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ANALYSIS OF DISTRIBUTION LAWS OF INSULATION INDICATORS OF HIGH-VOLTAGE OIL-FILLLED BUSHINGS OF HERMETIC AND NON-HERMETIC EXECUTION

Об'єктом дослідження є закони розподілу показників ізоляції конденсаторного типу, які отримані в ході профілактичних випробувань, як для справних, так і дефектних високовольтних вводів напругою 110 кВ герметичної і негерметичної конструкції. Одним з найбільших проблемних місць при діагностиці стану високовольтних вводів є недостатня вивченість і відсутність обгрунтування законів розподілу даних профілактичних випробувань ізоляції конденсаторного типу вводів.

В ході дослідження використовувався комплексний підхід до вирішення поставлених завдань, включаючи теорію ймовірності і статистичний аналіз, аналіз світового досвіду та логічний підхід. У перспективі передбачається поширення отриманих результатів на ввода других типів, що мають аналогічні проблеми при діагностиці стану.

Запропоновано метод статистичної обробки результатів періодичних випробувань високовольтних вводів, який дозволяє сформувати масиви з однорідними значеннями показників в умовах обмеженості вимірювальної інформації. Встановлено, що для вводів герметичної і негерметичної конструкції показники ізоляції, як для справного, так і дефектного стану, можуть бути описані розподілом Вейбулла. Отримано, що щільності розподілу для справного і дефектного стану високовольтних вводів перетинаються, а отже, не можуть бути вибрані гранично-допустимі значення параметрів ізоляції, які б не давали помилкових рішень. Пропонується гранично-допустимі значення показників ізоляції високовольтних маслонаповнених вводів визначати з використанням методів статистичних рішень і з урахуванням найбільш значущих експлуатаційних факторів. Показано, що для високовольтних вводів однієї і тієї ж конструкції має місце зміщення математичних очікувань, яке обумовлено розходженням тривалості експлуатації і різними коефіцієнтами завантаження трансформаторів. Дану обставину необхідно враховувати при коригуванні гранично-допустимих значень показників ізоляції високовольтних вводів.

Використання розроблених алгоритмів і процедур математичної статистики в задачах діагностування високовольтних вводів сприяють поліпшенню експертних оцінок і прийняття рішень.

Ключові слова: *високовольтні вводи, показники ізоляції, статистичні критерії, дисперсійний аналіз, критерії згоди, розподіл Вейбулла.*

1. Introduction

High-voltage bushings, along with windings and on-load tap-changers are one of the most damaged nodes of high-voltage power transformers [1–3], and the uninterrupted supply of electrical energy to consumers is largely dependent on the reliability of their operation. Damage to oil-filled bushings 110–500 kV with paper-oil insulation caused many accidents, both power transformers and oil circuit breakers [4, 5]. If the damage of the bushing installed, for example, on the transformer, is accompanied by an explosion and a fire, the material damage is very significant because of the need to repair the transformer at the factory. Currently, the oil systems in Ukraine are in operation oil-filled bushings, both non-hermetic execution, and the introduction of a hermetic execution. In addition, recently there has been an active replacement of oil-filled bushings with paper-oil insulation on the bushings with RIP (resin impregnated paper) insulation [6]. However, despite the execution change, the bushings continue to be one of the most damaged transformer nodes. In this case, it is quite interesting to change the nature of the damage for bushings with different executions.

For bushings of a non-hermetic execution [5, 7], the most typical damages are:

- humidification of oil and solid insulation, leading to thermal breakdown and overlapping on the surface of the core and the tire;
- an unreliable execution of the sealing components, leading to oil leakage, its wetting and oxidation.

In addition, in non-hermetic bushings, there are disruptions in the contact joints that lead to sparking and breakdown, as well as mechanical damage to the bushing when the temperature changes because of the insufficient volume of the oil conservator.

For the bushings of the hermetic execution, due to the limited access of oxygen to air and moisture, oxidative processes are not so intense. The main reason for the damageability of such bushings [7, 8] is the overlapping of the inner surface of porcelain of low porcelain cover, which is due to the deposition on the porcelain surface of the yellow-brown precipitate, which falls out of the oil in the form of a finely dispersed mixture. Another cause of damage to hermetic bushings [7] is partial discharges in the oil and on the surface of the core and the covers, leading to an overlap of the internal insulation. As well as oil contamination with aluminum particles formed in the pressure tank during vibration. In addition, in hermetic bushings there is a disruption of the electrical connection between the live tube and the pipe of the insulating frame when the transformer vibrates, resulting in an electric discharge, oil decomposition and the formation of gases. Also, hermetic bushings are characterized by damage due to the increase in the hydrostatic pressure inside it caused by the loss of airtightness of the bellows or the failure of the pressure vessel with the bushing and the pressure drop in the bushing due to leakage. In addition, X-wax deposits (waxy products formed on the surface or between sheets of insulation paper) are present for both hermetic and non-hermetic bushings filled with oil with a high content of paraffin fractions. For example, GK oil (an oil grade, which is produced from sulfur paraffinic oils using the hydrocracking process). This can lead to a thermal breakdown of the core [9, 10].

Despite the relatively low operating time (mass production of bushings with RIP insulation started in 2003–2004), solid-insulated bushings also have a sufficiently high level of damage. In [11] it is noted that in the period from 2010 to 2011, the damage statistics of these bushings, has reached an alarming scale, and a number of 330 and 500 kV bushings have been banned for installation. The main causes of damage to the RIP-insulated bushings [7, 11, 12] are the separation of the core, the development of partial discharges and damage to porcelain tires due to unacceptable mechanical influences.

The above analysis clearly illustrates that changing the execution of the bushings does not always lead to an increase in their operational reliability. In this regard, improving the methods of monitoring and diagnosing the insulation state of high-voltage bushings is an actual and practically significant task. Solving this problem will significantly improve the operational reliability of both the bushings themselves and the high-voltage equipment on which they are installed.

