Запропоновано метод визначення гранично допустимих значень показників ізоляції високовольтних маслонаповнених вводів, які забезпечують мінімальне значення ризику. Пропонований метод відрізняється тим, що гранично допустимі значення показників визначаються шляхом мінімізації функції середнього ризику, методом Ньютона, з урахуванням реальних умов експлуатації обладнання, що дозволяє підвищити експлуатаційну надійність вводів.

Отримано вираз для визначення середнього ризику з урахуванням закону розподілу показників ізоляції високовольтних вводів (Вейбулла), мінімізація якого дозволяє визначати гранично допустимі значення показників, з урахуванням їх терміну експлуатації, значення струмів завантаження, сорту трансформаторного масла і інших чинників.

Виконано порівняльний аналіз значень ризиків, які супроводжуються використанням гранично допустимих значень показників, регламентованих в Україні, з гранично допустимими значеннями показників, які отримані різними методами. Аналіз показав, що мінімальне значення ризиків забезпечують гранично допустимі значення показників, які отримані методом мінімального ризику з урахуванням умов експлуатації вводів. Виконано аналіз впливу значень ймовірностей справного і дефектного стану вводів, вартостей помилкових рішень, а також значення параметрів масштабу і форми розподілу Вейбулла на гранично допустимі значення показників ізоляції високовольтних маслонаповнених вводів герметичній конструкції. Встановлено, що збільшення ймовірності виникнення дефекту і його умовної вартості, а також збільшення терміну експлуатації вводів і завантаження призводить до зниження гранично допустимих значень показників. Доведено, що гранично допустимі значення показників ізоляції високовольтних вводів, що забезпечують мінімум економічних збитків, не є постійними. Для практичної реалізації методу мінімального ризику в процесі експлуатації запропоновано використовувати відношення правдоподібності, які дозволяють виконувати діагностику стану високовольтних вводів з мінімальним ризиком, але без визначення гранично допустимих значень показників

Ключові слова: високовольтний ввід, показники ізоляції, мінімальний ризик, ймовірності помилкових і правильних рішень, розподіл Вейбулла, відношення правдоподібності

UDC 621.314
DOI: 10.15587/1729-4061.2018.142185

DETERMINING THE MAXIMALLY PERMISSIBLE VALUES FOR THE INDICATORS OF INSULATION OF SEALED ENTRANCE BUSHINGS WITH A VOLTAGE OF 110 kV USING THE METHOD OF MINIMAL RISK

O. Shutenko
PhD, Associate Professor*
E-mail: o.v.shutenko@gmail.com
A. Zagaynova
Assistant*
E-mail: zagaynova@mail.com
G. Serdyukova
PhD, Associate Professor*
E-mail: serdukova.galina@gmail.com
*Department of transmission of electric energy
National Technical University «Kharkiv Polytechnic Institute»
Kyrpychova str., 2, Kharkiv, Ukraine, 61002

1. Introduction

One of the most pressing problems in the energy-generating industry is the aging fleet of equipment [1, 2]. For economic reasons, replacement of obsolete equipment is extremely slow and does not follow the pace of aging. Given this, ensuring the serviceability of equipment that exhausted its normative service life is a relevant and practically important objective. A node in the high-voltage power transformers, shunt reactors and oil circuit breakers that is most vulnerable [3, 4] is the oil-filled entrance bushings in a sealed structure, with a voltage of 110 kV.

One of the primary signs of a defect that appears in high-voltage entrance bushings could be exceeding the dielectric insulation indicators over certain values specified as the limiting ones. It is obvious that the reliability of equipment will largely depend on whether the threshold values for these indicators are selected correctly.

Given that failures in entrance bushings often lead to the need for repairs of power transformers, which is associated with high material damage, the improvement of methods for diagnosing the state of entrance bushings is a relevant and practically important task. Diagnosis is important not only to prevent accidents and failures, but also to confirm the high reliability of high voltage equipment during operation [5, 6]. In the theory of technical diagnosis, the limiting values for signs are determined based on an analysis of statistical distributions of diagnostic signs not only for defect-free objects, but also for the defect-prone ones.

In this context, investigation and analysis of maximally permissible values for the indicators of insulation of high-voltage oil-filled entrance bushings are a relevant and practically important objective.

2. Literature review and problem statement

One of the methods for monitoring the condition of insulation of high-voltage entrance bushings is the periodic tests, intended to measure the values of the following dielectric indicators of insulation [7, 8]:

– the tangent of the dielectric loss angle of the main insulation and the insulation of the measuring capacitor;

– capacity of the main insulation and capacity of the measuring output;

– insulation resistance of the measuring output.

Decision on the state of an entrance bushing is made based on the results of comparison of the measured values for indicators with the maximally permissible values that are regulated in [8]. In this document, the values of indicators are regulated only for the class of voltage, the type of insulation, and the grade of oil. At the same time, such factors as the duration of exploitation, values of working currents are not taken into consideration although the research reported in papers [9, 10] showed significant impact of these factors on the value for the indicators of insulation of entrance bushings. In addition, there is currently no method that allows energy generating companies to independently determine the maximally permissible values of indicators, taking into consideration the above factors. Papers [11, 12] propose, to diagnose the state of high-voltage entrance bushings, to adjust values for the tangent of angle of dielectric losses in the main insulation taking into consideration the temperature and frequency. At the same time, no issues related to determining the maximally permissible values for this indicator were addressed. Article [13] proposed a risk approach for diagnosing the equipment; however, it failed to highlight the assessment of maximally permissible values for the indicators. In [14, 15], authors suggested using the diagnostic methods based on an analysis of distribution laws for gas concentrations. However, the results reported in these papers had been obtained through the use of the normal distribution law, but no justification for the use of the normal law is given. In [16], determining the boundary values for the tangent of angle of the dielectric losses for power cables involved the integral distribution functions. The method of integral functions was also applied in studies [17, 18] in order to calculate the permissible and maximally permissible values for gas concentrations in high voltage entrance bushings and power transformers taking into consideration the most significant factors. It should be noted that using the method of integral distribution functions makes it possible to obtain the typical values of indicators rather than the maximally permissible ones, that is the values characteristic of 90–95 % of properly functioning equipment that has no signs of a defect. According to [19], equating the typical and maximally permissible values is incorrect. Paper [20], in order to determine the maximally permissible values for gases dissolved in oil, applied the Neumann-Pearson method. However, there is no justification for selecting the values for probabilities of erroneous solutions. In studies [21, 22], the limiting values for gas concentrations were determined using a minimum risk method for multidimensional distributions taking into consideration the grade of a transformer oil. Despite a sufficient body of research, the issues related to determining the maximally permissible values for the insulation of high-voltage entrance bushings have almost not been addressed: this circumstance has necessitated our present study.

3. The aim and objectives of the study

The aim of this work is to develop a method for determining the maximally permissible values for the indicators of insulation of the capacitor type in the oil-filled entrance bushings of a sealed structure, which would ensure a minimal risk value when they are diagnosed.

