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DEVELOPMENT OF A MODEL FOR DETERMINING A PRIORITY SEQUENCE OF POWER TRANSFORMERS OUT OF SERVICE

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Дослідження присвячене розробці моделі та алгоритму прийняття рішень щодо визначення пріоритету виведення з експлуатації силових трансформаторів. Зниження надійності функціонування ЕЕС, спричинене об'єктивно існуючим старінням парку трансформаторного обладнання, потребує врахування значущості обладнання при плануванні виведення з експлуатації силових трансформаторів. Для цієї мети пропонується використовувати теорію нечітких множин, метод Парето. Результатом рішення оптимізаційної задачі багатокритеріального аналізу є вектор найкращих альтернатив, побудований за принципом домінантності. Розроблений алгоритм комплексного моделювання режиму ЕЕС і технічного стану силового трансформатора для прийняття рішень щодо визначення пріорітету виведення з експлуатації силових трансформаторів 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 силових трансформаторів на основі оцінкою 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 технічного стану силового трансформатора дають підстави стверджувати щодо можливості впровадження в складі комплексу програм аналізу ризиків експлуатації в електроенергетичній системі для енергокомпаній

Ключові слова: силовий трансформатор, ризик, метод Парето, виведення з експлуатації, імовірність відмови

1. Introduction

For today one of the first places in its importance and complexity is the problem of ensuring the reliability of electricity supply in power market conditions. The functioning of Ukraine's electric power system (EPS) in recent years is characterized by a significant level of physical and moral depreciation of electrical equipment (more than 70 % of the total) and low rates of replacement. This further reduces reliability and leads to an increase in the number of emergencies.

A significant increase of the functional reliability level of electrical equipment and the EPS in general can be achieved by an objective assessment of the technical condition, prediction of lifetime, determination of failure probability and justification of possible terms for its maintenance or replacement.

Firstly, it is necessary to plan the possible time of out of service for equipment, based on technical condition assessment and total estimated technical resource, when its technical condition is characterized by a high level of possible failure. Secondly, the priority sequence of out of service of electrical equipment must also be determined by the level of its significance in the EPS. There are indicators that reflect the failure effect of the analyzed electrical equipment on the security level and operation efficiency of the EPS as importance indicators of electrical equipment for the EPS.

Planned and unscheduled power transformers out of service, sudden failure under the presence of critical damage, resource exploitation and external factors influence is an emergency disturbance for the EPS. This can lead to a further cascade emergency situation with significant losses.

In connection with this, the complex simulation problem of technical condition of electrical equipment and EPS states, decision to minimize the exploitation risk of the EPS under electrical equipment out of service today is an urgent task.

2. Literature review and problem statement

Mathematical models of technical condition diagnostics for the power transformer based on a complex of measurements and tests are presented in [1]. Fuzzy models for risk assessment of parametric failure for the power transformer under the presence of damage are considered in [2]. The model system of electrical equipment failures based on statistical data of the general event set adapted to real operating conditions was obtained in [3]. EPS state simulation to determine the quantitative indicators of emergency risk under electrical equipment failures is considered in [4]. But the issue of priority for the power transformer out of service based on the technical condition assessment and EPS state analysis was not sufficiently considered.

In each power system, there are usually several variants of the topology of electrical networks. The task for the operating personnel is to choose such a variant of disconnecting any element that would lead to the least disturbance of the power system, that is, provide the least emergency risk. Thus, there is a problem of selecting the sequence of output of individual units of electrical equipment, in particular power transformer, taking into account the above-mentioned features and factors.

In order to ensure reliable operation of the EPS, the topology is designed so that the disconnection of more than one element in the normal state at maximum load does not result in unacceptable overloads of elements or load constraints [5]. If the N-1 criterion is fulfilled in all calculation states, it is considered that the EPS is reliable. The subset N is the number of EPS power elements, which have a certain degree of influence on the EPS state. Otherwise, appropriate measures should be taken to ensure compliance with the established standards. This approach is deterministic because it does not take into account the probability of emergency situations and therefore does not give quantitative characteristics of EPS reliability, and characterizes the reliability on the basis of compliance with regulatory requirements [6].

Making sound decisions to ensure reliable operation of the EPS requires an integrated approach. It is necessary to take into account the chance of electrical equipment failure, the EPS stochastic state, possible scenario of the development of the 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 [7].

Quantitatively, the risk is defined as the product of the magnitude of the event A by the possibility of event q:

$$R(t)=A(t)*q(t).$$

The complexity of risk assessment $R(t)$ mainly occurs when determining the possibility of event $q(t)$, which is often used as a probability.

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 [8].

3. The aim and objectives of the study

The aim of the present research is to develop the model and algorithm of decision-making on the operation strategy of power transformers on the basis of technical condition assessment of the power transformer and emergency risk under out of service or replacement.

To achieve this aim, the following tasks were set:

– to develop the structure of the decision-making model for determining the priority of the power transformer out of service on the basis of complex simulation for the EPS state and technical condition of the power transformer;

– to develop the algorithm of complex simulation for the EPS state and technical condition of the power transformer for emergency risk assessment under the power transformer out of service;

– to carry out the complex simulation for the EPS state and technical condition of the power transformer for making decisions of determining the priority of the power transformer out of service.

4. Materials and methods for model development for making decisions on determining the priority of the power transformer out of service

4. 1. Experimental research base

The study was carried out using the statistical information about failures of power and switching electric equipment, which were registered in Ukraine's power grid.

4. 2. Model for making optimal decisions regarding the operation strategy of power transformers using the Pareto ranking method

Determination of the replacement or out of service sequence for the EPS power oil transformers repair belongs to the class of multicriteria problems of selection of alternatives in uncertainty conditions. For today, there are a number of methods for ranking objects by the detection degree of certain properties [9].

