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ПРИЛАДОБУДУВАННЯ ТА ІНФОРМАЦІЙНО-ВИМІРЮВАЛЬНІ СИСТЕМИ

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FEATURES OF STATISTICAL DATA PROCESSING AT INSULATION TESTING OF ENAMELED ELECTRIC WIRES

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Abstract. *The necessity of checking of variation series of voltage by insulation breakdown of enameled wire for the sharply differing values from statistical laws is substantiated. The need for additional research of causes of abnormal values of voltage breakdown of enameled wires insulation within standard testing methods is established. The methodology of enameled wire insulation testing by high voltage to evaluate the degree of their defectiveness using methods of statistical analysis is developed. The advantage of statistical modeling in the study of enameled coating directly in the locations of indulgence and insulation defects is proved.*

Key words: *enameled wire, high voltage tests, insulation defects, statistical methods*.

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Problem setting. Requirements for enameled wires used to manufacture winding elements of electrical devices, envisage (2 ... 3) – time breakdown voltage exceeding of lacquer layer of wire insulation, measured using a standard method of double wire «twist» samples according to IEC 60317-0-1 (GOST 14340.7-74), above standard value, which is considered a reasonable level of quality assurance of the winding technological process [1].

However, conducted control tests on winding elements after their winding process prove that the given excess does not always guarantee their quality. Moreover, testing has also revealed that the above stock voltage breakdown mostly does not exist due to peculiarities of the breakdown in the discharge gap of the standard sample.

This disadvantage of standard methodology is due to the fact that the breakdown of insulation is conducted under the scheme «dielectric – air – dielectric». The same occurs to the dielectric where there is insulation derogation and some defects.

The presence of the air layer in the discharge gap significantly alters the largest voltage breakdown of lacquer layer of enameled wire and causes it considerable variation, «masking» thus the real state of insulation, especially in its minimum voltage breakdown in the controlled samples [2].

Therefore, the standard method of determining the breakdown voltage insulation of enameled wire can be considered only as determining one with low information content of its defectiveness.

However, extreme values of the insulation voltage breakdown variations series from enameled wire sample the statistical test results in the recommended literature are often contradictory. Thus, the standard method of testing insulation using samples such as double

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wire «twist» allows rejection lowest from the five values of breakdown voltage insulation without appropriate regulation. The majority of special regulations (e.g. ISO GOST 5725-2:2005), including developed standards instead of outdated ones, recommend the researcher to reject and do not take into account the «problem» results of measurements that disturb statistical regularity of variation members.

The basis of the recommendations constitutes the techniques of the well-known researcher of statistical series Grubbs, in which a number of variations can be used to detect the minimum (maximum) anomalous values or both [3]. B. Lemeshko's recommendations are a further development of Grubbs' methods on the allocation of the normal number of variations of several anomalous minimum or maximum values in their various combinations [4]. Thus the presence of such values inevitably affects the measurement of dispersion and other studied characteristics of scattering value. Therefore, using Grubbs' criteria it is necessary to test statistical sample, consistently increasing the amount of the potential anomalous values.

More closer to reality are such researchers as M. Shcherbakov, A. Orlov, who cast doubt on the allegations of a comprehensive broad applicability of normal distribution and recommend a cautious attitude as to remove *measurements* that sharply differ, for safety reasons underlying statistical analysis and so as to the *allocation* of the special values in the statistics that may indicate the presence of new physical effect [5].

The purpose of the work is to suggest, using metrological analysis, new approaches to consideration of abnormal values in statistical research samples of electric strength of enameled wires insulation for a more adequate assessment and mathematical description of its defectiveness.

Material and methodology of the research. The study involved the most common for the winding elements of electrical machines and apparatus enameled wires of the following makrs PET – 155 TU U 31.3-20006134-015:2004, PET–155 GOST 21428-75, PETD – 200 TU U 31.3-20006134-014:2004, PETD2 – 200 TU U 13970259.001-97 and PEEIDKH2 – 200 TU U 31.3-0021534.035:2005 of nominal diameters from 0.18 to 1.50 mm.

The program includes the following studies of enameled wires insulation:

- establishing of normality of dispersion values of voltage breakdown of air gaps between weakened spots or defective insulation ones;
- metrological research of the breakdown voltage abnormal values;
- definition and mathematical description of the spread of values of real electric strength of weakened spot of insulation defect locations during testing its electric strength.

