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STATISTICAL MODEL OF PROCESSING THE RESULTS OF TECHNOLOGICAL CONTROL AT TESTING ENAMEL WIRE INSULATION BY HIGH VOLTAGE DURING THE PRODUCTION PROCESS

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Abstract: The results of non-destructive technological control of the number of defects in the enamel wire insulation based on polyetherimide polymer are presented. The application of statistical analysis of the measurement results of control indicators with the help of a mathematical trend model for the use in active technological control is considered. Recommendations for the practical use of the trend function parameters to control the probability of finding several parameters within the established limits are proposed. The main parameter of the trend is the flow parameter of the number of defects exceeding the established technological limit (the failure flow parameter) in short periods of the technological time, for example, for each spool of wire (several thousand meters of wire). The ability to quantitatively assess the tendency of enamel insulation defects for the wire with two-layer insulation with a nominal diameter of 0.63 mm during a continuous technological cycle has been theoretically explained and confirmed by measurements. Quantitative assessment of the tendency of changing the enamel insulation defectiveness allows using a model based on collating the information on a significant number of control parameters. At the same time, one parameter of the spectrum of interrelated ones is allowed to exceed a set technological limit, which ensures sensitivity to changes in this limit. Data on the sensitivity of this model to technological changes are presented.

Keywords: enamel wire, polyimide insulation, defectiveness, technological control, voltage tests.

1. Introduction

Enamel wire with double insulation based on polyimide copolymers is the state-of-the-art result of enamel wire production. Ensuring the electrical strength of enamel wire requires minimizing the dispersion of values of the breakdown voltage U_{br} (hereinafter for brevity U). For the manufacturer, it is especially relevant to study the change in the dispersion of U values during a continuous technological cycle, which includes the continuous production of a large number of enamel wire spools (thousa nds of meters) on modern high-speed enameling units. The problem of organizing such control in real time becomes important when introducing modern automated production lines. Significant product lengths lead to high requirements for uniformity in length for a number of parameters. The indicator of such uniformity, for example, is the discrete measurement of the current through the enamel wire insulation in the real-time technological mode under the action of high voltage direct current, which is provided by the licensed EFHP system of the MAG-ECOTESTER company [1]. This system provides non-destructive technological control within a wide range of parameters: test voltage is 300 V up to 4000 V with a 1 V step; critical current is 4 μA up to 40 μA with steps of 1 μA.

Determining the breakdown voltage remains a destructive procedure performed on a limited part of the product and, therefore, in parallel, there must be the non-destructive control of the wire uniformity provided along its length.

The high cost of innovative products, the production of which is based on the use of advanced technologies and materials (often imported) on the one hand, and the need for additional costs for the organization of control of the spectrum uniformity of technical parameters along the length in real time on the other hand, which, in turn, create the problem of economic efficiency of innovation implementation. Their efficiency directly depends on ensuring a sufficiently high level of the operational characteristics of innovative products.

Automated imported technologies being used, which is typical for the Ukrainian cable industry, the analysis of the specific technological control results as the basis for ensuring a sufficiently high level of operational characteristics remains the competence of the innovative technology developer. The problem of organization of specific technological control and analysis of its results during the implementation of modern automated production lines is one of the most urgent problems of cable industry.

This problem is so closely related to the economic component of innovative production that in [2] it is proposed to resolve the contradiction between the high cost of products and the price factor as a liquidity criterion for enameled wires with polyimide insulation by reducing the level of breakdown voltage requirements agreed with the customer. In essence, this is an announcement of capitulation to the problem of introducing this innovative product, caused precisely by the complexity of organizing the use of a modern technological online control system for determining insulation defects of enamel wires produced by enamel aggregates of world manufacturers of the corresponding equipment.

2. Analysis of literature review

There is a significant theoretical and technical difference between the tasks of acceptance and current technological control [3]. To estimate the guaranteed level of the technical parameters of products during the technological process, it is advisable to use the mathematical apparatus of marginal distributions [4]. Reliable determination of the probability of occurring inadmissible random variable values is still the subject of a search for specific solutions for specialists in the field of mathematical statistics [3,4]. First, we are talking about the dynamic voltage test (that is, directly during the cable product being moved along the production line), which is a dynamic [5] type of non-destructive control in cable production.

