Дослідження присвячене розробці моделі розподілу витрат на технічне обслуговування, ремонт та заміну електрообладнання при прийняття рішень щодо управлінням режимом електроенергетичної системи. Зниження надійності функціонування ЕЕС, спричинене об'єктивно існуючим старінням парку електрообладнання, потребує врахування значущості електрообладнання при плануванні його технічного обслуговування та ремонту. Для цієї мети пропонується використовувати теорію нечітких множин, метод парних порівнянь Сааті, метод булевого програмування. Результатом рішення оптимізаційної задачі багатокритеріального аналізу є вектор найкращих альтернатив, побудований за принципом домінантності. Розроблений алгоритм комплексного моделювання технічного стану і режиму ЕЕС, розподілу інвестиційних витрат на технічне обслуговування та ремонт для прийняття рішень щодо визначення пріорітету виведення з експлуатації електрообладнання дозволяє ефективно приймати рішення. Результати імовірнісно-статистичного моделювання режиму ЕЕС з використанням методу Монте-Карло дозволяють врахувати імовірнісний характер виникнення аварійних ситуацій в ЕЕС під час визначення її найбільш слабких елементів, які потребують першочергової заміни. Перевагою запропонованого підходу є врахування технічного стану електрообладнання для оцінки ризику виникнення аварійної ситуації в ЕЕС. Порівняльний аналіз результатів ранжування електрообладнання на основі оцінок значущості електрообладнання та ризику виникнення аварійної ситуації в ЕЕС підтвердив високу ефективність використання при розв'язанні задач превентивного управління і планування режимів ЕЕС. Розроблена модель буде використана для подальшого дослідження і розробки алгоритму прийняття ефективних рішень щодо превентивного управління режимом ЕЕС. Отримані результати комплексного моделювання режиму ЕЕС і розподілу витрат на проведення технічного обслуговування та ремонту дають підстави стверджувати щодо можливості впровадження в складі комплексу програм аналізу ризиків експлуатації в електроенергетичній системі для енергокомпаніях

Ключові слова: метод Сааті, ризик-менеджмент, імовірність відмови, технічне обслуговування і ремонт

UDC 621.311
DOI: 10.15587/1729-4061.2018.147622

DEVELOPMENT OF A MATHEMATICAL MODEL FOR COST DISTRIBUTION OF MAINTENANCE AND REPAIR OF ELECTRICAL EQUIPMENT

E. Bardyk
PhD, Associate Professor,
Head of Department*
E-mail: bardik1953@gmail.com
N. Bolotnyi
Postgraduate student*
*Department of
electric power plants
National Technical University
of Ukraine "Igor Sikorsky Kyiv
Polytechnic Institute"
Peremohy ave., 37, Kyiv,
Ukraine, 03056

1. Introduction

An analysis of the current state and further ways of development of the electric power industry shows that its reformation is carried out in a number of contradictions between economic relations and operation reliability of electric power system [1].

The efforts of owners of electrical engineering companies to maximize the use of the available resource of electrical equipment conflicts with the need to ensure its operation reliability and to minimize the number of emergencies due to electrical equipment failures.

The growth of the rate of technological failures and severity of the consequences of them is due to fixed assets aging and resource exhaustion of electrical equipment, adverse changes of climatic conditions in the external environment, organizational reasons, requiring a corresponding set of measures [2].

One of the ways to increase the electricity supply reliability is to create complex expert systems for managing production costs and decision-making support, risk assessment for reducing the reliability of consumers' electricity supply in the event of technological failure of electrical equipment [3]. The great importance under solving these problems is issues of cost distribution for maintenance, repair and replacement of outdated electrical equipment.

The problem solution of efficiency increasing and cost reducing of maintenance and repair, as well as the replacement of electrical equipment can be carried out in two stages. At the first stage, justified allocation of expenses for units and groups of electrical equipment is carried out taking into account the complex of operational factors, in particular, the emergency risk. This approach provides a rational allocation of costs within the allocated repair and maintenance fund. But it does not contain a mechanism that stimulates the energy company to save money. The second stage of problem solution involves a reasonable choice of maintenance and repair strategy of electric equipment by analyzing and comparing the options under several performance criteria.

The lack of a methodical approach to actual cost analysis of the energy company does not allow assessing the adopted strategy effectiveness of service management equipment and developing ways to correct it [4].

In this regard, the development of new models for assessing the technical condition of electrical equipment, maintenance and repair management, emergency risk analysis in the electric power system (EPS) during scheduled and emergency out of service is an urgent task.

2. Literature review and problem statement

Objectively, the significant wear and tear of electrical equipment lead to an increase in accidents and costs for the year of its maintenance and repair. The low level of investment in the modernization of electric networks and power plants, as well as the limited costs, forces the management of energy companies to find internal reserves to save costs in maintaining the capacity of the equipment. This requires the choice of a rational strategy for servicing and efficient use of allocated costs, taking into account the consequences of possible constraints in EPS operation management [5]. Currently, there are a number of works devoted to issues of optimal distribution and cost management in EPS. The EPS state simulation to determine the quantitative indicators of emergency risk under electrical equipment failures is considered in [6]. But the issue of the priority of electrical equipment out of service on the basis of technical condition assessment and EPS state analysis was not sufficiently considered.

The approach research results for making informed decisions to ensure reliable operation of EPS are presented in [7]. But it is necessary to take into account the probability of electrical equipment failure, the EPS stochastic state, possible scenario of an emergency situation, economic and environmental consequences, incompleteness and obscurity of information.

The risk is an integral indicator of the EPS operation state, which comprehensively takes into account the above-mentioned factors and most completely and sufficiently characterizes the technical condition of electrical equipment and the EPS state [8]. The most appropriate and effective method for estimating the probability risk component for EPS, in particular, which features are a large number of elements, complexity of the structure and a significant wear rate of electrical equipment, is the use of statistical simulation methods [9].

The evaluation results of technical condition of electrical equipment and their application in the mathematical failure models for problems solving of determining the EPS subsystem reliability are presented in [10]. But the issue of reliability assessment of electrical equipment failures is not considered, and no estimation of possible losses is given. In addition, the significance level of electrical equipment in terms of the priority of out of service or repair is not quantified.

The comprehensive approach to the cost management of EPS subsystems with minimization of total costs of operation, maintenance and repair is presented in [11]. But the issue of taking into account the incompleteness of statistical information about failures, the fuzziness of initial information of technical condition parameters of the electrical equipment is not considered. In addition, the issue of optimizing the replacement of individual units and groups of electrical equipment in the face of limited investment costs remains open.

The most promising approach for cost optimization of electrical equipment is as follows. It provides an opportunity to determine the technical condition, the failure probability at the observation time interval, significance quantitative characteristics, taking into account the most important operational factors, the impact of out of service and replacement of electrical equipment on EPS reliability. This requires the development of the optimal distribution methodology of costs between groups of the same type of electrical equipment of the energy company, taking into account the most important operational factors. Solving this problem is possible through EPS complex simulation.

