Сформульовано підхід до окремих аспектів задачі стратегічного планування стійкого розвитку електроенергетичного підприємства як до багатокритеріальної задачі прийняття рішення, яка вирішується в умовах нечіткої вихідної інформації. Для вирішення цієї задачі запропоновано метод побудови множини припустимих рішень, виходячи зі специфіки функціонування підрозділів підприємства. Множина ефективних рішень формується відповідно до методу Парето. Оптимальне рішення обирається з урахуванням переваг особи, що приймає рішення

Ключові слова: електроенергетичне підприємство, розподіл, ризик, множина Парето, вагові коефіцієнти, метод Сааті

Сформулирован подход к отдельным аспектам задачи стратегического планирования устойчивого развития электроэнергетического предприятия как к многокритериальной задаче принятия решения, которая решается в условиях нечеткой исходной информации. Для решения этой задачи предложен метод построения множества допустимых решений, исходя из специфики функционирования подразделений предприятия. Множество эффективных решений формируется в соответствии с методом Парето. Оптимальное решение выбирается с учетом предпочтений лица, принимающего решения

Ключевые слова: электроэнергетическое предприятие, распределение, риск, множество Парето, весовые коэффициенты, метод Саати

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DEVELOPMENT OF FUZZY STATISTICAL METHOD OF OPTIMAL RESOURCE ALLOCATION AMONG TECHNICAL DEPARTMENTS OF AN ELECTRIC UTILITY COMPANY

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1. Introduction

Sustainable and stable development of an electric utility company implies the modernization of its structural units that provide technological process by updating fixed assets.

The process of the modernization of structural subdivisions of enterprises is associated with significant capital investments. Under modern market conditions, electric utility enterprises have limited financial resources for carrying out such modernization. Thus, the company management faces the task of optimal allocation of available funds among main technological units. When tackling this problem, it is necessary to take into account a large number of criteria that are often contradictory. So it is very important to find an agreed optimum for all considered criteria.

The criterion of efficient performance of technical units is the risk of reducing the reliability of electricity supply, which is necessary to minimize [1]. There are limited funds C for the modernization.

Under these objectively existing conditions, it is necessary to efficiently allocate available funds among the divisions, which are responsible for the equipment that needs a replacement. This task is multicriterial and it must be solved under conditions of incomplete initial data. In the case of non-optimal solution of this problem, which often occurs through the neglect of certain criteria or underestimation of incompleteness of the unitial information, the available funds can be spent inefficiently and thus reduce the overall efficiency of the modernisation of an electric utility company. Therefore, the task of determining the optimal allocation of funds among the divisions of an electric utility enterprise taking into account all the objectively existing factors is relevant.

2. Analysis of scientific literature and the problem statement

The known methods of allocation of resources among companies or divisions of an enterprise [2, 3] solve an optimizing task of profit or production output maximization under conditions of existing deterministic dependencies of the values that form the target function, on the volume of financing. In addition, very often the task of resource allocation (financial or energy) is limited to the distribution systems without taking into account systems of generation and transmission of electricity and electric power system as a whole [3, 4]. The paper [5] studied the issue of distribution and supply of electricity under conditions of the energy market of Ukraine, where there is an imbalance between the supply and consumption of electric power under conditions of scarcity of resources, but the task of their allocation is not addressed. In the paper [6] the author discusses the optimization of distribution of generation in the power system in the presence of distributed energy resources in order to increase its reliability and reduce the cost of electricity, but the methods of allocation of finances among the objects of distributed generation are not considered. In the article [7], the issue of the management of available resources was examined more comprehensively, but, yet again, only for a small scale electric utility enterprise with the sources of distributed generation.

During the allocation of available funds among enterprises of energy sector, optimization task is complicated by the necessity of taking into account not only the economic effect, but also the technical conditions of the functioning of an electric utility company, the analysis of which is in the area of risk evaluation [8, 9].

Technical and economic optimisation task of allocation of resources among units of an electric utility company in the general case is multicriterial and it can be solved under conditions of a large number of uncertainties. Under such conditions, it is advisable to apply the Pareto method, which allows determining the optimal scope of decisions by using expert assessments [10, 11].

