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PROBABILITY-STATISTICAL APPROACH DEVELOPMENT TO THE SURVIVABILITY INCREASING OF POWER PLANT AUXILIARY GRID

The object of research is the operating modes and ways to increase the survivability of the power plant's own needs network under the influence of external emergency disturbances.

The power system of Ukraine today operates in extremely complex conditions. This is a consequence of the fact that the existing problems associated with outdated equipment have been added by external destructive influence due to geopolitical events. These factors cause a decrease in the structural and regime reliability of electrical networks. Under such conditions, the survivability of power plants and their own needs systems becomes of particular importance. The task of increasing the survivability of the power plant's own needs network is one of the multi-criteria tasks with a large number of uncertainties. To solve it, it is advisable to apply a probabilistic-statistical approach that takes into account the available random factors and makes it possible to make effective decisions. In the course of the research, an approach to assessing the survivability of the power plant's own needs network using a random number generator was developed, and the effectiveness of measures to increase it was determined.

This approach allows for a quantitative assessment of the survivability of the power plant's own needs network under conditions of uncertainties associated with the network and surrounding power system modes. The approach also takes into account the probability of equipment failure over a time interval and the consequences of geopolitical influence on the power system of Ukraine. The risk of an emergency situation occurring in the power plant's own needs network is taken as a quantitative criterion for assessing survivability. The developed approach and its implementation algorithm allow for a comparative analysis of the effectiveness of measures to increase the survivability of the power plant's own needs network and to select the most effective ones among them. According to the results of probabilistic and statistical modeling of the HPP's own needs network, it was determined that when using survivability measures, the risk of an emergency situation is reduced by 32%.

Keywords: survivability, power plant, own needs network, technical condition, emergency situation, probabilistic and statistical approach, risk.

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1. Introduction

The current operating modes of the electric power system (EPS) of Ukraine are extremely complex. This is due to the fact that the previously existing problems with outdated equipment and the slow pace of its replacement have been supplemented by an external destructive impact on the EPS due to geopolitical events. This destructive impact has caused a decrease in the structural and regime reliability of electrical networks and has led to a significant limitation of electrical energy generation. Under such conditions, the survivability of power plants and their self-demand systems becomes particularly important. The concept of “survivability” defines the ability of the EPS and its subsystems, in particular the self-demand networks of power plants, to maintain partial operability during external emergency disturbances. Such disturbances are a consequence of system failures that lead to a short-term or long-term decrease in voltage in the power supply nodes of the self-demand systems of power plants [1]. For the self-demand network of the power plant, this threatens with the occurrence of a voltage avalanche, which will lead to the loss of self-demand with the station going “to zero”.

Thus, increasing the survivability of the network of own needs of power plants is an important task that requires a quantitative solution in the conditions of a significant number of uncertainties related to the network operating modes and the technical condition of the equipment.

When external disturbances occur in the EPS, accompanied by a voltage drop, a disruption in the operation of generators operating in parallel and individual sections of the EPS may occur. The consequence of this is the occurrence of a voltage “avalanche” with the disconnection of generation facilities and consumers [2], including the own needs of power plants.

In [3], existing methods of increasing the reliability and survivability of the network of own needs of power plants are considered, in particular, automated allocation of own needs. In the event of the operation of this automation, several generators are separated into an isolated load – a network of own needs, which ensures that the frequency and voltage are maintained at the proper level for powering the equipment.

One of the most common methods of increasing survivability is generation redundancy, but this has a number of limitations, such as the cost, size and installation location of generating equipment. The solution of this problem should be considered in the topology of the system. In this case, the concept of “topological survivability” is intro-

duced – the ability to maintain the operational state of the system after its damage [4]. Due to the inability to determine which elements can be damaged, there is a need to analyze all possible failures [5]. The task of this analysis is to assess the possibility of connecting equipment to the system after the action of a disturbance and calculate the power flows that can be used to restore power to the consumer load.

In works [6, 7], the use of FACTS devices – flexible alternating current transmission systems, which are used as a measure to increase the reliability and flexibility of electrical networks, as well as to reduce the risk of accidents. The results obtained in these works indicate that these tools can also be effective for ensuring the survivability of networks for the own needs of power plants.