Dynamic insulation tests are poorly studied in the world [5], and there are significant contradictions in their practical using. Thus, in the countries of the Soviet Union, only alternating voltage was standardized, while in the world alternating, pulsed, and (mostly) direct voltage is used [5, 6, 7, 8].

Under these conditions, the use of modern imported automated technological lines at cable factories led to the fact that dynamic tests of insulation with spark DC voltage tests exist as an element of technology, but their results are not used. Firstly, the methods of the results analysis remain the property of the innovative technology developer and, secondly, these results are beyond the scope of current regulatory documents [9].

In [10], distributions of discrete random values of minimum insulation breakdown voltages normalized to a unit length of the enameled wire were obtained basing on the results of PET 155–0.71 wire tests. Four groups of defects were distinguished with the corresponding limit values of the insulation electrical strength (breakdown voltage): theoretically defect-free enameled wire, low-level defect enameled wire, average-level defect enameled wire, and high-level defect enameled wire.

The division into defect groups based on the analysis of the statistical (integral) breakdown voltage distribution function $F^*(U)$ is theoretically and experimentally justified in this article. It is possible that a division by defect groups similar to this one is the basis of the licensed technological control applied in enamel aggregates of the MAG company.

The idea of dividing the enameled wire into 4 defect groups, proposed in [10], is relevant and indicates that in the case of dynamic tests, control lengths (100 m) with different defect levels differ not only statistically in terms of the number of defects, but and at least by their size. This is confirmed by the fact that we observed the results consistency of non-destructive testing in the real-time technological mode with the results of typical testing of the produced wire only in the case of the presence of all 4 defect groups.

However, the quantitative results of [10] cannot be used in this research for comparison or analysis for at least two reasons:

1) objects are different both by construction (solid insulation) and by the chemical nature of the insulation;

2) the test method is static and destructive with the breakdown voltage determination (can be normalized) provided for specially made samples.

Technological non-destructive control of defects in real-time production mode is a comparative method that should ensure the presence of all four groups of defects.

This work is devoted to the development of a statistical model for processing the results of multiparametric technological control in real time during insulation tests by spark DC voltage and to the verification of the possibility of its application under the conditions of modern wire production with insulation based on polyimide copolymers.

3. Main results

Fig. 1 shows a fragment of the results of insulation defect control by spark DC voltage in real time (EFHP system of MAG-ECOTESTER company [1]), which is an element of manufacturing technology of modern high-speed enamel machines.

The results of dynamic spark voltage tests of double insulated enameled wire (primary insulation is polyetherimide, the first cover is polyamide; insulation thickness is not less than 0.05 mm), nominal diameter of 0.63 mm, test voltage of 1500 V DC (voltage pulses lasting 10 ms) are presented in this paper. At the same time, the number of defects is fixed on each 100 m length. A defect is a segment with a length of 0.1 m in which the current through the insulation exceeds 10 μA.

On each spool of wire, the EFHP system records the number of wire control lengths belonging to one of four groups according to the number of defects (*er*):

– group 1 (practically defect-free): $er < 4$;

– groups 2 and 3 (low level of defectiveness): $3 < er < 9$ and $8 < er < 18$ respectively;

– group 4 (high level of defectiveness) $er > 18$.

To simplify understanding, the results are presented in graphic form as the frequency $f(t)$* of the different defects groups appearance in successive periods of the continuous automatic wire production. Fig. 1 shows the direct results of defectiveness control by four parameters: $f_1(t)$; $f_2(t)$; $f_3(t)$; $f_4(t)$. These parameters are statistically not mutually independent, as they are connected by the condition of: $\sum f_i(t) = 1$. However, both electrophysically and, as shown in Fig. 1, statistically, they differ significantly, and their difference is the main information for the analysis of control results.

The system provides a wide range of the test voltage and critical current adjustment, at which the presence of a defect is fixed.