3. The aim and objectives of the study

The aim of the present research is to develop a model and algorithm for making decisions on optimizing costs for maintenance, repair and replacement of electrical equipment.

To achieve this aim, the following objectives were set:

– to develop a mathematical model of aggregated estimation of the significance degree of groups of electrical equipment in terms of cost distribution for maintenance and repair;

– to develop a mathematical model and algorithm of optimal cost distribution for technical maintenance, repair and replacement of electrical equipment of power companies;

– to carry out the complex simulation of the technical condition of electrical equipment and EPS states for making decisions of optimal cost distribution for technical maintenance, repair and replacement of electrical equipment of power companies.

4. Materials and methods for model development for optimal cost distribution for technical maintenance and repair

4. 1. Experimental research base

The study was carried out using the statistical information about failures of power and switching electrical equipment, which was registered in Ukraine's power grid and real data of the productive assets value and load level for the energy company objects.

4. 2. Mathematical model of aggregated estimation of the significance degree of groups of electrical equipment in terms of cost distribution for maintenance and repair

The task of allocating investments between individual groups of electrical equipment of the energy company, as mentioned, relates to a class of optimal decision making tasks in the presence of several criteria and uncertainties.

The choice of the optimal variant of admissible solutions or the ordering of a plurality of solutions is possible provided that there is an adequate model for technical condition assessment of electrical equipment, the model justification for adoption and evaluation of decision [12].

At present, there is a sufficiently large number of methods for formalizing goal setting and decision-making with regard to uncertainty [13].

Let the function of total energy costs of a number of factors be given $f_j,\ j=\overline{1,N_f}$, where N_f is the number of operational factors.

It is expedient to determine the cost level for maintenance and repair of electrical equipment using appropriate equity participation coefficients.

Normalized equity participation coefficient of electrical equipment for cost formation to maintain in an operational state for the i-th group of electrical equipment is determined

$$k_{i,j}^{g}\left(f_j\right)=\sum_{i=1}^{L_j}k_{i,j}\left(f_j\right), \qquad (1)$$

where L_f is the number of objects in the j-th group of electrical equipment; $k_{i,j}\left(f_j\right)$ is the normalized equity participation coefficient of electrical equipment for cost formation to maintain in an operational state for the j-th electrical equipment.

Expert analysis has shown that the most important factors affecting the cost quantitative characteristics for maintenance and repair are listed below.

1. Value of production costs of electrical equipment in monetary equivalent V. This factor characterizes the object in terms of complexity and labor intensity of operation.

The distribution coefficient by the value of production costs by groups and objects

$$k_{Fj}^{g}=\frac{V_j^g}{\sum_{j=1}^{N}V_j^g},\quad k_{Fi,j}^{g}=\frac{V_{ij}^g}{\sum_{j=1}^{N}V_j^g}, \qquad (2)$$

where V_j^g, V_{ij}^g, $\sum_{j=1}^{N}V_j^g$ are the values of production costs for the i-th electrical equipment, the j-th group of electrical equipment and in total of the energy company objects, respectively; N is the number of electrical equipment group.

2. Object load level E by electricity during the year, kWh. This factor characterizes the demand of the i-th object in the process of transmission and distribution of electricity by electrical networks of different voltage classes for the estimated year. In addition, this factor indirectly characterizes the wear rate of electrical equipment.

The distribution coefficient by the load level for the electrical equipment group and the object is determined

$$k_{Lj}^{g}=\sum_{j=1}^{L_f}E_{ij},\quad k_{Lij}=\frac{E_{ij}}{\sum_{j=1}^{N}E_j}, \qquad (3)$$

where E_{ij}, $\sum_{j=1}^{N}E_j$ are the load levels by electricity for the i-th electrical equipment, the j-th group of electrical equipment and in total of the energy company objects, respectively.

3. The failure probability Δp of the object at the observation time interval, which is its reliability index and allows you to indirectly take into account the quality of repair and maintenance service.

The distribution coefficient by the failure probability at the observation time interval for individual electrical equipment and groups of electrical equipment is determined

$$k_{EMj}^{g}=\sum_{j=1}^{L_f}k_{EMij},\quad k_{EMij}=\frac{\Delta p_{ij}}{\sum_{j=1}^{N}\Delta p_j^g}, \qquad (4)$$

where Δp_{ij}, $\sum_{j=1}^{N}\Delta p_j^g$ are the ratios of equity participation coefficients in failure probability at the observation time interval for the i-th electrical equipment, the j-th group of electrical equipment and in total of the energy company objects, respectively.

4. Technical emergency risk under failure, out of service, replacement of a specific unit of electrical equipment or unit of the electrical equipment group. This factor characterizes the equity participation coefficients of electrical equipment, groups of electrical equipment for cost formation to maintain in an operational state and replacement.

It is necessary to distribute optimally the costs for maintenance, repairs and investment costs for replacement of electrical equipment between groups of electrical equipment.

The quantitative assessment of the significance degree of electrical equipment in cost formation, taking into account the most important operational factors is required for making decisions on optimal allocation of costs for maintenance, repair or replacement of electrical equipment.

The choice of the optimal variant of cost distribution for maintenance, repair and investment in the upgrade is associated with the presence of various uncertainties in the options for evaluating decision variants, the inadequate reasonableness of the decision makers. For this goal, the most effective is to use the theory of fuzzy sets [14].

For finding generalized aggregated estimates, significance degree of units and groups of electrical equipment, taking into account the main operational factors and objectively existing uncertainties, it is effective to use a fuzzy inference system, first of all, to determine the ratings of groups of electrical equipment $A=\{A_i\}$.

The inputs of the fuzzy inference system are linguistic variables Ci (i=1,4), which meet the following criteria and have the following term sets:

– value of production costs for the group of electrical equipment $C_1=\{T_H^1,T_C^1,T_B^1\}$,

– load level by electricity for the group of electrical equipment $C_2=\{T_H^2,T_C^2,T_B^2\}$,

– failure probability at the observation time interval for the group of electrical equipment $C_3=\{T_H^3,T_C^3,T_B^3\}$,

– technical emergency risk in EPS $C_4=\{T_H^4,T_C^4,T_B^4\}$,

where T_H^i, T_C^i, T_B^i are "low", "medium", "high" values of the i-th parameter.

All inputs of the fuzzy inference system have 3 membership functions, the basic forms and parameters of which are presented in Fig. 1, respectively.

To account for the objectively existing tolerance of the recognizable class to change of importance degree for groups of electrical equipment in a certain range (for example, from [0…1] for C_1), the triangular membership functions were used.

These data are sent to the fuzzy inference system to obtain the result. For this purpose, a Mamdani fuzzy inference system has been used.

The output of the Mamdani fuzzy inference system is the importance degree for groups of electrical equipment Ai with the following term set:

$$A_i=\{T_H,T_C,T_B\},$$

where T_H, T_C, T_B are "low", "medium", "high" values of the parameter.

