FEATURES OF THE ENAMELED WIRES INSULATION DIAGNOSING BY VOLTAGE

Oleksandr Vakulenko[1], Ivan Sysak[2], Serhii Babiuk[3] Bunko Vasyl[4]

[1]*Ternopil National Ivan Puluj Technical University, Rus'ka str. 56, 46001, Ternopil, Ukraine;*
vakol1811@gmail.com
[2]*Ternopil National Ivan Puluj Technical University, Rus'ka str. 56, 46001, Ternopil, Ukraine;*
sisak.tntu@gmail.com
[3]*Ternopil National Ivan Puluj Technical University, Rus'ka str. 56, 46001, Ternopil, Ukraine;* sermuk@gmail.com
[4] *Separated Subdivision of National University of Life and Environmental Sciences of Ukraine BEREZHANY AGROTECHNICAL INSTITUTE, Academichna st. 20, 47501, Berezhany, Ternopil region, Ukraine;*
VBunko@gmail.com

Abstract: It is established that the standard methods of the enameled wires insulation tests by voltage have low informativeness.The advantage of statistical modeling in the study of the enamel wires insulation defects is proved. The mathematical model of technological process influence of the electrical device coil element winding on the electrical strength of enameled wire insulation is presented.

Keywords: *Enameled wire, voltage insulation tests, insulation defects, statistical methods*

1. Introduction

Insulation of enameled wire during the manufacture of electrical appliances coiled elements is subject to intense technological factors. As a result, the varnish layer of the enameled wire insulation decreases in thickness, there are places with weakened insulation, as well as obvious defects. It is obvious that when testing the insulation of such a wire for electrical strength, a significant variation will be obtained: from the minimum values at the locations of obvious defects to the nominal values which inherent in the insulation of this type enamel wire.

It should be noted that currently there is no single methodologically sound approach to the method of determining the electrical strength of winding enameled wires insulation, which would allow to assess the actual state of insulation at both the point micro and macro level of uniaxially oriented long object. Here, various types of loads, including voltage, are applied to the enameled wire as an object of research, and different sample lengths are set. However, after conducting such tests, the researcher often does not receive an answer about the real state of the enamel wire insulation, about its reserve of electrical strength.

The problem of uncertainty is that the recognized methods of insulation tests to determine its main indicator - breakdown voltage: two-wires "twisting" of a specially wound sample of enamel wire (the method is supported by Ukrainian and international standards: TU U 31.3-20006134-015, TU U 13970259.001, TU U 31.3–00214534.035, GOST 21428, GOST 26615, IEC 60317, DIN 46416, etc.), two-node wires system with mechanical tensile load (according to the Japanese standard JIS C 3003), two-turn wires model of the well-known electrotechnical firm "Vossloh Schwabe Urbach" (according to the instruction LS – QW – 03) are constructed in such a way that there is always an air gap in the discharge gap, and of different lengths (depending on the test method and mutual placement of insulation defects). This causes a significant variation in the values of insulation breakdown voltages and their overestimation, which does not allow to unambiguously assess the quality of the winding enamel wires insulation, as well as the degree of the technological factors influence on its deterioration.

In addition, quite often the statistical series of test results for breakdown voltages of enamel insulation, obtained, for example, on samples such as two-wire "twisting", contain individual results that "fall out" from the statistical pattern. These "emissions" also increase uncertainty in assessing the quality of their insulation. It should be noted that the extreme values of this series are recommended by the relevant regulations to be rejected as "problematic" measurement results and those that violate the normality of the variation series members. These recommendations are based on the methods of the well-known researcher of statistical series F. Grubbs (Grubbs Frank E.) [1]. The development of Grubbs's methods is the recommendations [2], which can be used to distinguish from the normal range of variation several abnormal minimum or maximum values in their various combinations. Greater constructiveness is inherent in other researchers who question the claims of the all-encompassing broad applicability of the normal distribution law at the study of statistical series [3].

Obviously, the researcher is most interested in these "emissions" in the variation series. Investigation of their origin and establishment of the occurrence reasons by means of other test methods would allow to estimate a real condition of an enamelled wire insulation.