To implement the program the following research methods are used:

- breakdown voltage insulation of the investigated enameled wire is determined using standard double wire «twists» according to the methods IEC 60317-0-1 (GOST 14340.7-74). Processing of the received measurements for determining the metrological characteristics of the distributions of voltage breakdown is done with GOST ISO 5725-2:2005 method;
- dielectric strength of the lacquer insulation layer in defects spots is determined by «continuous contact» according to [6].

Research results. For research the impact of technological and structural factors during manufacture of winding elements of various structural dimensions on the lacquer layer of enameled wire insulation, they are unwind without insulation damage and the electric strength along the element is determined.

Sample of the groups controlled by electric vehicles (semi-finished) are tested. Their winding elements are made, for example, from enameled wire mark PET–155-0.56 TU U 31.3-20006134-015:2004 as rectangular products with combined folding frame and aspect ratio (2.0 ... 2.5): 1 with 900 convolutions and their winding speed is about 1600 turns / min.$^{-1}$ on one and the same winding machine.

The breakdown of voltage variation row with this sampling $n_1 = 10$ units of standard samples for insulation breakdown by «twists» method have ~ (2 ... 3) – time exceeding electric strength of insulation (standard one is at least 4600*V*), namely *kV*: 8.2; 10.4; 10.4; 10.6; 10.8; 10.8; 11.0; 11.0; 11.2; 11.6, as well as statistical series options: voltage average value $\bar{U}_{n_1} = 10{,}6\,kV$, standard deviation $S_{n_1} = 0{,}92\,kV$.

As the statistical characteristics of random variables of insulation breakdown voltage *u* of controlled winding elements enameled wires are unknown, the results evaluation is conducted to test abnormality with Grubbs' methods according to [7, Table 5]. Namely, for the value of bilateral probability of a random variable *u* in the interval (u_{min} ... u_{max}) $\gamma = 0.95$ or appropriate level of significance $\alpha = 0.05$ the coefficient $\beta_1 = 2.29$ at n_1=10 units of samples. Since the coefficient of variation x_{1_i} of the sample extreme values (8.2 *kV* and 11.6 *kV*) is:

$$x_{1_1} = \frac{U_1 - \bar{U}_{n_1}}{S_{n_1}};\ x_{1_1} = 2{,}61 \geq 2{,}29 \text{ and } x_{1_{10}} = \frac{U_{10} - \bar{U}_{n_1}}{S_{n_1}};\ x_{1_{10}} = 1{,}09\,, \tag{1}$$

then the value $U_1 = 8{,}2\ kV$ is abnormal and should be excluded from the sample results as a gross mistake and whose probability is less than the significance level *α*.

However, this output cannot satisfy the researcher due to its uncertainty of the result [5]. To clarify the statistical characteristics of insulation breakdown voltage from the other winding element of the same products groups a sample form with double units, where n_2=20 units, are formed and tested with the number of standard samples («twists») variation range of which has the following values, *kV*: 5.6; 7.4; 9.2; 9.6; 9.6; 10.0; 10.2; 10.4; 10.4; 10.6; 10.8; 10.8; 10.8; 11.0; 11.0; 11.2; 11.2; 11.4; 11.4, 12.2 and statistical characteristics: $\bar{U}_{n_2} = 10.24\ kV$, $S_{n_2} = 1.49\ kV$.

Abnormality verification suggests the following values of spread coefficient x_{2_i}: $x_{2_1} = 3.11$; $x_{2_2} = 1.91$; $x_{2_{20}} = 1.32$, when $\alpha = 0.05$ and the corresponding coefficient $\beta_2 = 2.709$ [7, Table 5] again indicates abnormality of the smallest breakdown voltage value $U_1 = 5.6\ kV$. Thus, the second minimum result $U_2 = 7.4\ kV$ has a spread coefficient of $x_{2_2} = 1{,}91$ is less than the coefficient β_2 and, therefore, belongs to the normal voltage distribution of breakdown insulation *u*, although the absolute value is less than the abnormal value $U_1 = 8.2$ *kV* in the first sample.