Let us specify the set of feasible solutions to the task of allocation of funds C among the n units of an electric utility company:

$$\{D\}=\{D_1,D_2,...,D_n\}, \tag{1}$$

and objective functions (criteria) $f_1,...,f_m$ that are specified on the set D. It is necessary to find an optimal solution on the set D, which minimizes the functions $f_1,...,f_m$:

$$f(x)=(f_1(x),...,f_m(x))\xrightarrow{x\in D}\min, \tag{2}$$

where f(x) is the m-vector-function of the argument $x\in D$.

We defined Pareto-effective area $D^E\in D$, which maintains all Pareto optimal points. Displaying the set D^E in the space of optimizing criteria is indicated by Y^E. The set $Y^E=f(D^E)$ is called the Pareto set in the criteria space.

Pareto-optimal solution to a multi-criteria task of allocating the funds among departments is to be searched only among the elements of the set of Pareto-effective area D^E. In this area not a single element D_i can be improved without worsening of at least one of the other elements. An important feature of the Pareto set D^E is the possibility of removing a decision which is in advance inefficient and inferior to others by all criteria, from the total set of solutions D. Another valuable feature of the Pareto set is that the Pareto principle proposes less stringent requirements to the notion of optimality (unlike other principles, for example, the Nash principle), as a result of which the Pareto-optimal set exists always and it is not empty [9].

Efficient solutions are only between the points of the optimum, which were obtained at solving a mult-icriteria task separately for each criterion. The solution to a multi-criteria task should begin with the selection of the set D^E. In the absence of additional information about the system of priorities of the person that makes the decision, another approach is impossible.

3. The purpose and objectives of the study

The aim of this work is to define the method of optimal allocation of limited resources among the technical units of an electric utility company (energy system, supplying company, electric utility plant) by the criterion of minimizing the risk of an emergency situation under conditions of a large number of uncertainties.

According to the set goal, the following tasks are solved:

– the formation of a set of feasible decisions in the allocation of resources among units of an electric utility enterprise;

– determination of optimal set of solutions on a set of the feasible ones by using the Pareto method;

– design of an approach to analytical solution of the set optimization task on the basis of the results of probabilistic-statistical evaluation of the risk of an emergency in an electric utility company.

4. Method of optimal allocation of funds among the divisions of an electric utility enterprise

The formation of a set of feasible solutions. When solving a multi-criteria problem of decision-making, it is necessary in the first place to create a set of feasible solutions, based on the specifics of functioning of the units that are parts of the company. In the set problem, technological units of an electric utility plant are considered. The equipment, for which these units are responsible for, must be upgraded. Integrated assessment of the reliability of the equipment of these units is a risk of an accident due to the equipment failure in the interval of time.

The task of reducing the risk of an accident due to an equipment failure. An electric utility company has to select the equipment that needs a replacement (or repair) to minimize the risk of an accident occurrence in a power system due to its failure, and the cost of the equipment would not exceed a certain amount C. In this case the cost of power equipment is known: transformers (C_T), lines (C_L), switchers (C_S). Then the task of reducing the risk of the occurrence of an accident in the power system due to the equipment failure in the interval of time is formulated as follows: it is necessary to find such integer values of variables K_m so that to fulfill the following inequality:

$$\sum_{m=1}^{N} C_m\cdot K_m < C, \tag{3}$$

and in this case the risk of an accident occurrence in the power system would be minimally possible:

$$R=\sum_{i=1}^{L}\sum_{i=1}^{N} P(S_i)\cdot P(H_j/S_i)\cdot M_j\to\min, \tag{4}$$

where L is the number of possible emergency scenarios; N is the number of units of equipment, which this department is responsible for; M_j are the effects of an emergency situation; is the probability of occurrence of j emergency at the failure of i-th element; $P(S)_i$ is the probability of failure of i element in the time interval Δt [8].

To define variants for replacement of equipment, let us assume that out of the total amount for the replacement of the equipment of the k-th unit, the amount

$$C_K = \{0,1C; 0,2C;...; 1,0C\} = \lambda_i \cdot C, 0 < \lambda_i < 1$$

can be allocated.

As a result of solving the obtained task of integer programming, we receive the variants of solution D_i: the value of minimal risk, depending on the means allocated to C_i^K.