To ensure the most effective application of the considered measures to increase the survivability of the power plant's own needs network, it is necessary to conduct a multi-criteria analysis under conditions of a significant number of uncertainties. The solution of such problems, as indicated in [8, 9], is based on probabilistic and statistical modeling of processes and provides satisfactory quantitative results under conditions of uncertainty of the initial data.

In the considered works, the issues of quantitative assessment of the survivability of the power plant's own needs networks and the comprehensive selection of measures to increase it under conditions of multi-criteria selection remained unresolved.

The object of research is the operating modes and ways to increase the survivability of the power plant's own needs network under conditions of external emergency disturbances.

The aim of research is to quantitatively assess the survivability of the power plant's own needs network and the most effective use of available measures to increase it.

In accordance with the set aim, the following research objectives have been formulated:

- to develop a probabilistic-statistical approach to assessing the survivability of the power plant's own needs network;
- to determine the most effective measures to increase the survivability of the power plant's own needs network.

2. Materials and Methods

The subject of research is the assessment and increase of the survivability of the power plant's own needs network.

The term survivability, unlike the term reliability, which is mathematically described by well-known quantitative indicators [10], does not have generally accepted quantitative characteristics. Therefore, to solve the set task of increasing the survivability of the power plant's own needs network, it is necessary to reasonably determine a quantitative criterion for assessing survivability. Using the selected criterion, it is necessary to conduct a comparative analysis of the survivability of the power plant's own needs network in the event of emergency disturbances and when applying measures to counteract them. An integral criterion that takes into account the probability of an external disturbance, a possible emergency scenario in the electrical network and possible consequences (preservation or violation of static stability) is the risk of an emergency situation in the electrical power system subsystem [9, 11]. Since the electrical network of the power plant's own needs is part of a single electrical power system, it can be considered as its separate subsystem to which the concept of the risk of the occurrence and development of an accident can be applied.

The task of increasing the survivability of the network of the power plants' own needs belongs to the class of multi-criteria. To solve it, it is necessary to take into account the technical condition of the equipment, the risk of an emergency situation in the electrical power system and the stochasticity of the regime at the time of the emergency situation and/or failure of an element of the network of the own needs. To solve this problem, it is advisable to apply a probabilistic-statistical approach [12] that takes into account the above-mentioned factors and makes it pos-

sible to make effective decisions. Its use will make it possible to quantitatively assess the ability of the station's own network to counteract emergency disturbances and select effective measures to increase its reliability and operability in difficult operating conditions.

3. Results and Discussion

3.1. Development of a probabilistic-statistical approach to assessing the survivability of a power plant's own needs network

Below is proposed a probabilistic-statistical approach to assessing the survivability of a power plant's own needs network and determining the effectiveness of measures to improve it. This approach is implemented using the following algorithm:

1. A set of external disturbances in the power system A is formed.
2. A set of possible emergency scenarios in the own needs network N is formed.
3. A set of elements of the own needs network M is formed, the failure of which can lead to the occurrence of an event from the set N .
4. A set of measures to increase the survivability of the own needs network of the power plant L is formed.
5. For electrical equipment elements from the set M , a set of states' S is formed according to fuzzy models for assessing the technical condition of the corresponding objects (transformers, cables, switches, diesel generators) [13].
6. Using the statistical integral functions of the probability distribution of failures of the corresponding types of equipment $F(t)$, the a priori probabilities of failure $p(H_1)$ and failure-free operation $p(H_2)$ of the elements of the set M in the time interval $\Delta t = t_2 - t_1$ are determined:

$$p(H_1) = \frac{F(t_2) - F(t_1)}{1 - F(t_1)}, \quad (1)$$

$$p(H_2) = 1 - p(H_1). \quad (2)$$

7. Using fuzzy Zadeh inference using the cause-effect matrices RP and RQ, the conditional probabilities $p(B/H_1)$ and $p(B/H_2)$ for the elements of the subset M are determined [8, 13]:

$$p(B/H_1) = \varphi(S_1), \quad (3)$$

$$p(B/H_2) = \psi(S_2). \quad (4)$$

8. According to Bayes' theorem, the failure probabilities of elements from the set M in the time interval Δt are determined taking into account their technical condition $p(H_1/B)$

$$p(H_1/B) = \frac{p(H_1) \cdot p(B/H_1)}{p(H_1) \cdot p(B/H_1) + p(H_2) \cdot p(B/H_2)}, \quad (5)$$

and the values of statistical functions $F(t)$ are refined at time t_2

$$F'(t_2) = F(t_1) + p(H_1/B). \quad (6)$$

9. Using GHE, the following are determined:

9.1. Active and reactive power of loads of the power plant's own needs network at the time of equipment failure within the limits of $[P_{\text{MIN}}; P_{\text{MAX}}]$ and $[Q_{\text{MIN}}; Q_{\text{MAX}}]$;