Since both samples with their mutual overlapping of their confidence intervals of random variable insulation change of voltage breakdown, it is necessary to define their homogeneity. In order to do this, we take into account «problem» results in both samples, the value offset of their average values is estimated using Student's *t*-criterion [8] according to the expression (2):

$$t = \frac{\left|\bar{U}_{n_1} - \bar{U}_{n_2}\right|}{\sqrt{\frac{n_1 + n_2}{n_1 \cdot n_2} \cdot \frac{n_1 \cdot (n_1 - 1) \cdot S_{n_1}^2 + n_2 \cdot (n_2 - 1) \cdot S_{n_2}^2}{n_1 + n_2 - 2}}}; \tag{2}$$

$$t = 0.162.$$

With the value of bilateral probability of a random variable *u* in the interval ($\mathrm{u}_{\mathrm{min}}$ ... $\mathrm{u}_{\mathrm{max}}$) γ = 0.95 and the number of degrees of freedom $k = n_1 + n_2 - 2$; *k* = 28, according to [8] confidence factor is $t_\gamma = t_{0,95} = 2{,}048 \ge t$. Thus, according to this criterion of compatibility sample medium $\bar{U}_{n_1}$ and $\bar{U}_{n_2}$ are differ insignificantly and samples can be considered as being derived from a general summation of the random variable *u*.

The results of some research [9] may question the latter conclusion, arguing that the *t*-criterion only allows to test the hypothesis of equality of mathematical expectations considering the limited volume samples (at least two orders of magnitude). Instead of Students' criteria to test homogeneity Cramer – Welch's *T*-criterion is proposed to use being based on such statistics (3) which adapted for these studies:

$$T = \frac{\sqrt{n_1 \cdot n_2} \cdot \left(\bar{U}_{n_1} - \bar{U}_{n_2}\right)}{\sqrt{n_2 \cdot S_{n_1}^2 + n_1 \cdot S_{n_2}^2}}. \tag{3}$$

There follows a decision based on asymptotic normality of *T*-statistics: if $|T| \le u_{1-\frac{\alpha}{2}}$, where $u_{1-\frac{\alpha}{2}} = u_p$, – quantile of normal distribution with probability *p* (in this case – the critical value for significance level *α*), then the hypothesis of homogeneity (equality) mathematical expectations is taken at significance level *α*. This means that investigating the statistical characteristics of both samples (including their anomalous values) with probability γ = 0.95 from equation (3) a disparity is received which confirms this hypothesis: $|T| = 0{,}814 \le u_{0{,}975} = 1{,}96$.

Admissibility of average-deviation spread is checked using Fisher's *F*-criterion [10] according to (4) with regard to anomalous values of breakdown voltage and inequality $S_{n_2} \ge S_{n_1}$:

$$\frac{1}{F_{1-\gamma}\left(f_1;\, f_2\right)} \le F = \frac{S_{n_2}^2}{S_{n_1}^2} \le F_\gamma\left(f_2;\, f_1\right), \tag{4}$$

where for value *γ* = 0.95 with the numbers of freedom degrees $f_1 = n_1 - 1$; $f_1 = 9$ and $f_2 = n_2 - 1$; $f_2 = 19$ formed by the expression (4) inequality [7] $0{,}396 \le 2{,}623 \le 2{,}908$ indicates equal accuracy of the conducted measurements of enameled wire insulation voltage breakdown of both samples according to standard «twists» method. The measurements themselves are devoid of systematic error.

Finally, as both samples contain some anomalous values and are homogeneous, it can be suggested that understated abnormal voltages have some information about technological and constructive factors. These ones act on the enameled wire insulation in the process of winding elements formation whose essence is not disclosed by this standard method of testing. Their movement beyond confidence intervals of values of the random variable indicates a slight deviation from the normal distribution of the insulation breakdown voltage.

Rank nonparametric Wilcoxon's *T*-criterion is applied to prove deviation from the normal law of insulation voltage breakdown values in both samples and homogeneity of the results. According to this criterion [9] two samples of experimental data: $x_1, x_2, \ldots x_{n_1}$ and $y_1, y_2, \ldots y_{n_2}$ $\left(n_2 \ge n_1 \ge 5\right)$ are considered as relatively homogeneous comparing to their average arithmetic, if the calculated value of the sum $W = \sum_{i=1}^{n_1} R_i$ satisfies the condition:

$$|T| = \frac{W - M(W)}{\sqrt{D(W)}} \le u_{1-\frac{\alpha}{2}} \tag{5}$$

where R_i – elements ranks x_i-y_i in both samples, equal to their numbers (1, 2, ... 30) in the ranking table according to the variational series of insulation voltage breakdown [8];

$M(W) = \frac{n_1 \cdot (n_1 + n_2 + 1)}{2}$ – mathematical expectation of the rank sum *W*;

$D(W) = \frac{n_1 \cdot n_2 \cdot (n_1 + n_2 + 1)}{12}$ – variance of the rank sum *W*;

$u_{1-\frac{\alpha}{2}} = u_{0,975} = 1{,}96$ – quantile of normal distribution (see (3)).