For multicriteria problems of alternatives evaluation, commonly accepted approaches is the construction of a permissible solutions set, for which it is impossible to simultaneously improve all partial performance indicators (Pareto region), as well as the use of different aggregate indicators [10]. This decision-making approach involves the construction of a non-dominant alternatives set based on a fuzzy preference relation.

Let a set of decision-making variants (alternatives) be $A=(a_1, a_2,..., a_m)$. Each alternative is characterized and compared with the other by several features (criteria) $C= =(c_1, c_2,..., c_m)$. As a result of a pairwise comparison of alternatives by each feature, n preference relations $c_j,\ j=\overline{1,n}$ on the set of alternatives $a_i,\ i=\overline{1,m}$ are formed. It is necessary to choose the alternative a^* from the set $(A, c_1, c_2,..., c_m)$ based on this information.

Determination of a Pareto subset of effective solutions is based on the consideration of two types of convolutions: minimization $Q_1 = C_1 \cap C_2 \ldots \cap C_m$, which defines a set of non-dominated alternatives (A, Q_1) in the set; linear

$$Q_2 = \sum_{j=1}^{n} c_j \cdot \omega_j,$$

which uses alternatives according to the degree of non-domination, where ω_j is the weighting coefficient. The solution (alternative), which has the maximum degree of non-domination in both convolutions is considered optimum.

An important issue when solving the problem of making optimum decisions is to determine the weighting factors of the criteria obtained mainly by expert methods. The complexity of obtaining the necessary expert information and the degree of consistency of expert considerations significantly affect the choice of the method for determining the weighting coefficients. The most rational method of weighting coefficients under incomplete and contradictory expert information is the Saati pairwise comparison method [11].

The procedure for solving the selection problem consists of the following steps:

1. Formation of preference relations $R_j, \left(j=\overline{1,m}\right)$ on the set of alternatives A and determination of their membership functions

$$\mu_{R_S}\left(a_k,a_l\right)=\begin{cases}\mu_R\left(a_k,a_l\right)-\mu_R\left(a_l,a_k\right), if\ \mu_{R_j}\left(a_k,a_l\right)>\mu_{R_j}\left(a_l,a_k\right),\\ 0, \text{if } \mu_{R_j}\left(a_k,a_l\right)<\mu_{R_j}\left(a_l,a_k\right).\end{cases}$$

2. Construction of the convolution of relations R_j in the form of the section

$$Q_1=\bigcap_{j=1}^{m} R_j$$

with the membership function

$$\mu_{Q_1}\left(a_k,a_l\right)=\min_{j=1,m}\left(a_k,a_l\right), \quad k,l=\overline{1,m},$$

where m is the number of alternatives.

3. Determination of a fuzzy subset of non-dominant alternatives $\left(A,\mu_{Q_1}\right)$

$$\mu_{Q_1}^{ND}\left(a_i\right)=1-\sup_{a_j\in A}\left(\mu_{Q_1}\left(a_i,a_j\right)-\mu_{Q_1}\left(a_j,a_i\right)\right).$$

4. Construction of the fuzzy relation Q_2 (the second convolution of output relations $\{R_j\}$):

$$\mu_{Q_2}\left(a_i,a_j\right)=\sum_{j=1}^{m}\omega_j\cdot\mu_j\left(a_i,a_j\right), \quad \sum_{i=1}^{n}\omega_i=1, \omega_i>0, \quad j=\overline{1,n},$$

where m is the number of criteria; ω_i is the coefficient of the relative importance of the criteria.

5. Determination of the fuzzy set of non-dominant alternatives $\left(A,\mu_{Q_2}\right)$ in the set $\left(A,\mu_{Q_2}\right)$, ordering of alternatives by the degree of their non-domination

$$\mu_{Q_2}^{\mathrm{ND}}\left(a_i\right)=1-\sup_{a_i\in A}\left(\mu_{Q_2}\left(a_i,a_j\right)-\mu_{Q_2}\left(a_j,a_i\right)\right).$$

6. Finding the general set of non-dominant alternatives (the intersection of sets $Q_1^{\mathrm{ND}}\cap Q_2^{\mathrm{ND}}$ with the membership function)

$$\mu^{\mathrm{ND}}\left(a_i\right)=\min\left\{\mu_{Q_1}^{\mathrm{ND}}\left(a_i\right),\mu_{Q_2}^{\mathrm{ND}}\left(a_i\right)\right\}.$$

7. Determination of the best alternative a^* from the condition

$$\mu^{\mathrm{ND}}\left(a^*\right)=\sup_{a\in A}\mu^{\mathrm{ND}}\left(a\right).$$

Consider the fleet of power oil transformers of the power system, which have different operating periods. It is necessary to determine the optimal sequence of scheduled, unscheduled or emergency removal for repair or replacement of power transformers. That is, at a certain time interval, the operational personnel (manager) has the following alternatives a_i to decision-making: $a_1^{CT}, a_2^{CT},\ldots,a_n^{CT}$ out of service or to replace with the new CT_1, CT_2, ..., CT_n, respectively.

An assessment of alternative solutions should be carried out according to the following criteria: C_1 is the probability of failure of the power transformer in the interval of observation time; C_2 is the risk of disturbance of the dynamic stability of the system during the introduction into the repair or replacement of the power transformer; C_3 is the losses of consumers due to violation of dynamic stability, expenses for repair or full replacement of the power transformer; C_4 is the term for eliminating the consequences of an emergency situation and restoring the scheme of the normal regime.

Quantitative evaluation of alternatives according to individual criteria requires the power transformer modeling to assess the technical condition and failure probability, as well as analysis of the EPS state and emergency risk determination in case of electrical equipment failure in the conditions of planned or emergency out of service of the power transformer.