The purpose of the research was to propose new approaches to determine the real state of enameled wires insulation defectness on the basis of performed analysis and features comparison of the existing voltage test methods.

Enameled wires for winding elements of electrical machines and devices of the following nominal diameters were subjected to research: 0.30; 0.40; 0.56; 0.67; 0.71; 1.0 and 1.18 *mm*. The breakdown voltages of air discharge gaps and the distance between the weakened insulation points on the samples of the enamel wires "twisting" type were measured. The presence of weakened insulation points before the breakdown of the discharge gap was assessed by visual observation of the visible corona discharge development on the working part of the two-wire "twists".

2. The results of the enameled wires insulation research.

It is known that the duration of the discharge process in the intervals between weakened or defective places in the lacquer film of enameled wire, as in any discharge gap, is subject to statistical scatter and consists of the discharge formation duration and, depending from the rate of voltage rise on the discharge gap, time the onset of the voltage initial value at which the discharge process becomes possible [4]. In addition, during the voltage rise, the insulating lacquer film is in the zone of intensive discharge process, which for this system of the two segments wires "twist" type is a discharge in a sharply inhomogeneous electrical field - corona discharge, can heat up and break. Thus, at voltages which used to test the "twist" type of enamel wires samples, it is possible to pre-break the air gap and then burning of the lacquer insulation by spark, if there is enough time for this process.

Observations of the visible crown location on the working part of the "twisting" (see Fig. 1, 2) confirmed the assumption that at the location of the defect or weakening of the insulation is an increase in electrical field strength as a consequence of proportional reduction of the dielectric constant. which is accompanied by a characteristic glow in the purple region of the visible light spectrum. At sufficient voltage between the defects there is a streamer discharge, which very quickly turns into an arc (see Fig. 3).

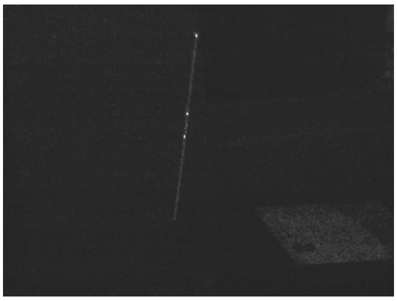

Fig. 1 Beginning of corona discharge visualization in places of insulation weakening (U_k = 3.8 *kV*)

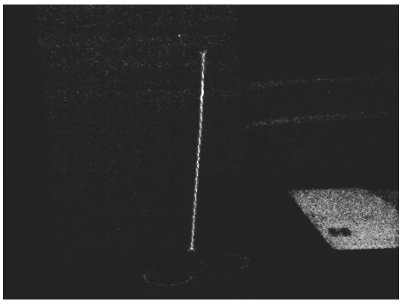

Fig. 2 Development of corona discharge along the sample and increase in the brightness of the defect (U_k = 6.4 *kV*)

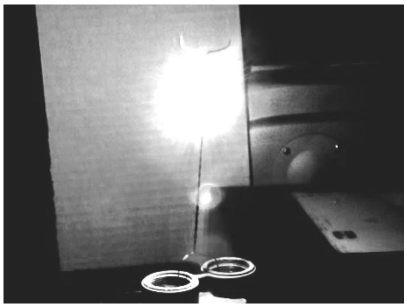

Fig. 3 Breakdown of the discharge gap in places of the insulation weakening (U_{br} = 10.2 *kV*)

The voltage of the visible corona discharge occurrence U_k (see (2)) practically coincided with the calculated value according to the empirical formula [4] for the electrical field intensity E_k of the corona discharge occurrence (see (1)). In fact, when the air density at the test plase changes within δ = 0.98 ... 1.03, the diameters of the investigated enamel wires with denomination d = (0.30; ...; 0.71) *mm* and the roughness coefficient m = 0.99 … 1.00 the electrical field strength E_k occurrence of corona discharge in the visible region of the light spectrum is equal to:

$$E_k = 30.3 \cdot m \cdot \delta \cdot \left(1 + \frac{0.301}{\sqrt{\frac{d}{2} \cdot \delta}} \right); \quad E_k = \left(78.6 \ldots 104.2\right) kV \cdot cm^{-1}. \tag{1}$$