The following components of Wilcoxon's *T*-criterion are received as a result of compiling rank table and the corresponding calculations: *W* = 168.5 ≈ 169; *M(W)* = 155; *D(W)* ≈ 517.

Since in the process of ranking revealed some spots of interconnectedness of both variational series, variance *D (W)* is adjusted by the factor k_W according to the expression (6):

$$k_W = 1 - \frac{\sum_{i=1}^{l} t_i \cdot (t_i^2 - 1)}{(n_1 + n_2) \cdot (n_1 + n_2 - 1) \cdot (n_1 + n_2 + 1)}; \tag{6}$$

$$k_W = 1 - 0{,}01 = 0.99,$$

where t_i – size *l* connection, which includes ranks in both samples. According to the ranking table one can received: $t_1 = 4$; $t_2 = 2$; $t_3 = 5$; $t_4 = 4$; $t_5 = 3$.

Thus, according to (5) and (6) obtained inequality $T = 0{,}62 \le 1{,}96$ indicates the validity of the null hypothesis about homogeneity of the two sample distributions of enameled wire insulation breakdown voltage which differs from the normal law.

To eliminate uncertainty about abnormal voltage values by insulation breakdown there has been developed a special technique to diagnose enameled wires. Given method allows increasing accuracy and informative contents of test results compared to the standard ones. In addition, it provides opportunity to bind defects to the technological level during manufacturing winding items of electrical equipment, and the homogeneity of lacquer layer of enameled wire in the initial state. The methodology has been verified by numerous tests and based on the patent use [6]. As a result of the experiment a statistical number of discrete values of minimum quantities of insulation voltage breakdown in its most heterogeneous, clearly weakened or defected locations, normalized to a unit of length of enameled wire is obtained.

The most effective mathematical laws for modeling distributions of breakdown voltage insulation of enameled wire, taking into account their existing asymmetry and kurtosis are derived from normal distribution convergent Gram-Charlier's statistical series, which is described using the density distribution function $f_S(x)$ by equation [10]:

$$f_S(x) = \varphi(x) - \frac{S_k}{6} \cdot \varphi^{III}(x) + \frac{\varepsilon}{24} \cdot \varphi^{IV}(x), \tag{7}$$

where $\varphi(x)$ – density of the standard normal distribution; $\varphi^{III}(x)$, $\varphi^{IV}(x)$ – 3rd and 4th derivatives order of the function $\varphi(x)$; S_k, ε – asymmetry and kurtosis of investigational distribution.

The method of «continuous contact» according to [6] is used to test given above enameled wires in course of the research program. Synthesized result is shown below in the following example of the same make of enameled wire mark PET–155–0.56 TU U 31.3-20006134-015: 2004 mounted from winding element of the investigated group using the methodology in [11].

The distribution of voltage by insulation breakdown N_1 = 34 units of samples along array of winding element and N_2 = 16 units at the beginning of winding in their intervals ΔU are given in Table 1, where the number of intervals in accordance with Sturges' rules r = 7; n_U – interval number of samples; h – value of interval voltage change, kV.

Table № 1.
The distributions of enameled wire insulation breakdown voltage PET – 155 – 0.56

ΔU_1, кV	[1.54 ... 2.24)	[2.24 … 2.94)	[2.94 … 3.64)	[3.64 … 4.34)	[4.34 … 5.04)	[5.04 … 5.74	[5.74 … 6.40)
n_{U1}	1	3	10	8	7	3	2
ΔU_2, кV	[0.46 ... 0.60)	[0.60 … 0.74)	[0.74 … 0.88)	[0.88 … 1.02)	[1.02 … 1.16)	[1.16 … 1.30	[1.30 … 1.44)
n_{U2}	2	4	4	2	2	1	1

As a result of these calculations the following statistical characteristics of insulation breakdown voltage are obtained:

- mathematical expectation $M_1(U)$ = 3.99 кV; $M_2(U)$ = 0.86 кV;
- mode $\mathcal{M}_1 \approx 3.29$ кВ $< M_1(U)$; $\mathcal{M}_2 \approx 0.76$ кВ $< M_2(U)$;
- standard deviation $\sigma_1(U)$ = 1.01 кV; $\sigma_2(U)$ = 0.24 кV;
- asymmetry $S_{k1} = +0.24 \geq 0$; $S_{k2} = +0.60 \geq 0$;
- kurtosis $\varepsilon_1 = -0.60 \leq 0$; $\varepsilon_2 = -0.50 \leq 0$.