Forming the set of Pareto efficient solutions. According to the general solution of the multi-criteria problems, we perform a narrowing of the set of feasible solutions of the total set D to the set of Pareto efficient solutions D^E. Defining the set of efficient solutions is performed according to the algorithm of construction of Pareto-optimal vectors P(Y) [12]. The algorithm is constructed so that the the required set of Pareto-optimal vectors is derived from Y by sequential deleting of vectors that are non-optimal in advance [9, 10]:

Step 1. Put P(Y)=Y, i=1, j=2. This forms the so-called current set of Pareto-optimal vectors, which in the beginning of the algorithm work matches the set *Y*, and in the end it will form the required set of Pareto-optimal vectors.

Step 2. Check out the performance of inequality $y_i>y_j$. If it is true, then skip to step 3. Otherwise, proceed to step 5.

Step 3. Remove vector y_j from the current set of vectors P(Y), as it is not Pareto-optimal.

Step 4. Check out the fulfillment of inequality j<N. If it exists, then put j=j+1 and return to step 2. In the opposite case, return to step 7.

Step 5. Check out validity of inequality $y_j>y_i$. In the case when it is true, proceed to step 6. In the opposite case, return to step 4.

Step 6. Remove the vector y_i from the current set of vectors P(Y).

Step 7. Check out the fulfillment of inequality j<N-1. In the case this inequality is true, we should put consistently i=i+1 and then j=i+1. After this, it is necessary to return to step 2. In the opposite case (i. e. When j>N-1), complete the calculations.

The choice of the optimal solution is performed with taking into account the priorities of persons who make decisions. Instead of L partial criteria we will consider one scalar criterion, which is obtained by a combination of partial criteria using the additive method of convolution of criteria.

Assume the criteria are commensurate [9] and the vector of weighting coefficients of the criteria $\bar{\alpha} = \{a_1, a_2, ..., a_P\}$ that characterize the importance of appropriate criteria is defined. This means that $a_i \geq a_j$, if the criteria f_i has priority over the criterion f_j. In this case the weighting coefficients of the criteria are inalienable and meet the normalization condition:

$$\sum_{i=1}^{P} \alpha_i = 1. \quad (5)$$

For the additive method of selecting the optimal solution, objective function is built:

$$f(D) = \sum_{i=1}^{P} \alpha_i \cdot f(D_i), \quad (6)$$

in this case:

$$f(D_i) = R_i(C_i), \quad (7)$$

where $R_i(C_i)$ is the value of the risk of accident occurrence in EUC due to a failure of equipment that is administered by the i-th unit, in case the amount C_i is allocated for the modernization of the equipment of the i-th unit.

Given the limitations of the available financial resources C, the following equality must be fulfilled:

$$\sum_{i=1}^{P} C_i = C, \quad (8)$$

where C_i is the amount allocated for the i-th unit, P is the total number of units in the electric utility company.

In this case the task of optimization of scalar criterion is solved:

$$Z = f(D) \to \min, \forall D_i \in D^E. \quad (9)$$

The calculation of weighting coefficients is advisable to carry out by the method of pairwise comparisons of Saaty [13], which allows taking into account the priority of the people who make decisions, as well as their subjectivity.

By the priorities of experts, the Saaty matrix A with dimension $p \times p$ is formed, for which its own number is determined from the expression:

$$\det|A - \lambda E| = 0. \quad (10)$$

A system of equations is compiled for determining the weighting coefficients:

$$[A - \lambda E] \cdot [\alpha] = 0, \quad (11)$$

In which the last equation is replaced by the normalization condition (5). From the obtained system of equations, the vector of weighting coefficients $\bar{\alpha}$ is defined, which is substituted in the expression (6) of target function to determine the optimal solution.

To determine Pareto-optimal resource allocation among units of EUC that will minimize the risk of an emergency situation, we used analytical method of the risk evaluation of an emergency in EUC without PSM, presented in [14, 15], where the overall risk is the sum of local risks from failures of the elements that form the subset M_1:

$$R = \sum_{i=1}^{n} r_i = \sum_{i=1}^{n} A_i \cdot p_i(\Delta t) \cdot P_i^*, \quad (12)$$

where each local risk, in turn, is described by the expression:

$$r_i = A_i(P_i) \cdot p_i(\Delta t) \cdot P_i^*, \quad (13)$$

where $p_i(\Delta t)$ is the probability of failure of an element in the interval of time, P_i^* is an average pre accident flowing of power through the i-th element (in relative units), $A_i(P_i)$ is the coefficient that is determined from the expression for local risk.