9.2. External disturbance from the set A , which is defined as the voltage at the node of connection of the power plant's own needs network to the EES within the limits of $[U_{\text{MIN}}; U_{\text{MAX}}]$.

10. The static characteristics of the loads of the power plant's own needs network are determined using the interval method [14, 15].

11. Using the GHF, the value of the probability of failure D_i is determined for each element of the set M at the time of its failure t

$$D_i = F_i(t_{fail}) = \text{Random}[0;1], i=1, \dots, n_1. \quad (7)$$

12. On the set of elements M , a subset of elements M_1 is selected, the failures of which fall into the interval $[F(t_1); F(t_2)]$, i. e. elements that will fail in the time interval Δt .

13. From the subset M_1 , an element is selected that, taking into account its own individual characteristics, will fail first in the interval Δt

$$t_{fail} = \min\{F_i^{-1}(D)\}, i=1, \dots, n_1. \quad (8)$$

14. The steady-state mode of the own-demand network under certain conditions is calculated and the occurrence (or non-occurrence) of an event from the set N (emergency situation) is determined. The load stability is checked using the stability criterion dQ/dU [16].

15. In the event of an event from the set N , a measure (measures) is selected from the set L and the steady-state mode of the own-demand network of the power plant is calculated under the condition of implementing the selected measure (measures). The occurrence (or non-occurrence) of an event from the set N (emergency situation) is determined. The load stability is checked according to the dQ/dU criterion.

16. Points of the algorithm 9–15 are repeated K times, where K is the number of network modes calculated during probabilistic-statistical modeling.

17. On the obtained set of modes K , a subset K_1 of consumer connections with a negative load regulation effect (LRE) is determined according to the dQ/dU criterion.

18. A set K_2 of consumer connections is formed, which have a negative LRE remaining after the implementation of the measure(s) from the set L .

19. The risk R_1 of an emergency situation in the absence of measures from the set L is determined:

$$R_1 = \frac{\sum_{i=1}^K k_{1i}}{K \cdot F}, \quad (9)$$

where F – the total number of consumer connections in the power plant's own needs network, k_1 – the number of connections with negative LRE before the implementation of measures (measures) from the set L .

20. The risk R_2 of an emergency situation occurring when implementing measures from the set L is determined

$$R_2 = \frac{\sum_{i=1}^K k_{2i}}{K \cdot F}, \quad (10)$$

where k_2 – the number of connections with negative LRE after the implementation of measures (measures) from the set L .

21. A comparative analysis of the obtained risk values R_1 and R_2 is performed and a decision is made on the effectiveness and feasibility of using measures from the set L to increase the survivability of the power plant's own needs network.

3.2. Assessment of the survivability of the power plant's own needs network and determination of the most effective measures to increase it

The proposed approach was used to assess the survivability of the hydroelectric power plant's own needs network under external disturbances. The electrical diagram of the hydroelectric power plant's own needs network is presented in Fig. 1. The network consists of three sections. Section No. 1 is powered by a 110/6.3 kV transformer TVP1, sections No. 2 and No. 3 by a 110/6.3 kV transformer TON2. A generator for the own needs of the GON is connected to section No. 2.

The set of external disturbances consists of emergency events that lead to long-term voltage changes in the nodes connecting the own needs network to the HPP to the 110 kV EPS network within $0.9-1.1 \cdot U_{nom}$.

The set of possible emergency scenarios in the own needs network N consists of the following events:

N_1 – loss of power supply to consumers of the own needs of the HPP;

N_2 – loss of static stability of the load of the own needs network of the HPP.