4. 3. Power transformer simulation to assess the failure probability

For today, as stated, there is a sufficient number of mathematical models for the technical condition diagnostics of the power transformer, determination of the type, nature and extent of the defect, as well as, failure probability in the interval of observation time [12]. Depending on the available information about the technical condition of individual units; of the power transformer, two types of models to determine the probability of failure were developed.

The dynamics of changes in diagnostic parameters over time can be obtained based on information of complex tests for the power transformer, in particular, the DGA results.

In this case, the use of corresponding mathematical models for predicting changes in technical condition and residual life of units of electrical equipment is the most appropriate. It is possible to determine the term of the diagnostic parameter violation of the permissible limits or the probability of a parametric failure at any moment of time in the observation time interval Δt.

Secondly, for the power transformer, there is no information about the technical condition on the basis of which it is possible to reliably identify the possible defect and determine the probability of its parametric failure.

Statistical data on the functioning of the power transformer of the given type, the voltage and power class to form the distribution functions of failure probability are used to estimate the power transformer probability in the corresponding mathematical failure models [13]. The distribution functions of failure probability on the basis of the general set of events are formed and in the general case are not probabilistic characteristics of a separate power transformer. The use of these distribution functions of failure probability allows us to obtain an approximate estimate of failure probability of a particular unit of equipment that needs to be adjusted taking into account the operation history, the recovery level of the resource after repair and other factors.

For the power transformer and other EPS elements, on the basis of statistical data on failures of the general set of objects at the interval of observation, the types of distribution functions *F*(*t*) were determined. The obtained types of distribution functions *F*(*t*) were checked in accordance with the Pearson χ-squared test in all areas of observation. Also, the parameters of the distribution functions *F*(*t*) are determined based on the use of least squares and maximum likelihood methods. Formation of the functions *F(t)* of units of electrical equipment of a certain type of EPS, for which there are no retrospective data on failures, was performed on the basis of expert evaluation. Parameters of the function of failure-free operation with the subsequent approximation in the form of functions with fuzzy set parameters are determined [14].

The basic distribution functions of failure probability for power transformers, which are derived from the general set of events, are shown in Fig. 1.

Ensuring reliable prediction of failure probability of power transformers on the time interval Δ*t* by modifying the failure probability distribution function of the power transformer is performed taking into account the following factors [15]:

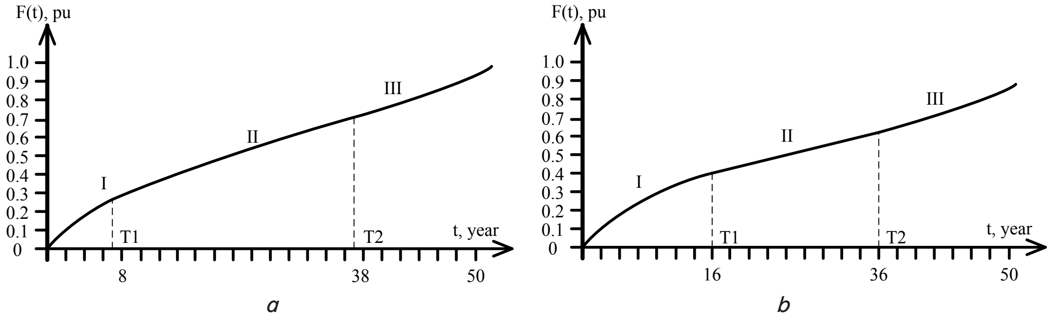
– availability of a workable state at the time of observation;

– taking into account the value of the total operational technical resource;

– the level of recovery of the resource after repair at the time of observation.

4. 4. Simulation of the EPS state and technical condition of the power transformer for emergency risk assessment

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 power transformer on the emergency risk under electrical equipment failure, in particular, the technical risk assessment of disturbance of dynamic stability. Fig. 2 represents the algorithm of priority determination of power transformers developed on the basis of risk assessment of an emergency situation in the EPS.



a *b*

Fig. 1. Distribution functions of failure probability for power transformers: *a* — power unit; *b* — system

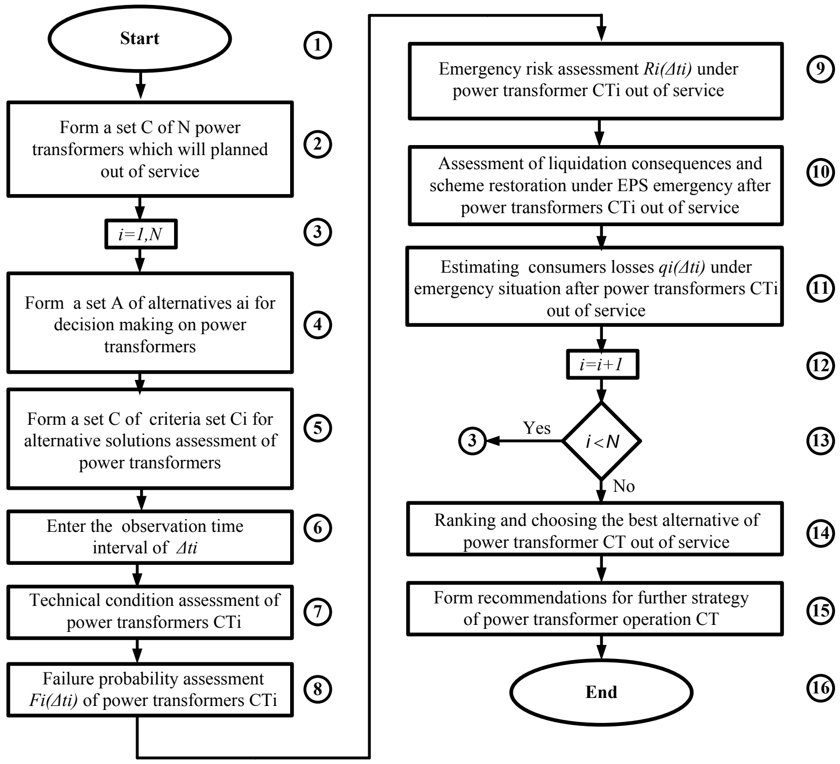


Fig. 2. Algorithm of priority determination of power transformers developed on the basis of risk assessment of an emergency situation in the EPS

To determine the probabilistic risk component according to a given model of EPS functioning, the developed mathematical and software RISK-ST, RISK-EPS 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.