The output linguistic variable of the fuzzy inference system has 3 membership functions, the basic forms and parameters of which are presented in Fig. 2.

81 fuzzy inference rules for the output set A_i are suggested in Table 1.

Table 1

Schematic codes in the fuzzy inference system

No.	Input linguistic variables				Output linguistic variable
	C_1	C_2	C_3	C_4	A_i
1	T^1_H	T^2_H	T^3_H	T^4_H	T_H
2	T^1_H	T^2_H	T^3_H	T^4_H	T_C
3	T^1_H	T^2_H	T^3_H	T^4_H	T_B
...	...	...	...	...	...
81	T^1_B	T^2_B	T^3_B	T^4_B	T_B

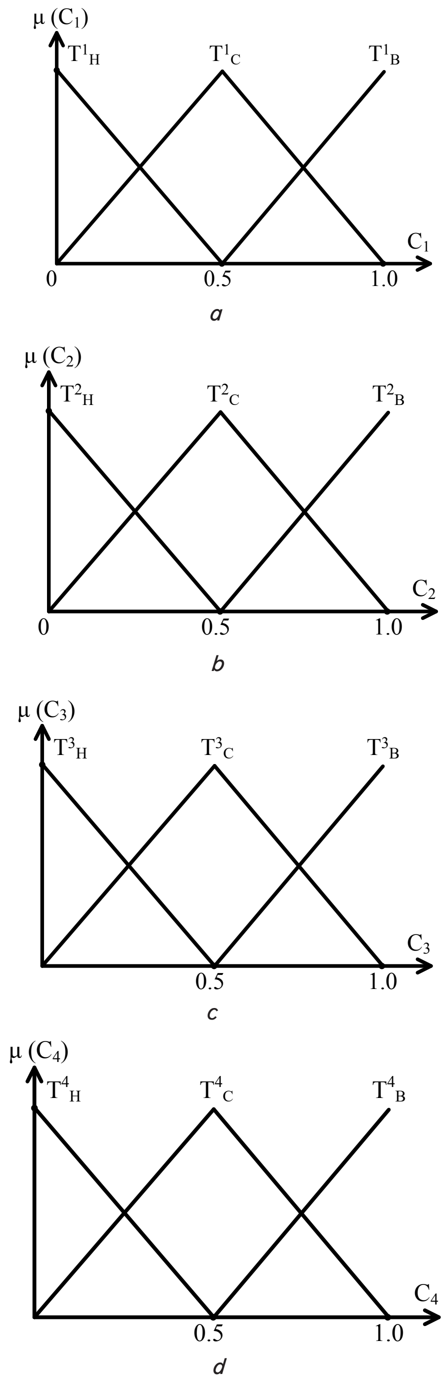

Fig. 1. Membership functions: *a* — input variable of C_1; *b* — input variable of C_2; *c* — input variable of C_3; *d* — input variable of C_4

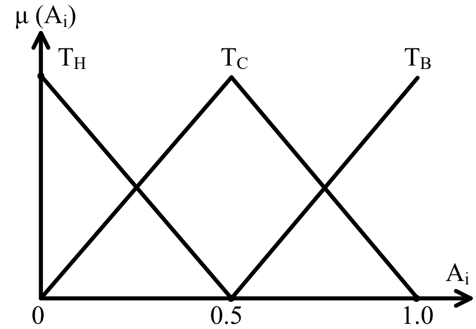

Fig. 2. Membership functions of term sets for the output linguistic variable A_i

The above rule base of the fuzzy inference system is the base and the only one for determining the aggregate estimates for each of the groups of electrical equipment.

An important task is also to determine the weight of the criteria and to take them into account in determining the estimates of A_i and the cost distribution for maintenance and repair of units and groups of electrical equipment. Weights are determined on the basis of Saati's method and the Fishburn's preferences system.

4. 3. Model of optimal cost distribution of technical maintenance and repair of electrical equipment on the basis of Boolean programming

Let the set of the electric equipment group of the energy company be given $X=\{x_i\}$, $i=\overline{1,n}$ and the set of aggregated estimates of the electric equipment group of the energy company $A=\{A_i\}$, $i=\overline{1,n}$. The cost of allocated investments to finance the maintenance of electrical equipment of the energy company B_{TOiP} and replacement of electrical equipment B_{inv} is known. Also the volume of investments for replacement of certain groups of electrical equipment of the energy company B_i^{inv}, $i=\overline{1,n}$ is known.

It is necessary to optimally allocate financial resources between groups of electrical equipment in order to maximize the usefulness of distribution implementation taking into account the importance of the above criteria.

The task of distributing the allocated costs of the energy company for maintenance and repair B_{TOiP} is solved by their distribution between groups of electrical equipment in proportion to the normalized value of indicators of aggregated significance assessment $A=\{A_i\}$. The task of distributing investments between groups to replace the electrical equipment B_{inv} with a view to maximize the result is formulated as a Boolean programming. For each element of the set of electrical equipment $X=\{x_i\}$, we assign a value of 1 or 0 depending on whether the investment costs B_{inv} are allocated or not allocated.

$$x_i = \begin{cases} 1, \text{ if costs are allocated for group } x_i\, Binv, \\ 0, \text{ if costs are not allocated for group } x_i\, Binv. \end{cases}$$

The problem of Boolean programming is formulated as follows

$$\sum_{i=1}^{n} A_i \cdot x_i \to \max,$$

with restrictions

$$\sum_{i=1}^{n} B_i^{inv} \le B_i,\ x_i \in \{A_i\}.$$

It is necessary to determine separately the weight coefficients W_{jt}, $j=\overline{1,n}$ of the criteria C_t, $t=\overline{1,4}$ for each group of electrical equipment based on the Saati's method [15] and the Fishburn's preferences system under working out the cycles of the fuzzy inference system. It is important to take into account the importance of the criteria in the very rules of the fuzzy inference system.

The reference rule base in the applied fuzzy inference system is the same for each of electrical equipment groups, and the importance (and, consequently, the weight coefficients) is assumed to be the same. Next, the process of adjusting the fuzzy inference system taking into account the investment values of criteria weight coefficients is performed. Weight coefficients should be normalized.

The above criteria for which it is necessary to allocate costs for maintenance and repair or investment costs for modernization of electrical equipment have different significance levels and are not the same for all groups of electrical equipment. Therefore, it is necessary to reassess these criteria expertly for each group of electrical equipment and determine the relevant weight coefficients W_{jt} for the i-th group of electrical equipment. The most appropriate approach is the method of pairwise comparison of objects, which is widely used in various methods of expert evaluation.

4. 4. EPS state simulation for cost distribution assessment of maintenance and repair

In this article, we considered the influence of accidental changes in the electrical network topology associated with the planned or emergency out of service of the electrical equipment or group of electrical equipment on the emergency risk under electrical equipment failure, in particular, the technical risk assessment of disturbance of dynamic stability.

The mathematical model and algorithm for emergency risk assessment under electrical equipment failure are described in detail in [16].