5. An example of the optimal allocation of funds among the divisions of an electric utility enterprise

The top management of an electric utility enterprise (electric utility system), the electric scheme of which is presented in Fig. 1, has to allocate the amount of UAH 100 mln, which is meant to replace physically obsolete equipment, among the three technological units:

– the department of the main equipment of the substations (transformers, reactors);

– the department of distribution plants of substations (switches, disconnectors, busbars);

– the department of electric power lines.

The EUC defined elements, failure of which can lead to the occurrence of an accident by scenarios of breaching stability. These elements form the subset M_1:

1) Lines: L100–202, L5–8, L8–200, L100–101;

2) Transformers: T200–202, T5–6;

3) Switches: S13, S14, S15, S20, S22, S23, S27, S28, S29, S30, S34, S35.

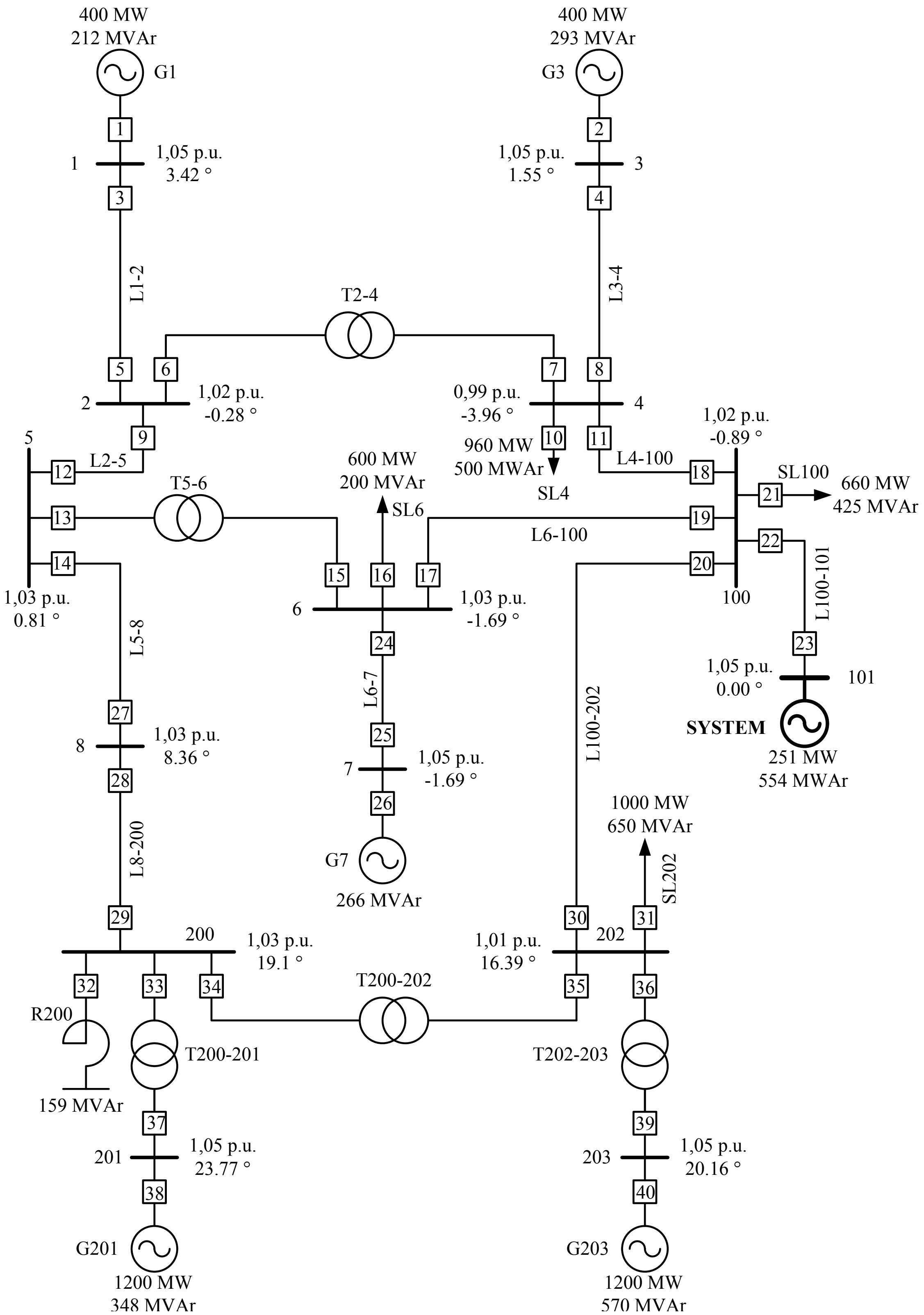

Fig. 1. EUC scheme

The prices for the new equipment for replacement of the elements, the refusal from which can lead to an emergency, are available:

1) Lines:

– EPL 220 kV (L100–101; L100–202) – UAH 500 000/km;

– EPL 500 kV (L5–8; L8–200) – UAH 750 000/km.

2) Transformers:

– T5–6 – UAH 40 mln;

– T200–202 – UAH 60 mln.

3) Switches:

– ES 220 kV (S20, S22, S23, S30, S35) – UAH 5 mln;

– ES 500 kV (S13, S14, S15, S27, S28, S29, S34) – UAH 10 mln.

The cost of a complete replacement of the equipment listed in the EUC is UAH 461.5 mln. As noted above, the existing amount of funds is UAH 100 mln. It is necessary to allocate these funds so as to minimize the risk of accidents in the EUC.

To do this, by using the method outlined in [15], we defined probabilistic characteristics of equipment from the subset M_1, the refusal from which can lead to the occurrence of accidents (Table 1). Probabilistic characteristics are defined for the time interval $\Delta t = 3$ months.