To accomplish the aim, the following tasks have been set:

– to select and substantiate a criterion for determining the maximally permissible values for the indicators of insulation in the high-voltage oil-filled entrance bushings of the sealed structure;

– to derive an expression to determine the value of moderate risk, taking into consideration the distribution laws of insulation indicators for high-voltage entrance bushings;

– to estimate reliability of the proposed method for determining the maximally permissible values of indicators, through a comparative analysis of the average-risk values, which is accompanied by the use of the maximally permissible values, both regulated in Ukraine and obtained via other methods;

– to analyze the impact of probability values for the proper and faulty state of entrance bushings, the cost of erroneous solutions, as well as the impact of the value for scalability parameters and the shape of Weibull distribution, on the maximally permissible values for the insulation of high-voltage entrance bushings.

4. Method for determining the maximally permissible values for the indicators of insulation of high-voltage entrance bushings

When diagnosing condition of the equipment using methods of statistical solutions [23], two types of errors are possible:

1) error of the first kind (decision about a defect is made for the proper entrance bushing);

2) errors of the second kind (decision on the proper operation is made for the entrance bushing with a developing defect).

Depending on the ratio between a conditional cost of these errors, as well as the availability and completeness of the *a priori* information about reliability of the equipment, the boundary (maximally permissible) values for diagnostic signs could be defined employing the following criteria [23]:

– a minimal number of erroneous decisions;

– a minimal value of average risk;

– a minimal value of average risk for the most unfavorable conditions (a minimax approach);

– a minimal value for the probability of one of the errors at the assigned level for another one (the Neumann-Pearson method).

Damage to high voltage entrance bushings could lead to quite severe consequences, not only for the entrance bushings themselves, but also for transformers, at which they are installed. This means that the cost of failure of the second kind is much higher than the cost of error of the first kind, and, in this case, one should minimize not the number of erroneous solutions but possible risks in case of making erroneous decisions. Currently, the open scientific literature gives enough information on both the probability and the causes of damaging the high-voltage entrance bushings. The data reported make it possible to apply actual values for the probabilities of the proper and defective state of high-voltage entrance bushings when implementing the minimal risk method.

In a general form, the method of minimal risk could be described in the following way [23]. Let a technical object's state be diagnosed based on a single parameter x. We shall consider that D_1 is a proper state, D_2 implies the existence of a defect. We assume that the object functions properly at $x > x_0$, where x_0 is the boundary value for indicator x; the object is defective at $x > x_0$. The decision rule takes the form:

$$x \in D_1 \text{ at } x < x_0,$$

$$x \in D_2 \text{ at } x > x_0. \quad (1)$$

Suppose that the x parameter describes ambiguously the state of the object and its distribution for defective and proper-functioning objects could be represented in the form of Fig. 1.

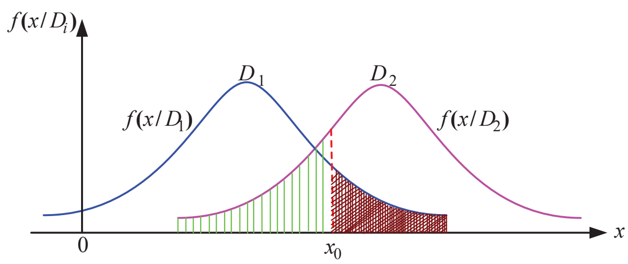

Fig. 1. Statistical distribution of probability density of the diagnostic parameter x for the proper D_1 and defective D_2 states

The magnitude of average risk when applying rule (1) for a single diagnostic sign is determined from [23]:

$$R = C_{21} P_1 \int_{x_0}^{\infty} f(x/D_1)\,\mathrm{d}x + C_{12} P_2 \int_{-\infty}^{x_0} f(x/D_2)\,\mathrm{d}x, \quad (2)$$

where

$$P_{21} = \int_{x_0}^{\infty} f(x/D_1)\,\mathrm{d}x$$

is the probability of a false alarm, that is, the case when a decision is made about a defect, but in fact the object is in a proper-functioning state (instead of D_1, D_2 is accepted);

$$P_{12} = \int_{-\infty}^{x_0} f(x/D_2)\,\mathrm{d}x$$

is the likelihood of missing a goal, that is, a decision about the proper-functioning state is made, whereas the object has a defect (instead of D_2, D_1 is accepted);

$$P_1 = P(D_1)$$

is the *a priori* probability to diagnose D_1;

$$P_2 = P(D_2)$$

is the *a priori* probability to diagnose D_2; C_{21} is the cost of a false alarm; C_{12} is the cost of missing a goal.

Determining the maximally permissible value for the diagnostic indicator x comes down to minimizing the risk function (2), that is to determining a certain value x_0 at which expression (2) returns the minimally possible value for the preset values of P_1, P_2, C_{21} and C_{12}.

The study [9], performed by authors, has shown that values for the insulation parameters of both the proper-functioning and defective high-voltage entrance bushings in a sealed implementation could be described by the Weibull distribution. The values for parameters of the Weibull distribution laws for the indicators of insulation of both the proper-functioning and defective high-voltage entrance bushings in a sealed structure with a voltage of 110 kV, obtained in [9], are given in Table 1.

It should be noted that the properly functioning high-voltage entrance bushings are examined using the three data arrays obtained by authors based on the results of testing the entrance bushings with different operation duration and with varying values of load [9, 10].

Table 1

Values of parameters for the Weibull distribution laws for the indicators of insulation of the proper-functioning and defective high-voltage entrance bushings in a sealed structure, 110 kV voltage

Indicator	Array	State of entrance bushing			
		Proper		Defective	
		α	β	α	β
tgδ$_1$	M_1	0.424122	5.414246	3.150824	3.933431
	M_2	0.530256	4.008926		
	M_3	0.973090	2.073233		
tgδ$_2$	M_1	0.462615	5.837836	2.575944	3.113934
	M_2	0.535515	6.670923		
	M_3	0.939447	2.222901		

Theoretical distribution densities for the values of the tangent of angle of dielectric losses in the main insulation of the high-voltage entrance bushings in a sealed structure with a voltage of 110 kV for the proper (M_1–M_3) and defective (D_2) states are shown in Fig. 2.

Fig. 2 shows that an increase in the duration of operation and (or) a rise in the load currents shift the mathematical expectations tgδ$_1$ of entrance bushings to the domain of higher values. In this case, for entrance bushings with a low value of the load factor and a small duration of operation (arrays M_1 and M_2) the values for tgδ$_1$ are far below the maximally permissible value (a vertical dashed line in Fig. 2), governed by the acting Ukrainian normative document [8].

Therefore, the maximally permissible values of tgδ$_1$, which ensure the minimal risk, will vary significantly for different operating conditions.