The algorithm of EPS complex simulation for cost distribution assessment for technical maintenance and repair of electrical equipment or group of electrical equipment is presented in Fig. 3. It differs in that it takes into account emergency risk assessment in EPS under electrical equipment failure to rank the electric equipment park requiring out of service.

To determine the probabilistic risk component according to a given model of EPS functioning, the developed RISK-ST, RISK-EPS software was used. With the help of statistical simulation, the random process of changes in the electric network state, which is determined by the state of elements efficiency and load change at the estimated time interval of observation is simulated.

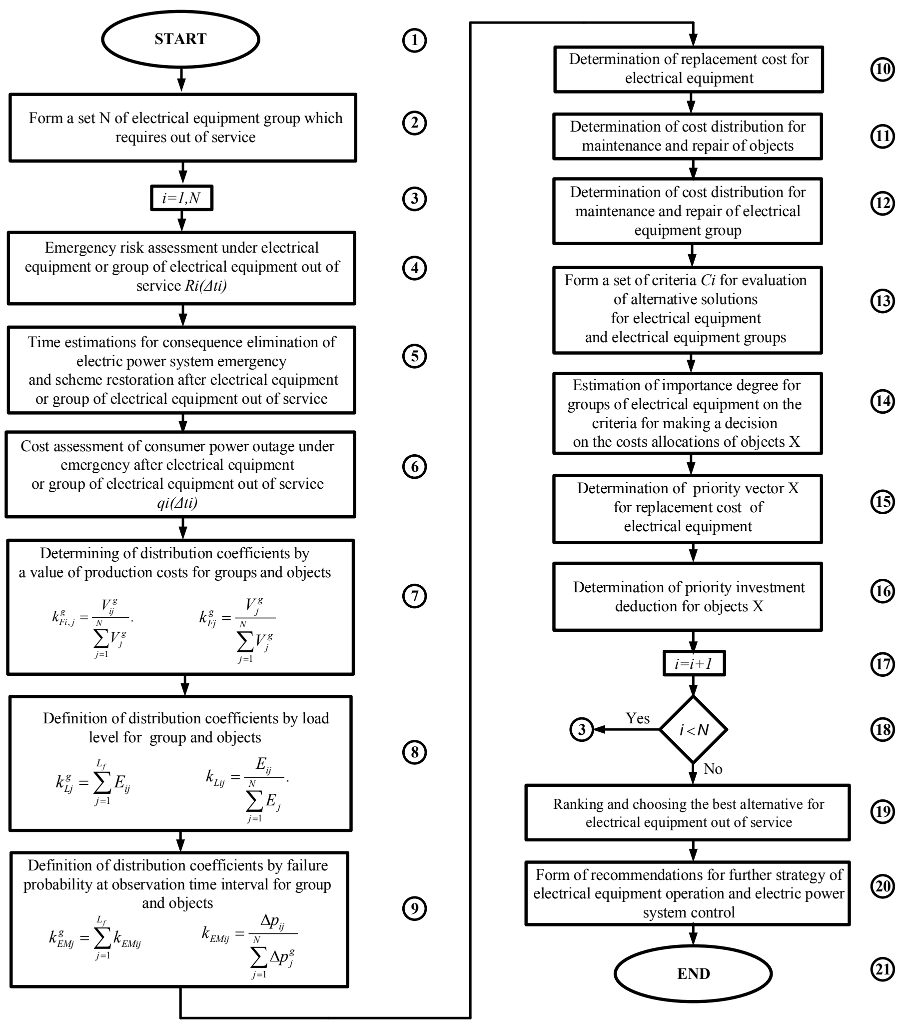

Fig. 3. Algorithm of EPS complex simulation for cost distribution assessment for technical maintenance and repair of electrical equipment or group of electrical equipment

5. Test results of decision-making on optimal cost distribution for maintenance and repair of electric equipment of energy companies

Fig. 4 shows an equivalent test scheme of electric connections of the integrated power system of Ukraine with a voltage level of 35–750 kV was considered for the quantitative indicators determination of risk failure of individual elements and instability of EPS normal state. The test scheme contains TPP No. 1 with a total capacity of 210 MW, TPP No. 2 with a total capacity of 500 MW, TPP No. 3 with a total capacity of 250 MW, TPP No. 4 with a total capacity of 700 MW, TPP No. 5 with a total capacity of 1800 MW, HPP No. 1 with a total capacity of 444 MW. The presented test scheme of the EPS model is meshed, has a limited throughput capacity of overhead transmission lines and designed for operation at a centralized electricity supply, which corresponds to the characteristics of Ukraine electric networks.

Table 2 presents the calculation series results for post-fault steady-state load flow parameters of the EPS test model.

Table 2 shows the results, which indicate the possible consequences in planning maintenance and repair of electrical equipment at a given observation time interval [17].

The analysis of probable deviations of voltage at control nodes and current overload of EPS subsystem elements was used in Monte Carlo simulation [18], the results of which are summarized in Table 3.

Analyzing the simulation results of emergency risk in the EPS subsystem, one can identify the most probable scenarios of power system instability and eventually provide for preventive measures [18].

A set of electrical equipment was created on the basis of regular technical diagnostics results of electrical equipment, which requires out of service for the purpose of maintenance or replacement.

Determination of cost distribution for maintenance and repair by groups and units of electrical equipment is carried out according to the following criteria:

– value of production costs;
– load level by electricity for the object;
– failure probability at the observation time interval.

This energy company includes six groups of power objects: electric substation 35 kV (ES35kV), electric substation 110 kV (ES110kV), overhead transmission line 35 kV (OTL35kV), overhead transmission line 110 kV (OTL110kV), electrical cable 35 kV (EC35kV), electrical cable 110 kV (EC110kV).

In turn, each of the groups has the following number of power objects: electric substation 35 kV – 9 units; electric substation 110 kV – 24 units; overhead transmission line 35 kV – 6 units; overhead transmission line 110 kV – 30 units; electrical cable 35 kV – 28 units; electrical cable 110 kV – 8 units. The total number of objects on the balance sheet of the energy company is 105 units, the parameters of which are presented in Tables 4, 5.