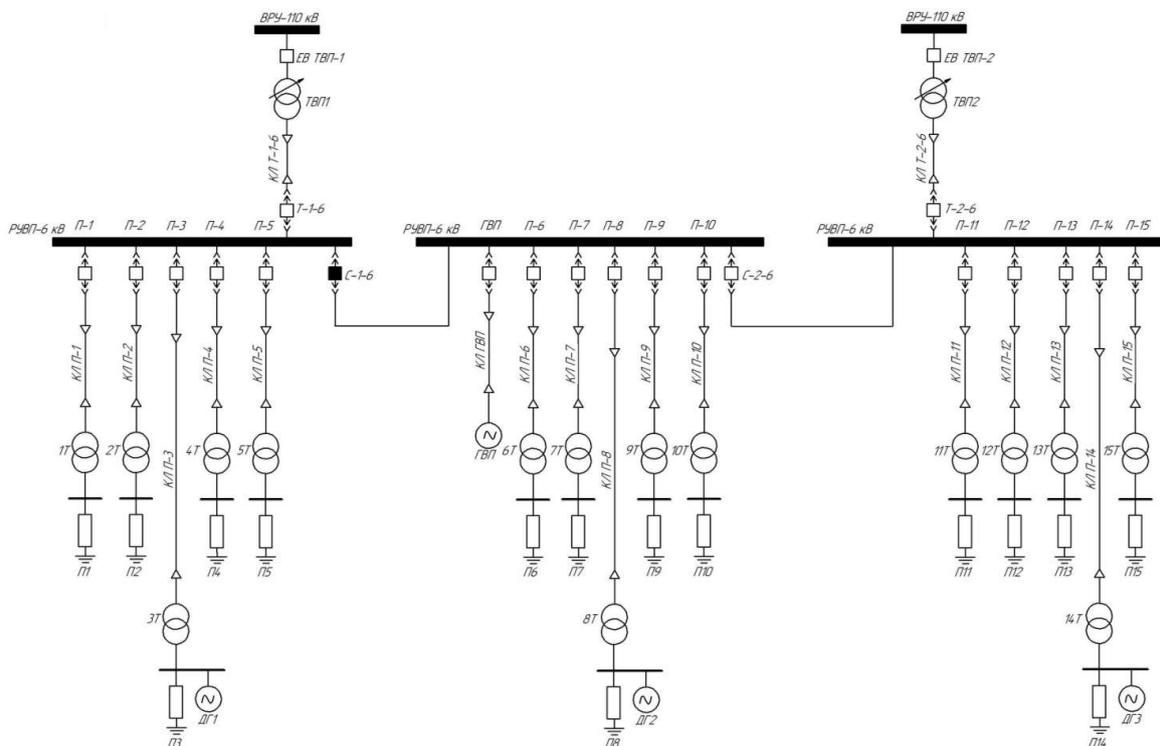


Fig. 1. Electrical diagram of the HPP own network

The set of elements of the HPP self-demand network M , the failure of which can lead to certain events from the set N , is determined by the topology of the electrical diagram of the network:

- M_1 – diesel generator DG1;
- M_2 – diesel generator DG2;
- M_3 – diesel generator DG3;
- M_4 – generator of own needs GON;
- M_5 – transformer of own needs TON1;
- M_6 – transformer of own needs TON2;
- M_7 – transformer 3T;
- M_8 – transformer 8T;
- M_9 – transformer 14T;
- M_{10} – circuit breaker TON-1;
- M_{11} – circuit breaker TON-2;
- M_{12} – circuit breaker P-3;
- M_{13} – circuit breaker P-8;
- M_{14} – circuit breaker P-14;
- M_{15} – circuit breaker GON;
- M_{16} – switch T-1-6;
- M_{17} – switch T-2-6;
- M_{18} – switch S-1-6;
- M_{19} – switch S-2-6;
- M_{20} – cable P-3;
- M_{21} – cable P-8;
- M_{22} – cable P-14;
- M_{23} – cable GON;
- M_{24} – cable TON-1;
- M_{25} – cable TON-2.

According to fuzzy models of equipment condition assessment [13], the technical condition of the equipment from the set M is determined. The models used have a fuzzy output of the Mamdani type. The fuzzy terms of the initial value of the models “Technical condition” S are built on the intervals of the standard Harrington scale. Quantitative assessments of the condition are given in Table 1.

