UDC 621.315.2 **doi: 10.20998/2074-272X.2017.1.08**

O.V. Golik, L.A. Shchebeniuk

STATISTIC METHODS OF POLYIMIDE ENAMEL ISOLATION DEFECTIVE NON-DESTRUCTIVE CONTROL AT THE CONDITIONS OF PRODUCTION

In this paper can be used to not-destructive technological testing of defects isolation enameled wire with polyimide polymer. The thesis is devoted to the statistical method for processing, comparison and analysis of results of measurements of parameters isolation it enameled wire because of mathematical model of trend for application in active technological monitoring is developed; to development used of the recommendations for parameters of such testing. Is theoretically justified and the possibility of a diminution of dependence of an error from a velocity of movement of a wire for want of quantifying of defects enameled isolation not destroying tests by high voltage. This work is devoted to the statistical method for processing, comparison and analysis of results of measurements of parameters of polyimide isolation. The method is operating not destroying technological monitoring an amount of enameled isolation defect. The dependence of average value of amount of defects for enameled wire ПЭЭИДХ2 – 200 with two–sheeted polyimide by isolation in a range of nominal diameter 0.56 mm is experimentally determined. The technological monitoring purpose is reducing of quantifying of enameled isolation defect. References 7, tables 1, figures 8.

Key words: **enameled wire, polyimide isolation, isolation defective, statistical model of the trend, non-destructive testing.**

Представлены результаты применения статистической модели тренда к анализу показателей дефектности изоляции при неразрушающем технологическом контроле эмаль провода на основе полиимидного полимера в условиях производства. Рассмотрено применение такого контроля для использования результатов в активном технологическом контроле. Предложены рекомендации для практического использования параметров функции тренда в технологическом контроле. Параметром тренда является скорость уменьшения (или увеличения) длины провода с заданной дефектностью в течение технологического цикла. Теоретически показана и измерениями подтверрждена возможность количественной оценки тенденции изменения в течение технологического цикла дефектности эмальизоляции для провода ПЭЭИДХ2 – 200 с двухслойной полиимидной изоляцией номинальным диаметром 0,56 мм. Выделение тенденции изменения дефектности эмаль изоляции в течение непрерывного технологического цикла и количественная оценка этой тенденции позволяет количественно оценить случайную ошибку технологического контроля – суммарную ошибку результатов технологического контроля, которая является характеристикой случайной составляющей стабильности технологического контроля и обусловлена большим количеством причин, влиянием каждой из которых можно пренебречь по сравнению с суммой. Библ. 7, табл. 1, рис. 8.

Ключевые слова: **эмаль провод, полиимидная изоляция, дефектность изоляции, статистическая модель тренда, технологический неразрушающий контроль.**

Problem definition. In cable production introduction of relatively expensive product innovation makes use as the main criterion of liquidity price factor. Such innovative product for the domestic cable industry is based enamel wire polyimide synthetic copolymers with a temperature index of 200 °C. These enamel wires are the highest to date electrical and mechanical properties of insulation [1, 2]. For their production they use complex and expensive manufacturing equipment with high speed enamelling (up to 1000 m/min) and deep catalytic combustion of solvent enamel paints [2]. The introduction of such innovative types of cable products in production ensures the highest level of modern electrical, mechanical strength and thermal resistance of winding insulation of electrical machinery and apparatus. According ensure competitiveness electromechanical engineering.

The contradiction between the relatively high cost of innovative products, production of which is based on the use of advanced technologies and materials, on the one hand, and using as the main criterion of liquidity price factor, on the other hand, requires the manufacturer of such implementing innovative technical and organizational solutions to technological support the highest modern level of production while decreasing costs of its production.