Definition of distribution coefficients by the value of production costs for groups of electrical equipment

$$\begin{bmatrix} k_F^{\text{OTL35kV}} \\ k_F^{\text{OTL110kV}} \\ k_F^{\text{EC35kV}} \\ k_F^{\text{EC110kV}} \\ k_F^{\text{ES35kV}} \\ k_F^{\text{ES110kV}} \end{bmatrix} = \begin{bmatrix} V_1^{\text{OTL35kV}} \\ V_2^{\text{OTL110kV}} \\ V_3^{\text{EC35kV}} \\ V_4^{\text{EC110kV}} \\ V_5^{\text{ES35kV}} \\ V_6^{\text{ES110kV}} \end{bmatrix} \times \left[\sum_{i=1}^{N} V_i^g \right]^{-1} =$$

$$= \begin{bmatrix} 5878401 \\ 197062234 \\ 343812154 \\ 60498561 \\ 299918213 \\ 43714294 \end{bmatrix} \times [950883857]^{-1} = \begin{bmatrix} 0.006 \\ 0.207 \\ 0.362 \\ 0.064 \\ 0.315 \\ 0.046 \end{bmatrix}.$$

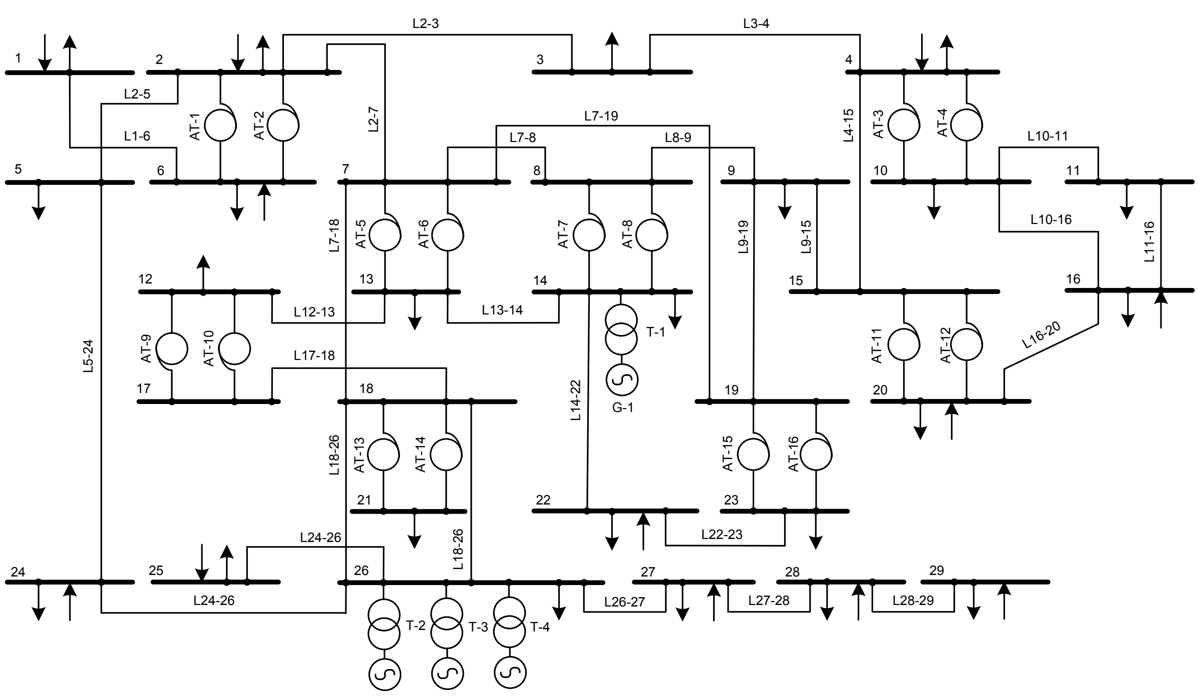

Fig. 4. Calculation scheme of the EPS test model

Table 2

Monitoring of drops of voltage levels at control nodes and loads of EPS electrical equipment

Experiment No.	Small-disturbance voltage instability of nodes for the EPS test model	Overload security of EPS electrical equipment
1	none	Electric substation 330 kV /110 kV No. 18: Current load of AT-1 is 103 % of Inom Current load of AT-2 is 103 % of Inom
2	Voltage level is 110.26 % of Unom at nodes 110 kV No. 20	none
3	none	none
...	...	...
7	none	Electric substation 330 kV /110 kV No. 24: Current load of AT-2 is 138 % of Inom
8	none	Electric substation 330 kV /110 kV No. 24: Current load of AT-1 is 139 % of Inom
...	...	...
24	Small-disturbance voltage instability of nodes 110 kV No. 3	none
...	...	...
30	none	Electric substation 330 kV /110 kV No. 24: Current load of AT-2 is 129 % of Inom
...	...	...
40	none	Electric substation 330 kV /110 kV No. 24: Current load of AT-1 is 131 % of Inom
...	...	...
46	Small-disturbance voltage instability of nodes 110 kV No. 3	none
47	none	Electric substation 330 kV /110 kV No. 24: Current load of AT-2 is 128 % of Inom
48	none	Electric substation 330 kV /110 kV No. 24: Current load of AT-2 is 144 % of Inom
49	Voltage level is 111.4 % of Unom at nodes 110 kV No. 20	none
50	none	none
51	none	Electric substation 330 kV /110 kV No. 18: Current load of AT-1 is 135 % of Inom
...	...	...
58	none	Electric substation 330 kV /110 kV No. 24: Current load of AT-1 is 142 % of Inom
59	none	Electric substation 330 kV /110 kV No. 24: Current load of AT-2 is 128 % of Inom
...	...	...
65	none	Electric substation 330 kV /110 kV No. 9: AT-2 124 % of Inom
...	...	...
94	none	Electric substation 330 kV /110 kV No. 24: Current load of AT-2 is 132 % of Inom
95	none	Electric substation 330 kV /110 kV No. 9: Current load of AT-1 is 123 % of Inom
...	...	...
1000	none	none

Definition of distribution coefficients by the load level for electrical equipment groups

$$\begin{bmatrix} k_L^{OTL35kV} \\ k_L^{OTL110kV} \\ k_L^{EC35kV} \\ k_L^{EC110kV} \\ k_L^{ES35kV} \\ k_L^{ES110kV} \end{bmatrix} = \begin{bmatrix} E_1^{OTL35kV} \\ E_2^{OTL110kV} \\ E_3^{EC35kV} \\ E_4^{EC110kV} \\ E_5^{ES35kV} \\ E_6^{ES110kV} \end{bmatrix} \times \left[\sum_{i=1}^{N} E_i^g\right]^{-1} =$$

$$= \begin{bmatrix} 56940 \\ 706932 \\ 378432 \\ 189216 \\ 176076 \\ 1162452 \end{bmatrix} \times [2670048]^{-1} = \begin{bmatrix} 0.021 \\ 0.265 \\ 0.142 \\ 0.071 \\ 0.066 \\ 0.435 \end{bmatrix}.$$

Definition of distribution coefficients by the failure probability at the observation time interval for groups of electrical equipment

$$\begin{bmatrix} k_{EM}^{OTL35kV} \\ k_{EM}^{OTL110kV} \\ k_{EM}^{EC35kV} \\ k_{EM}^{EC110kV} \\ \mathrm{k}_{\mathrm{EM}}^{ES35kV} \\ k_{EM}^{ES110kV} \end{bmatrix} = \begin{bmatrix} \Delta p_1^{OTL35kV} \\ \Delta p_2^{OTL110kV} \\ \Delta p_3^{EC35kV} \\ \Delta p_4^{EC110kV} \\ \Delta p_5^{ES35kV} \\ \Delta p_6^{ES110kV} \end{bmatrix} \times \left[\sum_{i=1}^{N} \Delta p_i^g\right]^{-1} =$$

$$= \begin{bmatrix} 0.0697674 \\ 0.2986919 \\ 1.0 \\ 0.2093023 \\ 0.0004845 \\ 0.0004845 \end{bmatrix} \times [1.579]^{-1} = \begin{bmatrix} 0.0441921 \\ 0.1891975 \\ 0.6334203 \\ 0.1325763 \\ 0.0003069 \\ 0.0003069 \end{bmatrix}.$$

On the principle of dominance, the maximum value of the coefficient of failure probability at the observation time interval for the group of electrical equipment is

$$k_{EM}^{max} = k_{EM}^{EC35kV} = 0.63342.$$

Table 6 shows the results of cost distribution coefficients for maintenance and repair by groups of electrical equipment.