2. The object of research and its technological audit

The object of research is the laws of distribution of capacitor-type insulation values that were obtained during preventive tests for both faulty and defective high-voltage bushings with a voltage of 110 kV of a hermetic and non-hermetic execution. As indicators characterizing the insulation state of high-voltage oil-filled bushings, the following values were analyzed:

– tangent of the dielectric loss angle of the basic insulation (tgδ_1);

– capacity of the main insulation (C_1);

– tangent of the dielectric loss angle of the measuring capacitor insulation (tgδ_2);

– capacitance of the measuring capacitor (C_2);

– insulation resistance of the bushing for measurement (R).

Despite the fact that such tests are carried out regularly, at least once every three years, and to date, a sufficient amount of statistical material has been accumulated, the laws of distribution of these indicators have not been investigated. This circumstance does not allow to use more advanced methods of decision making when diagnosing the state of bushings.

3. The aim and objectives of research

The aim of research is analysis of the distribution laws of insulation indicators for serviceable and faulty high-voltage bushings of hermetic and non-hermetic execution.

To achieve this aim, it is necessary to solve the following tasks:

1. To develop an algorithm for statistical processing of the results of operational tests of high-voltage bushings and perform an assessment of the statistical homogeneity of the results of periodic tests.
2. To check the statistical hypothesis about the similarity of theoretical and empirical distribution laws, for the values of the insulation state indicators of serviceable and defective high-voltage bushings.
3. To analyze the values of scale factors and forms for the distribution of indicators in serviceable and defective high-voltage bushings.
4. To analyze the joint location of the theoretical densities of the distribution of the insulation performance of bushings with different states.

4. Research of existing solutions of the problem

One of the directions for improving the methods and procedures for decision-making in the diagnosis of high-voltage oil-filled equipment is the use of statistical recognition methods. As analysis of literary sources shows, the use of methods of statistical solutions allows to solve a rather wide range of problems. Thus, the results of adjusting the maximum permissible values of gas concentrations on the basis of an analysis of integral distribution functions are presented in [13, 14].

In [15] the analogous problem is solved by the Neyman-Pearson method, and in [16, 17] by the method of minimal risk. In [18], a method for diagnosing oil-filled equipment based on the Bayesian rule for constructing boundaries for the partition of state classes is proposed, and in [19] a method for detecting developing malfunctions based on an analysis of the Gaussian distribution is given.

In [20], the problem of forecasting transformer failures is solved on the basis of analysis of gas concentration distributions in transformers with different states, taking into account the duration of operation, nominal power and voltage.

In [21], an analysis of the risks accompanying the diagnostics of the state of oil-filled equipment is given.

However, the practical use of statistical methods of diagnosis is possible if the laws of distribution of diagnostic indices are known, both for serviceable and for defective equipment states. In open literary sources, only the laws of the distribution of gas concentrations are described, both for high-voltage bushings and for power transformers [15, 22]. And also the laws of distribution of transformer oil parameters [23]. At the same time, the laws of distribution of indicators of the main insulation of high-voltage bushings have not been investigated.

5. Methods of research

To study the distribution laws of insulation indicators, the authors use the results of periodic monitoring for 87 serviceable high-voltage oil-filled bushings with a voltage of 110 kV of hermetic and non-hermetic execution from three regions of Ukraine (Kharkiv, Poltava, Sumy). The total volume of the analyzed sample is 593 values. To study the distribution laws of tgδ$_1$ for the defective state of the bushings, the results of preventive tests on 60 high-voltage leads of a hermetic structure are used, in which defects of various types are detected.

The data obtained as a result of the operational control are statistically non-uniform, since the analyzed bushings are put into operation at different times, are operated in different conditions, differ in the grades of the oil to be filled and the different values of the load factor. All this leads to the fact that the values of the insulation parameters in the various bushings can vary significantly. The presence of heterogeneity in the arrays of the initial data does not allow to obtain the correct density functions of the distribution laws (Fig. 1).

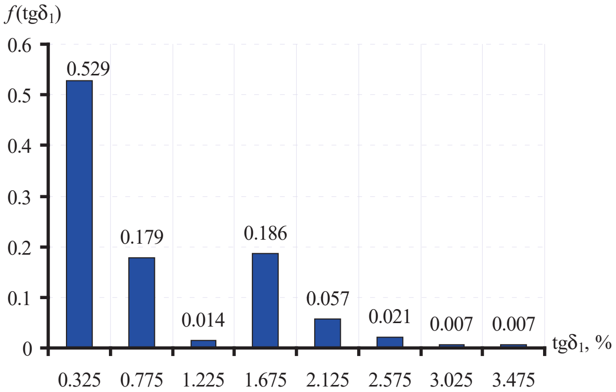


Fig. 1. Histogram of the empirical distribution of the tangent of the dielectric loss angle of the main insulation for serviceable high-voltage bushings of a non-hermetic execution

In this regard, there is an objective need for a procedure for preliminary statistical processing of initial data. At present, two main approaches to processing the results of periodic tests of insulation indicators for oil-filled equipment are given in open literature sources. The first approach [13, 14] is based on the use of the mathematical apparatus of factor analysis, first using the models of single-factor analysis of variance, the most significant factors are identified and, with their account, arrays of homogeneous data are formed. Next, the «lazy smoothing» procedure is performed to reduce the statistical heterogeneity.

The second approach [22, 24] is based on testing of statistical hypotheses for individual groups of equipment, while homogeneous data arrays are formed based on the results of statistical testing. It should be noted that the use of the first approach is advisable, if full information is known not only about the nominal values of the equipment characteristics, but also information about the operating modes of this equipment, the features of its execution. The second approach allows to form homogeneous data arrays in conditions of limited or incomplete a priori information. Given the incompleteness of information on the operating modes of the researched bushings, which is available to the authors, a second approach is used to form homogeneous data arrays. Formation of arrays with homogeneous results of periodic tests is carried out using three statistical criteria [25], which are given in (Table 1):

- a rank non-parametric Wilcoxon test (W) – to test the statistical hypothesis of the similarity of the distribution laws of two independent samples;
- criterion Z – to test the statistical hypothesis about the equality of the expectations of two independent samples;
- Fisher-Snedecor criterion (F) for testing the statistical hypothesis about the equality of variances of two independent samples.