The solution to this problem for manufacturers during the development of the known world, but for them innovative products require innovative solutions to process control in order to significantly reduce the number of products which have not passed the acceptance control. This clearly demonstrates the modern concept of «Six Sigma» («6σ») [1]. It criterion of quality products is its high uniformity, ensuring the minimization of the number of products that the characteristics does not meet user requirements. In fact, the concept of «Six Sigma» (defined statistical procedure normal distribution [2]) is a demonstration of achievements in the protection and marketing products of mass production. The development of innovative products specific manufacturer requires development and implementation of innovative technical and organizational solutions process control with the obligatory reference to the technical parameters of the achieved level of technology. In this case presents a solution for the control parameters defects insulation in non-destructive testing process of wires from polyimide polymer in a production environment.

The feature of poliefirimid and poliamidimid enamel paints is that the full completion of the polymerization occurs only in thin layers (up to 2 ... 3 μm). Therefore, the modern enamel units used trails to the number of passes through the wire nail 24 at length a passage through the oven to 10 m. This necessitates:

1) use of high speed enameling (up to 1000 m/ min);
2) continuity of production cycle making the maximum number of coils of wire;
3) automatic monitoring the number of defects in the enamel insulation in non-destructive testing of high voltage to pass.

The problem is that the results of such monitoring, realized on modern enamel devices (e.g. EFHP system by the MAG-ECOTESTER Company [3]) is not normalized in the technical documentation to the wire in which one of the main criteria is the breakdown voltage and variance breakdown voltage [5]. In this case, nondestructive process control of statistical indicators of the number of defects enamel insulation, realized in modern enamel lines, which would ensure active component of the control system, practically are not used.

Analysis of the literature. The contradiction between the relatively high cost of production and use as the main criterion of liquidity price factor for wires with polyimide insulation in [1] proposed solved by setting lower breakdown voltage requirements for admission and the adjustments to the thickness of the insulation. For example, for low-voltage products lower level voltage breakdown of insulation is sufficient. That prompted the introduction of spectrum needs of different customers. Implementation of the range specifications to meet the needs of different customers greatly extends the range of the applicable technical requirements and that at least blurs the range of values of parameters of the same product and difficult relationship between producer and user of the products.

An example of modern process control, which criteria decision-making process sets manufacturer is the continuous use of statistical control specific number of defects (*er*) of isolation *online* [3]. Number of defects is the number of places in which current flows through the insulation exceeds the set. Discrete measurement of current through the insulation when exposed high voltage direct current (Fig. 1) provides the EFHP system by the MAG-ECOTESTER Company [3].

The need to estimate the number of defects of isolation wires is recognized. The concept of defect isolation wires enough conditional:

- from lack of insulation in the spot defects: defects in the place matches on adjacent coils winding breakdown voltage is zero [4];
- to set forward the increased current through the enamel insulation, indicating the presence in this place insulation defect [3].

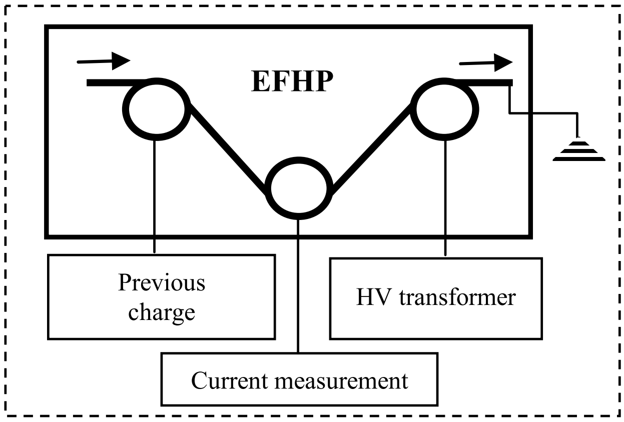

Fig. 1. Schematic diagram of monitoring the number of defects In enamel insulation at non-destructive testing by high voltage to pass

The current value which in [3] the detector circuit registers as a defect is regulated, for example, for a radial insulation thickness ≈30 μm is 10 μA at a test voltage of 1500 V.

So one of the key control parameters is normalized breakdown voltage [1, 3-5] and dispersion breakdown voltage is a parameter which indirectly corresponds to a specific number of local defects of isolation. Both characteristics (dispersion of breakdown voltage and specific defects) reflect the homogeneity of isolation.