The voltage U_k of the ionization process in the corona gap of a sharply inhomogeneous electrical field of the test wires "twisting" at a distance between their centers D = (0.328; ...; 0.786) *mm* is equal to:

$$U_k = E_k \cdot \frac{d}{2} \cdot \ln \frac{2D}{d}; \quad U_k = \left(0.98 \ldots 2.96\right) kV. \tag{2}$$

In the conditions of the conducted researches the appearance of the visible corona is fixed at voltages U_k = (1.6 ... 3.2) *kV* that, taking into account subjectivity of visual perception of the observer, is quite sufficient confirmation validity of application for calculations of the above expression (2). It is obvious that the fixed point places of the corona discharge on the "twisting" correspond to the local weakening of the enamel insulation.

To establish the electrical strength of these points, it is necessary to get rid of the air gap in the test method. Thus, the investigated section of the two-wire twisting insulation at a length of 125 *mm* was immersed in a conductive liquid to create a continuous contact between the individual sections of the insulation. The breakdown voltage U_{br} of the insulation was recorded when the leakage current value (5.0 ± 0.5) *mA* was reached. It is obvious that the voltage thus obtained was corresponded to the minimum value at the investigated segment of the enamel insulation sample.

As a result of the investigated enamel wires tests, the distributions of insulation breakdowns relative frequencies were obtained by the standard method on samples of two-wire "twists" (designation 1), detection of defects by visual method in corona discharge (designation 2) and by continuous contact in current-conductive liquid (designation 3). Analyzing the obtained results and making the appropriate proportions of the most probable voltages U_{50}, we obtained the following relations: U_{50} (1) : U_{50} (2) : U_{50} (3) = (7.2 ... 10.0) : (1.6 ... 6. 8) : (1.6 ... 3.4) = 3.4 : 1.7 : 1.

Thus, the excess of the actual insulation breakdown voltages at the location of defects due to the presence of an air discharge gap in the standard tests of the investigated enamel wires was ~ 3 times, which is unacceptable, and such test methods can be considered only evaluative or suitable for comparative tests. The general regularity of the inverse dependence for scattering voltage of visual fixation and breakdown on the quality of insulation is also revealed: the insulation of the wire in the initial state has, as a rule, one weakened place on the normalized length of the standard sample. The insulation breakdown at high voltages for a given thickness of insulation with a minimum excess from the detected visual level.

It is established that the discharge on a two-wire "twisting" is a complex process that requires a separate study of the actual process enamel insulation destruction at the place of weakening or insulation defect under a sharply inhomogeneous electrical field, and the development of the discharge process through the air gap to the nearest place.

To describe such a complex process, a combined method is used: experimental and mathematical modeling. Before making two-wire "twists" on the insulation of enamel samples, such as Grade 2-0.56 IEC 60 317-3, artificial through defects are applied so that after making "twists" the distances between them at the smallest distance were within (2 .. 20) *mm*. The obtained statistical scatter of breakdown voltages U_{br}, *kV*, of the two-wire "twisting" samples according to the standard method (see Fig. 4) and depending on the distance between the artificial defects L_d, *mm*, (see Fig. 5) was subjected to mathematical modeling according to three factors in planning factorial experiment type 2^3.

The corresponding statistical polynomial model of the discharge gap breakdown voltage on samples of the two-wire "twists" type contains the response function (*Y*) - the dependence function of the discharge gap breakdown voltage U_{br}, *kV*, from the factors:

- a distance L_d along the curve of the smallest length between the breakdown points of artificial insulation defects (factor *X*1), *mm*;

- the same, for the distance L_{ins} between the places of insulation breakdown according to the standard method (factor *X*2), *mm*;

- nominal diameter of the investigated enameled wire (factor *X*3), *mm*.