Two independent samples are considered homogeneous if, according to the test results, statistical hypotheses:

- the similarity of the distribution laws of two independent samples ($S_1 > S_{n1,\ n2,\ 0.025}$, $S_2 < S_{n1,\ n2,\ 0.975}$);
- on the equality of the mathematical expectations of two independent samples ($Z_{obs} < Z_{cr,\ 0.95}$);
- on the equality of the variances of two independent samples ($F_{obs} < F_{(n1-1),\ (n2-1),\ 0.95}$) – were not rejected for a given level of significance $\alpha = 0.05$.

Combining the results of periodic monitoring obtained for different bushings into one data set was performed only if the sampling values for these bushings were equal, or if the discrepancy in the sample size did not exceed one value. The resulted algorithm of statistical processing of test results was realized in the form of the author's program «ODNORODN» [26], which allows to process significant volumes of initial data. The sample size N, the sample mean M_x, the sample variance D_x. And also the coefficients of asymmetry and kurtosis j_a and j_e for the arrays of the initial data (M_0), and the arrays obtained during the statistical processing (M_1, M_2, M_3) are given in Table 2.

Table 1

Statistical criteria used to form homogeneous data arrays

Criterion	Statistical model	Main hypothesis	Criteria statistics	Comparison statistics
W	$X_1 = (x_n^1 \ldots\ x_{n1}^1) \sim f(x_1)$; $X_2 = (x_n^2 \ldots\ x_{n2}^2) \sim f(x_2)$; $n = n_1 + n_2$	$f(x_1) = f(x_2)$	S_1 sum of the ranks of the set $\{x_i^1\}$ S_2 – sum of the ranks of the set $\{x_j^2\}$	$S_{n1,n2,\ 0.025}$ $S_{n1,n2,\ 0.975}$
Z	Sample 1: – the volume n; – sample mean m_1; – sample dispersion δ_1^2 Sample 2: – volume m; – sample mean m_2; – sample dispersion δ_2^2	$m_1 = m_2$	$Z = \dfrac{\bar{x}_1 - \bar{x}_2}{\sqrt{\dfrac{D(x_1)}{n} + \dfrac{D(x_2)}{m}}}$	Z_{cr}
F	Sample 1: – the volume n; – sample mean m_1; – sample dispersion δ_1^2 Sample 2: – volume m; – sample mean m_2; – sample dispersion δ_2^2	$\sigma_1^2 = \sigma_2^2$	$F = \delta_{\max}^2 / \delta_{\min}^2$	$F_{(n-1),(m-1),\ 0.95}$

Table 2

Statistical characteristics of arrays of indicators of high-voltage bushings

Indicator	Array	N	M_x	D_x	j_a	j_e
Bushing of non-hermetic execution						
tgδ$_1$	M$_0$	140	0.861	0.534	1.327	4.099
	M$_1$	67	0.499	0.0471	0.939	3.551
	M$_2$	73	0.372	0.0168	0.181	2.375
tgδ$_2$	M$_0$	140	0.870	0.318	0.791	2.589
	M_1	75	0.619	0.109	0.858	3.678
	M_2	65	0.946	0.233	0.571	3.173
C_1	M$_0$	140	382.276	48512.412	0.564	2.732
	M_1	91	414.570	64913.923	0.217	2.030
C_2	M$_0$	140	452.888	50967.463	0.219	2.352
	M_1	87	385.522	39879.529	0.353	2.794
Bushing of hermetic execution						
tgδ$_1$	M$_0$	453	0.577	0.104	2.296	10.599
	M$_1$	102	0.392	0.00684	0.764	4.840
	M_2	243	0.481	0.0180	0.195	3.547
	M_3	103	0.861	0.186	0.172	2.883
tgδ$_2$	M$_0$	453	0.722	0.181	1.808	7.115
	M_1	159	0.429	0.0072	1.020	5.403
	M_2	98	0.500	0.00759	–0.727	4.287
	M_3	128	0.831	0.153	0.456	3.150
C_1	M$_0$	453	309.393	18264.817	0.976	4.021
	M_1	128	268.846	9369.472	1.022	5.795
	M_2	115	314.753	34278.386	0.828	2.997
	M_3	70	321.662	10654.203	1.180	5.418
C_2	M_0	453	388.889	28013.380	0.495	3.215
	M_1	118	312.299	34197.433	0.698	3.190
	M_2	140	340.767	33439.218	0.477	3.011
	M_3	104	514.483	28968.568	–0.442	2.806

As can be seen from Table 2, the values of sample means for the arrays obtained as a result of the statistical processing procedure are significantly different. It is also easy to see that as a result of statistical processing there is a significant decrease in the sample dispersion for tgδ$_1$ and tgδ$_2$ of the obtained data arrays in comparison with the original arrays. At the same time, the values of sample variances for C_1 and C_2 not only did not decrease, but also for some arrays increased.

All data arrays without exception have a positive kurtosis coefficient value, which means that the distribution curve has a higher and «sharp» vertex than the curve of the normal law. At the same time, the distribution asymmetry coefficient has both positive and negative values. The positive value of the asymmetry coefficient indicates that the «long part» of the distribution curve is located to the right of the mathematical expectation, with a negative value of the asymmetry coefficient, the «long part» of the distribution curve is on the left.

It should be noted that, despite the fact that for the insulation resistance values of the measuring terminal, several arrays with homogeneous values could be identified in the hermetic bushings, it was not possible to determine the distribution law of this indicator. This is due to the presence in the test results of the prevailing number of measurements with the maximum resistance values (Fig. 2).

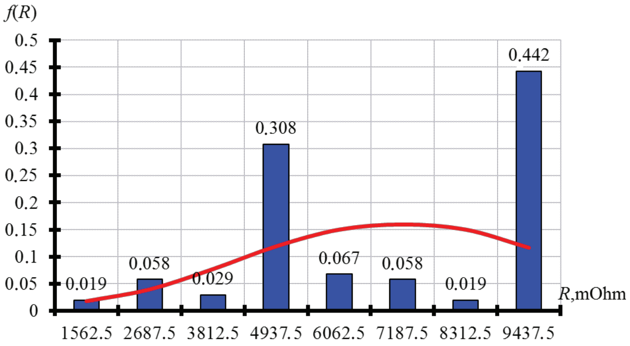


Fig. 2. A characteristic histogram of the empirical distribution of the insulation resistance values of the measuring terminal for a homogeneous array of data, serviceable high-voltage bushings of hermetic execution

At the same time, for values of the insulation resistance of the measuring lead in the non-hermetic bushings, it was not possible to form a single array with uniform data. In this regard, this indicator has not been analyzed further.