Control of dispersion of main technical parameters of products serves the information base for the implementation of the principle of continuous improvement of quality according to ISO 9001:2000. However, such control is not provided normative technical documentation.

Using EFHP system [3] for statistical indicators to monitor the number of defects of isolation wires polyimide copolymers based on a real technological measure that provides the necessary information to implement the principle of continuous improvement of quality under ISO 9001.

To determine the statistical indicators of defects in the EFHP system unified statistical software modules are used. Each coil fixed number of monitoring sites wire (100 m) of four groups of defects: group 1 – 0 to 3 defects; group 2 – 4 to 9 defects; Group 3 – 10 to 18 defects; Group 4 – more than 18 defects (defects refer *er*). Also three major statistical indicators are recorded: the average number of defects in the control region, $M[er]$; defects in the control region with the most defects, er_m; the standard deviation of the number of defects in the control region, $\sigma[er]$.

Obviously, the recorded test results with the help of EFHP system depend on the dispersion of many parameters wire: mechanical properties and diameter of the conductor d_p, process parameters of enameling and insulation thickness Δ, value the test voltage U and the minimum current through the isolation I in which the system records the defect .

Therefore, the analysis of the current process control defect isolation enameled wires is a complex multidimensional problem. The adoption of technological solutions based on the results of such monitoring depends on the experience of the responsible engineer and is not normalized. In the end, an arbitrator at the receiving control is the breakdown voltage and breakdown voltage variance [5]. In this case, control of statistical indicators of the number of defects enamel insulation, realized in modern enamel lines, hardly used. In our view, this is due to a fundamental difference between the tasks of receiving and process control.

A task of acceptance control in mass production is to match the basic parameters of the finished product technical regulatory requirements. The problem of process control is timely **warnings** of out the basic parameters of the product outside of the established process for admission to a particular production line.

The very task includes preventing the need to synchronize control engineering, process parameters and process time in one form or another. For example, for cables and wires in the tests «to pass» technology time is determined by the length of product that passes through the meter multiplied by the speed.

Evaluation changing trends in the technical and technological parameters for the process time is the main task of process control.

The goal of the work is to analyze the results of non-destructive testing by high voltage to pass of wires from polyimide-based synthetic copolymers with double insulation and with temperature index of 200 °C made at the domestic cable factory which lets you split:

- ***trend*** of the process – a significant change in the results of deterministic process control during the manufacturing process to establish technological factors that cause this change decision-making process of correction parameters; ***trend*** is deterministic quantitative characteristic of the stability of the process;
- ***random error*** of the technological process – total error of the process control which is a quantitative characteristic of the random component of the stability of the process and due to many factors influence each of which is negligible compared with the sum.

The purpose of this division is to develop deterministic and statistical criteria for the stability of high-speed automated manufacturing process of wires from polyimide-based synthetic copolymers with double insulation and a temperature index of 200 °C in the non-destructive testing of high voltage to pass.

The main results obtained. *er* number of defects in each unit length of 100 m for fifty reels of enamel wires (total of 180,000 meters of wire) in the chronological order in continuous production automatic technological process is experimentally determined.

Current control of diameter d_p of copper conductor in the enameling (Fig. 2) indicating the presence in the process as a trend of gradual changes in parameters (for route enameling is technological extract conductor – the trend of the technological process) and random component diameter d_p (after passing the calibers No. 4 and No. 10 increase the diameter d_p is the measurement error) which is part of the random component of the stability of the technological process.