Taking into consideration the Weibull distribution, expression for a average risk takes the following form:

$$R = C_{21} P_1 \int_{\mathrm{tg}\delta_{mp}}^{\infty} \frac{\beta_1}{\alpha_1^{\beta_1}} \cdot \mathrm{tg}\,\delta^{\beta_1 - 1} \cdot e^{-\left(\frac{\mathrm{tg}\delta}{\alpha_1}\right)^{\beta_1}} d\,\mathrm{tg}\,\delta +$$

$$+ C_{12} P_2 \int_{-\infty}^{\mathrm{tg}\delta_{mp}} \frac{\beta_2}{\alpha_2^{\beta_2}} \cdot \mathrm{tg}\,\delta^{\beta_2 - 1} \cdot e^{-\left(\frac{\mathrm{tg}\delta}{\alpha_2}\right)^{\beta_2}} d\,\mathrm{tg}\,\delta, \quad (3)$$

where α_1, β_1 are the values for parameters of scale and shape for the distribution of values tgδ in proper-functioning entrance bushings; α_2, β_2 are the values for parameters of scale and shape for the distribution of values tgδ in defective entrance bushings, $\text{tg}\delta_{mp}$ is the maximally permissible value for tgδ, to be determined.

It is known [23] that the minimal value for a function of average risk ensures the values for parameter $\text{tg}\delta_{mp}$ for which the following two conditions are satisfied:

$$\frac{dR}{d\text{tg}\delta_{mp}}=0 \text{ and } \frac{d^2R}{d\text{tg}\delta_{mp}^2}>0. \quad (4)$$

Given that the precise analytical solution for function (3) with conditions (4) is missing, we then employed, to determine the maximally permissible values for tgδ, a numerical method by Newton [24].

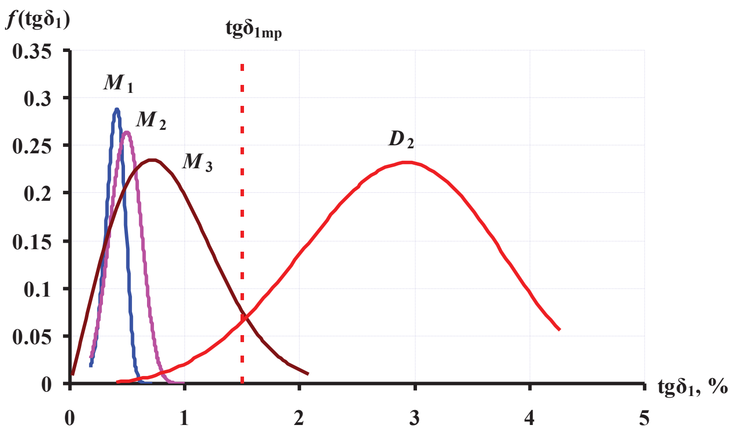

Fig. 2. Theoretical distribution density for values of $\text{tg}\delta_1$ for the high-voltage entrance bushings in a sealed structure with a voltage of 110 kV for the proper (M_1–M_3) and defective (D_2) states [9]

According to [23], for the unimodal distributions (including a Weibull distribution), the boundary value that ensures the minimal risk is between the mathematical expectations for the densities of distributions of the two states, which greatly simplifies the calculation process.

The value of mathematical expectations for the indicators of the proper-functioning ($m_{1\text{tg}\delta}$) and defective ($m_{2\text{tg}\delta}$) entrance bushings for the Weibull distribution was defined from:

$$m_{\text{tg}\delta_i}=\alpha_i\cdot\Gamma\left(1+\frac{1}{\beta_i}\right), \quad (5)$$

where α_i, β_i are the values for parameters of scale and shape of values tgδ for the Weibull distribution in the proper-functioning and defective entrance bushings;

$$\Gamma(\alpha)=\int_0^\infty t^{x-1}\cdot e^{-t}dt$$

is the Euler's gamma function.

Fig. 3 shows dependences of the average risk value on value $\text{tg}\delta_1$, for the values of parameters distribution for the proper state corresponding to the array of M_1. Calculation results at different values for the conditional cost of probability of the second-kind error, and at the conditional cost of probability of the first-kind error equal to unity, are illustrated in Fig. 3, *a*. Fig. 3, *b* shows dependences of the average risk value on value $\text{tg}\delta_1$, for the values of parameters distribution for the proper state corresponding to the array of M_1, at different values for the probability of the proper state and, consequently, the likelihood of a defect equal to $1-P_1$. Vertical dotted lines denote value of the mathematical expectation, for the proper ($m_{1\text{tg}\delta}$) and defective ($m_{2\text{tg}\delta}$) state of entrance bushings.

Fig. 3 shows that an increase in the conditional cost of «missing a defect» and the growing likelihood for the emergence of a defect ($P_2=1-P_1$) shift the minimum of an average-risk function towards a selective mean for the proper-functioning state. Risk values could vary by several orders of magnitude at the same parameter values for the distribution law, depending on the values for conditional costs of erroneous decisions, the probabilities of the proper-functioning and defective states of an entrance bushing. The magnitude of risk depends also on a change in the value of the indicator itself.

The results reported in [6], based on analysis of actual operational data, indicate that specific damageability of entrance bushings is not constant, but varies depending on operation duration and several other factors. To calculate the maximally permissible values for the indicators of insulation of high-voltage entrance bushings, we chose the most unfavorable value for the probability of occurrence of a defect among those given in [6], $P_2=0.1$, with the probability of the proper state being, respectively, $P_1=1-P_2=0.9$.

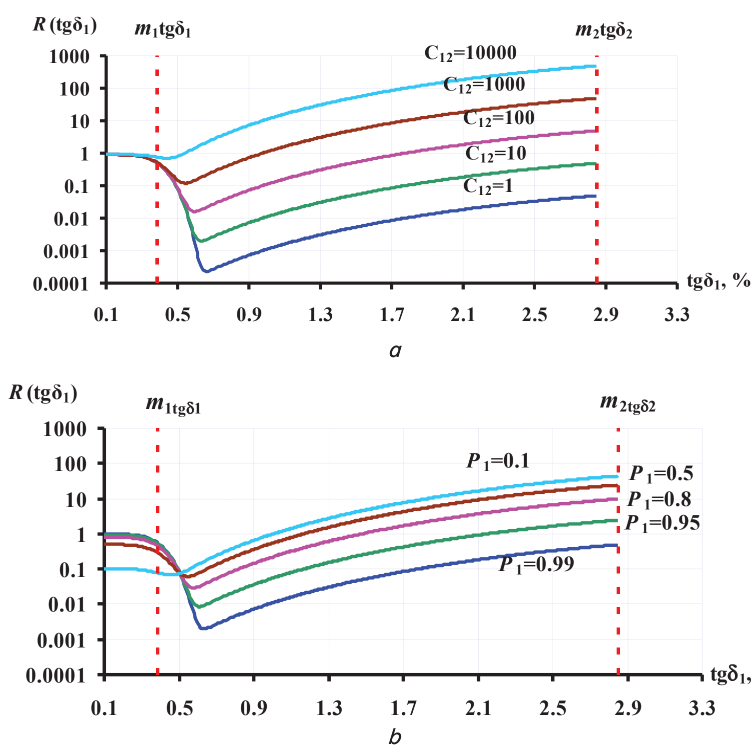

Fig. 3. Dependences of average-risk values on values $\text{tg}\delta_1$, for array M_1: *a* — at different values for the cost of «missing a defect»; *b* — at different values for the probabilities of the proper state

Values for the conditional costs of incorrect decisions are also not constant. The cost of the probability of a second-kind error depends on the type of defect. As well as on effect of its being overlooked (repair of an entrance bushing, replacement of an entrance bushing, replacement of an entrance bushing and repair of a transformer, or complete replacement of a transformer, electric power deficiency, etc.).