Table 7 shows the results of cost distribution coefficients for maintenance and repair by individual objects.

Allocated costs B_Σ for distribution on maintenance and repair of the energy company amounted to 95 000 000 USD. We assume that the weight of the distribution coefficients is the same $r_1=r_2=r_3=$ $=0.33$. Then the distribution of allocated costs B_Σ between groups and objects has the following form

$$\begin{bmatrix} B_1^{\mathrm{OTL35kV}} \\ B_2^{\mathrm{OTL110kV}} \\ B_3^{\mathrm{EC35kV}} \\ B_4^{\mathrm{EC110kV}} \\ B_5^{\mathrm{ES35kV}} \\ B_6^{\mathrm{ES110kV}} \end{bmatrix} = B_\Sigma \times \left(r_1 \times \begin{bmatrix} k_F^{\mathrm{OTL35kV}} \\ k_F^{\mathrm{OTL110kV}} \\ k_F^{\mathrm{EC35kV}} \\ k_F^{\mathrm{EC110kV}} \\ k_F^{\mathrm{ES35kV}} \\ k_F^{\mathrm{ES110kV}} \end{bmatrix} + r_2 \times \begin{bmatrix} k_L^{\mathrm{OTL35kV}} \\ k_L^{\mathrm{OTL110kV}} \\ k_L^{\mathrm{EC35kV}} \\ k_L^{\mathrm{EC110kV}} \\ k_L^{\mathrm{ES35kV}} \\ k_L^{\mathrm{ES110kV}} \end{bmatrix} + r_3 \times \begin{bmatrix} k_{EM}^{\mathrm{OTL35kV}} \\ k_{EM}^{\mathrm{OTL110kV}} \\ k_{EM}^{\mathrm{EC35kV}} \\ k_{EM}^{\mathrm{EC110kV}} \\ k_{EM}^{\mathrm{ES35kV}} \\ k_{EM}^{\mathrm{ES110kV}} \end{bmatrix} \right) =$$

$$= 95000000 \times \left(0.333 \times \begin{bmatrix} 0.006 \\ 0.207 \\ 0.362 \\ 0.064 \\ 0.315 \\ 0.046 \end{bmatrix} + 0.333 \times \begin{bmatrix} 0.021 \\ 0.265 \\ 0.142 \\ 0.071 \\ 0.066 \\ 0.435 \end{bmatrix} + 0.333 \times \begin{bmatrix} 0.0442 \\ 0.1892 \\ 0.6334 \\ 0.1326 \\ 0.0003 \\ 0.0003 \end{bmatrix} \right) =$$

$$= \begin{bmatrix} 2252412 \\ 20917062 \\ 35981649 \\ 8465526 \\ 12062426 \\ 15225926 \end{bmatrix}.$$

Table 8 shows the results of cost distribution assessment for maintenance and repair by groups of electrical equipment.

An analysis of calculation results of cost distribution in Table 8 provides for the largest amount of allocated costs for maintenance and repair and is 35981649 USD for the group of electrical equipment EC35 kV.

Table 9 shows the results of cost distribution assessment for maintenance and repair by objects.

Analyzing the results of Table 9, it is possible to allocate the object electric substation ES24 with the largest amount of allocated costs for maintenance and repair 820010 USD.

The next step is to determine the cost distribution of electrical equipment replacement with limited cost. In Tables 10–12, a list of the most important electrical equipment in terms of ensuring the reliability of power supply and electric power system stability on the basis of calculation results of EPS emergency risk under electrical equipment out of service is formed. The total volume of allocated costs for the energy company aimed at replacement of electric equipment is 21000000 USD.

The analysis of calculation results of replacement cost of electrical equipment of energy companies in Table 10 showed that the highest cost of replacing the high-power auto-transformer AT61 is 12500000 USD.

We create the following system on the basis of received priorities of electrical equipment and its replacement cost:

$$\begin{cases} 0.048 \cdot n_1 + 0.139 \cdot n_2 + 0.047 \cdot n_3 + 0.04 \cdot n_4 + \\ +0.206 \cdot n_5 + 0.37 \cdot n_6 + 0.044 \cdot n_7 + 0.106 \cdot n_8 = 0; \\ 7100000 \cdot n_1 + 4500000 \cdot n_2 + 12500000 \cdot n_3 + 600000 \cdot n_4 + \\ +750000 \cdot n_5 + 900000 \cdot n_6 + 850000 \cdot n_7 + \\ +700000 \cdot n_8 \le 21000000. \end{cases}$$

Table 3

Simulation results of emergency risk assessment in the EPS subsystem with TPP at the observation time interval Δt=12 months

Branch No.	Branch name	Branch element	Year of instal-lation	Year of observa-tion start	Emergency risk		
					Rf(Δt)	Ro(Δt)	R(Δt)
1	28–29	L1	1960	2010	0.01	0	0.01
		B2	1960	2010			
		B3	1960	2010			
2	15–20	AT4	1977	2010	0.04	0	0.04
		B5	1982	2010			
		B6	1982	2010			
3	15–20	AT7	1982	2010	0.03	0	0.03
		B8	1982	2010			
		B9	1982	2010			
...	...	...	...	...	...	...	...
11	18–21	AT31	1983	2010	0.01	0.01	0.02
		B32	1983	2010			
		B33	1983	2010			
12	18–21	AT34	1984	2010	0.01	0.01	0.02
		B35	1984	2010			
		B36	1984	2010			
...	...	...	...	...	...	...	...
63	24	AT187	1985	2010	0.03	0.06	0.09
		B188	1985	2010			
		B189	1985	2010			

Table 13 shows the system solution results by the binary integer programming method, which indicate for the replacement of what object investments will be allocated.

Analysis of determination results of priority cost allocation for objects in Table 13 showed that in the presence of such an investment, the high-power auto-transformer AT61 will not be replaced at this observation time interval.

A comparative calculations analysis of dynamic stability of EPS under out of service of the considered power transformers according to the developed model [19] confirmed the coincidence with the characteristics of emergency situations that arose during the actual operation of power grids for the energy company.

The determination results of priority of cost allocation for objects were used to simulate the EPS state by conducting calculations of EPS dynamic stability during electrical equipment out of service presented in Table 13 according to the developed model [19].