Optimal for such an enamel wire is a linear model of the form: $Y = 9.1 + 0.24 \cdot X1 + 2.74 \cdot X2 + 0.81 \cdot X3$. The statistical significance of the model coefficients corresponds to the standards [3]: $\frac{a_{i\,\max}}{a_{i\,\min}} = \frac{a_2}{a_1} \le 50$; $\frac{2.74}{0.24} = 11.4 = 50$. In this case, the adequacy of the model at the level of: $r_{\bar{y}} = 0.98$. Influence of the maximum factor *X*2 on the response function *Y*: $\delta Y_{+-}(X2) = \pm 30.1\%$. Influence of concomitant factor *X*1 on the response function *Y*: $\delta Y_{+-}(X1) = \pm 2.6\%$.

From the type of the breakdown voltages statistical series for the discharge process in air at intervals of length *L* for the factor *X*1 use the modeling method - approximation by a quadratic function of the form: $\varphi(x) = a_0 \cdot x^2 + a_1 \cdot x + a_2$. The coefficients of the function a_0, a_1, a_2 are calculated by the least squares method. Then for two-wire "twists" with pre-applied defects on the enameled wire type Grade 2–0.56 IEC 60 317-3 (see Fig. 6) the quadratic function for breakdown voltages will look like: $U_{mod}(L) = -0{,}034 \cdot L^2 + 0{,}89 \cdot L + 0{,}239$.

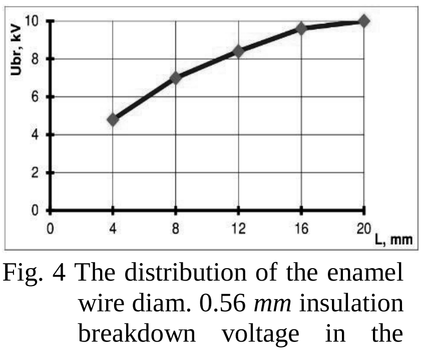

Fig. 4 The distribution of the enamel wire diam. 0.56 *mm* insulation breakdown voltage in the initial state according to the standard method

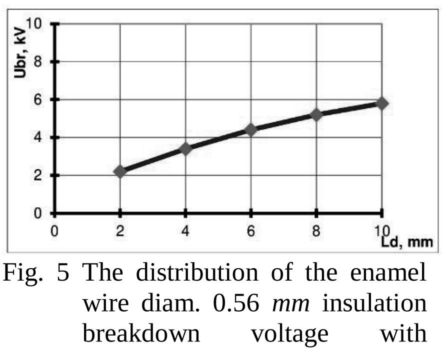

Fig. 5 The distribution of the enamel wire diam. 0.56 *mm* insulation breakdown voltage with artificially applied defects

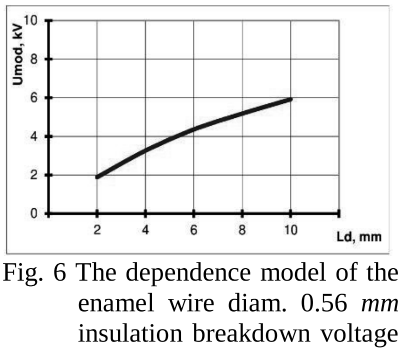

Fig. 6 The dependence model of the enamel wire diam. 0.56 *mm* insulation breakdown voltage from the distance between defects

The influence of factor *X*2 on the response function is estimated at (27 ... 30)%, and the reason is the statistical distribution of the insulation electrical strength, depending from its longitudinal inhomogeneity, and the length of the corresponding air discharge gaps. To establish the contribution of factor *X*2 to the insulation breakdown voltage, tests are performed to assess the longitudinal inhomogeneity of the enameled wire insulation by the method of so-called “continuous contact” in a current-conductive liquid on samples with a length of (1.0 ± 0.1) *m* [5]. As a result of tests, a statistical series of discrete random values of the minimum insulation breakdown voltages, which are normalized to a unit of enamel length, is obtained.

After mathematical processing of this variation series, a probabilistic estimate of the favorable for the discharge process location of defects or places of insulation weakening is obtained, as well as the type of breakdown voltage distribution function at the locations of insulation defects or its weakening.