The cost of the first-kind error probability will be largely determined by qualification of personnel, and by the decision that will be taken in the case when the parameter exceeds the maximally permissible value in the proper entrance bushing. For example, retesting, additional analyses (physical-chemical analysis of oil, analysis of gases dissolved in oil, etc.), repair of an entrance bushing, replacement of an entrance bushing.

Under such conditions, in order to calculate the maximally permissible values for the indicators of insulation of high-voltage entrance bushings, the conditional value of the first-kind error probability was accepted to be equal to unity ($C_{12}=1$), and the conditional value of the second-kind error probability was adopted to equal 100 ($C_{12}=100$), as it is recommended, for example, in [23].

The maximally permissible values of $tg\delta_1$ that ensure the minimal risk, obtained by minimizing a function (3) using the Newton's method, for values $P_1=0.9$, $P_2=0.1$, $C_{12}=100$ and $C_{12}=1$, are given in Table 2.

Table 2

Maximally permissible values for the indicators of insulation of high-voltage entrance bushings that ensure the minimal risk

Indicator	Array	Maximally permissible values
$tg\delta_1$	M_1	0.596
	M_2	0.775
	M_3	1.117
$tg\delta_2$	M_1	0.593
	M_2	0.659
	M_3	0.754

Table 2 shows that the boundary values that ensure minimal risk for different data arrays on the insulation of the proper-functioning high-voltage entrance bushings differ considerably. This suggests a need to adjust the maximally permissible values for the indicators of insulation of entrance bushings, taking into consideration the impact of specific operating conditions of the equipment that is diagnosed.

5. Comparative analysis of average risks

The maximally permissible values for the indicators of insulation of the capacitor type high-voltage entrance bushings, given in Table 2, minimize the value for a possible risk only, rather than eliminate it completely.

In this regard, it is of interest to consider results of comparing the values for risk, which is accompanied by the use of the derived maximally permissible values, with the risks, which are accompanied by the use of the maximally permissible values, governed by the acting Ukrainian standard [8]. In addition, it is particularly interesting to assess the risks, which are accompanied by the use of the maximally permissible values for the indicators of insulation, obtained by applying different methods, specifically the method of integral functions [16].

According to the method of integral functions, the maximally permissible value for an indicator is the value below which are the values of a given indicator for 90 per cent of the total number of the examined entrance bushings. Typical values were determined based on the integral distribution functions (F_i) for the values of indicators of high-voltage entrance bushing insulation with distribution parameters given in Table 1, in the following way:

1. Values of each indicator for each array of homogeneous data were split into L intervals (the number of intervals was determined using the Sturgess formula):

$$L = 1 + 3.322 \lg N, \quad (6)$$

where N is the volume of sampled values.

2. At each interval we determined the likelihood of sampled values matching a given interval:

$$P_{Li} = \frac{n_{Li}}{N}, \quad (7)$$

where n_{Li} is the number of values in a given interval.

3. Values for the integral distribution function with respect to (6) were derived from:

$$F_{Li} = \sum_{i=1}^{i=k} P_{Li}, \quad (8)$$

where $k < L$.

4. The maximally permissible value for each indicator was determined graphically at $F_{Li}=0.9$ (Fig. 4).

Calculation results are given in Table 3.

By comparing the values from Tables 2, 3, it is easy to see that the maximally permissible values for the indicators of insulation of entrance bushings that are obtained for the same data but using different methods, differ considerably. Consequently, their application will be accompanied by different values of risks. In the process of analysis, we estimated not only the value for risk, but also values for the probability of erroneous and correct decisions.

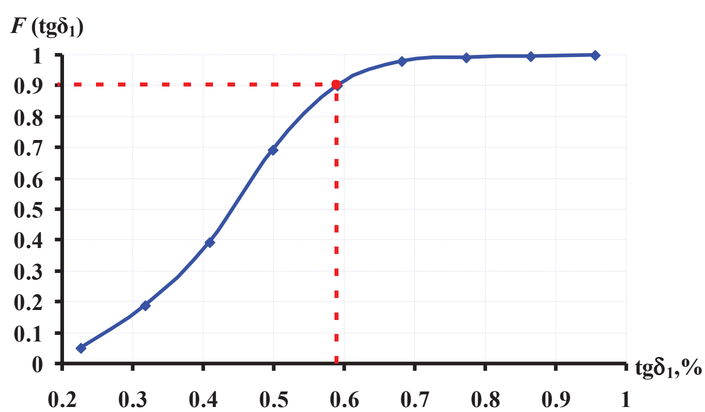

Fig. 4. Determining the maximally permissible value for the tangent of angle of dielectric losses in the main insulation of sealed entrance bushings, for data array M_2 using the method of integral distribution functions

Table 3

The maximally permissible values for the indicators of insulation of high-voltage entrance bushings obtained using the method of integral functions

Indicator	Array	Maximally permissible values for indicators
tgδ$_1$	M_1	0.46
	M_2	0.59
	M_3	1.27
tgδ$_2$	M_1	0.49
	M_2	0.57
	M_3	1.2

A probability of correct decision when diagnosing the state of proper-functioning entrance bushings is the probability that for the proper entrance bushing values of the indicator do not exceed the maximally permissible value:

$$P_{11}=\int_{0}^{\operatorname{tg}\delta_{mp}}\frac{\beta_1}{\alpha_1^{\beta_1}}\cdot\operatorname{tg}\delta^{\beta_1-1}\cdot e^{-\left(\frac{\operatorname{tg}\delta}{\alpha_1}\right)^{\beta_1}}d\operatorname{tg}\delta. \quad (9)$$

A probability of correct decisions when diagnosing the state of proper-functioning entrance bushings is the likelihood that for a defective entrance bushing values for the indicator will exceed the maximally permissible value:

$$P_{22}=\int_{\operatorname{tg}\delta_{mp}}^{\infty}\frac{\beta_2}{\alpha_2^{\beta_2}}\cdot\operatorname{tg}\delta^{\beta_2-1}\cdot e^{-\left(\frac{\operatorname{tg}\delta}{\alpha_2}\right)^{\beta_2}}d\operatorname{tg}\delta. \quad (10)$$

Values for the probabilities of correct (P_{11} and P_{22}) and incorrect decisions (P_{21} и P_{12}), as well as the values for risks, obtained when using the maximally permissible values, derived while applying different methods, are given in Table 4.