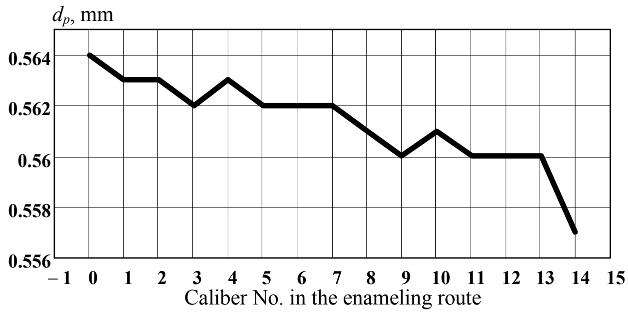

Fig. 2. The diameter of the copper conductor d_p after passing the appropriate caliber enameling route: the route is over the hood conductor technology which is more than one percent

For the analysis of a number of observations *er* per number of defects in each unit length of 100 m enamel wires we applied statistical trend model error (only error is a random variable) for a number of observations on the value x [6]:

$$x_i = f(t_i) + \delta_i, \qquad (1)$$

where t_i is the deterministic variable that is a technological time, which in this case is proportional to the number of manufactured wire coil; $f(t_i)$ is the deterministic function (process trend); δ_i is the random variable (random component of the stability of the technological process).

The values of δ_i are independent and identically normally distributed. The function $f(t)$ is given by the formula or algorithm calculations and depends on a number of unknown parameters $c_1,\dots, c_k$ whose values are determined by maximum likelihood.

In the case of the linear function for each t the value of x is normally distributed with a mean $x(t) = a + b\,(t - t_m)$ and mean-square σ. Estimations of unknown parameters a, b and σ:

$$a^* = x_m; \qquad (2)$$

$$b^* = \Sigma(t_i - t_m)(x_i - x_m)/[\Sigma(t_i - t_m)^2]; \qquad (3)$$

$$\sigma^* = \{n^{-1}\,\Sigma[x_i - a^* - b^*(t_i - t_m)]^2\}^{0,5}, \qquad (4)$$

where t_m is the the average of the determined variable t; x_m is the the average number of observations on the value x.

Credible p-percent boundaries for $x(t)$ for given parameter t are determined by the γ_p Student distribution parameter with $n - 2$ degrees of freedom:

$$a^* + b^* (t - t_m) \pm \gamma_p \sigma^* (n-2)^{-0.5}[1 + (t - t_m)^2 n / \Sigma(t_i - t_m)^2]^{0.5}. \quad (5)$$

For enamel wire with double insulation based on polyimide copolymers in Fig. 3 shows the results of determination of the number of unit length (100 m) containing 18 or more defects. Conventionally, these individual lengths can be considered the most defective (hereinafter: «the worst 100 m»).

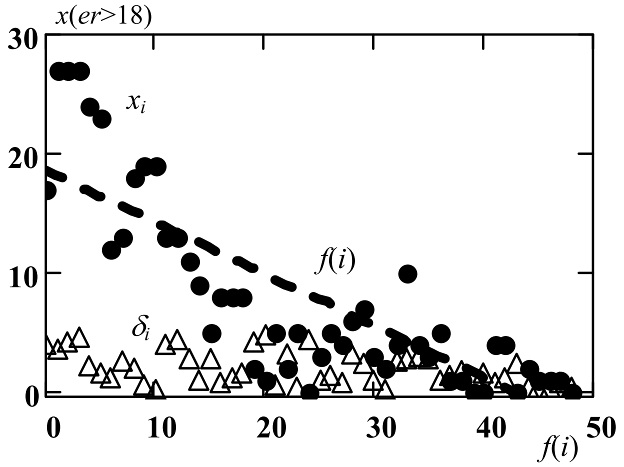

Fig. 3. The results determine the number of unit length (by 100 m) containing 18 or more defects for enamel wire with double insulation based on polyimide copolymers: x_i – the number of «worst 100 m» (18 defects and more) on the reel at the number i in continuous technological cycle of production; $f(i)$ – deterministic function (process trend) defined by (2), (3); δ_i – random part of the process, defined as $\delta_i = ([x_i - f(i)]^2)^{0.5}$

The trend of reducing the number of «worst 100 m» during the process quantifies the observation period is determined by the function $f(i)$. The random component of the stability of the process is represented as an array of values δ_i of absolute deviation number of «worst 100 m» x_i determined by the function $f(i)$:

$$\delta_i = ([x_i - f(i)]^2)^{0.5}. \quad (6)$$

In the presented example, the array δ_i has no pronounced trend and average value δ_m is a quantitative assessment of technological error during the process observation period, in particular – the error control method used.