The mathematical model and algorithm for emergency risk assessment under electrical equipment failures (Fig. 3) are described in detail [15].

The considered algorithm for determining the emergency risk of the EPS under electrical equipment failure is presented for the case when the emergency situations set consists of one event: dynamic stability disturbance of the EPS.

5. Test results of decision-making on power transformers operation in the EPS

Fig. 4 shows the test 6-machine scheme of the EPS subsystem which contains five power oil transformers CT_1-CT_5 with different operation lifetime. 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.

The state parameters of the test scheme change in the following ranges:

1. The voltage at the node number № 101 varies in the range of [0.95;1.05] Unom.
2. The power of load nodes varies in the following ranges:

– № 4 $P\in[860;1{,}060]$ MW, $Q\in[450;550]$ MVAr;
– № 6: $P\in[540;660]$ MW, $Q\in[180;220]$ MVAr;
– № 100: $P\in[585;715]$ MW, $Q\in[380;470]$ MVAr;
– № 202: $P\in[900;1{,}100]$ MW, $Q\in[580;720]$ MVAr.

The active power in the generation nodes is accepted unchanged and equal to:

– № 1: P=400 MW;
– № 3: P=400 MW;
– № 7: P=0 MW (synchronous compensator);
– № 201: P=1,200 MW;
– № 203: P=1,200 MW.

According to the results of power transformers diagnosis using the developed mathematical models in [16, 17], defects with significant development were not identified. At the same time, the high level of the total operating resource of the power transformer with a significant lifetime increases the risk of the power transformer failure. The failure probabilities of the power transformer at the observation time interval determined using the basic distribution functions of failure probability, which are adapted to the actual operating conditions by the expert estimation of the failure rate $\lambda(\Delta t)$, are given in Table 1.

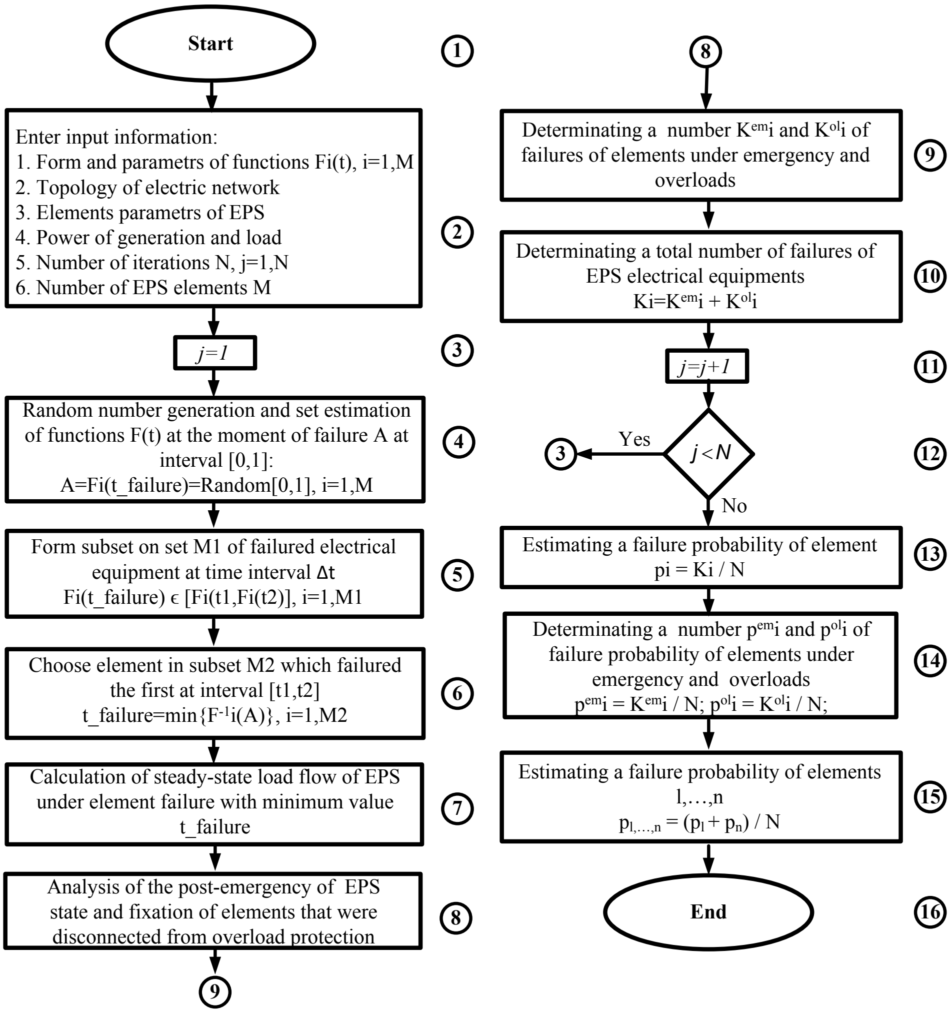


Fig. 3. Algorithm for emergency risk assessment under electrical equipment failures