Analyzing the data from Table 4, it could be stated that:

1) Using the values for indicators obtained by different methods as the maximally permissible ones is accompanied by different risk values. The minimal risk values are ensured by the maximally permissible values for indicators, which are obtained by the method of minimal risk taking into consideration the operating conditions for entrance bushings. In this case, the maximally permissible values for indicators, obtained by authors of this paper, ensure that the risk values are 1.5–33 times less than the maximally permissible values regulated by the acting Ukrainian standard and are 1.1–13 times lower than the maximally permissible values that were obtained using the method of integral functions. The maximum risk value ensures the maximally permissible values for indicators, governed by the acting Ukrainian document [8].

2) When comparing risk values that accompany the use of the maximally permissible values for indicators obtained by the method of integral functions and the risk values derived using the maximally permissible values for indicators, regulated by the acting Ukrainian standard, it is easy to see that accounting for the operating conditions for entrance bushings reduces possible risks, even when using the method of integral functions.

3) For all, without exception, maximally permissible values for indicators (regardless of the method used to derive them), there is a decrease in the probability values for making correct decisions as the operating conditions for proper-functioning entrance bushings deteriorate. Prolonging the period of operation and increasing load currents lead to an increase in the risk value.

Table 4

Values for probabilities of correct and incorrect decisions, as well as risk values obtained when using the maximally permissible values for indicators, derived by applying different methods

Indicator	Array	Probability values for incorrect and correct decisions				R
		P_{11}	P_{21}	P_{22}	P_{12}	
Maximally permissible values for indicators, in line with the acting Ukrainian standard [8]						
tgδ$_1$	M_1	1	0	0.9475	0.0525	0.526
	M_2	1	0	0.9475	0.0525	0.526
	M_3	0.9139	0.0861	0.9475	0.0525	0.602
tgδ$_2$	M_1	1	0	0.8306	0.1694	1.694
	M_2	1	0	0.8306	0.1694	1.694
	M_3	0.9410	0.0590	0.8306	0.1694	1.747
Maximally permissible values for indicators, obtained by the method of integral functions						
tgδ$_1$	M_1	0.7882	0.2118	0.9995	0.0005	0.195
	M_2	0.7844	0.2156	0.9986	0.0014	0.207
	M_3	0.8239	0.1761	0.9723	0.0277	0.435
tgδ$_2$	M_1	0.7532	0.2469	0.9943	0.0057	0.279
	M_2	0.7805	0.2195	0.9909	0.0091	0.288
	M_3	0.8215	0.1785	0.9115	0.0885	1.045
Maximally permissible values for indicators, obtained by the method of minimal risk						
tgδ$_1$	M_1	0.9982	0.0018	0.9986	0.0014	0.016
	M_2	0.9904	0.0096	0.9959	0.0041	0.048
	M_3	0.7360	0.2640	0.9832	0.0168	0.406
tgδ$_2$	M_1	0.9859	0.0141	0.9897	0.0103	0.115
	M_2	0.9815	0.0185	0.9858	0.0142	0.158
	M_3	0.4585	0.5415	0.9784	0.0216	0.703

6. Analysis of factors that influence the maximally permissible values for indicators determined by the method of minimal risk

The maximally permissible values for indicators that were determined applying the method of minimal risk ensure minimal risk only for the assigned values for the cost of erroneous decisions, probabilities of states, and the distribution laws parameters, that is, they are «point-wise». In practice, the diagnosis probability values, as well as the cost values for incorrect decisions, as well as the values for distributions parameters, may vary widely.

As shown in Fig. 3, changing at least one of the enumerated parameters will change the average risk values and, therefore, the maximally permissible values for the indicator that ensure minimal risk will change. In this regard, it is of direct interest to analyze influence of these parameters on the maximally permissible values for indicators. At the first stage we analyzed the impact of values for a scale parameter α and values for a shape parameter β in the Weibull distribution on the maximally permissible values for indicators. To this end, by assigning the fixed value for a shape parameter β, we calculated the maximally permissible values for indicators at different values for parameter α. Calculation was performed for values P_1=0.9, P_2=0.1, C_{12}=100 and C_{12}=1. The dependences constructed are shown in Fig. 5. Fig. 5 shows that increasing the value for a scale parameter a in the Weibull distribution for the proper state of entrance bushings leads to an increase in the maximum permissible values for tgδ$_1$. This is due [21] to the fact that an increase in the value for parameter a leads to the shift in the mathematical expectation of the distribution curve for the proper state towards the domain of higher tgδ$_1$.

By analogy, we studied the effect of a shape parameter. To this end, at the fixed values for a scale parameter α, we calculated the maximally permissible values for tgδ$_1$ at different values for parameter β. Calculation was performed for values P_1=0.9, P_2=0.1, C_{12}=100 and C_{12}=1. Results of the calculation are shown in Fig. 6. The value of the shape parameter defines the scattering of values tgδ$_1$ relative to the mathematical expectations.

Increasing a given variance causes the reduction of value b and the displacement of intersection point of distribution densities tgδ$_1$ for the proper-functioning and defective entrance bushings towards the domain of higher values [21]. Therefore, with an increase in the scale parameter, the maximally permissible values of tgδ$_1$ decrease (Fig. 6).

Next, we analyzed the influence of probabilities for the proper and defective states of entrance bushings, as well as conditional costs of erroneous decisions on the maximally permissible values for indicators. As the distribution laws parameters, for the proper state we used values α and β for the array of the tangent of angle of dielectric losses in the main insulation of entrance bushings M_3 from Table 1, for which the limiting permissible value is maximal. Considering P_2=1–P_1, and by assigning the values of cost in the relations of incorrect decisions C_{12}/C_{21} (ratio of the second-kind error to the cost of the first-kind error), accepting C_{21}=1, we calculated the maximally permissible values for tgδ$_1$ for various probability values for the proper state of entrance bushings. The dependences constructed are shown in Fig. 7.

As shown in Fig. 7, with a decrease in the probability for the proper state (with an increase in the likelihood of a defect) the maximally permissible values for tgδ$_1$ decrease, for example, increasing the likelihood of a defect from 0.75 to 0.9, at C_{12}/C_{21}=100, leads to a decrease in the maximally permissible values for tgδ$_1$ by 1.33 times. In this case, the dependences derived are nonlinear. With the increasing cost of a second-kind error relative to the cost of a first-kind error the dependences shift towards the domain of the lower maximally permissible values for tgδ$_1$.

Next, we investigated dependences of the maximally permissible values for tgδ$_1$ on ratio of the cost of erroneous decisions. To this end, by assigning the fixed values for a first-kind error probability and considering P_2=1–P_1, we calculated the maximally permissible values for tgδ$_1$ for different values of cost ratio of erroneous decisions. The dependences constructed are shown in Fig. 8.