There are five options for the random values distribution of breakdown voltage U, which make it possible to estimate the degree of insulation defectness of the investigated enamel wire using numerical characteristics of the probability distribution laws of random variables: mathematical expectation $M(U)$, mode $\mathcal{M}$, median μ, asymmetry S_k, excess ε, statistical (integral) distribution function $F^*(U)$ and compare with the mathematically described laws of random variables distribution (Gram-Charlier, with uniform density, normal), applying the Kolmogorov's consistency criterion for the integral distribution function. Namely [5]:

– defect-free enamel wire (theoretically): $S_k = 0$, $\varepsilon = 0$, $M(U) = \mathcal{M}$;

initial nominal electrical insulation strength at the values of the distribution functions $F^*(U) = 0.1$ and $F^*(U) = 0.75$, respectively: $E_{init}(0.1) > 200\ kV{\cdot}mm^{-1}$, $E_{nom}(0.75) > 250\ kV{\cdot}mm^{-1}$;

– enamel wire with a low degree of defectnees: $S_k < 0$, $\varepsilon \geq 0$ or $\varepsilon < 0$, $\mathcal{M} > M(U)$;
$E_{init}(0.1) > 20\ kV{\cdot}mm^{-1}$, $E_{nom}(0.75) \geq 200\ kV{\cdot}mm^{-1}$;

– enamel wire with a medium degree of defectness: $S_k < 0$, $\varepsilon \geq 0$ or $\varepsilon < 0$, $\mathcal{M} > M(U)$, or $\mathcal{M} \approx M(U)$;
$E_{init}(0.1) > 20\ kV{\cdot}mm^{-1}$, $E_{nom}(0.75) \geq 150\ kV{\cdot}mm^{-1}$;

– enamel wire with a high degree of defectness: $S_k > 0$, $\varepsilon \geq 0$ or $\varepsilon < 0$, $\mathcal{M} < M(U)$;
$E_{init}(0.1) > 20\ kV{\cdot}mm^{-1}$, $E_{nom}(0.75) \geq 100\ kV{\cdot}mm^{-1}$;

– enamel wire with a raised degree of defectness: $S_k > 0$, $\varepsilon \geq 0$, $\mathcal{M} \approx M(U)$;
$E_{init}(0.1) < 20\ kV{\cdot}mm^{-1}$, $E_{nom}(0.75) < 100\ kV{\cdot}mm^{-1}$;
the extreme case is the normal distribution law ($S_k \approx 0$, $\varepsilon \approx 0$) with extremely small values of insulation breakdown voltages at the level (0… 0.2) kV and $E_{init}(0.1) \approx 0$, $E_{nom}(0.75) < 20\ kV{\cdot}mm^{-1}$.

It should be noted that the above term "electrical insulation strength" at the point of breakdown, i.e. at the point of weakening of the insulation or its defect corresponds to the measured breakdown voltage reduced to the nominal half diametrical thickness of the insulation.

The test results according to the method [5] confirm their accuracy and homogeneity of samples. In addition, depending on the intensity of the factors acting on the insulation, there is a clear abnormality of modal breakdown voltage groups: obvious defects are accompanied by accumulation of results with low voltage values, which have asymmetry towards smaller values, thus eliminating uncertainty about insulation defectness in standard tests "twisting" of enameled wires samples.

The most effective mathematical law for modeling the breakdown voltage distributions of enameled wires, which takes into account their existing asymmetry and excess, is the Gram-Charlier's convergent statistical series derived from the normal distribution law [6], which is described by the distribution density function equation (3):

$$f_s(x) = \varphi(x) - \frac{S_k}{6} \cdot \varphi^{III}(x) + \frac{\varepsilon}{24} \cdot \varphi^{IV}(x), \tag{3}$$

where $\varphi(x) = \frac{1}{\sqrt{2 \cdot \pi}} \cdot \exp\left(-\frac{y^2}{2}\right)$ - the density of the normal standard distribution; $\varphi^{III}(x) = -\left(y^3 - 3 \cdot y\right) \cdot \varphi(x)$; $\varphi^{IV}(x) = \left(y^4 - 6 \cdot y^2 + 3\right) \cdot \varphi(x)$ - derivatives of III-th and IV-th orders from the function $\varphi(x)$, respectively; $y = \frac{x - \mu_1}{\sqrt{\mu_2}}$ - centered and normalized function variable $\varphi(x)$; $S_k = \frac{\mu_3}{\left(\sqrt{\mu_2}\right)^3}$; $\varepsilon = \frac{\mu_4}{\mu_2^2} - 3$ - asymmetry and excess of the researched distribution, respectively; $\mu_1 = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i$; $\mu_k = \frac{1}{n} \cdot \sum_{i=1}^{n} \left(x_i - \mu_1\right)^k$, where k = 2, 3, 4 - centering moments of a random variable x.