The data in Fig. 3 indicate the theoretical possibility of separation and quantitative assessment of:

- first, the trend of the process, the causes of which appropriate technological measures should be established by technological service;
- second, the random component of the stability of the process, the average of which is a quantitative assessment of technological error, which is the subject of statistical process control.

Obviously, should be envisaged the possibility of a trend of stable random component of the process. In this case, should be applied a statistical model of the trend with an error to the random component δ_i (Fig. 4).

The sequence of statistical arrays and relevant statistical parameters specified by formulas recurrent procedures (2) – (6) is given in Table 1.

Settings trend identified statistically with the required accuracy (formula (5)), are parameters determined functions. In the example in Fig. 3 is the parameter b^* of the function $f(i)$ – the rate of reducing the number of «worst 100 m»: $b^* = -86.88 \pm 9.25$ (m/h), which is approximately one to reduce the «worst 100 m» for the manufacture of two coils (down 1.4 % relative to the length of the defective enamel wire on one coil).

Table 1

No.	Arrays	Trend parameters	Statistical parameters of random component	
			Average	Standard deviation
1	x_i, δ_i	a^*, b^*, σ^*	δ_m	$s\delta$
2	δ_i, $\delta 2_i$	$a2^*$, $b2^*$, $\sigma 2^*$	$\delta 2_m$	$s\delta 2$
3	$\delta 2_i$, $\delta 3_i$	$a3^*$, $b3^*$, $\sigma 3^*$	$\delta 3_m$	$s\delta 3$
…	…	…	…	…

Automation of control and statistical data, allocation deterministic trend and presenting the results in a quantitative parameter trend provides the possibility of the technological process current adjustment.

The simultaneous selection of the random component of the process δ_i ($\delta_i = ([x_i - f(i)]^2)^{0.5}$) allows to quantify the error process, the causes of which can be very much and reduce what by necessity requires a comprehensive approach that in the world practice called by Deming method [7].

The presented example (a linear trend, a random part of the process) is the easiest. Deterministic function $f(i)$ can not be linear (it can be periodic [6]). For example, an array x_i in Fig. 3 can be best described by a decreasing exponential function that change the coordinate system can be represented as a straight line. Completed relevant calculations are more complex, but technological findings remained unchanged.

Fig. 4 shows the results of the statistical analysis of the stability of the process of manufacturing the same enamel wire on the number of defect-free single lengths on the reel in a number x_i unit length (by 100 m), containing three or fewer defects: x_i is the number of «best 100 m» on the reel at the number i in continuous technological cycle of production.

The number of such recurrent procedures n can be limited by the presence of the random component of the trend, but it is insignificant because the variance of each subsequent random component $D[\delta n]$ rapidly approaching zero (Fig. 5).

The most effective is the procedure for the selection of the first trend, as this random component coefficient of variation $\delta 1_i$ close to unity, indicating the approximate equality $\delta 1_m$ average and standard deviation of the random component $s\delta1$ of the process (Fig. 6). Importantly, the dependences $V[\delta n] = f(n)$ (Fig. 5) are similar in character arrays (see Fig. 3, 4) which differ in shape of the visual pass (Fig. 3 – exponential decay, Fig. 4 – linear growth), and the direction of the trend (Fig. 3 – decrease; Fig. 4 – growth).