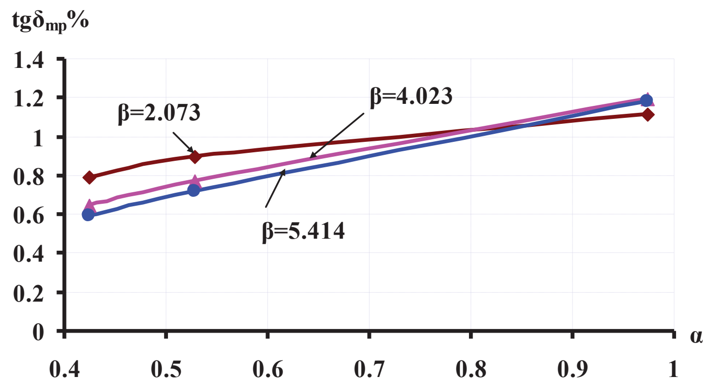

Fig. 5. Dependence of the maximally permissible values of tgδ$_1$ on values for a shape parameter α, at different values for a scale parameter β in the Weibull distribution

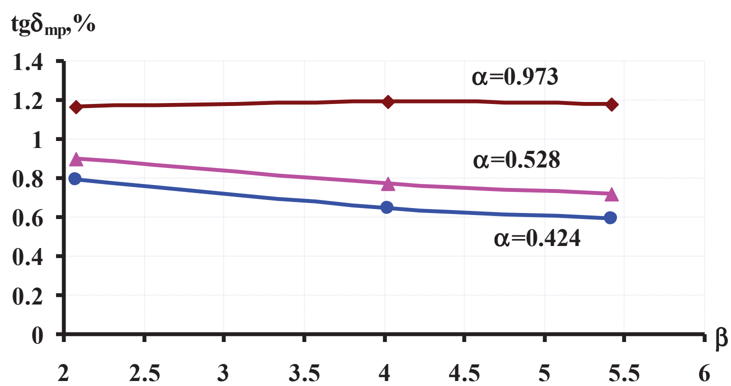

Fig. 6. Dependence of the maximally permissible values of tgδ$_1$ on values for a scale parameter β at different values for a shape parameter α in the Weibull distribution

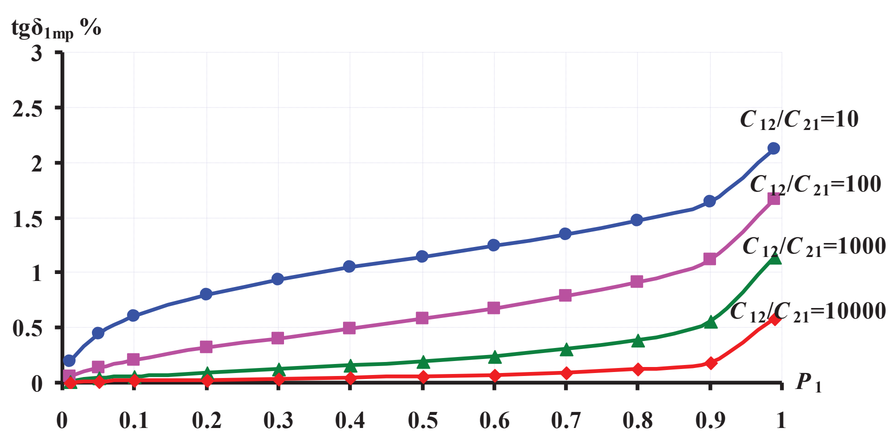

Fig. 7. Dependence of the maximally permissible values for tgδ$_1$ on values for the probability of the proper state of entrance bushings at different values for conditional cost of erroneous decisions

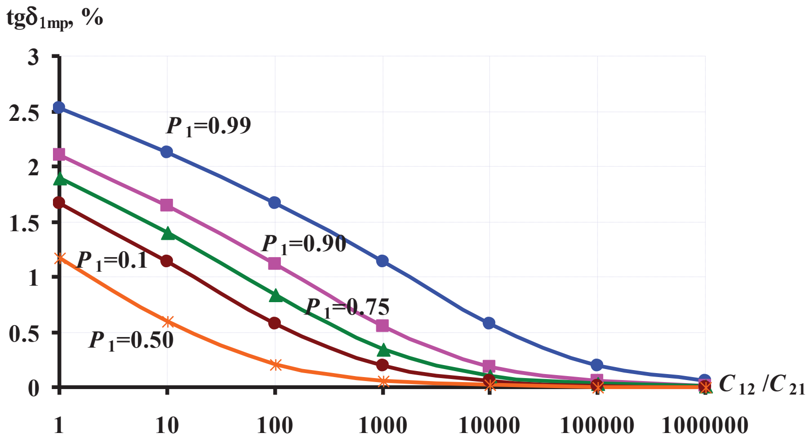

Fig. 8. Dependence of the maximally permissible values of tgδ_1 on ratio of the costs of incorrect decisions at different values for probabilities of the proper state of entrance bushings

Fig. 8 shows that with an increase in the second-kind error ratio to the cost of a first-kind error the maximally permissible values for tgδ_1 decrease, for example, increasing the conditional cost of missing a defect from 100 to 1000 c. u. (conventional units), at P_1=0.9, leads to a decrease in the maximally permissible value for tgδ_1 by 2 times. With an increase in the likelihood of a defect, the dependences shift to the domain of the lower maximally permissible values for tgδ_1.

The above results showed that the maximally permissible values for the indicators of insulation of high-voltage entrance bushings that ensure the minimal risk value are not constant. Insulation indicators values vary depending on values for the parameters of indicator distribution law in the proper-functioning and defective entrance bushings, on values of the cost of incorrect decisions, and probabilities of the defective and faultless state of equipment. Hence, the maximally permissible values for indicators of insulation of high-voltage entrance bushings that ensure the minimal economic loss should be determined by energy generating companies by taking these factors into consideration.

If one knows parameter values for the indicators of distribution laws for the proper and defective state of entrance bushings, then, according to [23], in order to diagnose the state of equipment one could apply values of the likelihood ratios. The likelihood ratio is the ratio of the densities of the probability distributions of diagnostic signs at two states.