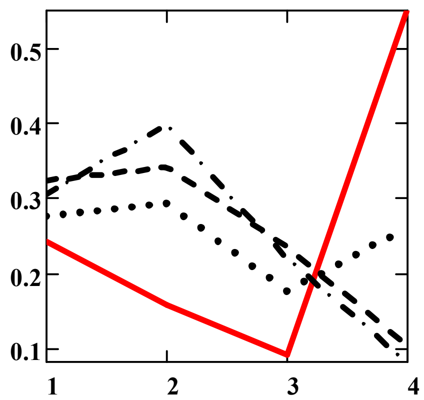

Fig. 1 A fragment of the results of insulation defects control obtained by using DC spark voltage in real time according to $f_1(t)$; $f_2(t)$; $f_3(t)$; $f_4(t)$ which are the frequencies $f(t)$ of the appearance of groups of different defects in successive periods of continuous automatic wire production: during the first 5 hours the frequency of occurrence of $f(t)$* for groups with the small number of defects (1st, 2nd, 3rd groups) is significantly lower than for the 4th (the most defective), which is the evidence of increased defectiveness (the run-in period [9]).*

Fig. 1 is the evidence of the technological process instability, for example: the instability of the wire speed, or the presence of at least two significantly different types of defects.

During the next 15 hours, the maximum frequency of the second group of defect appearance is observed (from 4 to 8 defects), and over time the maximum frequency increases. In accordance to this, the appearance frequency of the 4th group (most defective) decreases, which means decreasing the insulation defectiveness at the same time with high control sensitivity (period of normal technological process). Thus, the EFHP system is not an alternative control system (acceptable or unacceptable number of defects), in contrast to traditional online insulation quality tests [5], but it is the way of adjusting the technological process by means of flexible non-destructive control of insulation defects in accordance with reached level.

It is important that the DC voltage control in real time according to four parameters, which are the frequencies $f(t)$* of the appearance of different defect groups, makes it possible to adjust the control procedure by choosing the values of the test voltage and the critical current through the insulation in such a way, so that the control procedure might record the presence of all groups of defects at the achieved level of the enameled insulation uniformity. If the sensitivity is too high (low critical current and too high test voltage), all control sections of the wire belong to the fourth group, and the number of defects shows the discreteness of the measurements. If the sensitivity is too low (too high critical current and low test voltage), all or almost all control sections of the wire belong to the first group and the control becomes traditional voltage test for checking the insulation integrity (alternative control).

The conformity of the non-destructive testing results in the real-time process with the typical testing results of the produced wire is observed only in the presence of all four defect groups. With such a setting (the presence of all four defect groups with the maximum frequency for the 2nd or 3rd group), the values of the critical current and the test voltage are important interdependent control parameters that mean the electrophysical properties of the insulation, and the assessment of distribution of the number of defects along the spool means its statistical homogeneity.

Setting the maximum frequency of the 2nd or 3rd groups occurrence provides information about the insulation defects level in the form of three values: test voltage, critical current and modal number of defects per unit of wire length.

Thus, the first obvious analysis of the results of the MAG-ECOTESTER company EFHP system testifies to the fundamental necessity and possibility of using many parameters (multi-parameter control), including interdependent ones, for technological control in real time by high-voltage insulation tests during the cable production, characterized by significant product lengths.

At the same time, the purpose of technological control is to identify and evaluate changes in the technological process. Theoretically, this means that each current result can be an element of an unknown statistical array. Therefore, a specific algorithm for processing and presenting results is necessary for current analysis, which is capable of ensuring technical decisions both in real time and remote analysis.

The main requirements for this model are:

1) Evaluation of the tendency of control parameter change as a function of technological time (technological trend) and separation of the trend and random deviations.

Such a separation is possible with the help of a well-known statistical trend model with an error [11]. It is used to estimate the trend during the high voltage tests of enamel insulation [10].

2) Ignoring the classical principle "more measurements – greater accuracy" by selecting an elementary segment Δt of technological time for which statistical data processing is performed. Application of statistical procedures of discrete interval models [11] to analyze and make current technical decisions regarding each wire spool (EFHP system) or during a defined technological period (hour [9], day, etc.) as part of the entire technological cycle.