By the algorithm presented in [15, 16], we fulfilled the probabilistic-statistical modeling of EUC, the results of which determined the technical risk of an emergency situation (breach of stability) in EUC in the case of emergency from the subset M_1. Results of probabilistic-statistical modeling are presented in Table 2.

The total number of implementations of the algorithm PSM k=200. The number of implementations in which there was a failure in the stability k_1=92. Technical risk in this case is:

$$R = k_1/k = 92/200 = 0,46 . \quad (14)$$

Table 1

Probabilities of failure of EUC equipment

Element (term of service)	S, p. u.	$F(t_1)$	$F(t_2)$	$p(H_1)$	$p(H_2)$	$p(B/H_1)$	$p(B/H_2)$	$p(H_1/B)$	$F'(t_2)$
T5-6 (25 years)	0,625	0,507	0,512	0,010	0,990	0,355	0,658	0,005	0,512
L100-202 (75 km)	0,423	0	0,051	0,051	0,949	0,579	0,403	0,072	0,072
L5-8 (125 km)	0,499	0	0,056	0,056	0,944	0,500	0,493	0,057	0,057
L8-200 (175 km)	0,429	0	0,076	0,076	0,924	0,609	0,408	0,109	0,109
T200-202 (21 years)	0,312	0,461	0,463	0,004	0,996	0,726	0,279	0,010	0,471
L100-101 (8 km)	0,866	0	0,006	0,006	0,994	0,215	0,796	0,002	0,002
S13 (25 years)	0,625	0,731	0,740	0,033	0,967	0,396	0,606	0,022	0,753
S14 (15 years)	0,676	0,502	0,507	0,010	0,990	0,361	0,641	0,006	0,508
S15 (25 years)	0,467	0,731	0,740	0,033	0,967	0,578	0,432	0,044	0,775
S20 (18 years)	0,593	0,587	0,591	0,010	0,990	0,396	0,609	0,007	0,594
S22 (28 years)	0,514	0,833	0,841	0,048	0,952	0,477	0,537	0,043	0,876
S23 (28 years)	0,532	0,833	0,841	0,048	0,952	0,482	0,523	0,044	0,877
S27 (15 years)	0,225	0,502	0,507	0,010	0,990	0,728	0,229	0,031	0,533
S28 (15 years)	0,246	0,502	0,507	0,010	0,990	0,727	0,227	0,031	0,533
S29 (15 років)	0,347	0,502	0,507	0,010	0,990	0,584	0,414	0,014	0,516
S30 (18 years)	0,359	0,587	0,591	0,010	0,990	0,609	0,392	0,015	0,602
S34 (21 years)	0,500	0,671	0,674	0,009	0,991	0,500	0,500	0,009	0,680
S35 (21 years)	0,474	0,671	0,674	0,009	0,991	0,572	0,436	0,012	0,683