Table 1

Technical condition of equipment

Element of the set M	Technical condition, S_i	Element of the set M	Technical condition, S_i	Element of the set M	Technical condition, S_i
M_1	0.526	M_9	0.708	M_{17}	0.504
M_2	0.511	M_{10}	0.715	M_{18}	0.664
M_3	0.452	M_{11}	0.771	M_{19}	0.617
M_4	0.293	M_{12}	0.547	M_{20}	0.5
M_5	0.624	M_{13}	0.617	M_{21}	0.723
M_6	0.624	M_{14}	0.545	M_{22}	0.82
M_7	0.707	M_{15}	0.646	M_{23}	0.731
M_8	0.706	M_{16}	0.576	M_{24}	0.722
–	–	–	–	M_{25}	0.702

According to points 6–8 of the algorithm, the failure probabilities of the elements of the set M are determined in the time interval $\Delta t = 1$ year. Statistical distribution functions of the probability of equipment failure are presented in [13, 17]. The failure probabilities of the elements of the set M , determined by expressions (1)–(5), are presented in Table 2.

- L_1 – switching on the diesel generator DG1;
- L_2 – switching on the diesel generator DG2;
- L_3 – switching on the diesel generator DG3;
- L_4 – switching on the sectional switch C-1-6.

The quantitative criterion for the effectiveness of the specified measures to increase the survivability of the network of own needs of the station is the risk of an emergency situation developing in this network under various external disturbances, emergency scenarios and electri-

cal modes. To determine the risk, using the approach proposed above, probabilistic and statistical modeling was performed for $K = 100$ operating modes of the power plant’s VP network.

Table 2

Failure probabilities of the elements of the set M in the time interval $\Delta t = 1$ year

Element of a set M	$p(H_1)$	$p(H_2)$	$p(B/H_1)$	$p(B/H_2)$	$p(H_1/B)$
M_1	0.470	0.530	0.524	0.508	0.478
M_2	0.006	0.994	0.514	0.505	0.006
M_3	0.183	0.817	0.518	0.537	0.178
M_4	0.73	0.27	0.685	0.335	0.847
M_5	0.432	0.568	0.565	0.502	0.461
M_6	0.432	0.568	0.565	0.502	0.461
M_7	0.252	0.748	0.336	0.691	0.140
M_8	0.416	0.584	0.336	0.691	0.257
M_9	0.416	0.584	0.336	0.692	0.257
M_{10}	0.439	0.561	0.335	0.687	0.276
M_{11}	0.439	0.561	0.238	0.724	0.205
M_{12}	0.250	0.750	0.536	0.516	0.257
M_{13}	0.250	0.750	0.563	0.503	0.271
M_{14}	0.250	0.750	0.534	0.516	0.257
M_{15}	0.250	0.750	0.340	0.717	0.137
M_{16}	0.250	0.750	0.551	0.515	0.263
M_{17}	0.250	0.750	0.506	0.508	0.250
M_{18}	0.250	0.750	0.342	0.714	0.138
M_{19}	0.250	0.750	0.563	0.503	0.271
M_{20}	0.289	0.711	0.472	0.470	0.290
M_{21}	0.289	0.711	0.287	0.685	0.146
M_{22}	0.289	0.711	0.340	0.847	0.140
M_{23}	0.229	0.771	0.287	0.684	0.111
M_{24}	0.229	0.771	0.287	0.685	0.110
M_{25}	0.229	0.771	0.335	0.685	0.127

For this, the value of the voltage of the power supply node of the network of own needs, active and reactive load powers at the time of equipment failure was formed using GHF. These values are determined at the intervals between their minimum and maximum values. Based on the technical condition of the equipment and the probability distribution function of failure using GHF, a set of states of this equipment is formed, among which the unit of equipment that will fail first is determined.

Below is the implementation of the algorithm of the probabilistic-statistical approach using the example of mode No. 1. The calculated data for mode 1 are presented in Table 3.

According to the method presented in [15], the static load characteristics of the connections P1...P15 were determined. Based on the obtained static load characteristics, the LRE was estimated using the dQ/dU criterion. The calculation results are presented in Table 4.

According to the obtained values, four connections have a negative LRE . This increases the possibility of an emergency situation – a violation of the static stability of the load of the network of the hydroelectric power plant’s own needs (event N_2). To obtain a positive REN of connections, measures to increase survivability are selected from the set L . Such measures for a given network mode include measures L_1, L_2, L_4 . After applying the selected measures, a recalculation of the steady-state mode and determination of LRE were performed. The calculation results are presented in Table 5.

