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A STATISTICAL MODEL OF MONITORING OF INSULATION BREAKDOWN VOLTAGE STABILITY IN THE PROCESS OF ENAMELED WIRES PRODUCTION

This paper is devoted to non- destructive technological monitoring of defects of insulation of enameled wires with poliimid polymer. The authors present a statistical method for processing, comparison and analysis of outcomes of measurements of parameters of insulation of enameled wires. A mathematical model of trend for application in active technological monitoring is developed to develop recommendations for parameters of such monitoring. It is theoretically justified and the possibility of a diminution of dependence of an error on the velocity of movement of a wire for want of quantifying defects of enameled insulation using non- destructive tests by high voltage is shown. The dependence of average value of amount of defects for enameled wires with two-sheeted poliimid insulation in a range of nominal diameter* 0.56 *mm is experimentally determined. The technological monitoring purpose is to reduce quantifying defects of enameled insulation. References 12, figures 4.

Key words: **enameled wire, poliimid insulation, insulation defectiveness, technological monitoring, statistical model, voltage tests.**

Представлено результати технологічного контролю напруги пробою ізоляції емаль проводу на основі поліімідного полімеру. Розглянуто застосування статистичного аналізу результатів вимірювання показників контролю за допомогою інтервальної статистичної моделі для використання результатів в активному технологічному контролі. Запропоновано рекомендації щодо практичного використання інтервальної статистичної моделі для визначення гарантованого рівня відносної дисперсії контрольованого параметру. Представлена кількісна оцінка відносної дисперсії δ напруги пробою U впродовж тривалого технологічного циклу. Теоретично показана і вимірюваннями підтверджена можливість надійної кількісної оцінки тенденції зміни дефектності емаль ізоляції для проводу ПЭЭИДХ2 – 200 з двохшаровою поліімідною ізоляцією номінальним діаметром 0,56 мм впродовж тривалого технологічного циклу. Визначення кількісної оцінки тенденції зміни дефектності емаль ізоляції дозволяє також виділити і кількісно оцінити випадкову похибку технологічного процесу – сумарну похибку результатів технологічного контролю, яка є кількісною характеристикою випадкової складової стабільності технологічного процесу. Застосування методів інтервальної статистики дозволяє одержувати достовірні (надійна ймовірність дорівнює одиниці) числові оцінки навіть для окремої серії невеликої кількості вимірів, до яких не ставлять вимоги ні статистичної сталості, ні взаємної незалежності. Бібл. 12, рис. 4.

Ключові слова: **емаль провід, поліімідна ізоляція, дефектність ізоляції, технологічний контроль, статистична модель, випробування напругою.**

Представлены результаты определения напряжения пробоя изоляции эмаль провода на основе полиимидного полимера. Выполнен статистический анализ результатов с помощью методов интервальной статистики с целью использования интервальной статистической модели в активном технологическом контроле. Представлена количественная оценка относительной дисперсии δ напряжения пробоя U в течение длительного технологического цикла. Теоретически показана и экспериментально подтверждена возможность количественной оценки тенденции изменения дефектности эмальизоляции для провода ПЭЭИДХ2 – 200 с двухслойной полиимидной изоляцией номинальным диаметром 0,56 мм в течение технологического цикла. Это позволяет выделить и количественно оценить случайную ошибку технологического процесса – суммарную ошибку результатов технологического контроля, которая является количественной характеристикой случайной составляющей стабильности технологического процесса. Использование методов интервальной статистики дает возможность получать достоверные (доверительная вероятность единица) интервальные оценки даже для небольшого количества измерений, к которым не предъявляют требования ни статистической устойчивости, ни взаимной независимости. Библ. 12, рис. 4.

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

Problem definition. The introduction of enameled wires based on poliimide synthetic copolymers with a temperature index of 200 ºC, which have the highest modern level of electrical, mechanical strength and minimum thickness of insulation [1, 2], encountered contradictions characteristic of innovation in cable products. This is a contradiction between the relatively high cost of products and the need to organize the use of advanced state-of-the-art monitoring technologies. In the case of the mentioned wires it is an online monitoring of insulation defectiveness immediately after the exit from the enamel furnace by non-destructive test on passage with high constant voltage. The system of this monitoring is part of the automatic lines with high speeds (MAG unit up to 1000 m/min) [2].