3) We need to ignore the normative mathematical principles of assessing the reliability of technological systems [12], which are the limit of the number of controlled parameters. Technical and economic considerations lead to this limit, but not mathematical ones. It is obvious that the more control parameters, the more information, the more accurate the forecast is. The usage of well-known universal mathematical procedures for the empirical parameter evaluation of the flow of events (intensity of events) to estimate the probability of finding a technological system in a controlled state should provide an open spectrum of control parameters necessary for analysis (multi-parameter control).

The presence of a technological trend of $f(t)^*$, frequencies of appearance of different defect groups in successive producing periods (Fig. 1) is obvious. For its quantitative assessment (requirement 1), the data from Fig. 1 are presented in Fig. 2 in the form of the average number of defects in all four groups of defects during successive segments of technological time Δt = 5 hours (requirement 2).

For all four control parameters $f_1(t)$; $f_2(t)$; $f_3(t)$; $f_4(t)$ trend is different not only in magnitude, but also in sign, so it must be evaluated separately.

For sufficiently small Δt compared to the technological cycle (several days), the simplest linear approximation of the trend is shown in Fig. 3.

According to the data in Fig. 3 we obtain:

$$er(t) \ = a + b \cdot (t - t_{av}) \,, \qquad (1)$$

where a = 345,5 *er*; b =– 209,8 *er/h*

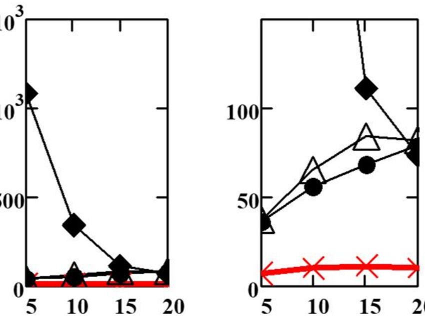

Fig. 2. The average number of defects in all four groups of defects during consecutive segments of the technological time Δt = 5 hours at different scales along the er axis: × – group 1, er < 4; Δ – group 2 (3< er < 9); ● – group 3 (8< er < 18); ♦ - group 4, er > 18.

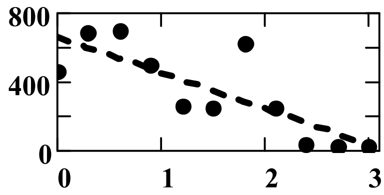

Fig. 3. The example of evaluating the trend of the defects number by linear approximation during the production of 11 coils of wire.

A rough trend calculation makes it possible to estimate the flow parameter $\omega^*(t)$ of the defect number exceeding the current technological limit, for example by $M^*[er] + k{\cdot}\sigma^*[er]$, where M^* and σ^* are mean and root mean square deviation estimates of the technological time segment Δt. Thus, the flow parameter $\omega^*(t)$ is:

$$\omega^*(t) = er(t) \,/\, (M^*\left[er\right] + k \cdot \sigma^*[er]) \cdot \Delta t \,, \qquad (2)$$

where k can be chosen for technical reasons like the basic value for the exponential distribution of the defects number [9]: k = 1.

The simple evaluation of the flow parameter $\omega^*(t)$ of the defect number exceeding the set technological limit (the "failure" flow parameter) during short segments of the technological time, for example, for each spool of wire (several thousand meters of wire), allows quantitative comparison of the influence of different control parameters on the probability of finding the technological system in a controlled state. The results of evaluating $\omega^*(t)$ according to formula (2) during 20 hours of continuous operation of the enamel line are in a fairly narrow range from 0.4 h^{-1} to 0.6 h^{-1} for parameters $f_1(t)$; $f_2(t)$; $f_3(t)$ (low-defective groups of 100 m wires) and a significantly wider range from 0.1 h^{-1} to 1.2 h^{-1} for $f_4(t)$ (groups of the most defective 100 m wires).

The instability of the parameter $f_4(t)$ is its feature, which is shown in Fig. 4.