By the method of "continuous contact" in the current-conductive liquid according to [5] tests the above enameled wires according to the research program, which includes testing the electrical strength in the initial state and after the action of technological factors at the manufacture of electrical appliances winding elements.

The generalizing result is given below on an example of enamelled wire brand Grade 2–0.56 IEC 60 317-3, wound from a winding element of the investigated batch before impregnation with sealing compound, according to the method [7].

Variation series of insulation breakdown voltages, which contained the following values, in kV: 0.32; 0.56; 0.62; 0.68; 0.68; 0.70; 0.76; 0.78; 0.82; 0.86; 0.98; 1.00; 1.04; 1.12; 1.26; 1.40, distributed at intervals of 0.14 kV in accordance with the Sturges's rule. As a result of their statistical processing, the following characteristics of the insulation breakdown voltage distribution are obtained: mathematical expectation $M(U) = 0.86\ kV$; mode $\mathcal{M} \approx 0.76\ kV < M(U)$; standard deviation $\sigma(U) = 0.24\ kV$; asymmetry $S_k = +0.60 \geq 0$; excess $\varepsilon = -0.50 \leq 0$, as well as interval values of relative frequencies *w* (see Fig. 7).

Given the existing asymmetry, it is assumed that the breakdown voltage distribution of the insulation is mathematically described by Gram–Charlier's statistics (3) with the calculated coefficients S_k, as well as ε and the relative frequency w_s (4):

$$w_s = \frac{h}{\sigma(U)} \cdot \frac{1}{\sqrt{2 \cdot \pi}} \cdot \exp\left(-\frac{y^2}{2}\right) \left\{1 + \frac{S_k}{6} \cdot y \cdot \left(y^2 - 3\right) - \frac{\varepsilon}{24} \cdot \left[y^2 \cdot \left(y^2 - 6\right) + 3\right]\right\}. \tag{4}$$

Then the relative frequency of the enameled wire insulation breakdown distribution after winding according to the simulation results, taking into account (4) can be represented by expression (5), as well as the corresponding histogram (see Fig. 7):

$$w_{s_2} = \frac{0.14}{0.24} \cdot \frac{1}{\sqrt{2 \cdot \pi}} \cdot \exp\left(-\frac{y_2^2}{2}\right) \left\{1 + 0.1 \cdot y_2 \cdot \left(y_2^2 - 3\right) - 0.021 \cdot \left[y_2^2 \cdot \left(y_2^2 - 6\right) + 3\right]\right\}; \quad y_2 = \frac{U - 0.86}{0.24}. \tag{5}$$

To confirm the hypothesis about the Gram–Charlier's statistical series, the criterion of modeling accuracy - the parametric Kolmogorov's criterion (*D* - criterion) is used [6]. To do this, calculate the corresponding statistical distribution function *F*(x)* and the theoretical (integral) distribution function *F(x)*, which is used in this criterion to determine the parameter λ according to the equation: $\lambda = D \cdot \sqrt{N}$; $D = \max\left|F^*(U) - F(U)\right|$, where the maximum interval difference D = 0.040; λ = 0.27. Then, the numerical value of the probability $P(\lambda) = 1 - \sum_{j=-\infty}^{+\infty} (-1)^j \cdot \exp\left(-2 \cdot j^2 \cdot \lambda^2\right)$ (in this case $P(0.27) \approx 1.0$) indicates the validity of the accepted hypothesis (see Fig. 7).