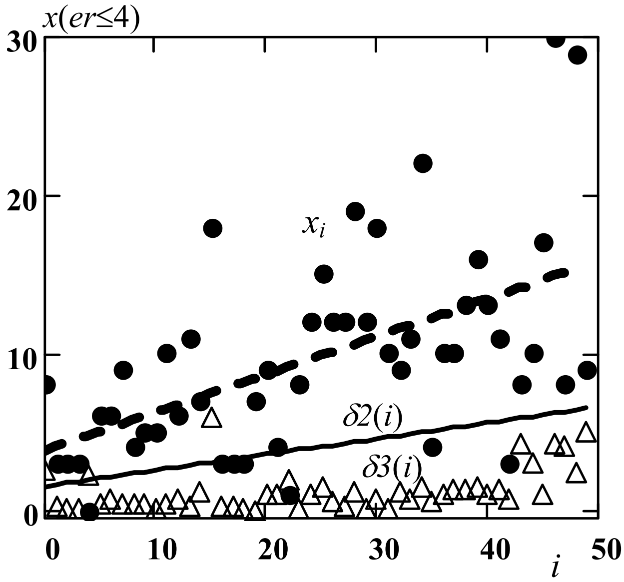

Fig. 4. Number of single lengths that contain three or fewer defects: x_i – the number of «best 100 m» on the reel at the number i in continuous technological cycle of production; $f(i)$ – deterministic function (process trend), defined by (2), (3); $\delta2(i)$ – the second process trend (random component δ_i); $\delta3_i$ – an array of random component

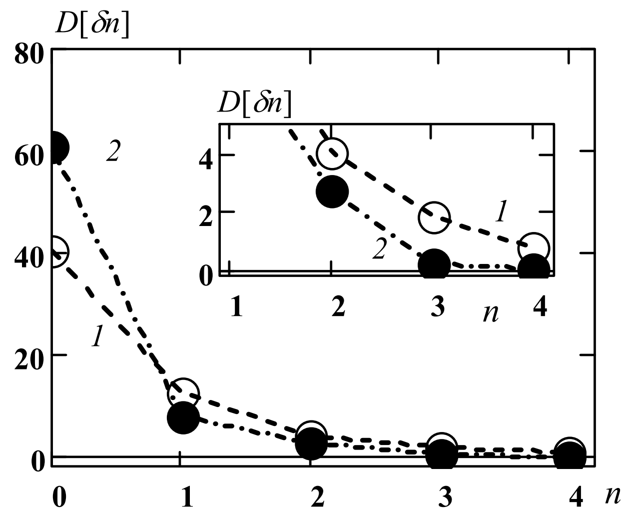

Fig. 5. The dependence of the variance of the random component $D[\delta n]$ on n number of recurrent statistical procedure: 1 – $D[\delta n(er \le 3)]$; 2 – $D[\delta n(er > 18)]$

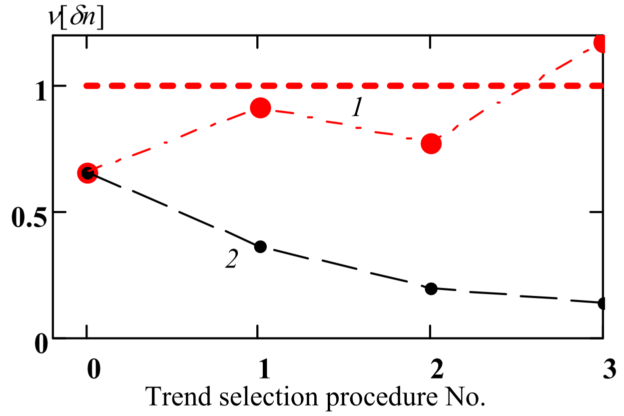

Fig. 6. The dependence of the coefficient of variation random component $v[\delta n]$ on n number of recurrent statistical procedure $v[\delta n] = f(n)$: 1 – $v[\delta n(er \le 3)]$: the coefficient of variation increases and is close to unity (1), and the relative standard deviation decreases exponentially (2)

It is advisable to use a coefficient of variation is random component $v[\delta]$ data set as a criterion for the number of recurrent procedures n which allows you to select a random part of the technological process δn_i ($\delta n_i = ([\delta(n\text{–}1)_i - \delta(n\text{–}1)(i)]^2)^{0.5}$) and thus estimate error process. Accuracy of process control is ± 1 «best 100 m».