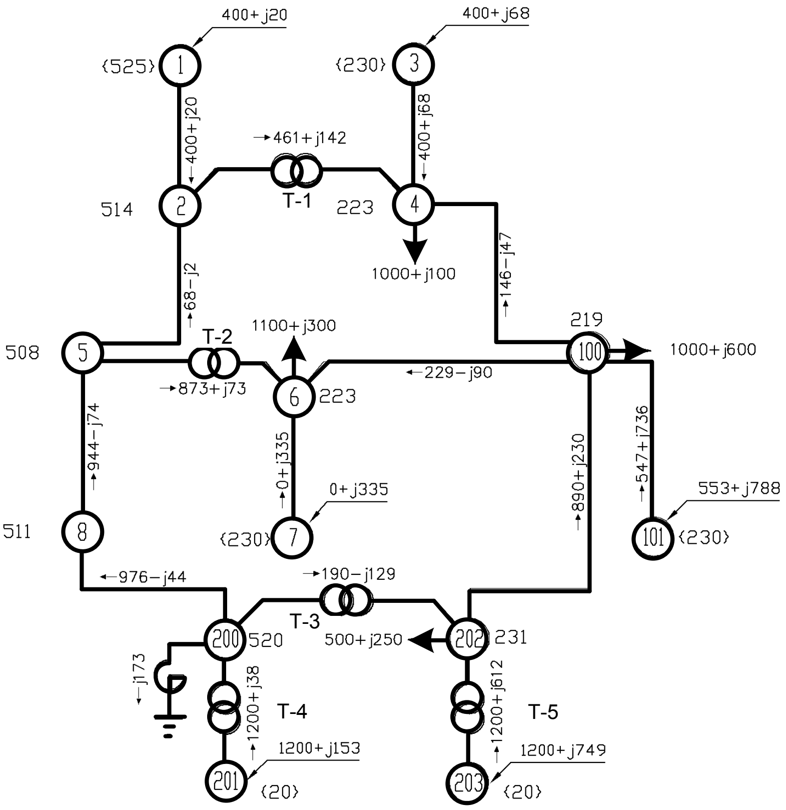


Fig. 4. Calculation scheme of the EPS test model

Table 1

Failure probabilities of the power transformer *F*(Δ*t*) on the observation time interval Δ*t*=3 months

Name	CT_3	CT_4	CT_5	CT_1	CT_2
	ATDCTN-26700/500/220	ORDC – 533000/500	ORDC – 533000/500	ATDCN-500000/500	AODCTN 333000/500
Operation lifetime t_1, year	47	47	46	29	24
$F_1(t_1)$	0.999998	0.99926	0.99905	0.62168	0.57136
$F_2(t_1+\Delta t)$	0.999999	0.99942	0.99926	0.63118	0.58181
$F(\Delta t)=\frac{F_2(t_1+\Delta t)-F_1(t_1)}{1-F_1(t_1)}$	0.5	0.223	0.2195	0.0251	0.0244

As a result of power transformers ranking at the observation time interval Δ*t*=3 months, CT_3 has the highest failure probability *F*(Δ*t*)=0.5 pu.

The forecast dispatch schedule of the EPS maximum load for the I–IV observation time intervals is shown in Fig. 5.

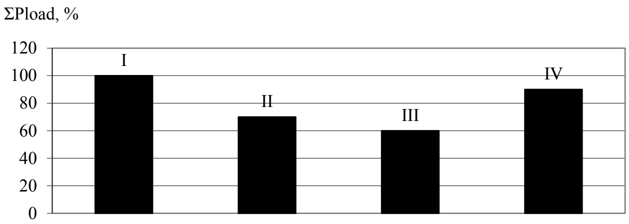


Fig. 5. Forecast dispatch schedule of the EPS maximum load for the I–IV observation time intervals

The results of statistical simulation of the operation mode of the EPS test scheme in the initial state for risk assessment of dynamic stability disturbance under electrical equipment failures for different seasonal loads at the I-IV observation time intervals are presented in Table 2.

The algorithm implementations number for statistical simulation of the operating conditions of the EPS test scheme is *n*=1,000.

Fig. 6 shows the histogram of influence distribution of elements failure for the test scheme on the total risk of EPS dynamic stability disturbance on the IV observation time interval.

Analysis of the histogram in Fig. 6 and Table 2 shows that in the normal initial mode, the total risk of EPS dynamic stability disturbance in the IV observation time interval is respectively *R*(Δ*t*)=0.0078 pu.

The greatest contribution to the risk of EPS dynamic stability disturbance on the IV observation time interval is made by failures of the overhead transmission lines L1-2, L5-6, L8-200 and power transformer.

Table 2

Simulation results for risk assessment of dynamic stability disturbance of EPS under electrical equipment failures at the I–IV observation time intervals

№	Element name of the EPS scheme	EPS risk of dynamic stability disturbance $R_i(\Delta t)$, pu			
		Observation time intervals Δt=3 months			
		I	II	III	IV
1	G–1	0.002	0.003	0.001	0.002
2	L1–2	0.003	0.011	0.005	0.009
3	CT$_1$	0	0	0	0
4	L3–4	0	0	0	0
...	...	...	...	...	...
7	L2–5	0.007	0.01	0.009	0.007
...	...	...	...	...	...
30	G203	0.005	0.004	0.003	0.005

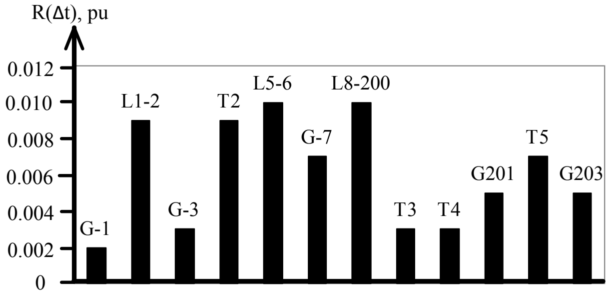


Fig. 6. Histogram of influence distribution of elements failure for the test scheme on the total risk of EPS dynamic stability disturbance on the IV observation time interval

The calculation results of quantitative characteristics for the risk of EPS dynamic stability disturbance after out of service of power transformers CT$_1$–CT$_5$ in the mode of passing the load schedule of the EPS subsystem are given in Table 3.