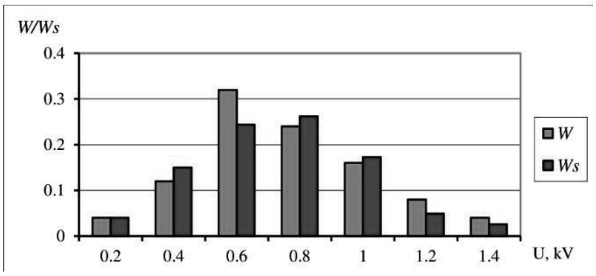

Fig. 7 Histograms of the enamel wire diam. 0.56 *mm* insulation breakdown voltage relative frequencies after winding:
- according to statistical data (*w*);
- according to the applied model (w_s)

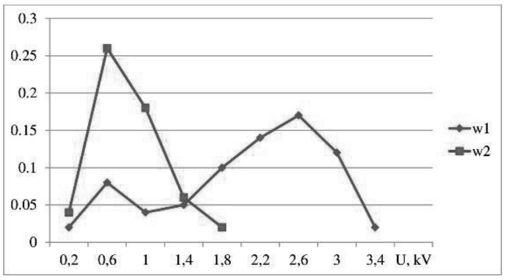

Fig. 8 Diagrams of the enamel wire diam. 0.56 mm insulation breakdown voltage relative frequencies:
- in the initial state (*w*1);
- after winding (*w*2)

Since the initial and nominal electrical insulation strengths of enamelled wire type Grade 2–0.56 IEC 60 317-3 with a diametrical insulation thickness (0.052 ... 0.060) *mm* after winding are, respectively:

$$E_{2\,init}(0.1) = \frac{2 \cdot (0.46 \ldots 0.52)}{0.052 \ldots 0.060} = (16 \ldots 20)\; kV \cdot mm^{-1} \le 20\; kV \cdot mm^{-1}$$

and

$$E_{2\,nom}(0.75) = \frac{2 \cdot (0.88 \ldots 0.92)}{0.052 \ldots 0.060} = (32 \ldots 36)\; kV \cdot mm^{-1} \le 100\; kV \cdot mm^{-1},$$

then, according to [5], the investigated enameled wire should be referred to the classification group: insulation with a raised degree of defectness.

The same statistical calculations are applied to the variation series of the insulation breakdown voltages enameled wire type Grade 2–0.56 IEC 60 317-3 in the initial state, in *kV*: 0.36; 0.48; 0.64; 0.78; 0.86; 1.12; 1.24; 1.32; 1.46; 1.62; 1.84; 1.92; 2.12; 2.36; 2.48; 2.64; 2.86; 3.02; 3.16; 3.34; 3.48, which is distributed at intervals of 0.45 *kV* according to the Sturges's rule. As a result of their statistical processing, the following characteristics of the insulation breakdown voltage distribution are obtained: mathematical expectation *M(U)* = 2.28 *kV*; mode $\mathcal{M} \approx 2.06$ *kV* < *M(U)*; standard deviation *σ(U)* = 1.01 *kV*; asymmetry $S_k = +0.24 \ge 0$; excess $\varepsilon = -0.60 \le 0$, as well as interval values of relative frequencies *w*1 (see Fig. 8).

According to (4), the relative frequency of the enameled wire insulation breakdown voltage in the initial state according to the simulation results taking into account (4) can be represented by expression (6):

$$w_{s_1} = \frac{0.45}{1.01} \cdot \frac{1}{\sqrt{2 \cdot \pi}} \cdot \exp\left(-\frac{y_1^2}{2}\right) \left\{1 + 0.039 \cdot y_1 \cdot \left(y_1^2 - 3\right) - 0.025 \cdot \left[y_1^2 \cdot \left(y_1^2 - 6\right) + 3\right]\right\}; \quad y_1 = \frac{U - 2.28}{1.01}. \qquad (6)$$

Since the electrical insulation strength of the enamel wire in the initial state is:

$$E_{1\,init}\left(0.1\right) = \left(78\,...\,92\right) kV \cdot mm^{-1} \geq 20\; kV \cdot mm^{-1} \quad \text{and} \quad E_{1\,nom}\left(0.75\right) = \left(152\,...\,164\right) kV \cdot mm^{-1} \geq 150\; kV \cdot mm^{-1},$$

then, according to [5], the investigated enamel wire should be referred to the classification group: insulation with a medium degree of defectness.