Trends parameters that are deterministic functions technologically parameters may be analyzed, as they are not random.

The gap between the rate of increase in the number of «defect-free 100 m» (≈ 48 m/h) on the one hand, and the rate of decrease in the number of «worst 100 m» (≈ –86 m/h) on the other, clearly shows that the work cycle isolation on high-speed automatic enamel units in principle is not stable. It should be distinguished using technical terminology reliability, grinding in period (increased insulation defects), the normal isolation (insulation defects characterizes the level of technology) and the period of «fatigue» (defective insulation is growing faster than during normal isolation).

The duration of these periods, and hence logistics of enameling technology in a particular production is to be determined by separate and quantify the parameters of insulation defects, such as:

- insulation defect trends, causes and which appropriate technological measures should be established technological service;
- random component of the stability of the technological process, the average of which is a quantitative assessment of statistical process control error.

To quantify the relevant parameters trend superposition model and the random component of the database are necessary. Fig. 7 shows a model for the array data shown in Fig. 4.

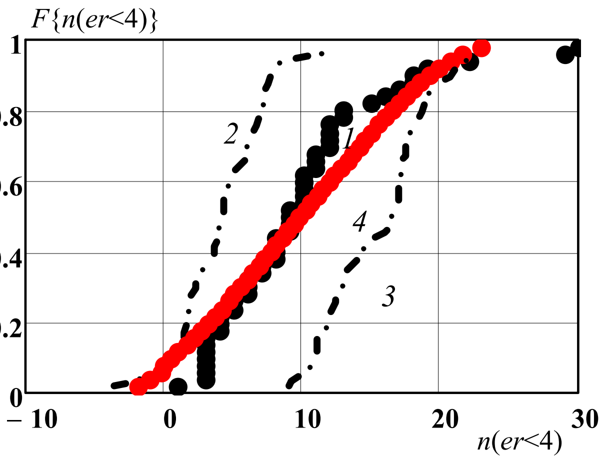

Fig. 7. Model of empirical distribution function of the number of defect-free reference lengths in a normal distribution function with the expectation that varies linearly over the manufacturing process and stable dispersion error control: 1 – empirical distribution function $F^*\{n(er<4)\}$; 2 – distribution function at the beginning of the observation period; 3 – distribution function at the end of the observation period; 4 – model distribution function

Because the value of the control parameter is positive and the procedure for normal distribution model involves the appearance of negative values for determining the random component used Weibull distribution (WD) (Fig. 8) that, first, rather than a normal distribution (ND) describes an array of data (for ND the Kolmogorov criterion is 0.71, for WD is 0.95).

Second, it permits to evaluate the random component of the array as a parameter exponential distribution, which degenerates WD at a value parameter form that is unity.

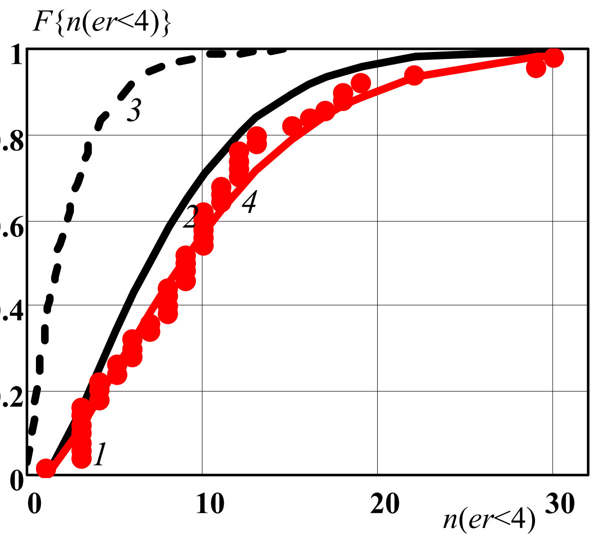

Fig. 8. Model of empirical distribution function of the number of defect-free control as a function of length of Weibull distribution: 1 – empirical distribution function $F^*\{n(er<4)\}$ (points); 2 – approximation of function $F^*\{n(er<4)\}$ by Weibull distribution function; 3 – distribution function of the random component of the array (dashed, forms parameter in the Weibull distribution $bv = 1.01$); 4 – model of distribution function $F\{n(er<4)\}$ as a superposition of trend and the random component array

Conclusions.