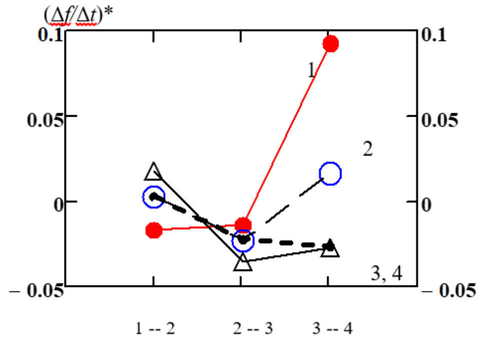

Fig. 4. Evaluations of changes in the frequency of appearance of various defect groups per unit of technological time for four consecutive periods of the technological cycle:
• – 0 ... 5 hours; ○ – 5 ... 10 hours; Δ, • – 10 ... 20 hours.

In Fig. 4, the dependence ($\Delta f/\Delta t$)* (empirical estimate of the distribution density of the number of defects in the spool) of the defectiveness growth is the important indicator of the insulation defectiveness in different technological periods: dependences Δ and • are characteristics of a normal period; • is the characteristic of a run-in period; ○ has a transitional character.

Additional parameter $f_5(t)$ = ($\Delta f/\Delta t$)* with sufficiently small Δt can be used as information about the duration of the run-in period (desirable to be reduced), the normal isolation period (desirable to be increased), the "fatigue" period (it is desirable to limit the duration of continuous cycle). Thus, the more control parameters, the more information, the more accurate the forecast is.

Technological control in real time should be multiparametric, but the role of each of them in the process of analyzing the results may be different depending on the specific parameters of the technological process. The ability to make operational decisions in real time requires using statistical control model, which makes it possible to summarize the information of the entire range of parameters, taking into account their weight when making operational decisions.

The idea of convolution of several event flows with different parameters of stationary flows is not new [13]. Its use in each specific case requires matching the mathematical apparatus of the convolution of functions with the technical meaning of the parameters and with its technological capabilities under production conditions. It is obvious that such a definition in production conditions should take into account the volume of production and should be based on well-known and indisputable statistical models. A one-time, even multiple, study of statistical stability is practically impossible to be performed. The concept of solving applied problems for estimating probabilities is the known concept of Mises [7]: the frequency $f^*(A)$ of an event A is the fraction in which a numerator is the number of occurred events $m^*(A)$ and a denominator is the number of independent attempts n^* in identical conditions under which those events could occur: $f^*(A) = m^*(A)/n^*$. Here and further, the sign "*" is used for values determined experimentally. The requirement of reproducibility of the phenomenon with frequency determination acquires a quantitative expression in the form of the frequency constancy principle:

$$m_1{}^*(A)/n_1{}^* \cong m_2{}^*(A)/n_2{}^* \cong \cong m_2{}^*(A)/n_2{}^* \cong ..m_k{}^*(A)/n_k{}^*, \qquad (3)$$

that is, Δt in formula (2) should be small enough as compared with the technological cycle or its part to be analyzed. In this case, the generally accepted statistical procedure in practice is the use of the exponential law of distribution and the corresponding flow of events.

The developed algorithm uses a convolution of four exponential functions according to four control parameters:

$$\begin{aligned} P(t) &= p(t) + p_1(t) + p_2(t) + p_3(t) + p_4(t) \\ p(t) &= e^{[-\Sigma\omega(t)_i \cdot t]},\ i = 1,\ 2,\ 3,\ 4 \end{aligned}, \qquad (4)$$

$$p_1(t) = \frac{\omega(t)_1 \cdot [e^{(-2\omega(t)_1 \cdot t)} - e^{(-t\cdot(\omega(t)_2+\omega(t)_3+\omega(t)_4))}]}{\omega(t)_2 + \omega(t)_3 + \omega(t)_4 - 2\omega(t)_1}, \qquad (5)$$

$$p_2(t) = \frac{\omega(t)_2 \cdot [e^{(-2\omega(t)_2 \cdot t)} - e^{(-t\cdot(\omega(t)_1+\omega(t)_3+\omega(t)_4))}]}{\omega(t)_1 + \omega(t)_3 + \omega(t)_4 - 2\omega(t)_2}, \qquad (6)$$