Active online defectiveness monitoring by non-destructive test on the pass is one of the most promising methods of monitoring in cable production, which is characterized by significant lengths of products with high homogeneity along the length. Particularly relevant online defect monitoring by non-destructive test on the pass is for enameled wires, for which the length to the diameter ratio reaches tens of millions.

The effectiveness of using such monitoring for a particular manufacturer when introducing enameled wires on the base of poliimide synthetic copolymers leads is that the control parameters must be determined by the user from wide available ranges (for example, test voltage of 400 V to 4000 V every 100 V) that should be defined for each type of product. Consequently, the analysis of results and the development of technical requirements for each type of product is a separate scientific and technical task, the solution of which requires considerable time and cost.

As a result, one of the most promising methods of monitoring in cable production, for which there is a ready-made modern verified equipment, remains unused in real production.

The problem is the need to develop and implement a system of technical and organizational solutions for the use of a modern online monitoring system for insulation defectiveness during tests on the passage under production conditions with the obligatory connection of technical parameters of monitoring to the achieved level of technology and technical requirements, which requires significant additional costs.

The problem, at first glance, is such that for manufacturers during the development period of known in the world, but innovative for these product manufacturers, there is no solution from an economic point of view. The well-known concept of «Six Sigma» («6σ») [3] can serve as an indirect but real confirmation of this pessimistic conclusion. In it, the criterion for the quality of mass products or services in marketing is the ratio of the size of the range of admissible values of the main parameter to the experimentally determined root of the square of the dispersion ($\sigma = \sqrt{D}$). The concept of «Six Sigma Methodology» is a demonstration of the achievements of leading manufacturers and does not include a methodology for achieving achievements (why not «7σ»?). And the more the technological cycle is automated, the problem of organizing the use of the modern system of technological online defectiveness monitoring is more urgent, since between the tasks of receiving and current technological monitoring there is a significant theoretical and technical difference [4]. The problem of organizing active online technological monitoring is conceptualized for automated mass production.

Analysis of literature. The first works devoted to the tasks of technological monitoring, dated from the beginning of 60-ies of the twentieth century, and the result is formulated in [5], where the main thing is that in the very formulation of the question of technological monitoring, it was recorded the possibility of changes in the technological process and the need to identify and quantify these changes [1]. In theory, this means that each measurement result is an element of an unknown statistical array. Therefore, the classical (canonical) measurement model, which requires the fulfillment of three conditions below, is not applicable to the results of the measurements of technological monitoring. These conditions are [3]:

- measurement time is not limited;
- measured value retains the true value unchanged throughout the measurement cycle;
- all factors affecting the result are identified.

None of these conditions can be a condition for the implementation and analysis of the results of technological monitoring.

Since the problem of organizing the use of the modern system of technological online monitoring is closely linked to the economic component of innovation in mass production, in [11] it is proposed to resolve the contradiction between the high cost of products and the price factor as a liquidity criterion precisely for wires with poliimide insulation by reducing the level of requirements for voltage breakdown agreed with the customer. In essence, it is an announcement of capitulation to the problem of the introduction of this innovative product due to the complexity of the organization of the use of the modern system of technological online defectiveness insulation monitoring, with which enamel aggregates of world manufacturers of the equipment are equipped.

Technological monitoring in automated high-speed continuous cycles of modern cable production requires, apart from practically instantaneous efficiency (online mode) [2, 3, 5], the separation of the deterministic and random components of the array of measurement results.

Therefore, for the purposes of technological monitoring, firstly, a statistical model of measurements is acceptable, in which the measured value is a sequence of reflections of the current state of the object of measurement. Here, the true value of the measured value is uncertain [2], but their interval in this segment of the technological time is completely determined.