6. Research results

6.1. Estimation of the statistical homogeneity of the results of periodic tests. To check the homogeneity of the data in the received arrays, the single-factor variance analysis model was used. During the analysis, the amount of dispersion between the values of the insulation indices of the individual bushings that make up a given data set was estimated.

It is known [27, 28] that the sum of squares of deviations of all values of the components of the data array (y_{ij}) from the total average ($\bar{y}$)) is:

$$S=\sum_{i=1}^{m}\sum_{j=1}^{n}(y_{ij}-\bar{y})^2=n\cdot\sum_{i=1}^{m}(\bar{y}_i-\bar{y})^2+\sum_{i=1}^{m}\sum_{j=1}^{n}(y_{ij}-\bar{y}_i)^2$$

or

$$S=S_1+S_2, \tag{1}$$

where n – the volume of sample values; m – number of variation levels of the investigated factor (number of bushings in the data array);

$$S_1=n\cdot\sum_{i=1}^{m}(\bar{y}_i-\bar{y})^2$$

– the sum of the squares of deviations between the average values of the investigated indicator in different bushings, dispersion by factors;

$$S_2=\sum_{i=1}^{m}\sum_{j=1}^{n}(y_{ij}-\bar{y}_i)^2$$

– the sum of the squares of deviations of the values of the indicator from the mean for the same bushing – residual dispersion of the random experimental errors;

$$S=\sum_{i=1}^{m}\sum_{j=1}^{n}\left(y_{ij}-\bar{y}\right)^2$$

– total or total sum of squares of deviations of individual observations from the total average $\bar{y}$.

The evaluation of the significance of the factor reduces to a comparison of the dispersion σ^2 obtained due to S_1, with the same variance, but obtained due to S_2, which is easy to verify with respect to:

$$F=\frac{S_1\cdot(m-1)^{-1}}{S_2\cdot(m\cdot(n-1))^{-1}}\sim$$
$$\sim F_{(m-1);m(n-1)}. \qquad (2)$$

The statistics F is a random variable having an F-distribution with $(m-1)$ and m $(n-1)$ degrees of freedom.

If for a given a (usually $\alpha=0.05$) $F>F_\alpha$ (the numerator predominates), then the factor is significant. This indicates the heterogeneity of the values of the indicator in the analyzed data array.

The above calculations were carried out if the sample value for all bushings constituting the analyzed data array was the same.

If the number of measurements in different bushings is different by one, namely, there is a k_1 value for bushing m$_1$, k_2 values for bushing m_2, k_p values for bushing m_p, in this case the total sum of squared deviations was determined by the formula [25]:

$$S=\left[P_1+P_2+\ldots+P_p\right]-$$
$$-\left[\frac{\left(R_1+R_2+\ldots+R_p\right)^2}{n}\right], \qquad (3)$$

where

$$P_i=\sum_{j=1}^{k_i} y_{ji}^2$$

– the sum of the squares of the y values for bushing m_i;

$$R_i=\sum_{j=1}^{k_i} y_{ji}$$

the sum of the values of the indicator y for bushing m_i; n – the total number of tests (sample size).

The factor sum of squares of deviations was determined by the formula:

$$S=\left[\frac{P_1}{n_1}+\frac{P_2}{n_2}+\ldots+\frac{P_p}{n_p}\right]-\left[\frac{\left(R_1+R_2+\ldots+R_p\right)^2}{n}\right], \qquad (4)$$

where n_i – the sample value of y for bushing m_i.

The rest of the calculations were made, as in the case of the same number of tests. The single-factor analysis of variance was carried out using the author's program «ODA» [26]. The results of the calculation are given in Table 3.

Table 3

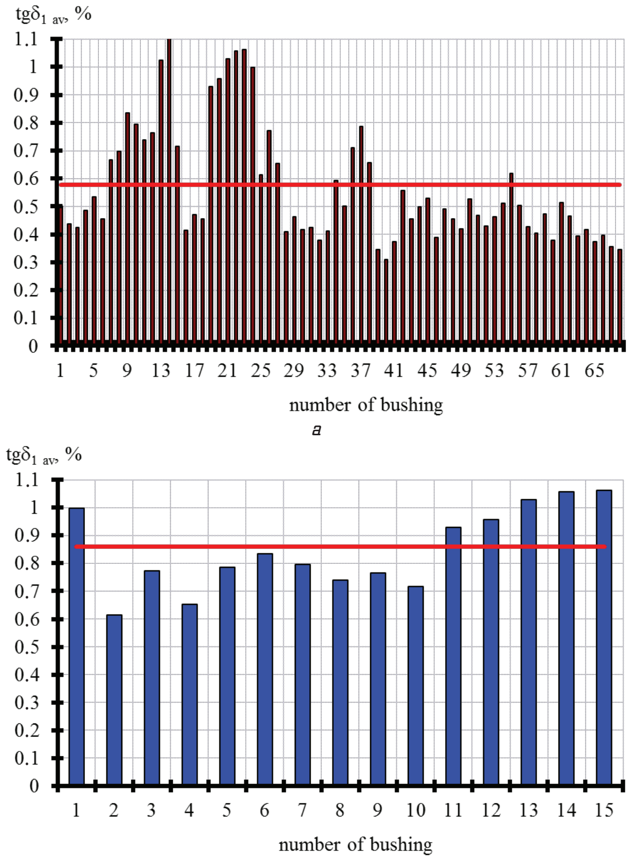
The results of estimating statistical homogeneity for arrays of source data and arrays obtained as a result of statistical processing