$$p_3(t) = \frac{\omega(t)_3 \cdot [e^{(-2\omega(t)_3 \cdot t)} - e^{(-t\cdot(\omega(t)_1+\omega(t)_2+\omega(t)_4))}]}{\omega(t)_1 + \omega(t)_2 + \omega(t)_4 - 2\omega(t)_3}, \qquad (7)$$

$$p_4(t) = \frac{\omega(t)_4 \cdot [e^{(-2\omega(t)_4 \cdot t)} - e^{(-t\cdot(\omega(t)_1+\omega(t)_2+\omega(t)_3))}]}{\omega(t)_1 + \omega(t)_2 + \omega(t)_3 - 2\omega(t)_4}, \qquad (8)$$

where $\omega(t)_i$ is the flow parameter $\omega^*(t)$ of the number of defects beyond the current technological limit of the parameter $f_i(t)$.

Estimates of the probability that the number of defects does not exceed the established limit for at least three of the four parameters $f_i(t)$ are shown in Fig. 5.

It is important that according to formula (4), the possibility of one of the spectrum of interrelated parameters exceeding the technological limit is acceptable for the tasks of current technological control, since the control is nondestructive and the parameters are interrelated. The control is designed to record and analyze the changes in parameters at production in short segments of technological time, for example, for each spool of wire (several thousand meters of wire).

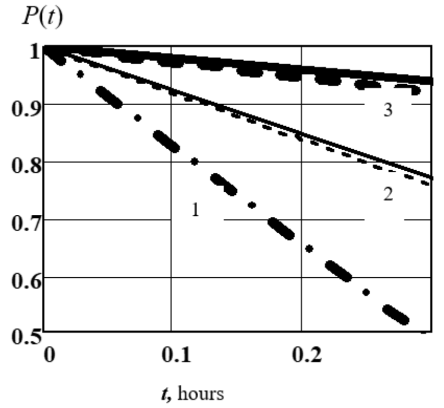

Fig. 5.The probability P(t) that the control parameters are within the established technological limits during the production of one spool of wire (≈ 3600 m): 1 – the fault-free model for 4 parameters, according to which none of them exceeded the limits accepted for it (the more parameters, the lower the fault-free); 2 – the fault-free model for the 1st parameter (it is not permissible for the parameter to exceed the limit set for it) in the normal technological period (the defectiveness is constant): solid line for the parameter $f_2(t)$; dashed line for parameter $f_3(t)$; 3 – the failure-free model for 4 parameters, according to which it is permissible for one of any parameters to exceed the limit set for it: the solid line corresponds to the extended permissible range.

The comparison of the curves in Fig. 5 shows that the use of a no-failure model in technological control for the parameters spectrum, according to which none of them would exceed the accepted limits (increasing the number of control parameters leads to a sharp no-failure decrease) is theoretically unacceptable (the control parameters are not completely independent). Applying this principle even to one parameter in the most favorable technological period (curves 2) does not ensure sensitivity to technological changes (solid and dashed).

The use of a model that allows one of the interrelated parameters to exceed its limit ensures sensitivity to changes in this limit (curves 3 differ only in the value of the coefficient k in formula (2): solid k=1; dashed k=0.2). Fig. 6 shows more detailed data on this model sensitivity to technological changes. Additionally, the model based on the information convolution of a significant number of control parameters is quite flexible. If one or more parameters are absolutely independent and (or) critically important for making a current technological decision, then the influence of such parameter(s) can be taken into account by removing the corresponding application (formulas 5-8) and leaving this parameter in formula (4).

The use of multi-parameter technological control is a means of adjusting the technological process by flexible non-destructive control of insulation defects according to the achieved level and sensitivity of both of them to the established technological limit of each control parameter and to changes in the technological process. The estimation of $P(t)$ during the production of the wire spool allows the quantitative comparison of the influence of various control parameters on the probability of the system being under control.