The selected survivability improvement measures are effective for the considered regime, since the number of feeders with negative LRE has decreased from four to two. The results of $K = 100$ implementations of the probabilistic-statistical modeling algorithm are given in Table 6.

Table 3

Region data for calculating the steady-state network mode

Parameters	Value		
Power supply voltage, kV	105.6		
Failed element	DG3		
Connection	U, V	P, kW	$Q, kVAr$
P-1	373.75	49.1	42.3
P-2	371.87	920.1	181.6
P-3	373.95	19.3	24.0
P-4	359.68	242.5	157.5
P-5	373.15	30.4	26.2
P-6	388.43	41.7	29.1
P-7	396.64	23.2	30.2
P-8	398.36	33.2	27.8
P-9	396.20	24.7	12.637
P-10	397.41	13.8	32.6
P-11	398.33	14.2	19.8
P-12	398.71	13.6	14.1
P-13	397.86	110.1	72.3
P-14	392.77	80.1	72.5
P-15	396.28	65.9	29.5

Table 4

The regulatory effect of the load of the connections of the network of the hydroelectric power plant's own needs

Connection	Static characteristic $Q(U)$	LRE
P-1	$0.009 \cdot (1 + 0 \cdot U + 0 \cdot U^2)$	0
P-2	$0.05 \cdot (8.64 - 20.48 \cdot U + 12.84 \cdot U^2)$	0.171
P-3	$0.844 \cdot (0.237 + 0.948 \cdot U - 0.185 \cdot U^2)$	0.935
P-4	$0.02 \cdot (10 - 26.85 \cdot U + 17.85 \cdot U^2)$	0.105
P-5	$0.364 \cdot (1.115 - 0.313 \cdot U + 0.198 \cdot U^2)$	0.021
P-6	$0.007 \cdot (5.429 - 14 \cdot U + 9.571 \cdot U^2)$	0.032
P-7	$0.007 \cdot (13.286 - 26 \cdot U + 13.714 \cdot U^2)$	0.009
P-8	$0.005 \cdot (18.4 - 34.4 \cdot U + 17 \cdot U^2)$	-0.027
P-9	$0.014 \cdot (5.571 - 8.929 \cdot U + 4.357 \cdot U^2)$	-0.004
P-10	$0.006 \cdot (20.667 - 40 \cdot U + 20.333 \cdot U^2)$	0.003
P-11	$0.014 \cdot (5.571 - 8.929 \cdot U + 4.357 \cdot U^2)$	-0.004
P-12	$0.007 \cdot (4.286 - 11.857 \cdot U + 8.571 \cdot U^2)$	0.037
P-13	$0.031 \cdot (10.097 - 18.065 \cdot U + 8.968 \cdot U^2)$	-0.006
P-14	$0.015 \cdot (10.4 - 23.067 \cdot U + 9.143 \cdot U^2)$	0.057
P-15	$0.014 \cdot (6.857 - 15 \cdot U + 0 \cdot U^2)$	0.0437

Table 5

Regulatory effect of the load of connections of the network of the hydroelectric power plant's own needs after applying measures to increase survivability

Connection	Static characteristic $Q(U)$	LRE
P-1	$0.008 \cdot (1 + 0 \cdot U + 0 \cdot U^2)$	0
P-2	$0.039 \cdot (11.077 - 31.692 \cdot U + 21.6215 \cdot U^2)$	0.432
P-3	$0.846 \cdot (0.239 + 0.946 \cdot U - 0.184 \cdot U^2)$	0.483
P-4	$0.028 \cdot (7.143 - 18.893 \cdot U + 12.75 \cdot U^2)$	0.154
P-5	$0.378 \cdot (1.111 - 0.302 \cdot U + 0.19 \cdot U^2)$	0.028
P-6	$0.002 \cdot (18.5 - 51 \cdot U + 33.5 \cdot U^2)$	0.028
P-7	$0.006 \cdot (15.167 - 30.333 \cdot U + 16.167 \cdot U^2)$	0.01
P-8	$0.01 \cdot (0.8 + 0 \cdot U + 0.2 \cdot U^2)$	0.004
P-9	$0.113 \cdot (1.363 - 1.522 \cdot U + 1.159 \cdot U^2)$	0.087
P-10	$0.007 \cdot (18 - 34.286 \cdot U + 17.286 \cdot U^2)$	0.0003
P-11	$0.022 \cdot (3.909 - 5.682 \cdot U + 2.733 \cdot U^2)$	-0.004
P-12	$0.003 \cdot (8.667 - 27.667 \cdot U + 20 \cdot U^2)$	0.036
P-13	$0.097 \cdot (3.907 - 5.733 \cdot U + 2.866 \cdot U^2)$	-0.006
P-14	$0.007 \cdot (22.286 - 49.571 \cdot U + 28.286 \cdot U^2)$	0.059
P-15	$0.013 \cdot (7.308 - 16.154 \cdot U + 9.846 \cdot U^2)$	0.041