Indicator	Array	n	m	The values of the sums of the dispersion expansion			F-test value	
				S	S_1	S_2	F_{obs}	F_{cr}
Bushing of non-hermetic execution								
tgδ$_1$	M_0	140	19	74.8850	58.2168	16.6682	23.47	1.608
	M_1	67	9	3.1608	0.6050	2.5557	1.716	2.105
	M_2	73	10	1.2323	0.1914	1.0409	1.287	2.036
tgδ$_2$	M_0	140	19	44.5408	27.2961	17.2446	10.64	1.608
	M_1	75	9	8.2149	1.4275	6.7874	1.735	2.088
	M_2	65	7	15.1511	2.4458	12.7053	1.860	2.262
C_1	M_0	140	19	6791737.7	1059577.57	5732160.1	1.242	1.608
	M_1	91	13	5907167.0	791003.03	5116164.0	1.004	1.892
C_2	M_0	140	19	7135444.9	3961189.48	3174255.4	8.388	1.608
	M_1	87	12	3469519.0	446578.325	3022940.7	1.007	1.953
Bushing of hermetic execution								
tgδ$_1$	M_0	453	68	47.5053	21.6049	25.9004	4.793	1.306
	M_1	102	19	0.6986	0.1444	0.5542	1.201	1.749
	M_2	241	34	4.3848	0.4376	3.9472	0.702	1.439
	M_3	103	15	19.1592	2.1754	16.9838	0.805	1.823
tgδ$_2$	M_0	453	68	82.4260	35.6870	46.7390	4.387	1.306
	M_1	159	24	1.1452	0.1515	0.9938	0.894	1.530
	M_2	98	16	0.7444	0.1688	0.5756	1.603	1.804
	M_3	128	19	19.6596	2.9851	16.6745	1.084	1.711
C_1	M_0	453	68	8273962.3	4350940.64	3923021.66	6.373	1.306
	M_1	128	21	1199292.4	126620.376	1072672.04	0.631	1.678
	M_2	115	18	3942014.4	593762.101	3348252.34	1.011	1.747
	M_3	70	12	745794.22	168485.723	577308.499	1.538	1.963
C_2	M_0	453	68	12690061.	8744069.82	3945991.4	12.73	1.306
	M_1	118	17	4035297.1	777868.802	3257428.38	1.507	1.759
	M_2	140	24	4681490.6	1112448.35	3569042.27	1.572	1.627
	M_3	104	17	3012731.1	602464.221	2410266.94	1.359	1.779

Fig. 3 shows the distributions of group mean values relative to the general average tangent of the dielectric loss angle of the main insulation of the hermetic bushings from the source data array (M_0) and the M_3 array obtained as a result of statistical processing.

As can be seen from Table 3, in practically all the arrays of initial data, with the exception of the main insulation capacity for non-hermetic bushings, the observed values of the F-test are higher than the tabulated ones, at the significance level $p=0.95$ and the number of degrees of freedom $(m-1)$ and $m(n-1)$. This indicates that the values of the parameters in different bushings differ significantly from each other, and, consequently, the initial data are not homogeneous.

In spite of the fact that in the initial array of the C_1 indicator for non-hermetic bushings, according to the results of the variance analysis, the data are homogeneous, with the help of the statistical processing procedure, one data set was also extracted from it. This discrepancy is due to the fact that single-factor analysis of variance analyzes the dispersion by mean values, and the formation of homogeneous data arrays was carried out both for equality of means and for equality of variances and similarity of distribution laws.



a

b

Fig. 3. Distributions of group mean values relative to the general average tangent of the dielectric loss angle of the main insulation of the bushings of hermetic execution: *a* – from the array of initial data M_0; *b* – from the array M_3, obtained as a result of statistical processing

This circumstance once again emphasizes the effectiveness of the procedure used to form arrays of homogeneous data, under conditions of a priori limitation of the measurement information. From Table 3 it is also clear that for all arrays without exception, obtained as a result of statistical processing, the observed values of the F-test do not exceed the tabulated ones, at a significance level of $p=0.95$ and the number of degrees of freedom $(m-1)$ and $m(n-1)$. This indicates that there is no difference between the average values of the indicators from the various bushings that make up the data arrays being analyzed.

The performed analysis of the composition of arrays with homogeneous values of the indicators made it possible to establish that the values of indicators of bushings from different regions of Ukraine, of different types and manufactured according to different numbers of factory drawings, fell into homogeneous data arrays. But in this case, the value of the indices, which make up homogeneous data arrays, have a close working time, and are installed on transformers with a close value of the load factors. This circumstance shows the necessity to take into account these factors when diagnosing the state of high-voltage oil-filled bushings.

6.2. Investigation of the distribution laws for the insulation of serviceable high-voltage bushings. The construction of histograms of the empirical distribution, the estimation of the parameters of the 18 known distribution laws, the calculation of the values of the agreement criteria (Pearson's χ^2 and the Kolmogorov-Smirnov test) were carried out with the help of the author's program «ZR» [26].

Based on the results of the analysis carried out with the help of the «ZR» program, it was possible to establish that the distribution of the insulation indices of serviceable high-voltage oil-filled bushings, both hermetic and non-hermetic, can be described by the Weibull distribution law, with density:

$$p(x;\alpha,\beta)=\frac{\beta}{\alpha^{\beta}}\cdot x^{\beta-1}\cdot e^{-\left(\frac{x}{\alpha}\right)^{\beta}}, \tag{5}$$

where α, β – the parameters of the distribution law, interpreted, respectively, as a scale parameter and shape parameter.

The values of the scale and shape parameters for the Weibull distribution law were determined from the expressions:

$$\beta=\frac{N-1}{N}\cdot\left(0.465\cdot\frac{\sqrt{D}}{M}+1.282\cdot\frac{M}{\sqrt{D}}-0.7\right), \tag{6}$$

$$\alpha=\frac{M}{1-0.427\cdot(\beta-1)\cdot\beta^{-1.9}}, \tag{7}$$

where N – the volume of sample values; M – values of the sample mean; D – the value of the sample variance.

The values of the distribution parameters α and β, the agreement criteria χ^2 and the Kolmogorov-Smirnov criterion are given in Table 4.