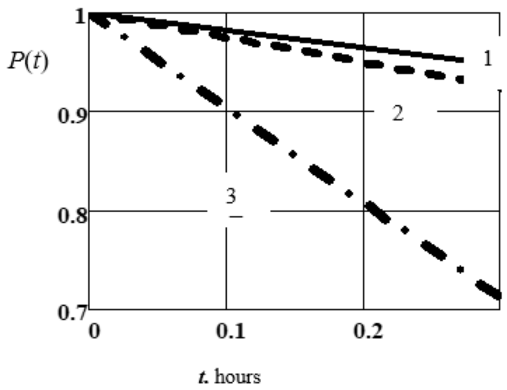

Fig. 6. The probability P(t) that the control parameters does not exceed technological limits during the production of one spool of wire (≈ 3600 m) according to the fail-safe model for 4 parameters, according to which it is permissible for one of any parameters to exceed the limit set for it: 1, 2 – correspond to the run-in period (from 0 to 5 hours, defectiveness is increasing, trend – defectiveness is decreasing): solid curve (1) corresponds to an extended permissible range compared to the range for dashed curve (2); dotted line (3) corresponds to the data of the run-in period and, if the range of permissible values is narrow, the period of a normal technological process (defectiveness is relatively small and constant)

The comparison of the curves in Fig. 6 shows that the use of a model allowing one of the interrelated parameters spectrum to go beyond its limit provides sensitivity to technological changes.

3. Conclusions

1. A statistical model (formulas (1) ... (8)) of processing the results of four-parameter technological control in real time during the high voltage spark tests under the conditions of automated production of modern enameled wires has been developed.

2. Insulation testing with high voltage during the production of modern enameled wires based on polyimide copolymers is a means of setting up the technological process by means of flexible non-destructive control of insulation defects according to the achieved level. Real-time control of four parameters by the DC spark voltage test, which are the frequencies $f(t)$* of the appearance of different defect groups, makes it possible to adjust the control procedure by choosing the values of the test voltage and the critical current through the insulation, whose values are important control parameters.

3. It is proposed to use the fifth additional parameter $f_5(t)$ – the empirical estimate of the density distribution

of the number of spool defects. It is shown that this parameter is an important indicator of insulation defects in different technological periods and can be used as information about the duration of the run-in period (it is desirable to reduce it), the normal period of isolation (it is desirable to increase it), the onset of the "fatigue" period (it is desirable to limit the duration of a continuous cycle).

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СТАТИСТИЧНА МОДЕЛЬ ОБРОБЛЕННЯ РЕЗУЛЬТАТІВ ТЕХНОЛОГІЧНОГО КОНТРОЛЮ ПРИ ВИПРОБУВАННЯХ ІЗОЛЯЦІЇ ЕМАЛЬПРОВОДУ ВИСОКОЮ НАПРУГОЮ НА ПРОХІД В УМОВАХ ВИРОБНИЦТВА

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Представлено результати неруйнівного технологічного контролю кількості дефектів в ізоляції емаль проводу на основі поліефірімідного полімеру. Розглянуто застосування статистичного аналізу результатів вимірювання показників контролю за допомогою математичної моделі тренду для використання результатів в активному технологічному контролі. Запропоновано рекомендації щодо практичного використання параметрів функції тренду для контролю ймовірності знаходження кількох параметрів у встановлених межах. Основним параметром тренду є параметр кількості дефектів за встановлену технологічну межу (параметру потоку «відмов») на коротких відрізках технологічного часу, наприклад для кожної котушки проводу (кілька тисяч метрів проводу). Теоретично показана і вимірюваннями підтверджена можливість кількісної оцінки тенденції зміни дефектності емаль ізоляції для проводу ПЕЕІДХ2 – 200 з двошаровою ізоляцією номінальним діаметром 0,63 мм впродовж не-перервного технологічного циклу. Кількісна оцінка тенденції зміни дефектності емаль ізоляції дозволяє застосувати модель, основану на згортанні інформації про значну кількість контрольних параметрів. При цьому допускається вихід одного з спектру взаємопов'язаних параметрів за встановлену технологічну межу, що забезпечує чутливість до зміни цієї межі. Наведено дані про чутливість цієї моделі до технологічних змін.

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