Table 2

Results of probabilistic-statistical modeling

№	Loading in the nodes of scheme								Voltage in node 101, U, p. u.	Failure		Breach of dynamic stability in the scheme
	4		6		100		202			Failed EPL	P, p. u. in pre-fault regime	
	P, MW	Q, MVAr	P, MW	Q, MVAr	P, MW	Q, MVAr	P, MW	Q, MVAr				
1	823	535	545	218	653	482	928	703	1,04	Л5-8	0,867	+
2	856	459	548	207	643	351	1030	647	0,99	Л100-202	0,960	+
3	1095	577	497	211	701	505	874	722	1,00	–	–	–
4	1002	499	719	219	594	500	1048	740	0,99	B27	0,805	+
5	779	527	631	196	694	389	929	749	1,00	B13	0,669	+
6	1034	543	635	167	668	450	952	643	1,01	–	–	–
7	902	517	555	194	643	387	1106	643	0,96	B29	0,793	+
8	829	477	528	182	635	442	1173	605	1,01	B22	1,112	+
9	1070	523	601	233	672	394	948	544	1,04	–	–	–
10	1132	565	554	185	698	447	1194	539	1,04	–	–	–
...	...	...	...	...	...	...	...	...	...	...	...	...
200	972	426	711	211	677	436	850	717	1,05	–	–	–

To identify variants for replacement of equipment, it is considered that the amount $C_K = \{0{,}1C;\ 0{,}2C;...;\ 1{,}0C\}$ can be allocated for the replacement of equipment of the k-th unit from the total amount of C=UAH 100 mln.

The number of pieces of equipment of the k-th unit is determined (taking into account the probability of failure of a piece of equipment in the interval of time $\Delta t = 3$ months), which can be substituted at the allocated amount C_k (Table 3).

Table 3

Equipment to be replaced

C_k, UAH mln.	Switches to be replaced	Transformers to be replaced	EPL to be replaced (length of the EL section to be replaced, km)
0,1 C=10 mln	S15	–	L100-202 – 20 km
0,2 C=20 mln	S15, S22, S23	–	L100-202 – 40 km
0,3 C=30 mln	S15, S22, S23, S27	–	L100-202 – 60 km
0,4 C=40 mln	S15, S22, S23, S27, S28	T200-202	L100-202
0,5 C=50 mln	S13, S15, S22, S23, S27, S28	–	L100-202, L5-8 – 18 km
0,6 C=60 mln	S13, S15, S22, S23, S27, S28, S29	T5-6	L100-202, L5-8 – 31 km
0,7 C=70 mln	S13, S15, S22, S23, S27, S28, S29, S30, S35	–	L100-202, L5-8 – 45 km
0,8 C=80 mln	S13, S15, S22, S23, S27, S28, S29, S30, S34, S35	–	L100-202, L5-8 – 63 km
0,9 C=90 mln	S13, S14, S15, S22, S23, S27, S28, S29, S30, S34, S35	–	L100-202, L5-8 – 77 km
1,0 C=100 mln	S13, S14, S15, S20, S22, S23, S27, S28, S29, S30, S34, S35	T5-6, T200-202	L100-202, L5-8 – 90 km

To determine Pareto-optimal allocation of available resources among the units of EUC that will minimize the risk of breach in stability, an analytical method of the risk evaluation of an emergency in the EUC was applied without PSM, presented in [17], which is described by the expressions (12), (13). The coefficients $A_i(P_i)$, defined for the elements of the subset M_1 on the basis of the PSM results (Table 2), are presented in Table 4.

Table 3 shows that the funds in the amount of

$$\{0{,}1C; 0{,}2C;...;1{,}0C\}$$

are not sufficient to complete the full replacement of the power lines, but only to replace sections of a certain length. Based on this, the probability of a failure of EPL L100-202 and L5-8 in the time interval was determined, in case of their partial replacement (Table 5).