1. Results of control of defects of enamel insulation polyimide-based synthetic copolymers in the process of non-destructive testing technology for the passage of high voltage indicate the possibility and feasibility of the selection of technological process ***trend*** – determined quantitative characteristics of the stability of the technological process. Feasibility of the trend allocation is to establish technological factors that cause change deterministic control parameter to decide the process correction.

2. Selection of the technological process ***trend*** makes it possible to quantify the ***random error*** of the technological process which is a quantitative characteristic of the random component of the stability of the technological process and due to many factors influence each of which is negligible compared with the sum.

3. It is selected ***trend*** of the technological process of wire isolation with double insulation polyimide copolymers based on high-speed automatic enamel units as speed (trend parameter b^*) reduction of defects during the production cycle: $b^* = –86.88 \pm 9.25$ (m/ h) which is approximately 1.4 % decrease relative to the length of the defective enamel wire on a reel.

4. Comparison of speed reduction of defects in different periods of technological cycle shows that the work cycle of isolation on high-speed automatic enamel units in principle is not stable. It should be distinguished using technical terminology reliability, grinding in period (increased insulation defects), the normal isolation (defective insulation is stable and reflects the level of technology) and the period of «fatigue» (defective insulation is growing faster than during normal isolation). The duration of these periods, and hence logistics of enameling technology in a particular production is to be determined by limiting the duration of continuous work cycle of the normal period of isolation (defective insulation is stable and reflects the level of technology). The criterion for this limitation should change the sign for speed reduction defects elements of continuous production cycle, the duration of which is determined on the basis of the Mises principle [6].

REFERENCES

1. Zelenetsky Yu.A. About the improvement of technical documentation for enameled wires. *Cables and wires*, 2013, no.5, pp. 19-23. (Rus).

2. Shchebeniuk L.A., Antonets S.Yu. Statistical method purpose is the reduce of quantifying defects of enameled wire. *Bulletin of NTU «KhPI»*, 2012, no.23, pp. 166-169. (Ukr).

3. Golik O.V. Quantifying of defects for enameled wire with two-sheeted poliimid isolation by tests by high voltage. *Ukrainian metrological journal*, 2009, no.1, pp. 15-18. (Rus).

4. Andrianov A.V., Andrianov V.K., Bykov E.V. About the statistics of pin-hole damages of winding wires and inter-turn short-circuits in windings. *Cables and wires*, 2013, no.5, pp. 28-31. (Rus).

5. Technical Report IVA Laboratories: Breakdown voltage. – classified: October 2007. – p. 18.

6. Tutubalin V.N. *Statisticheskaia obrabotka riadov nabliudenii* [Statistical analysis of observation series]. Moscow, Znanie Publ., 1973. 64 p. (Rus).

7. Mary Walton. *The Deming Management Method*. Foreword by W. Edward Deming. New York: NY 10016 Copyright, 1986. 262 p.

Received 05.11.2016

O.V. Golik[1], *Candidate of Technical Science, Associate Professor,*
L.A. Shchebeniuk[1], *Candidate of Technical Science, Professor,*
[1] National Technical University «Kharkiv Polytechnic Institute»,
21, Kyrpychova Str., Kharkiv, 61002, Ukraine,
e-mail: unona.2013@mail.ru, agurin@kpi.kharkov.ua

How to cite this article:
Golik O.V., Shchebeniuk L.A. Statistic methods of polyimide enamel isolation defective non-destructive control at the conditions of production. *Electrical engineering & electromechanics*, 2017, no.1, pp. 47-53. **doi: 10.20998/2074-272X.2017.1.08.**