The increase in the defectness degree of the enamel wire insulation as a result of technological action is shown in Fig. 8 by shifting the relative frequencies of the insulation test results towards lower voltage values. The same figure shows that the breakdown voltage distribution is bimodal in nature with some concentration in the low voltage range. Such distributions are typical for enamel wires either due to the presence of areas with weakened insulation in the initial state, or acquired damage under the action of technological loads, or during operation.

In the mathematical description of such statistical series there is a problem of taking into account the so-called. “emissions” of individual modalities, i. e. random results that clearly fall out from the statistical regularity. Then it is effective to use the credibility function $L\left[M\left(U\right); \sigma\left(U\right); S_k; \varepsilon\right]$ according to the method of “maximum credibility” in combination with the robust method of grouping a data set in a sample with equal probability intervals, as a result of which the estimation of the individual modalities distribution parameters becomes most resistant to deviations. At the same time the new characteristics of the each modalities law distribution with the corresponding relative frequencies corrected by such procedure are receive [8].

Therefore, researches using the method [5], which eliminated the air gap from the discharge gap and, thus, increased the accuracy of the tests, found that in the manufacture of the electrical appliances coiled elements from enameled wire, its insulation due to the action of intensive technological factors [7] acquires significant damage, which, however, are manifested in tests using standard methods only implicit “emissions” of the statistical distribution law.

3. Conclusions.

The conducted researches have established that the informativeness increase of the enameled wires insulation tests methods for the purpose of revealing their weakened or defective places should occur in the direction of defects immediate research. One of such directions is the application of the “continuous contact” method in a current conductive liquid with a simultaneous mathematical description of the insulation defects distribution density along the unit length of the enamel wire.

As a result of elimination from the discharge gap uncontrolled air component it is possible to build a mathematical model of the insulation breakdown voltage distribution density in its most defective places, which is quite consistent with the statistical model obtained during the insulation tests of the enameled wire both in the initial state and after the action of technological factors at the manufacture of coiled elements.

The proposed methodology is a more accurate tool at the research of the enameled wires insulation, which allows to increase the informativeness of the existing standard methodology, especially at the presence in statistical samples of the breakdown voltage minimum values.

The application of the developed methodology significantly increases the efficiency of diagnosis and reliability of the enamelled wires test results, as a result of which it becomes possible to adjust the technological units for defect-free production of the electrical machines and devices coiled elements.

References

1. Grubbs, F.E., Beck, G. (1972). Extension of sample sizes and percentage points for significance tests of outlying observations. *Technometrics*, *14*(4), 847–854.

2. Lemeshko, B.Yu. (2005). Rasshyreniie oblasti primienieniia kritieriiev tipa Grabbsa, ispolzuiemykh pri otbrakovkie anomalnykh izmierienii. *Izmieritielnaia tiekhnika*, 6, 13–19 (in Rus.).

3. Orlov, A. I. (2004). *Prikladnaia statistika*. Moskva: Ekzamien (in Rus.).

4. Brzhezyts′kyy, V., Isakova, A., Rudakov, V. (2005). *Tekhnika i elektrofizyka vysokykh napruh*. Kharkiv: Tornado (in Ukr.).

5. Patent Ukrainy 54560 UA. 2003. Sposib otsinky stupenia defektnosti izoliatsii emalprovodiv. Vakulenko O., № 2000042307, Biuleten №3/2003 (in Ukr.).

6. Kobzar, A. I. (2006). *Prikladnaia matiematichieskaia statistika. Dlia inzhenierov i nauchnykh rabotnikov*. Moskva: Fizmatlit.

7. Yevtukh, P., Vakulenko, O. (2010). Modeliuvannia defektnosti izoliatsii emalprovodiv pid chas vyhotovlennia obmotkovykh elementiv elektrychnykh aparativ. *Visnyk NU “Lvivska politekhnika”*, *677*, 138–147 (in Ukr.).

8. Rudenko, V. M. (2012). *Matematychna statystyka. Navchalnyi posibn*. Kyiv: Tsentr uchbovoi lit. (in Ukr.).