Given the existing asymmetry, it is assumed that the distribution of insulation breakdown voltage is mathematically described by Gram-Charlier's statistics (7) with the computed coefficients S_k, and ε and relative frequency w_s (8):

$$w_S = \frac{h}{\sigma(U)} \cdot \frac{1}{\sqrt{2\cdot\pi}} \cdot e^{-\frac{y^2}{2}} \cdot \left\{1 + \frac{S_k}{6} \cdot y \cdot \left(y^2 - 3\right) - \frac{\varepsilon}{24} \cdot \left[y^2 \cdot \left(y^2 - 6\right) + 3\right]\right\}. \qquad (8)$$

Then the relative frequencies distributions of insulation breakdown voltage of enameled wire along winding element and at the beginning winding according to the simulation results can be presented by the following expressions, respectively:

$$w_{S_1} = \frac{0.70}{1.01} \cdot \frac{1}{\sqrt{2\cdot\pi}} \cdot e^{-\frac{y_1^2}{2}} \cdot \left\{1 + 0.039 \cdot y_1 \cdot \left(y_1^2 - 3\right) - 0.025 \cdot \left[y_1^2 \cdot \left(y_1^2 - 6\right) + 3\right]\right\};\ y_1 = \frac{U - 3.99}{1.01};$$

$$w_{S_2} = \frac{0.14}{0.24} \cdot \frac{1}{\sqrt{2\cdot\pi}} \cdot e^{-\frac{y_2^2}{2}} \cdot \left\{1 + 0.1 \cdot y_2 \cdot \left(y_2^2 - 3\right) - 0.021 \cdot \left[y_2^2 \cdot \left(y_2^2 - 6\right) + 3\right]\right\};\ y_2 = \frac{U - 0.86}{0.24}.$$

Fig. 1 shows graph distribution functions of given voltage U by insulation breakdown of enameled wire mark PET-155-0.56, winded off from the winding element.

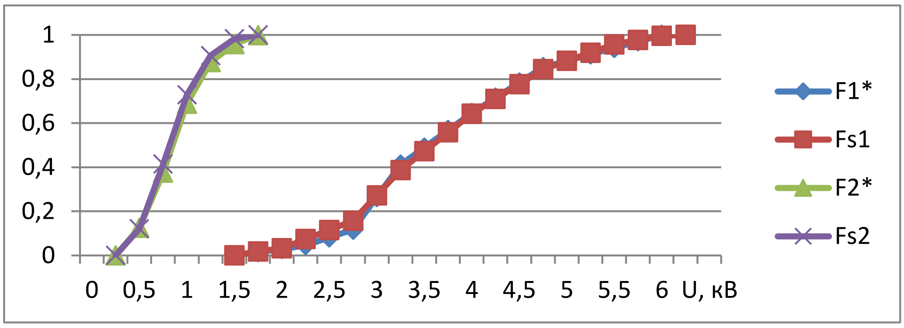

Figure 1. Graphs of distribution functions of insulation breakdown voltage:
*F1** – along winding element without beginning of the coiling; *Fs1* – is the same, according to the simulation results; *F2** – beginning of the coiling; *Fs2* – is the same, according to the simulation results.

To confirm the hypothesis of test precision modeling, namely Kolmogorov's parametric test (D – criterion), [10] is used. Having calculated the corresponding statistical distribution function *F*(x)* and theoretical (integral) distribution function *F(x)* parameter λ in this criterion is defined:

$$\lambda = D\cdot\sqrt{N}\ ;\ D = \max\left|F^{*}(U) - F(U)\right|, \tag{9}$$

where $D = 0.040$; $\lambda_1 = 0{,}23$; $\lambda_2 = 0.27$.

Then [10], the numerical value of probability $P(\lambda) = 1 - \sum\limits_{j=-\infty}^{+\infty}(-1)^j\cdot e^{-2\cdot j^2\cdot\lambda^2}$: $P_1(0.23) \approx 1.0$ and $P_2(0.27) \approx 1.0$ indicates the validity of the accepted hypotheses.