In accordance with rule (1), in line with a minimal risk method, we made the following decision about the state of the entrance bushing that has a given value for the parameter tgδ of insulation:

$$\begin{cases} x\in D_1, \text{ if } \dfrac{\dfrac{\beta_1}{\alpha_1^{\beta_1}}\cdot \operatorname{tg}\delta^{\beta_1-1}\cdot e^{-\left(\frac{\operatorname{tg}\delta}{\alpha_1}\right)^{\beta_1}}}{\dfrac{\beta_2}{\alpha_2^{\beta_2}}\cdot \operatorname{tg}\delta^{\beta_2-1}\cdot e^{-\left(\frac{\operatorname{tg}\delta}{\alpha_2}\right)^{\beta_2}}} > \dfrac{C_{12}P_2}{C_{21}P_1}; \\ x\in D_2, \text{ if } \dfrac{\dfrac{\beta_1}{\alpha_1^{\beta_1}}\cdot \operatorname{tg}\delta^{\beta_1-1}\cdot e^{-\left(\frac{\operatorname{tg}\delta}{\alpha_1}\right)^{\beta_1}}}{\dfrac{\beta_2}{\alpha_2^{\beta_2}}\cdot \operatorname{tg}\delta^{\beta_2-1}\cdot e^{-\left(\frac{\operatorname{tg}\delta}{\alpha_2}\right)^{\beta_2}}} < \dfrac{C_{12}P_2}{C_{21}P_1}. \end{cases} \quad (11)$$

In practical calculations, rule (11) is more conveniently represented in the form:

$$\begin{cases} x\in D_1, \text{ if } D>0, \\ x\in D_2, \text{ if } D<0, \end{cases} \quad (12)$$

where

$$D=\frac{\beta_1\cdot(\alpha_1^{\beta_1})^{-1}\cdot \operatorname{tg}\delta^{\beta_1-1}\cdot e^{-\left(\frac{\operatorname{tg}\delta}{\alpha_1}\right)^{\beta_1}}}{\beta_2\cdot\left(\alpha_2^{\beta_2}\right)^{-1}\cdot \operatorname{tg}\delta^{\beta_2-1}\cdot e^{-\left(\frac{\operatorname{tg}\delta}{\alpha_2}\right)^{\beta_2}}}-\frac{C_{12}P_2}{C_{21}P_1}.$$

As an example of diagnosing the state of entrance bushings using the likelihood ratios, Fig. 9 shows dependences of magnitude D on the tgδ_1 values for the three data sets analyzed.

Fig. 9 shows that for all three data sets the magnitude D alternates the plus sign to the minus sign. which, pursuant to rule (1), is equivalent to a transition from the proper-functioning to the defective state, at the tgδ_1 values corresponding to the maximally permissible values from Table 2.

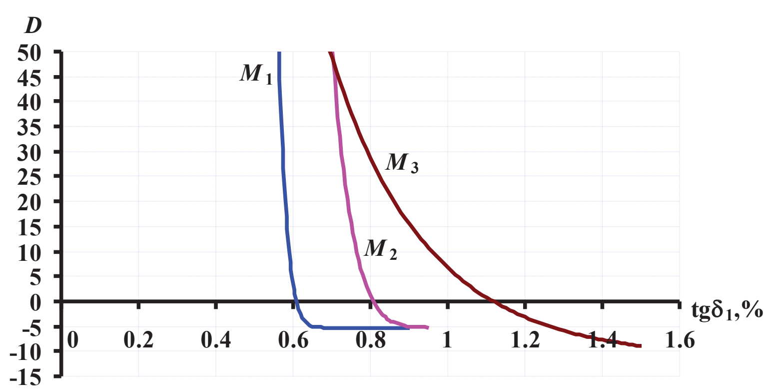

Fig. 9. Diagnosing the state of high-voltage entrance bushings using the likelihood ratios

7. Discussion of results of studying the adjustment of the maximally permissible values for the indicators of entrance bushings insulation

The application of results obtained in the present work makes it possible in the first place to improve the operational reliability of high-voltage oil-filled entrance bushings by the more precise and correct determining of the maximally permissible values for indicators, using the method of minimal risk.

An analysis revealed that the maximally permissible values for the indicators of insulation of high-voltage entrance bushings that ensure the minimal risk value vary depending on many factors. If one knows the values of parameters for the distribution laws of indicators for the proper and defective states of entrance bushings, diagnosing the state of equipment could then employ values for the likelihood ratios. Using the likelihood ratio to diagnose the state of high-voltage entrance bushings is especially convenient during operation, since it does not require determining the maximally permissible values for the indicators.

Improving the methods to diagnose the state of entrance bushings is a relevant and practically important objective. Diagnosing is crucial not only for the prevention of accidents and failures, but also to confirm the high operational reliability of high-voltage equipment.

An important limitation of the proposed method is the need for a preliminary assessment of distribution laws of the insulation indicators for the proper and defective state of high-voltage entrance bushings. Solving a given task requires skilled personnel in energy generating companies.

The disadvantage of this work is that the study addressed only the values for indicators of the main insulation of entrance bushings, without taking into consideration the indicators that characterize the state of a transformer oil. This is predetermined by the limited number of values for the indicators of oils for entrance bushings with developing defects.

One of the directions for the further development of this study is to determine the maximally permissible values for indicators of transformer oils for high-voltage entrance bushings both in an airtight and non-sealed structure, taking into consideration the influence of the most significant factors. Most difficulties might occur when determining the most influential factors, given the scarcity and uncertainty of measurement information.

The results obtained are algorithmically implemented as a separate module in an information-analytical system (IAS) to diagnose the state of high-voltage oil-filled equipment.

8. Conclusions

1. To determine the maximally permissible values for the indicators of insulation of high-voltage entrance bushings, it has been proposed to apply the criterion of a minimal average risk in order to minimize the possible economic damage in case of making incorrect decisions. We have constructed a method for determining the maximally permissible values for the indicators of insulation of high-voltage oil-filled entrance bushings that provide the minimal risk value. The proposed method differs in that the maximally permissible values for indicators are determined by minimizing the function of average risk, using the Newton's method, taking into consideration the actual operating conditions of equipment, which makes it possible to improve the operational reliability of entrance bushings.

2. We have derived an expression to determine the average risk with respect to the distribution law of indicators for the insulation of high-voltage entrance bushings (by Weibull), the minimization of which makes it possible to determine the maximally permissible values for the indicators, taking into consideration the duration of their operation, the values of load currents, the grade of a transformer oil, and other factors.

3. We have performed a comparative analysis of risk values, which are accompanied by using the maximally permissible values for indicators that are regulated in Ukraine with the maximally permissible values for indicators, which were obtained by applying different methods. The analysis revealed that the minimal value for risks is ensured by the maximally permissible values for indicators, which are derived by the method of minimal risk, taking into consideration the operating conditions of entrance bushings. In this case, the maximally permissible values for the indicators that we obtained ensure the risk values, which are 1.5–33 times less than the maximally permissible values regulated by the acting Ukrainian standard, and are 1.1–13 times lower than the maximally permissible values obtained by the method of integral functions. For all maximally permissible values without exception (regardless of the method used to obtain them), there is a decrease in the values for the probability of making correct decisions in proportion to the deterioration in the operational conditions for proper-functioning entrance bushings (when service life is prolonged and load currents increase), which leads to an increase in the risk value.

4. It was established based on the analysis results that an increase in the probability of a defect and its conditional cost, as well as prolonging the operation of entrance bushings and their loading (increasing a scale parameter in the Weibull distribution for proper-functioning entrance bushings) leads to a decrease in the maximally permissible values for the indicators. For example, increasing the likelihood of a defect from 0.75 to 0.9, at $C_{12}/C_{21}=100$, leads to a decrease in the maximally permissible value of tgδ_1 by 1.33 times, while an increase in the conditional cost of missing a defect from 100 to 1000 c. u., at $P_1=0.9$, results in a decrease in the maximally permissible value of tgδ_1 by 2 times. This indicates that the maximally permissible values for the indicators of insulation of high-voltage entrance bushings, which ensure the minimal economic loss, should be determined by energy generating companies themselves, taking these factors into consideration.