Table 4

The values of the parameters of the Weibull distribution law, as well as the calculated and critical values (at $\alpha=0.05$) of the Pearson and Kolmogorov-Smirnov criteria for homogeneous arrays of indicators of serviceable bushings

Indicator	Array	Parameters of the distribution law		Value of the Pearson test			Value of the Kolmogorov-Smirnov test	
		α	β	f	$\chi^2_{calc.}$	$\chi^2_{cr.}$	$\lambda_{calc.}$	$\lambda_{cr.}$
Bushing of non-hermetic execution								
tgδ1	M_1	0.563209	2.413753	2	0.488	5.990	0.213	1.360
	M_2	0.415860	3.093468	3	0.939	7.820	0.174	1.360
tgδ2	M_1	0.699454	1.923409	2	1.421	5.990	0.451	1.360
	M_2	1.069031	2.019215	2	1.012	5.990	0.361	1.360
C_1	M_1	464.4127	1.653419	3	2.677	7.820	0.406	1.360
C_2	M_1	435.3072	1.992624	3	1.350	7.820	0.268	1.360
Bushing of hermetic execution								
tgδ1	M_1	0.424122	5.414246	2	2.933	5.990	0.588	1.360
	M_2	0.530256	4.008926	4	4.396	9.490	0.604	1.360
	M_3	0.973090	2.073233	4	1.351	9.490	0.277	1.360
tgδ2	M_1	0.462615	5.837836	2	4.878	5.990	0.692	1.360
	M_2	0.535515	6.670923	2	2.539	5.990	0.644	1.360
	M_3	0.939447	2.222901	4	4.949	9.490	0.445	1.360
C_1	M_1	350.8528	1.725618	4	3.848	9.490	0.503	1.360
	M_2	353.7525	1.737734	5	3.933	11.100	0.450	1.360
	M_3	357.5067	3.395118	2	3.546	5.990	0.603	1.360
C_2	M_1	324.9421	1.708024	2	4.693	5.990	0.774	1.360
	M_2	384.5258	1.924692	3	5.862	7.820	0.860	1.360
	M_3	572.7063	3.297039	4	3.002	9.490	0.452	1.360

As can be seen from Table 4, for all data arrays, the calculated values of Pearson's agreement test and the Kolmogorov-Smirnov test do not exceed the critical points. On the basis of this, it can be concluded that there is no reason to reject the hypothesis that the Weibull distribution law is acceptable.

Empirical distribution histograms and Weibull distribution density functions for the tangent of the dielectric loss angle of the measuring capacitor insulation in serviceable hermetic 110 kV bushings are shown in Fig. 4.

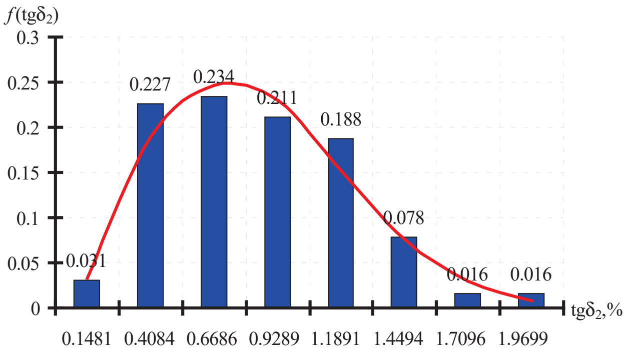


Fig. 4. The histogram of the empirical distribution and the distribution function of the Weibull law of the tangent of the dielectric loss angle of the measuring capacitor insulation in serviceable hermetic 110 kV bushings for the M_3 data array

6.3. Investigation of the distribution laws of insulation indicators of defective high-voltage bushings. For the formation of data sets of indicators of the state of defective high-voltage bushings, from three bushings, in which defects of different types were detected, three values for each index were selected. The first value corresponded to the value of the indicator just before it exceeded the maximum allowable value, according to [29], the second one – to the first value of the indicator, exceeding the maximum permissible, the third – to the last value before the output of the bushing for repair.

The arrays thus formed contain non-uniform values of the indicators, and the use of the above statistical processing procedure for the received arrays is ineffective, since each bushing is represented by only three values. To reduce the heterogeneity of the data, an approach based on the allocation of gross misses from among similar measurements was used.

Taking into account that the form of the distribution law is not known, Irwin's criterion was used to distinguish gross blunders [30]. To do this, for each relationship, for each bushing a variational series was constructed, and questionable values were estimated at one or both edges of the row. For this, the calculated value of the Irwin criterion was calculated:

$$I_{calc}=\frac{\left(x_k-x_{k\,pr}\right)}{S}, \qquad (8)$$

where x_k – a suspicious value; $x_{k\,pr}$ – the previous value in the variation series; S – the sample standard deviation (SD), calculated from the sample under consideration, taking into account the doubtful value.

The calculated value of the Irwin test was compared with the tabulated η_{tab}. If $\eta_{calc} \gg \eta_{tab}$, then the considered value was discarded and the following was checked. Statistical characteristics of arrays of indicators for defective bushings are given in Table 5.

Table 5

Statistical characteristics of homogeneous arrays of insulation condition indicators for defective bushings

Indicator	N	M_x	D_x	j_a	j_e
$\mathrm{tg}\delta_1$	100	2.858	0.650	–0.602	3.112
$\mathrm{tg}\delta_2$	108	2.307	0.645	0.033	2.586
C_1	128	239.735	10818.669	0.522	2.457
C_2	106	567.954	20538.449	0.512	2.689

As can be seen from Table 5, the use of Irvine criterion almost doubled the volume of sample values. At the same time, the statistical characteristics of the arrays of indicators for defective bushings practically do not differ from similar indicators for serviceable bushings, with the exception of sample means.

The performed analysis shows that the insulation indices for defective bushings as well as for serviceable bushings can be described by the Weibull distribution. The values of the parameters α, β of the Weibull distribution law, as well as the calculated $\chi^2_{calc.}$, $\lambda_{calc.}$ and the critical values $\chi^2_{cr.}$, $\lambda_{cr.}$ (for $\alpha=0.05$) of the Pearson and Kolmogorov-Smirnov criteria for the analyzed parameters are given in Table 6.