Table 3

Simulation results for the risk of EPS dynamic stability disturbance after out of service of power transformers CT$_1$–CT$_5$

Observaa tion time interval	Sample of power transformers in the EPS, which are out of service				
	CT$_1$	CT$_2$	CT$_3$	CT$_4$	CT$_5$
I	0.635	0.281	0.117	0.134	0.162
II	0.105	0.145	0.088	0.143	0.127
III	0.080	0.133	0.085	0.143	0.116
IV	0.271	0.152	0.104	0.134	0.151

Analysis of the results of Table 3, for example, for the power transformer CT$_1$, shows that out of service at the I time interval is characterized by a high level of total risk of EPS dynamic stability disturbance $R(\Delta t)=0.635$.

The simulation results of ranking of the power transformer out of service according to the evaluation criteria C_2–C_4 of alternative solutions for the I–IV observation time intervals are presented in Tables 4–6.

Table 4

Simulation results of ranking of the power transformer out of service for risk assessment of dynamic stability disturbance of EPS under electrical equipment failures at the I–IV observation time intervals

Observation time intervals	Preferences of alternatives a_i^{CT} at the observation time interval Δt=3 months
I	$a_3^{CT} \succ a_4^{CT} \succ a_5^{CT} \succ a_2^{CT} \succ a_1^{CT}$
II	$a_3^{CT} \succ a_1^{CT} \succ a_5^{CT} \succ a_4^{CT} \succ a_2^{CT}$
III	$a_1^{CT} \succ a_3^{CT} \succ a_5^{CT} \succ a_2^{CT} \succ a_4^{CT}$
IV	$a_3^{CT} \succ a_4^{CT} \succ a_5^{CT} \sim a_2^{CT} \succ a_1^{CT}$

Table 5

Simulation results of ranking of the power transformer out of service for consumer losses assessment due to electrical supply disruption at the I–IV observation time intervals

Observation time intervals	Preferences of alternatives a_i^{CT} at the observation time interval Δt=3 months
I	$a_4^{CT} \succ a_5^{CT} \sim a_3^{CT} \succ a_1^{CT} \succ a_2^{CT}$
II	$a_4^{CT} \sim a_5^{CT} \succ a_3^{CT} \succ a_1^{CT} \succ a_2^{CT}$
III	$a_4^{CT} \sim a_5^{CT} \sim a_3^{CT} \succ a_1^{CT} \succ a_2^{CT}$
IV	$a_4^{CT} \sim a_5^{CT} \sim a_3^{CT} \succ a_1^{CT} \succ a_2^{CT}$

Table 6

Simulation results of ranking of the power transformer out of service for restoration period estimation of the normal regime of EPS at the I–IV observation time intervals

Observation time intervals	Preferences of alternatives a_i^{CT} at the observation time interval Δt=3 months
I	$a_3^{CT} \succ a_4^{CT} \succ a_5^{CT} \succ a_2^{CT} \succ a_1^{CT}$
II	$a_3^{CT} \succ a_1^{CT} \succ a_5^{CT} \succ a_4^{CT} \succ a_2^{CT}$
III	$a_1^{CT} \succ a_4^{CT} \succ a_5^{CT} \succ a_2^{CT} \succ a_3^{CT}$
IV	$a_3^{CT} \succ a_4^{CT} \succ a_5^{CT} \sim a_2^{CT} \succ a_1^{CT}$

As an example, the simulation results of EES modes at the IV observation time interval are presented in order to justify the adoption of optimal decisions regarding the ranking of the power transformer out of service.

Using the Saati method and expert evaluation results of criteria importance, we will determine the weighting factors of the criteria importance based on the following preference system at the IV observation time interval of operation:

C_2 dominates C_1 with the rate of $b_{21}=5$;
C_2 dominates C_4 with the rate of $b_{24}=7$;
C_3 dominates C_2 with the rate of $b_{32}=4$;
C_3 dominates C_1 with the rate of $b_{31}=9$;
C_4 dominates C_3 with the rate of $b_{43}=3$;
C_1 dominates C_4 with the rate of $b_{14}=2$.

According to the formed relations, the paired comparison matrix is obtained and the eigenvalues of the matrix are determined:

$$A=\begin{bmatrix} b_{11} & 1/b_{12} & b_{13} \\ b_{21} & b_{22} & 1/b_{23} \\ 1/b_{31} & b_{32} & b_{33} \end{bmatrix}=\begin{bmatrix} 1 & 1/2 & 7 \\ 2 & 1 & 1/3 \\ 1/7 & 3 & 1 \end{bmatrix};$$

$$\lambda_1=5{,}087;\ \lambda_{2,3}=-1{,}044\pm j\cdot 3{,}087.$$

The system of equations for determining the weighting coefficients of importance of optimization criteria:

$$\begin{cases} (1-5{,}087)\cdot\omega_1+0{,}5\cdot\omega_2+7\cdot\omega_3=0; \\ 2\cdot\omega_1+(1-5{,}087)\cdot\omega_2+1/3\cdot\omega_3=0; \\ \omega_1+\omega_2+\omega_3=0. \end{cases}$$

The obtained vector of weighting coefficients of optimization criteria has the form

$$\Omega=\begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix}=\begin{bmatrix} 0{,}483 \\ 0{,}253 \\ 0{,}264 \end{bmatrix}.$$

We build convolutions $\mu_{R_s}\left(a_k^{CT},a_l^{CT}\right),k,l=\overline{1,5},$ and the elements r_{ij}^k will be determined in accordance with the rules on the basis of the preferences

$$r_{ij}^k=\begin{cases} 1, \text{ if i-th alternative is better } j\text{-th the } k\text{-th criterion;} \\ 0, \text{ if the alternatives are the same for the advantage or} \\ i\text{-th alternative the worst } j\text{-th by } k\text{-th criterion.} \end{cases}$$