Table 4

Determination of coefficients $A_i(P_i)$

Element	k_{1i}	R_i	$P_{cp\text{-}i}$	$P_i(H_1/B)$	A_i
T5-6	1	0,005	0,699	0,005	1,431
L100-202	13	0,065	0,942	0,072	0,958
L5-8	11	0,055	0,903	0,057	1,069
L8-200	21	0,105	0,887	0,109	1,086
T200-202	2	0,01	0,839	0,010	1,192
L100-101	1	0,005	0,792	0,002	3,157
S13	5	0,025	0,682	0,022	1,666
S14	1	0,005	0,799	0,006	1,043
S15	4	0,02	0,674	0,044	0,674
S20	1	0,005	0,942	0,007	0,758
S22	6	0,03	1,041	0,043	0,670
S23	8	0,04	1,02	0,044	0,891
S27	6	0,03	0,832	0,031	1,163
S28	4	0,02	0,806	0,031	0,800
S29	2	0,01	0,827	0,014	0,864
S30	3	0,015	0,911	0,015	1,098
S34	1	0,005	0,812	0,009	0,684
S35	2	0,01	0,822	0,012	1,014

We identified, by the expression (12), the risk of an emergency situation in the EUC in the case of spending $\{0{,}1C;\ 0{,}2C;...;\ 1{,}0C\}$ of the available funds for the replacement of equipment of the same type (switches, transformers, lines – according to Table 3). The results are presented in Table 6.

Table 5

Probability of failures of EPL after partial replacement

EPL	EPL section						The section that was not replaced						$p(H_1/B)$ Σ
	L, km	$p(H_1)$	$p(H_2)$	$p(B/H_1)$	$p(B/H_2)$	$p(H_1/B)$	L, km	$p(H_1)$	$p(H_2)$	$p(B/H_1)$	$p(B/H_2)$	$p(H_1/B)$	
Line L100-202	20	0,014	0,986	0,05	0,95	0,001	55	0,037	0,963	0,579	0,403	0,052	0,053
	40	0,027	0,973	0,05	0,95	0,001	35	0,024	0,976	0,579	0,403	0,034	0,036
	60	0,041	0,959	0,05	0,95	0,002	15	0,01	0,99	0,579	0,403	0,014	0,017
	75	0,051	0,949	0,05	0,95	0,003	0	0	1	0,579	0,403	0,000	0,003
Line L5-8	18	0,008	0,992	0,05	0,95	0,000	107	0,048	0,952	0,500	0,493	0,049	0,049
	31	0,014	0,986	0,05	0,95	0,001	94	0,042	0,958	0,500	0,493	0,043	0,043
	45	0,02	0,98	0,05	0,95	0,001	80	0,036	0,964	0,500	0,493	0,036	0,038
	63	0,027	0,973	0,05	0,95	0,001	62	0,027	0,973	0,500	0,493	0,027	0,029
	77	0,034	0,966	0,05	0,95	0,002	48	0,022	0,978	0,500	0,493	0,022	0,024
	90	0,04	0,96	0,05	0,95	0,002	35	0,016	0,984	0,500	0,493	0,016	0,018

Table 6

Risk of an emergency situation in EUC

C_K, UAH mln	Risk of an emergency situation		
	When replacing switches, R_s	When replacing transformers, R_T	When replacing EPL, R_l
0,1 C=10 mln	0,44	–	0,443
0,2 C=20 mln	0,371	–	0,427
0,3 C=30 mln	0,342	–	0,41
0,4 C=40 mln	0,322	0,453	0,398
0,5 C=50 mln	0,298	–	0,39
0,6 C=60 mln	0,288	0,456	0,384
0,7 C=70 mln	0,264	–	0,379
0,8 C=80 mln	0,26	–	0,37
0,9 C=90 mln	0,255	–	0,366
1,0 C=100 mln	0,251	0,447	0,36

Using the method of linear programming, the best allocation of funds among the three departments is determined. The problem setting in this case is as follows:

$$\begin{aligned} &Z(D_i)=\alpha_S\cdot R_S^i(C_S^i)+\\ &+\alpha_T\cdot R_T^i(C_T^i)+\alpha_L\cdot R_L^i(C_L^i)\rightarrow \min;\\ &C_S^i+C_T^i+C_L^i=100;\\ &\alpha_S+\alpha_T+\alpha_L=1. \end{aligned} \quad (15)$$

Weighting coefficients α_S, α_T, α_L are determined with the help of the expert priorities by the Saaty method [13]:

$\frac{V_S}{V_T}=4$ – moderate priority;

$\frac{V_L}{V_S}=5$ – essential priority;

$\frac{V_T}{V_L}=3$ – low priority.