Table 4

Input parameters of the overhead transmission line

No.	Name of transmission line	Type of transmission line	Voltage level, kV	Length, km	Year of installation	Cost size, USD	Power transmission, MW/year
1	ES14- ES 27	overhead transmission line	35	1.24	2001	894805.2	7008
2	ES22- ES28	overhead transmission line	35	1.3	1970	623225.9	23652
3	ES 37- ES 34	overhead transmission line	35	5.06	1958	865922.7	7008
...	...	...	...	...	...	...	...
72	ES 37- ES 15	electrical cable	110	2.188	1977	2552830	35040

Table 5

Input parameters of electric substations

No.	Name of electric substation	Voltage level, kV	Total nominal capacity, MVA	Year of installation	Cost size, USD	Power transmission, MW/year
1	ES 27	35	2×10	1994	3439251	3504
2	ES 28	35	2×25	2013	8523043	24528
3	ES 29	35	2×25	1982	6113128	35916
...	...	...	...	...	...	...
33	ES 38	110	1×63	1984	8870000	56064

Table 6

Definition of cost distribution coefficients for maintenance and repair by groups of electrical equipment

Group name of electrical equipment	k_F^g	k_L^g	k_{EM}^g
overhead transmission line 35 kV	0.006	0.021	0.04419
overhead transmission line 110 kV	0.207	0.265	0.1892
electrical cable 35 kV	0.362	0.142	0.63342
electrical cable 110 kV	0.064	0.071	0.13258
electric substation 35 kV	0.315	0.066	0.00031
electric substation 110 kV	0.046	0.435	0.00031

Table 7

Definition of cost distribution coefficients for maintenance and repair by individual objects

No.	Object name	k_F^O	k_L^O	k_{EM}^O
1	transmission line ES14-ES27	0.0009	0.003	0.00734
2	transmission line ES22-ES27	0.0007	0.009	0.00735
3	transmission line ES37-ES34	0.0009	0.003	0.00757
4	transmission line ES37-ES34	0.0016	0.003	0.00635
5	transmission line ES25-ES32	0.0021	0.002	0.00331
...	...	...	...	...
105	transmission line ES14-ES27	0.0009	0.004	0.00437

Table 8

Results of cost distribution assessment for maintenance and repair by groups of electrical equipment

No.	Group name	The amount of planned cost for maintenance and repair, USD
1	overhead transmission line 35 kV	2252412
2	overhead transmission line 110 kV	20917062
3	electrical cable 35 kV	35981649
4	electrical cable 110 kV	8465526
5	electric substation 35 kV	12062426
6	electric substation 110 kV	15225926

Table 9

Results of cost distribution assessment for maintenance and repair by objects

No.	Object name	The amount of planned cost for maintenance and repair, USD
1	transmission line ES14-ES27	266803
2	transmission line ES22-ES27	494078
3	transmission line ES37-ES34	424573
4	transmission line ES37-ES34	290011
...	...	...
105	electric substation ES24	820010

Table 10

Results of determination of replacement cost of electric equipment of the energy company

No.	Name of electrical equipment	Replacement cost of electric equipment, USD
1	High-power auto-transformer AT31	7100000
2	High-power auto-transformer AT34	4500000
3	High-power auto-transformer AT61	12500000
4	High-voltage circuit breaker B8	600000
5	High-voltage circuit breaker B9	750000
6	High-voltage circuit breaker B62	900000
7	High-voltage circuit breaker B63	850000
8	High-voltage circuit breaker B185	700000

Table 11

The results of comparing the importance criteria by the Saati's method

Criteria indicators	kf	kL	kEM	W	Wn
kf	1	1/5	1/7	0.253	0.043
kL	5	1	1/5	0.76	0.13
kEM	7	5	1	3.201	0.549
Total:	13	6.2	1.34	4.214	0.722

Table 12

Determination results of the priority vector X for objects

Object name	k_f	k_L	k_{EM}	Name of the vector variable X	Value of the vector variable X, p. u.
AT31	0.315	0.066	0.00031	X_1	0.048
AT34	0.046	0.435	0.00031	X_2	0.139
AT61	0.315	0.066	0.00031	X_3	0.047
B8	0.006	0.021	0.00442	X_4	0.04
B9	0.207	0.265	0.1892	X_5	0.206
B62	0.362	0.142	0.6334	X_6	0.37
B63	0.064	0.071	0.13258	X_7	0.044
B185	0.207	0.265	0.1892	X_8	0.106

Table 13

Prioritization results of cost allocation for objects

AT31	AT34	AT61	B8	B9	B62	B63	B185
1	1	0	1	1	1	1	1

The overall disturbance risk of EPS dynamic stability at the current observation time interval was characterized by a high level $R(\Delta t)=0.635$. On the basis of simulation results of the EPS state, taking into account the technical condition assessment, probability of electrical equipment failure, recommendations were given to conduct the maintenance and repair according to the forecast dispatch schedule of the EPS maximum load in the coming summer period with $R(\Delta t)=0.09$. The obtained result confirms the coincidence with the characteristics of emergency situations that arose during the real operation of electric networks of the energy company.

6. Discussion of the results of complex simulation of the EPS state and cost distribution for maintenance and repair

A comprehensive approach to the optimal cost distribution for maintenance, repair and replacement of electrical equipment, which, on the one hand, allows fulfilling the conditions for ensuring the necessary level of electrical capacity of electrical equipment in the conditions of limited financial resources is proposed. On the other hand, it provides the opportunity to minimize the blackout risks of electricity supply to consumers under electrical equipment failure and cascade of EPS accidents.

Such solution of the problem permits, first of all, to assess the technical condition and to determine the probability of electrical equipment failure on the basis of the developed mathematical models based on the use of available operative quantitative and qualitative diagnostic information.

The fuzzy mathematical model of quantitative assessment of the importance degree of electrical equipment in the formation of investment costs is based on the consideration of the most important operational factors, in particular, takes into account objectively existing uncertainties of information. This makes it possible to more objectively determine the priority of the primary out of service or replacement of electrical equipment.

The questions of choice simulation for optimal distribution of limited costs for different groups of electrical equipment by means of Boolean programming are considered.

The complexity of applying risk assessment at enterprises now consists in the absence of information about real losses in case of violation of power supply to consumers and electric supply companies. With the development of economic and legal aspects of the electricity market, this disadvantage will be less noticeable.

The advantages of this development in comparison with other analogues are as follows:

– the probability of failure of electrical equipment and overhead power lines is determined on the basis of technical condition assessment, taking into account the predicted type of defects by means of the developed mathematical models adapted to the real operation conditions;

– the priority of out of service or replacement of electrical equipment is formed on the basis of a complex assessment of facility significance taking into account the EPS emergency risk;

– the optimal cost allocation for replacement of electrical equipment between the units of the energy company on the basis of aggregated significance indicator;

– the consequences of electrical equipment failure for the consumer and electric supply company are taken into account;

– the possibility to form preventive decisions concerning maintenance of operational reliability of electrical equipment and EPS security on the basis of the resulted calculations.