To determine the optimal solution within the limits of the considered lifetime of the power transformer and EPS, we will perform the ranking of alternatives A according to the criteria C using indicators $\succ$ – «better»; $\prec$ – «worse»; $\sim$ – «equally».

$$\mu_{R_1}\left(a_k^{CT},a_l^{CT}\right)=\left(\begin{array}{cccccc} & a_1^{CT} & a_2^{CT} & a_3^{CT} & a_4^{CT} & a_5^{CT} \\ a_1^{CT} & 1 & 1 & 0 & 0 & 0 \\ a_2^{CT} & 0 & 1 & 0 & 0 & 0 \\ a_3^{CT} & 1 & 1 & 1 & 1 & 1 \\ a_4^{CT} & 1 & 1 & 0 & 1 & 1 \\ a_5^{CT} & 1 & 1 & 0 & 0 & 1 \end{array}\right),$$

$$\mu_{R_2}\left(a_k^{CT},a_l^{CT}\right)=\left(\begin{array}{cccccc} & a_1^{CT} & a_2^{CT} & a_3^{CT} & a_4^{CT} & a_5^{CT} \\ a_1^{CT} & 1 & 1 & 1 & 1 & 1 \\ a_2^{CT} & 0 & 1 & 1 & 1 & 1 \\ a_3^{CT} & 0 & 0 & 1 & 0 & 0 \\ a_4^{CT} & 0 & 0 & 1 & 1 & 0 \\ a_5^{CT} & 0 & 0 & 1 & 1 & 1 \end{array}\right),$$

$$\mu_{R_3}\left(a_k^{CT},a_l^{CT}\right)=\left(\begin{array}{cccccc} & a_1^{CT} & a_2^{CT} & a_3^{CT} & a_4^{CT} & a_5^{CT} \\ a_1^{CT} & 1 & 0 & 0 & 0 & 0 \\ a_2^{CT} & 1 & 1 & 0 & 0 & 0 \\ a_3^{CT} & 1 & 1 & 1 & 1 & 1 \\ a_4^{CT} & 1 & 1 & 0 & 1 & 1 \\ a_5^{CT} & 1 & 1 & 0 & 0 & 1 \end{array}\right),$$

$$\mu_{R_4}\left(a_k^{CT},a_l^{CT}\right)=\left(\begin{array}{cccccc} & a_1^{CT} & a_2^{CT} & a_3^{CT} & a_4^{CT} & a_5^{CT} \\ a_1^{CT} & 1 & 1 & 1 & 1 & 1 \\ a_2^{CT} & 1 & 1 & 1 & 1 & 1 \\ a_3^{CT} & 1 & 1 & 1 & 1 & 1 \\ a_4^{CT} & 0 & 0 & 0 & 1 & 1 \\ a_5^{CT} & 0 & 0 & 0 & 0 & 1 \end{array}\right).$$

Definition of the first convolution

$$\mu_{Q_1}\left(a_k,a_l\right)=\min_{j=1,m}\left(a_k,a_l\right),\quad k,l=\overline{1,m},$$

$$\mu_{Q_1}\left(a_k^{CT},a_l^{CT}\right)=\left(\begin{array}{cccccc} & a_1^{CT} & a_2^{CT} & a_3^{CT} & a_4^{CT} & a_5^{CT} \\ a_1^{CT} & 1 & 0 & 0 & 0 & 0 \\ a_2^{CT} & 0 & 1 & 0 & 0 & 0 \\ a_3^{CT} & 0 & 0 & 1 & 0 & 0 \\ a_4^{CT} & 0 & 0 & 0 & 1 & 0 \\ a_5^{CT} & 0 & 0 & 0 & 0 & 1 \end{array}\right).$$

Definition of a set of non-dominant alternatives for Q_1:

$$\mu_{Q_1}^{\mathrm{ND}}\left(a_i\right)=1-\sup_{a_j\in A}\left(\mu_{Q_1}\left(a_i,a_j\right)-\mu_{Q_1}\left(a_j,a_i\right)\right),$$

$$\mu_{Q_1^{ND}}\left(a_i^{CT}\right)=\left(1\quad 1\quad 1\quad 1\quad 1\right).$$

Definition of the second convolution

$$\mu_{Q_2}\left(a_i,a_j\right)=\sum_{j=1}^{m}\omega_j\cdot\mu_j\left(a_i,a_j\right),\quad \sum_{i=1}^{n}\omega_i=1,\quad \omega_i>0,\quad j=\overline{1,n},$$

$$\mu_{Q_2}\left(a_i^{CT},a_j^{CT}\right)=\left(\begin{array}{cccccc} & a_1^{CT} & a_2^{CT} & a_3^{CT} & a_4^{CT} & a_5^{CT} \\ a_1^{CT} & 1 & 0{,}6273 & 0{,}5393 & 0{,}5393 & 0{,}5393 \\ a_2^{CT} & 0{,}5778 & 1 & 0{,}5393 & 0{,}5393 & 0{,}5393 \\ a_3^{CT} & 0{,}6658 & 0{,}6658 & 1 & 0{,}6658 & 0{,}6658 \\ a_4^{CT} & 0{,}4606 & 0{,}4606 & 0{,}3341 & 1 & 0{,}6658 \\ a_5^{CT} & 0{,}4606 & 0{,}4606 & 0{,}3341 & 0{,}3341 & 1 \end{array}\right).$$

Definition of a set of non-dominant alternatives for Q_2:

$$\mu_{Q_2}^{\mathrm{ND}}\left(a_i^{CT}\right)=1-\sup_{a_i\in A}\left(\mu_{Q_2}\left(a_i^{CT},a_j^{CT}\right)-\mu_{Q_2}\left(a_j^{CT},a_i^{CT}\right)\right).$$

$$\mu_{Q_2^{ND}}\left(a_i^{CT}\right)=\left(0{,}8734\quad 0{,}8735\quad 1\quad 0{,}6682\quad 0{,}6673\right).$$