5. A method for determining the maximally permissible values for the indicators of insulation of high-voltage oil-filled entrance bushings that ensure the minimal risk value has been proposed. The proposed method differs in that the maximally permissible values for indicators are determined by minimizing the function of average risk, using the Newton's method, taking into consideration the actual operating conditions of equipment, which makes it possible to improve the operational reliability of entrance bushings.

References

1. Alekseev B. A. Kontrol' sostoyaniya (diagnostika) krupnyh silovyh transformatorov: monografiya. Moscow: «Izdatel'stvo NC ENAS», 2002. 216 p.
2. Anglhuber M., Velásquez C. J. L. Dispersing the clouds – gain clear insight into your bushings using advanced diagnostics method // Transformers Magazine. 2017. P. 126–132.

3. Osobennosti monitoringa tekhnicheskogo sostoyaniya osnovnoy izolyacii vysokovol'tnyh vvodov i transformatorov toka / Andrienko P. D., Sahno A. A., Konogray S. P., Spica A. G.,. Skrupskaya L. S. // Elektrotekhnika ta elektroenerhetyka. 2014. Issue 1. P. 43–48.
4. Rubanenko O. Ye., Humeniuk O. I. Vysokovoltni vvody. Konstruktsiya, ekspluatatsiya, diahnostyka i remont: monohrafiya. Vinnytsia: VNTU, 2011. 183 p.
5. Dolya O. E. Povyshenie nadezhnosti ekspluatacii vvodov // Materialy 10-oy ezhegodnoy konferencii «Metody i sredstva kontrolya izolyacii vysokovol'tnogo oborudovaniya». Perm': OOO «Dimrus», 2013.
6. Ocenka effektivnosti i celesoobraznosti diagnostiki vysokovol'tnyh vvodov na osnove opyta ekspluatacii / Kassihin S. D., Sipilkin K. G., Slavinskiy A. Z., Ustinov V. N., Pintal' Yu. S., Vereshchagin M. B. // Transformatory: ekspluataciya, diagnostirovanie, remont, prodlenie sroka sluzhby: materialy Mezhdunar. nauch.-prakt. konf., posvyashch. 70-letiyu Viktora Sokolova. Ekaterinburg: Izdatel'skiy dom «Avtograf», 2010.
7. Diagnosticheskie priznaki dlya otbrakovki vvodov vysokogo napryazheniya s bumazhno-maslyanoy izolyaciey / Anikeeva M. A., Arbuzov R. S., Zhivodernikov S. V., Lazareva E. A., Ovsyannikov A. G., Panov M. A. // ELEKTRO. 2009. Issue 1. P. 22–25.
8. Normy vyprobuvannia elektroobladnannia: SOU-N EE 20.302:2007 – Ofits. vyd., prykaz Minpalyvenerho 2007-01-15 h. No. 13. Kyiv: OEP «HRYFRE»: Minpalyvenerho palyva ta enerhetyky Ukrainy, 2007. 262 p.
9. Shutenko O., Zagaynova A., Serdyukova G. Analysis of distribution laws of insulation indicators of high-voltage oil-fillled bushings of hermetic and non-hermetic execution // Technology audit and production reserves. 2018. Vol. 4, Issue 1 (42). P. 30–39. doi: https://doi.org/10.15587/2312-8372.2018.140873
10. Zahainova O. A. Analiz vplyvu riznomanitnykh chynnykiv na intensyvnist starinnia izoliatsiyi kondensatornoho typu vysokovoltnykh vvodiv // Energosberezhenie. Energetika. Energoaudit. 2015. Issue 10 (141). P. 17–25.
11. Santos E., Schuette T. Breakdown Mechanism of Bushings and Life-Cycle Oriented Maintenance Strategies // TechCon Asia-Pacific. 2016. P. 1–27.
12. Dielectric Response Diagnoses For Transformer Windings / Gubanski S. M. et. al. // CIGRE report 414. 2010.
13. Felea I., Secui D., Oltean M. The impact analyze of electric stress level in content of insulating oil gases in power transforrmers // Journal of sustainable energy. 2011. Vol. 2, Issue 4.
14. Lin M.-J. Gaussian distribution Diagnoses in Transformer's Insulating Oil // Joint International Mechanical, Electronic and Information Technology Conference (JIMET 2015). 2015. P. 824–830.
15. Mirowski P., LeCun Y. Statistical Machine Learning and Dissolved Gas Analysis: A Review // IEEE Transactions on Power Delivery. 2012. Vol. 27, Issue 4. P. 1791–1799. doi: https://doi.org/10.1109/tpwrd.2012.2197868
16. Besprozvannyh A. V., Moskvitin E. S. Kriterii ocenki stepeni stareniya silovyh kabeley s bumazhno-propitannoy izolyaciey // Elektrotekhnika i Elektromekhanika. 2013. Issue 4. P. 32–36.
17. Davidenko I. V. Opredelenie dopustimyh znacheniy kontroliruemyh parametrov maslonapolnennogo oborudovaniya na osnove massiva nablyudaemyh dannyh // Elektrichestvo. 2009. Issue 6. P. 10–21.
18. Davidenko I. V. Issledovanie pokazateley, opisyvayushchih rabochee sostoyanie maslonapolnennyh vvodov, metodami matematicheskoy statistiki // Izvestiya vysshih uchebnyh zavedeniy. 2006. Issue 15. P. 31–33.
19. IEC Publication 60599. Interpretation of the analysis of gases in transformer and other oil med electrical equipment in &, Geneva, Switzerland, 1999.
20. Zaharov A. V. Obnaruzhenie defektov silovyh maslonapolnennyh transformatorov kak procedura proverki statisticheskih gipotez // Novoe v rossiyskoy energetike. 2001. Issue 2. P. 19–28.
21. Shutenko O. V. Opredelenie znacheniy granichnyh koncentraciy rastvorennyh v masle gazov metodom minimal'nogo riska // Elektrichestvo. 2017. Issue 8. P. 50–60. doi: http://dx.doi.org/10.24160/0013-5380-2017-8-50-60
22. Shutenko O. Determine the boundary value of the concentration of gases dissolved in oil of method minimum risk // 2017 IEEE First Ukraine Conference on Electrical and Computer Engineering (UKRCON). 2017. doi: https://doi.org/10.1109/ukrcon.2017.8100533
23. Birger I. A. Tekhnicheskaya diagnostika: monografiya. Moscow: Mashinostroenie, 1978. 240 p.
24. Chernoruckiy I. G. Metody prinyatiya resheniy: monografiya. Sankt-Peterburg: BHV-Peterburg, 2005. 416 p.