The cost allocation for replacement of electric equipment with limited investments gives grounds to assert that the application of this approach is justified in choosing the maintenance and repair strategy of electrical equipment of the energy company.

Fuzzy inference models for priority and importance estimation of each object group are developed. The practical value lies in the fact that on the basis of the offered models it is possible to objectively assess the technical condition and to determine which of the above elements are the priorities for repair or replacement.

For further research, it is necessary to accumulate information about models of the technical condition assessment of electrical equipment with more objects in different regions of the power system. This obviously requires the mobilization of significant organizational and technical measures with power supply companies. The results can be implemented at power plants and electric supply companies.

The application of the proposed methodology at enterprises will increase the efficiency, objectivity in assessing the real situation and, as a consequence, increase the lifetime of electrical equipment.

7. Conclusions

1. The mathematical model of aggregated estimation of the significance degree of groups of electrical equipment in terms of cost distribution for maintenance and repair was developed on the basis of using the theory of fuzzy sets, Saati's method, which has a high degree of consistency of ratings for various experts.

2. The mathematical model and algorithm of optimal cost distribution for technical maintenance, repair and replacement of electrical equipment of power companies were developed, which take into account emergency risk assessment in EPS under electrical equipment failure to rank the electric equipment park requiring out of service.

The proposed algorithm allows making decisions of dispatching, operational-technological and repair character in the conditions of limited financial resources, which provide sufficient reliability of consumer power supply and economic efficiency of the power company.

3. The complex simulation of technical condition of electrical equipment and EPS states was carried out for making decisions of optimal cost distribution for technical maintenance, repair and replacement of electrical equipment of power companies. The analysis of cost distribution between objects with real funds allocated for maintenance and repair confirms the high convergence with the results of electrical equipment repairs and modernization of the energy company. Carrying out calculations of emergency risk assessment without replacement of electrical equipment and taking into account the replacement allowed reducing the EPS emergency risk by 10 %. This confirms the acceptable efficiency of the applied approach when drawing up schedules of maintenance of electric equipment of power companies.

References

1. A study of Electrical Security Risk Assessment System based on Electricity Regulation / Dahai You A., QingQian Chen B., Xianggen Yin C., Bo Wang D. // Energy Policy. 2011. Vol. 39, Issue 4. P. 2062–2074. doi: https://doi.org/10.1016/j.enpol.2011.01.050
2. Wallnerstrom C. J., Hilber P. Vulnerability Analysis of Power Distribution Systems for Cost-Effective Resource Allocation // IEEE Transactions on Power Systems. 2012. Vol. 27, Issue 1. P. 224–232. doi: https://doi.org/10.1109/tpwrs.2011.2165226
3. Benefits of reliability centred asset management / Hilber P., Babu S., Wallnerstom J., Westerlund P., Rosenlind J. // 22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013). 2013. doi: https://doi.org/10.1049/cp.2013.0668
4. Ciapessoni E., Cirio D., Gagleoti E. A probabilistic approach for operational risk assessment of power systems // CIGRE. 2008. P. C4–114.
5. Review on Risk Assessment of Power System / Shiwen Y., Hui H., Chengzhi W., Hao G., Hao F. // Procedia Computer Science. 2017. Vol. 109. P. 1200–1205. doi: https://doi.org/10.1016/j.procs.2017.05.399
6. Louit D., Pascual R., Banjevic D. Optimal interval for major maintenance actions in electricity distribution networks // International Journal of Electrical Power & Energy Systems. 2009. Vol. 31, Issue 7-8. P. 396–401. doi: https://doi.org/10.1016/j.ijepes.2009.03.021
7. Moradkhani A., Haghifam M. R., Abedi S. M. Risk-based maintenance scheduling in the presence of reward penalty scheme // Electric Power Systems Research. 2015. Vol. 121. P. 126–133. doi: https://doi.org/10.1016/j.epsr.2014.12.006
8. Multiple failure modes analysis and weighted risk priority number evaluation in FMEA / Xiao N., Huang H.-Z., Li Y., He L., Jin T. // Engineering Failure Analysis. 2011. Vol. 18, Issue 4. P. 1162–1170. doi: https://doi.org/10.1016/j.engfailanal.2011.02.004
9. Yssaad B., Khiat M., Chaker A. Reliability centered maintenance optimization for power distribution systems // International Journal of Electrical Power & Energy Systems. 2014. Vol. 55. P. 108–115. doi: https://doi.org/10.1016/j.ijepes.2013.08.025
10. Transmission expansion planning: A discussion on reliability and "N−1" security criteria / Leite da Silva A. M., Rezende L. S., Manso L. A. F., Anders G. J. // 2010 IEEE 11th International Conference on Probabilistic Methods Applied to Power Systems. 2010. doi: https://doi.org/10.1109/pmaps.2010.5528652
11. Handschin E., Jurgens I., Neumann C. Long term optimization for risk oriented asset management // 16th Power Systems Computation Conference. Glasgow, 2008.
12. Goerdin S. A. V., Smit J. J., Mehairjan R. P. Y. Monte Carlo simulation applied to support risk-based decision making in electricity distribution networks // 2015 IEEE Eindhoven PowerTech. 2015. doi: https://doi.org/10.1109/ptc.2015.7232494
13. Wang B., Li Y., Watada J. A New MOPSO to Solve a Multi-Objective Portfolio Selection Model with Fuzzy Value-at-Risk // Lecture Notes in Computer Science. 2011. P. 217–226. doi: https://doi.org/10.1007/978-3-642-23854-3_23
14. Bardyk Ye. I. Modelling and assessment of chances of failure of power systems electrical equipment taking into account the after repair resource restoration level // Visnyk of National Mining University. 2014. Issue 3. P. 82–90.
15. Saaty T. L. Decision making with the analytic hierarchy process // International Journal of Services Sciences. 2008. Vol. 1, Issue 1. P. 83–98. doi: https://doi.org/10.1504/ijssci.2008.017590
16. Kosterev N. V., Bardyk E. I., Litvinov V. V. Preventive risk-management of power system for its reliability increasing // WSEAS TRANSACTIONS on POWER SYSTEMS. 2015. Vol. 10. P. 251–258.
17. Bardyk E. I. Models of reliability assessing of electricity supply of auxiliary NPP from external sources with fuzzy defined parameters of failures of equipments // Proceedings of the Institute of Electrodynamics of National Academy of Sciences of Ukraine. 2014. P. 34–38.
18. Bardyk E., Bolotnyi N. Parametric identification of fuzzy model for power transformer based on real operation data // Eastern-European Journal of Enterprise Technologies. 2017. Vol. 6, Issue 8 (90). P. 4–10. doi: https://doi.org/10.15587/1729-4061.2017.118632
19. Bardyk E., Bolotnyi N. Development of a model for determining a priority sequence of power transformers out of service // Eastern-European Journal of Enterprise Technologies. 2018. Vol. 3, Issue 3. P. 6–15. doi: https://doi.org/10.15587/1729-4061.2018.133570