A Saaty matrix is compiled based on the experts' priorities:

$$A=\begin{bmatrix} 1 & 4 & 1/5\\ 1/4 & 1 & 3\\ 5 & 1/3 & 1 \end{bmatrix}. \quad (16)$$

Its own number λ is determined:

$$\det|A-\lambda E|=\det\begin{bmatrix} 1-\lambda & 4 & 1/5\\ 1/4 & 1-\lambda & 3\\ 5 & 1/3 & 1-\lambda \end{bmatrix}=0 \Rightarrow$$

$$\Rightarrow \lambda=5{,}1703. \quad (17)$$

A system of equations is built for determining the weighting coefficients, taking into account $\sum\alpha_i=1$:

$$\begin{cases} -4{,}1703\alpha_1+4\alpha_2+0{,}2\alpha_3=0,\\ 0{,}25\alpha_1-4{,}1703\alpha_2+3\alpha_3=0,\\ \alpha_1+\alpha_2+\alpha_3=1. \end{cases} \quad (18)$$

We determine from the resulting system of equations:

$$\alpha_1=\alpha_S=0{,}3071,\ \ \alpha_2=\alpha_T=0{,}3006,$$
$$\alpha_2=\alpha_L=0{,}3923. \quad (19)$$

The solution to a linear programming problem (11) with the restriction in the form of equality is given below in the tabular form.

With the obtained coefficients, optimization problem is solved by using the method of integer programming [9, 10]. According to the obtained results, optimal allocation of funds among the divisions of an electric utility system, which minimizes the risk of accidents in EUC, has the form:

– the amount of C_1=0,7·C=70 mln UAH is allocated to replace the switches S13, S15, S22, S23, S27, S28, S29, S30, S35;

– the amount of C_3=0,3·C=30 mln UAH is allocated to replace 60 km of line L100-202.

To allocate funds for the replacement of transformers with the aim of reducing the risk is inappropriate, which means C_2=0. The magnitude of risk of stability disruption in the time interval $\Delta t=3$ months is determined by the expression (12) with regard to the replacement of the above equipment by the new one:

$$R=\sum_{i=1}^{n}A_i\cdot p_i(\Delta t)\cdot P_i^*=0{,}214. \quad (20)$$

The resulting value of the magnitude of risk is more than 2 times less compared to that received in the expression (14), indicating a significant efficiency of the measures taken under conditions of limited financing.

A modeled fuzzy statistical method of allocating funds among the units of electric utility company allows decision making under conditions of fuzzy initial information and minimizing the risk of accidents in an electric utility company by the most efficient allocation of available resources. To solve this task, the method was used for constructing the set of feasible solutions, based on the specific functioning of the enterprise divisions. The set of feasible solutions is formed according to the Pareto method. An optimal solution is chosen taking into account the priorities of the person who makes the decisions. For the evaluation of the risk during the solution of the linear programming problem, we used the method which allows determining the risk by analytic way without conducting a probabilistic-statistical modeling, which makes the designed method efficient for practical application in an express-estimation of the risk at different variants of the allocation of funds among departments of electric utility company without the use of probabilistic-statistical modeling.

6. Conclusions

Based on the results of the performed studies, we developed a fuzzy statistical method of optimal allocation of funds among the divisions of an electric utility company that allows:

1) forming a set of feasible variants for the allocation of the limited funds on the set of existing solutions with regard to the specifics in functioning of technological units. As an integral criterion for evaluation of the reliability of these units' performance, we adopted the risk of an accident occurrence due to a failure of the equipment in the interval of time;

2) determining the optimal solution on the compiled set of feasible variants using the Pareto method, when no element of the Pareto-set can be improved without worsening of at least one of the other elements, which makes it possible

to define a compromise allocation of funding, at which the minimum possible value of the risk of an accident in the electric utility enterprise's networks is provided;

3) applying analytical approach to the determination of the risk in solving the problem of linear programming, which will allow arriving faster at the optimal result of allocation of the funds among the divisions of an electric utility enterprise in comparison to multiple carrying out of probabilistic-statistical modeling, and analysing local components in the formation of the general value of the magnitude of risk.

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