Table 6

The values of the parameters of the Weibull distribution law, as well as the calculated and critical values (at $\alpha=0.05$) of the Pearson and Kolmogorov-Smirnov criteria for insulation state indices in defective bushings

Indicator	Parameters of the distribution law		Value of the Pearson test			Value of the Kolmogorov-Smirnov test	
	α	β	f	$\chi^2_{calc.}$	$\chi^2_{cr.}$	$\lambda_{calc.}$	$\lambda_{cr.}$
$\mathrm{tg}\delta_1$	3.150824	3.933431	3	3.128	7.820	0.598	1.360
$\mathrm{tg}\delta_2$	2.575944	3.113934	3	0.248	7.820	0.150	1.360
C_1	270.257889	2.437388	5	3.578	11.100	0.326	1.360
C_2	621.601752	4.455534	3	4.493	7.820	0.715	1.360

As can be seen from Table 6, for all data sets, the calculated values of the Pearson's agreement test and the Kolmogorov-Smirnov test do not exceed critical values. On the basis of this, it can be concluded that there is no reason to reject the hypothesis that the Weibull distribution law is acceptable.

6.4. Analysis of the obtained data. Analyzing the mutual arrangement of theoretical density distributions of insulation parameters for serviceable and defective bushings of one voltage class and one execution, which are shown in Fig. 5, a number of important conclusions can be drawn:

1) the values of the mathematical expectation for different arrays of the same indicator are shifted relative to each other. This indicates a different degree of aging of the insulation of high-voltage bushings in real operation, due to the different loading of transformers with bushing data and different operating times;

2) by analyzing the relative arrangement of the distribution densities for the serviceable bushings of a hermetic and non-hermetic execution, it should be noted that the distribution data is also displaced relative to each other. This indicates a significant effect of the oil protection type of high-voltage oil-filled bushings on the values of the main insulation;

3) the distribution densities for the faulty and working state of the high-voltage bushings intersect, and, consequently, it is impossible to select the maximum permissible values of insulation parameters that would not give erroneous solutions.

It is obvious that the maximum permissible values of insulation indicators of high-voltage oil-filled bushings should be determined using statistical methods and taking into account the most significant operational factors. It is known that the conditional costs of the probability of error of the first kind (a decision is made about the presence of a defect in an efficient bushing) will be much lower than the conditional cost of the probability of a second-kind error (a decision is taken on the defective state of defective bushing).

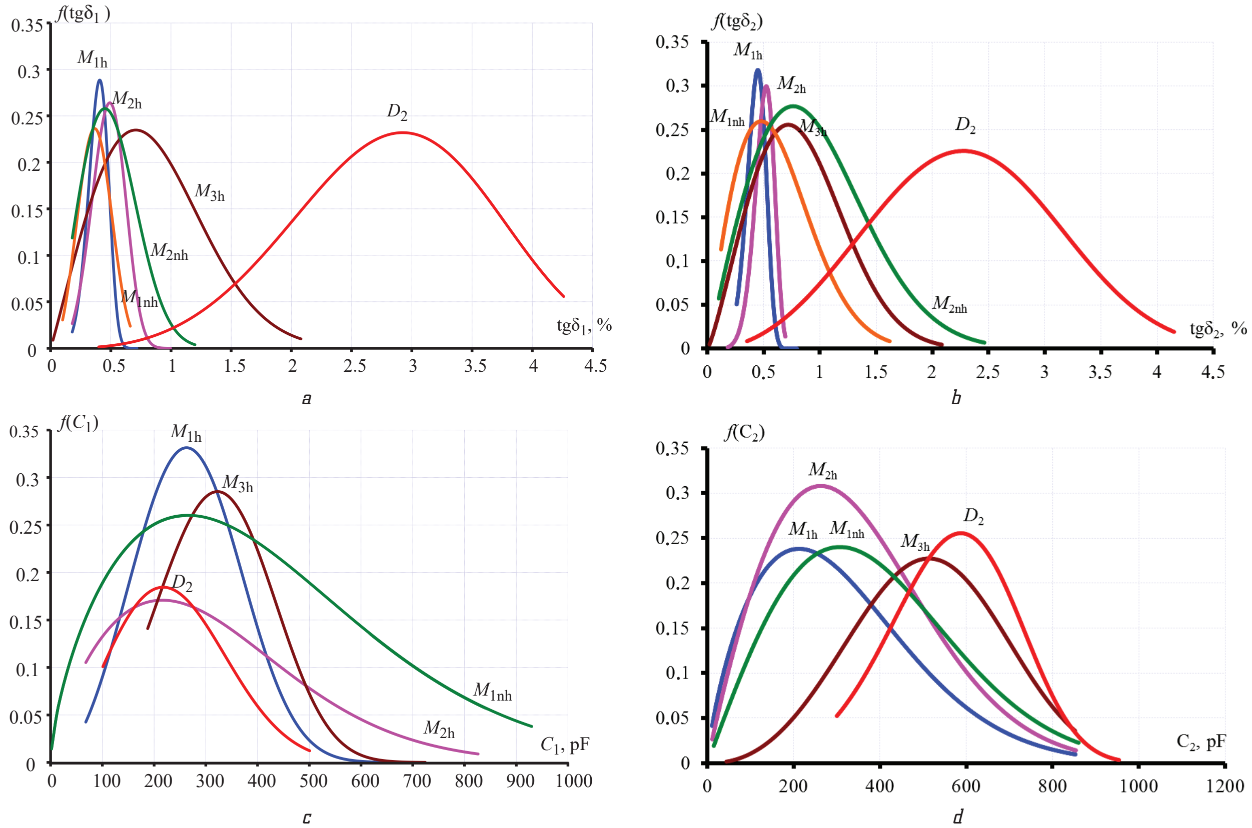
Therefore, to determine the maximum permissible values of indicators, it is reasonable to use the minimum risk method.

7. SWOT analysis of research results

Strengths. The use of the results obtained in the work allows, first of all, to improve the operational reliability of high-voltage oil-filled bushings, due to more accurate and correct determination of the maximum permissible values of the indicators, using the obtained distribution laws. Improving the reliability of bushings will reduce the costs of repairing and restoring both the bushings themselves and the equipment on which they are installed, as well as reducing the economic damage to energy companies caused by under-supply of electrical energy. Despite the sufficient number of publications devoted to the problem of improving the methods for monitoring and diagnosing the state of high-voltage bushings, the approach proposed in the work has not been implemented to date and has not been described in any of the open literature sources.