Since the threshold and nominal dielectric strength of insulation enameled wire mark PET-155-0.56 with diametrical insulation thickness of (0.052 ... 0.060) *mm* is respectively:

$$E_{1\,thresh}(0.1) = \frac{2\cdot(2.46\ldots2.52)}{0.052\ldots0.060} = (82\ldots96)\ kV\cdot mm^{-1} \geq 20\ kV\cdot mm^{-1}$$

and

$$E_{1\,nom}(0.75) = \frac{2\cdot(4.38\ldots4.42)}{0.052\ldots0.060} = (146\ldots170)\ kV\cdot mm^{-1} \geq 150\ kV\cdot mm^{-1},$$

then according to [6] investigated enameled wire along winding element should be attributed to the classification group: insulation with an average degree of defectiveness.

The same characteristics apply to coiling at the beginning, respectively:

$$E_{2\,thresh}(0.1) = \frac{2\cdot(0.46\ldots0.52)}{0.052\ldots0.060} = (16\ldots20)\ kV\,mm^{-1} \leq 20\ kV\cdot mm^{-1}$$

and

$$E_{2\,nom}(0.75) = \frac{2\cdot(0.88\ldots0.92)}{0.052\ldots0.060} = (30\ldots36)\ kV\cdot mm^{-1} \leq 100\ kV\cdot mm^{-1},$$

and therefore, according to [6] the researched enameled wire at the early stage of coiling of the winding element should be attributed to the classification group: insulation with a high degree of defectiveness. The most probable electrical insulation strength of this segment is:

$$E_2(0.50) = \frac{2 \cdot (0.72 \ldots 0.76)}{0.052 \ldots 0.060} = (24 \ldots 30)\ kV{\cdot}mm^{-1},$$

which is (5 ... 7) times less than electric insulation strength values of enameled wire along winding element.

Therefore, researches using methodologies [6] is found that at manufacturing of the winding elements party of electrical apparatus from the enameled wire mark PET-155-0.56 TU U 31.3-20006134-015:2004 its insulation at the beginning of winding as a result of intensive technological factors gets significant damage. However, these damages visualize in the tests using standard methodology only as implied «emission» of distribution statistical law.

It should be noted that a significant variation of enameled wire insulation breakdown voltage along the array of coiling element with obvious asymmetry towards small values indicates its heterogeneity, and increased breakdown probability due to the relative position of defective insulation spots at critically short distances within its thickness. During its exploitation the longitudinal defectiveness of insulation only increases, negatively acting on the operating time of winding element in electrical devices.

Conclusions. Insufficient informative contents of the widely used metrological procedures of objects research such as insulation electric strength of enameled wires using standard methods of their testing is detected.

The necessity of taking into account and additional research of abnormal test results without systematic errors, to improve the diagnosing efficiency of objects research is substantiated.

The proposed methodology is more accurate instrument for insulation research of the enameled wire. It enables improvement of information content of the existing standard methodologies, especially at presence in statistical samples minimal values of insulation breakdown voltage, which are substantiated by metrological procedures as abnormal.

The developed methodology enables to mathematically describe the breakdown voltage random variables distributions in weakened locations and insulation defects of enameled wires by using the derived from normal law Gram-Charlier's statistical series. The method makes it possible to create mathematical models that take into account the real insulation defectiveness both in the initial state of enameled wire and as a result traumatic actions of technological factors during manufacturing of electrical products with winding elements.

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ОСОБЛИВОСТІ ОБРОБЛЕННЯ СТАТИСТИЧНИХ ДАНИХ ПРИ ВИПРОБУВАННЯХ ІЗОЛЯЦІЇ ЕМАЛЬОВАНИХ ЕЛЕКТРИЧНИХ ПРОВОДІВ

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Резюме. *Обґрунтовано необхідність перевірки варіаційного ряду напруги пробою ізоляції емальованих проводів на наявність різко відмінних значень від виявленої статистичної закономірності. Встановлено необхідність додаткового дослідження причин появи аномальних значень напруги пробою ізоляції емальованих проводів при стандартних методиках випробувань. Розроблено методику випробувань ізоляції емальованих проводів підвищеною напругою для оцінювання ступеня їх дефектності методами статистичного аналізу. Доведено перевагу статистичного моделювання при дослідженні емальованого покриття безпосередньо у місцях розташування послаблень і дефектів ізоляції.*

Ключові слова: *емальований провід, випробування підвищеною напругою, дефектність ізоляції, статистичні методи.*

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