Fig. 2 presents a graphical representation of the number of connections with a negative LRE value (k_1 – for the case without the use of survivability measures, k_2 – for the case with the use of survivability measures) for each of the $K = 100$ calculated modes of operation of the HPP's own needs network. The histogram $k_1(K)$ corresponds to modes without the use of survivability measures, the histogram $k_2(K)$ – to modes when these measures were applied.

Fig. 2 shows that the application of measures to increase the survivability of the HPP's own needs network reduces the number of connections with negative LRE . To quantitatively assess the effectiveness of measures from the set L, in accordance with expressions (9), (10), the risk of an emergency without the implementation of survivability increasing measures and after their implementation was determined k_1, k_2 :

$$R_1 = \frac{295}{100 \cdot 15} = 0.197, \tag{11}$$

$$R_2 = \frac{201}{100 \cdot 15} = 0.134. \tag{12}$$

Table 6

Results of determining REN and selecting survivability improvement measures for $K = 100$ regimes

No.	Voltage at the load node, kV	Failed element	Number of feeders with negative LRE	Measures to increase survivability	Number of feeders with negative LRE after implementation of measures
1	105.6	M_3	4	L_1, L_2, L_4	2
2	112.2	M_{21}	2	L_1, L_2, L_3, L_4	1
3	115.5	M_{20}	4	L_1, L_3, L_4	2
4	105.6	M_5	4	L_1, L_2, L_3, L_4	3
5	121.0	M_8	2	L_1, L_2, L_3	1
6	112.2	M_{14}	2	L_2, L_4	1
7	104.5	M_9	3	L_2, L_4	2
8	100.1	M_{23}	5	L_4	5
9	104.5	M_{22}	2	L_3, L_4	1
10	119.9	M_9	1	L_3	-
...
99	110.0	M_{23}	4	L_4	3
100	115.5	M_{21}	3	L_1, L_2, L_3, L_4	2
Number of connections with negative REN			295	-	201