Weaknesses. Increase the labor and time costs of personnel of electric power companies in diagnosing the state of bushings, which are caused by the need to independently determine the maximum permissible values of indicators.

Opportunities. The obtained results can be algorithmically realized as a separate module of the information-analytical system (IAS) for diagnosing the state of high-voltage oil-filled equipment.



a *b*

c *d*

Fig. 5. Densities of theoretical distributions of insulation parameters of serviceable hermetic (M_{1h}, M_{2h}, M_{3h}), serviceable non-hermetic ($M1_{nh}$, $M2_{nh}$, $M3_{nh}$), and defective (D_2) bushings: *a* – for the dielectric loss tangent of the main insulation; *b* – for the tangent of the dielectric loss angle of the measuring capacitor; *c* – for the main insulation capacity; *d* – for the capacitance of the measuring capacitor

Threats. The introduction of the IAS is connected both with the material costs of the energy companies needed to purchase, install and adapt the product, and with the costs of personnel training.

8. Conclusions

1. A three-stage algorithm for statistical processing of the results of operational tests of high-voltage bushings is proposed. Formation of arrays with homogeneous values of diagnostic criteria is carried out under condition of similarity of distribution laws, equality of mathematical expectations and variances of individual samples obtained for different bushings. To verify the homogeneity of data in the resulting arrays, a one-way analysis of variance is used. The practical use of this algorithm has made it possible to substantially reduce the heterogeneity of the results of periodic tests of the insulation state of high-voltage bushings. For example, the original array M_0 for the dielectric loss tangent of the main insulation (M_0) of non-hermetic bushings has the F-test values: $F_{ob}=23.47$ and $F_{cr}=1.608$. For the formed homogeneous arrays, the F-test values are: M_1 – $F_{ob}=1.716$, and $F_{cr}=2.105$, for M_2 – $F_{ob}=1.287$, and $F_{cr}=2.036$.

2. The performed analysis of the laws of distribution of insulation indicators, both in serviceable and defective bushings of hermetic and non-hermetic execution, made it possible to establish that all the studied parameters: the tangent of the dielectric loss angle of the main insulation ($\mathrm{tg}\delta_1$) and the measuring capacitor ($\mathrm{tg}\delta_2$), the capacitance of the main insulation (C_1) of the measuring capacitor (C_2) can be described by the Weibull distribution law.

3. Based on the values of the scale and shape factors for the distribution of insulation indices in serviceable and defective high-voltage bushings, an analysis is made of the joint location of the theoretical densities of the distribution of the bushing indices with different states. The analysis shows that the values of the mathematical expectation for different arrays of the same indicator are biased relative to each other. This indicates the need to take into account the load of the transformers and the life of the bushings when determining the maximum permissible values of the indicators.

4. The distribution densities for serviceable and defective state of high-voltage bushings intersect, and, consequently, it is impossible to select the maximum permissible values of insulation parameters that would not give erroneous solutions. The maximum permissible values of insulation indicators for high-voltage oil-filled bushings should be determined using statistical methods and taking into account the most significant operational factors.

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INFLUENCE OF EXTERNAL FACTORS ON THE PROCESS OF HYDRATES DEVELOPMENT IN LABORATORY CONDITIONS

Об'єктом досліджень є вплив різноманітних факторів на процес синтезу гідрату пропану у лабораторних умовах. Відомо, що синтезований газовий гідрат може містити значну кількість льоду, яка знижує його газовміст. На якість гідрату впливають: тиск газу, температура води, час проведення досліду та концентрація поверхнево-активних речовин.

Для дослідження комплексного впливу цих факторів на якість отриманого гідрату була розроблена експериментальна установка. Після синтезу газового гідрату його газовміст визначався за допомогою спеціально розробленого стенду. В ході досліджень використовувалися різноманітні вимірювальні прилади: манометри, термометри, мірний посуд, електронні ваги та ін., які дозволили отримати достовірну інформацію про теплофізичні характеристики процесу синтезу та дисоціації газового гідрату.

В результаті виконання багатофакторного експерименту отримано масив даних для аналізу методами математичної статистики. Визначено коефіцієнти кореляції і встановлено, що домінуючими факторами є тиск газу і концентрація поверхнево-активних речовин. Температура води повинна бути в межах робочого діапазону 1–5 °C. Час утворення гідрату у барботажному режимі у межах 0,5–5 год теж не здійснює істотного впливу на якість отриманого гідрату. Для усіх факторів побудовано регресійні залежності та графіки. Встановлено, що для стандартних регресійних залежностей (лінійна, експоненційна, логарифмічна та поліноміальна) коефіцієнти множинної кореляції знаходяться в межах 0,19–0,46. Це означає, що стандартні регресійні залежності не дозволяють урахувати усі особливості отриманих результатів. Тому підбір оптимальної залежності виконано методом варіації коефіцієнтів та типів функціональних залежностей і отримано апроксимаційну формулу для визначення прогнозованого газовмісту гідрату.

Результати досліджень показали, що завдяки комплексному урахуванню різних факторів можна визначити діапазон оптимальних значень тиску, температури та концентрації поверхнево-активних речовин, що дозволяє швидко отримувати гідрат високої якості.

Ключові слова: *газові гідрати, газовміст гідрату, зовнішні фактори, статистичний аналіз.*

1. Introduction

Gas hydrates are the only non-cryogenic source of natural gas on Earth, which can constitute a real competition to traditional deposits. Significant potential gas resources in hydrate deposits for a long time will provide humanity with high-quality energy raw materials.

The development of gas hydrate deposits requires the development of new technologies for exploration, production, transportation and storage of gas, more efficient than existing ones. With their help, traditional gas fields can be used, as well as those which development is now unprofitable. Extraction of gas from hydrate deposits can very quickly change the situation in the gas market, which can affect the export opportunities of Ukraine.

Due to the thermodynamic properties of gas hydrates, the possibility to realize the processes of their formation and decomposition for relatively low pressures and temperatures makes it possible to perform a number of technological processes with greater efficiency than existing