Definition of the best solution for the convolutions $Q_1^{\mathrm{ND}}\cap Q_2^{\mathrm{ND}}$:

$$\mu^{\mathrm{ND}}\left(a_i^{CT}\right)=\sup_{a\in A}\mu^{\mathrm{ND}}\left(a_i^{CT}\right),$$

$$\mu_Q\left(a_i^{CT}\right)=\left(0\quad 0\quad 1\quad 0\quad 0\right).$$

The most effective preventive decision on risk reduction of dynamic stability disturbance is the alternative a_3^{CT} with the degree

$$\mu_Q\left(a_3^{CT}\right)=1{,}0,$$

that recommends the removal of the power transformer CT3 for repair.

The simulation results of determination of the optimal solution for the power transformer out of service according to the C_1–C_4 estimation criteria of alternative solutions for the I–IV observation time intervals are presented in Table 7.

Table 7

Results of decision on the order of the power transformer out of service

Observation time intervals	CT_1	CT_2	CT_3	CT_4	CT_5
I	0	0	1.0	0.50532	0
II	0	0	1.0	0.50534	0.50531
III	1.0	0	0.50534	0	0
IV	0	0	1.0	0	0

The most effective preventive decision on risk reduction of dynamic stability disturbance is the alternative a_4^{CT} with the degree $\mu_Q\left(a_4^{CT}\right)=1{,}0$, that recommends the removal of the power transformer CT_4 out of service, and on others the power transformer CT_3 out of service dominates.

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

6. Discussion of the results of complex simulation of the EPS state and technical condition of the power transformer

The developed approach to select of power transformers ranking is based on the technical condition assessment of the power transformer, risk assessment of emergency situations in the EPS and electrical network state under the power transformer out of service.

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

Advantages, in terms of risk assessment of the power transformer failure, are as follows:

– the consequences of failure, both for consumer and electricity supplier are taken into account;

– account is taken of operation lifetime and voltage level;

– the failure probability is determined on the basis of technical condition assessment taking into account the predicted location and defect nature.

The obtained information concerning the possible state of the EPS subsystem is the basis for developing an algorithm for making efficient decisions regarding the operation strategy of the power transformer and the preventive state control of the EPS subsystem.

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

7. Conclusions

1. The structure of the decision-making model was developed for priority determining of the power transformer out of service on the basis of using the Pareto method, which has a high degree of consistency of ratings for various experts.

2. The developed algorithm of complex simulation for the EPS state and technical condition of the power transformer for emergency risk assessment under the power transformer out of service can be used for “on-line” forecasting of the accident risk.

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 for the EPS state and technical condition of the power transformer was carried out for making decisions of priority determining of the power transformer out of service, which confirms the acceptable efficiency of the applied approach when drawing up schedules of power transformer maintenance. This approach allows predicting the EPS state both in terms of modes, and the technical state of electrical equipment.

References

1. Sun H.-C., Huang Y.-C., Huang C.-M. Fault Diagnosis of Power Transformers Using Computational Intelligence: A Review // Energy Procedia. 2012. Vol. 14. P. 1226–1231. doi: 10.1016/j.egypro.2011.12.1080
2. Velasquez R. M. A., Lara J. V. M. Expert system for power transformer diagnosis // 2017 IEEE XXIV International Conference on Electronics, Electrical Engineering and Computing (INTERCON). 2017. doi: 10.1109/intercon.2017.8079640
3. A risk assessment method of transformer considering the economy and reliability of power network / Lin D., Xu Y.-Y., Liang Y., Li Y., Liu N., Zhang G.-J. // 2017 1st International Conference on Electrical Materials and Power Equipment (ICEMPE). 2017. doi: 10.1109/icempe.2017.7982167
4. 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: 10.1016/j.procs.2017.05.399
5. Ciapessoni E., Cirio D., Gagleoti E. A probabilistic approach for operational risk assessment of power systems // CIGRE. 2008. P. 4–114.

6. 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: 10.1109/pmaps.2010.5528652
7. Handschin E., Jurgens I., Neumann C. Long term optimization for risk-oriented asset management // 16th Power Systems Computation Conference. Glasgow, 2008.
8. 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: 10.1109/ptc.2015.7232494
9. A practical approach to condition and risk based power transformer asset replacemen / Duarte E., Falla D., Gavin J., Lawrence M., McGrail T., Miller D. et. al. // 2010 IEEE International Symposium on Electrical Insulation. 2010. doi: 10.1109/elinsl.2010.5549580
10. 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: 10.1007/978-3-642-23854-3_23
11. Saaty T. L. Decision making with the analytic hierarchy process // International journal of services sciences. 2008. Vol. 1, Issue 1. P. 83–98.
12. Yang H., Zhang Z., Yin X. A novel method of decision-making for power transformer maintenance based on failure-probability-analysis // IEEJ Transactions on Electrical and Electronic Engineering. 2018. Vol. 13, Issue 5. P. 689–695. doi: 10.1002/tee.22618
13. 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.
14. Bardyk E. I. Models of reliability assessing of electricity supply of auxiliary NPP from external sources with fuzzy defined parametrs of failures of equipments // Proceedings of the Institute of Electrodynamics of National Academy of Sciences of Ukraine. 2014. P. 34–38.
15. 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.
16. 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: 10.15587/1729-4061.2017.118632
17. Bardyk E. I., Bolotnyi N. P. Electric power system simulation for risk assessment of power transformer failure under external short-circuit conditions // 2017 IEEE First Ukraine Conference on Electrical and Computer Engineering (UKRCON). 2017. doi: 10.1109/ukrcon.2017.8100527