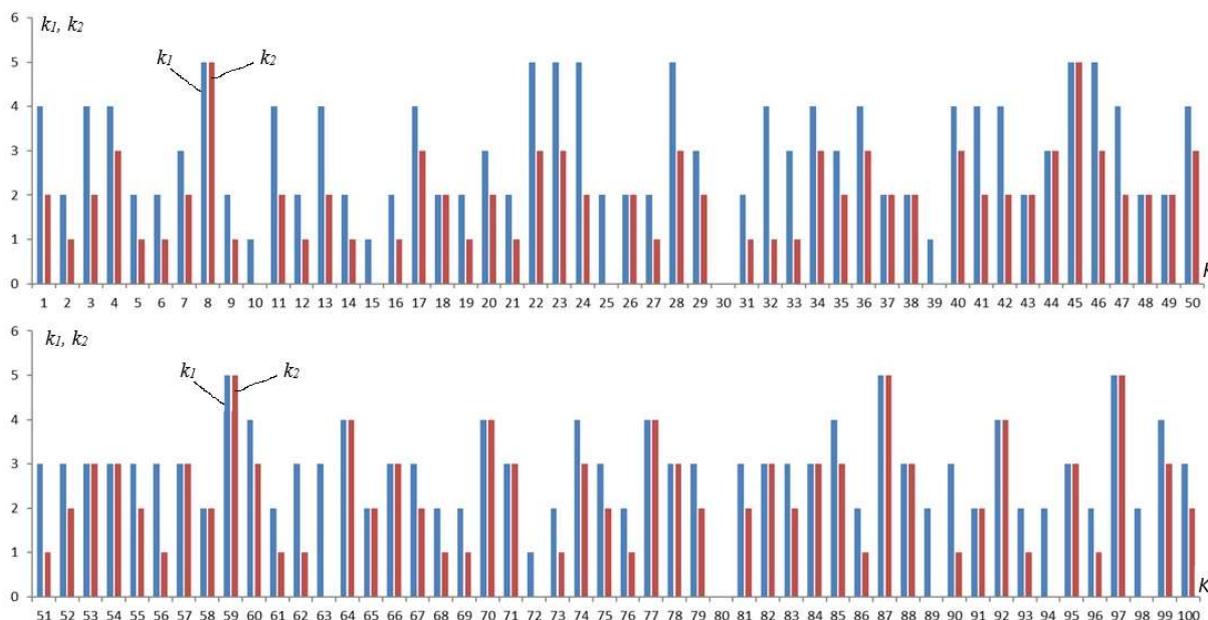


Fig. 2. Connection with negative *LRE* without the use of survivability increasing measures $k_1(K)$ and with their application $k_2(K)$

The obtained quantitative risk values R_1 and R_2 were compared with each other. Since $R_1 > R_2$, the risk of an emergency that would lead to a violation of the static stability of the load node of the HPP’s own needs network decreased when measures from the set L were implemented. The quantitative reduction in the risk of an emergency in the HPP’s own needs network is 32%. The greatest effect of improving the *LRE* is achieved by measures of combined use of diesel generators and unification of sections of the own needs network by switching on the section switch S-1-6.

3.3. Limitations of research and directions of its development

The developed probabilistic-statistical approach allows to quantitatively assess the survivability of the own needs network of power plants and its connections, to determine the effectiveness of measures to increase it, and also to conduct a comparative analysis of the effectiveness of the proposed measures based on the obtained quantitative results. This probabilistic-statistical approach can be used to assess the survivability of the own needs networks of power plants of any type (thermal, nuclear, hydraulic) and responsible power supply systems of industrial enterprises.

A limitation for using the proposed approach is branched and/or ring electrical networks, which, due to their complexity, should be divided into separate subsystems for assessing survivability. In distribution networks with three voltage levels, it is also advisable to divide such networks into subsystems with an assessment of the survivability of individual subsystems. Also, to obtain a reliable result, a quantitative assessment of the technical condition of each unit of equipment included in the set M is a prerequisite for specifying the probability of their failure in the time interval. Prospects for further research are to develop a method for determining the optimal combination of measures to increase the survivability of the network for own needs as a multi-criteria optimization problem.

4. Conclusions

1. A probabilistic-statistical approach to assessing the survivability of the power plant’s own needs network has been developed, which takes into account the actual technical condition of the equipment, the stochasticity of the occurrence of an emergency situation and the mode of the own needs network at the time of its occurrence. As a quantitative

criterion for assessing survivability, the technical risk has been defined and substantiated, which is determined based on the regulatory effect of the load of consumers of the power plant’s own needs network. Using this probabilistic-statistical approach, probabilistic-statistical modeling of the hydroelectric power plant’s own needs network has been performed to quantitatively assess its survivability and determine the most effective measures to increase it. The resulting probabilistic-statistical approach allows for a quantitative assessment of the survivability of the power plant’s own needs network under conditions of a significant number of uncertainties.

2. The most effective measures have been determined to increase the survivability of the power plant’s own needs network. According to the modeling results, measures have been identified, the implementation of which is the most effective for increasing the survivability of the power plant’s own needs network in the event of external emergency disturbances. The risk of an emergency situation in the hydroelectric power plant’s own needs network is reduced by 32%. Also, with the help of the developed approach and the algorithm that implements it, it becomes possible to conduct a comparative analysis of the effectiveness of measures to increase the survivability of the power plant’s own needs network and select the most effective ones.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship or other nature, which could affect the research and its results presented in this article.

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Data availability

The manuscript has no related data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work

Authors' contributions

Volodymyr Litvinov: Conceptualization, Methodology, Validation, Formal analysis, Writing – original draft, Project administration;
Oleksii Stetsiura: Software, Data curation, Visualization, Investigation;
Alina Yerofoieieva: Validation, Data curation, Visualization, Writing – review and editing.

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