5.1	0.989	6.3	0.009	4.1
	M	0.995	1.3	0.999	2.2	1.000	3.2	0.473	4.1	0.791	5.3	1.000	6.3	0.473	4.1
	L	1.000	1.3	1.000	2.2	0.817	3.2	1.000	4.1	1.000	5.3	0.943	6.3	1.000	1.3, 2.2, 4.1, 5.3
Chelyabinsk Oblast	*N*	0.002	1.3	1.000	2.4	0.316	3.2	0.001	4.1	0.071	5.2	0.002	6.2	0.002	1.3, 6.2
	M	0.044	1.3	0.560	2.4	0.865	3.2	0.177	4.1	0.865	5.3	0.004	6.2	0.004	6.2
	L	1.000	1.3	0.316	2.4	1.000	3.2	1.000	4.1	1.000	5.3	1.000	6.2	1.000	1.3, 3.2, 4.1, 5.3, 6.2
Kurgan Oblast	*N*	0.009	1.3	0.971	2.4	1.000	3.2	0.473	4.1	0.391	5.2	0.003	6.3	0.009	6.3
	M	0.619	1.3	1.000	2.4	0.989	3.2	1.000	4.1	1.000	5.2	0.005	6.3	0.005	6.3
	L	1.000	1.3	0.995	2.4	0.531	3.2	0.817	4.1	0.589	5.3	1.000	6.3	1.000	1.3, 6.3

Note: *RC* = Reliability characteristic; *DS* = the degree of situation belonging to a certain class of states; *DI* = determining indicator, i.e. indicator under which the situation is related to a certain class.

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Under the second unit, three regions (the Perm Krai, the Udmurt Republic and the Kurgan Oblast) get low or insufficient reliability assessments. Other areas are recognized more or less safe. An opposite situation is observed under the unit of power generation systems' structural and performance reliability. (unit 3). The mentioned areas have high or acceptable assessments and the rest of them – insufficient or low ones, and it is determined by the availability factor of the electric power generating equipment.

The unit of power cogeneration systems survivability (unit 4) is characterized by low assessments for all areas due to the strongly pronounced fuel balance mono-structure (indicator 4.1). Additionally, one can also note the poor assessments of the level of securing the demand for heat sources capacity in context of a sharply increased demand (indicator 4.3) for the Perm Krai and the Sverdlovsk Oblast.

The worst situation from the point of view of power supply's reliability has formed in the unit of power cogeneration systems' efficiency (unit 5). All indicators of this unit for all areas are at low or insufficient level. Along with a high wear degree of the main production facilities, rather low rates of new facilities putting in operation and power objects modernization are observed. This situation can be explained by a low investment attractiveness of power engineering, mainly due to long payback periods.

Another reason of the relatively poor state of main production facilities becomes visible at the analysis of the results of unit 6, reflecting the financial and economic performance of power companies. According to this unit, all the regions of the Urals get unsatisfactory assessments, and this is connected with the high level of accounts payable of power companies.

4 CONCLUSION

The complexity of cogeneration systems in the Urals region, the difficulties in their management, the complex interrelationships between energy facilities and their regime indicators may lead to conditions for the development of accidents and their turning into system accidents. This is confirmed by the requirement of a special consideration for the task of analyzing the reliability of energy supply of the regions based on tracking the structural systematic characteristics and conditions that contribute to appearance of system accidents leading to the loss of survivability by energy cogeneration systems.

The method of estimating indicator thresholds based on discriminant analysis has been developed and tested for the purpose of indicative analysis. It allowed obtaining the threshold indicator values from training samples and making a comprehensive assessment of the state of energy cogeneration systems in the Ural region in terms of energy supply reliability.

In our further research based on the suggested approach, we plan to study the effect of renewable energy sources on the system reliability, and to identify the optimal share of various types of renewable sources capacity that has an impact on the sustainable operation of regional electric power industry.

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