The interval approach to the statistical determination of technical parameters is proposed by the concept «6σ« [3], whereby the coefficient of homogeneity $K\sigma$ is determined by the dispersion of the controlled parameter X: $K\sigma = |CL - X_{av}|/(D[X])^{0.5}$ at the lower limit, $K\sigma = |CS - X_{av}|/(D[X])^{0.5}$ at the upper limit, where CL, CS are, respectively, the lower and upper limits, agreed with the customer of the product. A step forward in the concept of «6σ« is the definition of the coefficient of homogeneity by the value of the permissible margin of the parameter, agreed with the customer of the product. But, firstly, for the determination of $K\sigma$, large arrays of data obtained under the same conditions are required, which makes it impossible to make decisions in the conditions of operational technological monitoring.

Secondly, in this concept there are no components that would allow a gradual reduction of the dispersion of the controlled parameter that should be the main objective of operational technological monitoring in a stable production environment.

Modern methods of interval statistics are based on axioms, the first of which is: for all the restricted features f, belonging to J_{00}: = $\{f\colon \sup|f(x)| < \infty\}$ there are interval means $M_{\min}(f)$; $M_{\max}(f)$ which are within the limits of values of f. According to the axiom of the transform [6] for all the lower bounds of the features: $M_{\min}(-f) = -M_{\max}(f)$. That is, the replacement of a sign in the class features J_{00} leads to the class $-J_{00}$, which has lower means $M_{\min}(f)$, and there are interval means on the section of these classes [6].

The unambiguous connection between the lower and upper means, by replacing the array sign, convenient for the mathematical description [6], is not applicable to many control technical parameters. In the tasks of technological monitoring in cable technology, a situation is typical where the measured parameter x only accepts positive values, and the technological boundary can be both bi-sided and one-sided. In particular, when defectiveness control is monitored on MAG in online mode, the number of defects *er* on the length of 100 m is positive ($er \geq 0$) [4] (EFHP system of the MAG-ECOTESTER Company).

In this case, the entire set of functions of the primary features $f_j(x)$ of the technological monitoring can be represented by the weighting functions $g_{j,i}(x) \geq f_j(x)$, each of which belongs to a semi-linear shell with non-negative coefficients c^{+}_{i} and an arbitrary substitution c for each feature j: $g(x) = c + \sum c^{+}_{i}\, g_i(x)$. The approximation is more precise if Mg is known, in particular, if $Mg = 0$, i.e. the major function $g(x)$ is centered [6]. This can be achieved by using the difference between the measured and the mean values as the primary feature $Y = x – M[x]$.

The construction of secondary features consists in the choice of the values of arbitrary C and the non-negative coefficients $C_i^{(+)}$, so that the secondary features are minimally (as far as possible) majored primary ones, that is, $g_i(Y_j) \geq f_i(Y_j)$. This scheme can be applied to any parameter. Therefore, we will simply denote $g(Y), f(Y)$.

If the primary function $f(Y) = Y^2$, when the majored one $g(Y) = C + C_2^{(+)\cdot} Y^2$. If the upper bound as a limit of possible values of Y equals to $E_{\max}$, when at $C = 0$; $C_2^{(+)} = 1/E^2$. $g(Y)$ at $Y \geq E_{\max}$ majors $A(Y)$, which is a relative number of feature $Y = [E, E_{\max}]$ values:

$$A\{E \leq Y \leq E_{\max}\} \leq Y^2/E^2. \qquad (1)$$

By the axiom of the conservation of order, if $g(Y)$ majors $A(Y)$, then its upper average is no less than the upper average $A(Y)$, this inequality can be written for the corresponding mathematical expectations:

$$M_{\max}[A\{E \leq Y \leq E_{\max}\}] \leq M_{\max}[Y^2]/E^2, \qquad (2)$$

where in the left part of the inequality the upper average of the relative number of measurements in which the parameter has taken values in the specified interval is nothing more than the upper limit of the interval probability of exceeding the boundary E. Substituting in (2) the statistical estimate of the upper mean $M_{\max}[Y^2] = M^*[Y^2]$ gives a statistical estimate of the probability of exceeding the limit:

$$P_{\max}\{E \leq Y \leq E_{\max}\} \leq M^*[Y^2]/E^2. \qquad (3)$$

If the initial feature is $Y = x – M[x]$, then its mean is zero $M[Y – M^*[Y]] = 0$. Then the majoring function can be selected in the form of a parabola with three parameters:

$$g(Y – M^*[Y]) = C + C_2^{(+)}\,((Y – M^*[Y]) – C_1)^2, \qquad (4)$$

that after transformations gives the formula for maximum probability of output of the parameter Y from the upper technological limit α:

$$P_{\max}\{0 \leq Y \leq \alpha\} \leq (1+\alpha^2/M_{\max}[(\Delta Y)^2])^{-1}. \qquad (5)$$

The use of (5) gives a reliable (reliable probability equal to one) numerical estimates of $P_{\max}$ for a separate series of small amounts of measurements, which are not subject to either statistical stability or mutual independence. Inequality (1) is analogous to the well-known Chebyshev inequality, that is, the interval model (5) extends the possibilities of applied statistical methods without contradiction with the fundamental probability theory [6].

The main point is that the use of interval models allows to create unified statistical models that are adequate to the essence of the tasks of technological monitoring, since these tasks question the statistical stability of the measured features.

In [12], based on model (5), a method is proposed for controlling the output of a technical parameter from the normative limit. The technical tool of the method is a control card based on the application of (5) for determining the maximum probability of $P_{\max}$ of that the control technical parameter (for example, breakdown voltage of the enamel or other) will go beyond the prescribed normative limit. The $P_{\max}$ control card can be applied to any technical specification that is appropriate to control. Primary in this approach is the mean value of the feature, and the concept of probability corresponds to the average value of the relative number of such values (incidence).

The goal of the work. In order to increase the efficiency of technological monitoring in automated cable production (online mode is provided with innovative equipment), it is necessary to separate the deterministic and random components of the array of measurement results of the technological parameter:

- the deterministic trend of the parameter is evidence of changes in technology, the causes of which must be determined and a corresponding technological solution must be adopted;
- the random component is the sum of the statistical errors of the technological process, the individual reasons of which in the online mode is practically impossible to determine; this component must be reliably estimated for the entire set of control parameters as a comparable dimensionless value, for example, the relative variance of the parameter.

To obtain a reliable (reliable probability equal to one) numerical estimates of the relative parameter dispersion, to develop, based on the use of interval statistical models, a statistical control card applicable to the entire set of parameters that are controlled during the manufacture of the enameled wire and to verify its applicability in the production conditions.

Using the control card of the relative dispersion of the parameter in the system of ensuring homogeneity of the enterprise products will unify the definition of the random component for the whole set of parameters (in the manufacture of enamel wires based on poliimide synthetic copolymers of more than 10 parameters), which significantly reduces the amount of processing procedures for technological monitoring data and increases its efficiency.

Main results. The results of technological monitoring are a discrete array of numerical values $\boldsymbol{\chi}$. This array is the vector of primary features $\boldsymbol{\chi} = \{x_1, \ldots, x_r\}$, each element of which can be matched to the frequency of occurrence of this value, the average values of which for this array form the probability vector:

$$\boldsymbol{P} = \{p_1, \ldots, p_r\},$$

where r is the number of the measured values.

Vector of secondary features: $\boldsymbol{f} = \{fx_1, \ldots, fx_r\}$.

The mean value of the secondary feature of the array χ is the scalar product of the vectors $\boldsymbol{f}$ and $\boldsymbol{P}$:

$$Mf = \sum fx_i \cdot p_i, \text{ where } i = 1, \ldots, r. \qquad (6)$$

This formula is valid at the exact fulfillment of the condition

$$\sum p_i = 1,\ \text{where}\ i = 1,\ \dots,\ r, \qquad (7)$$

which in reality is impossible, first of all, due to the limited data. Therefore, for the mean value of the secondary feature of the array χ, the only reliable estimate is the interval:

$$M_{\min} f = \inf Mf; \qquad M_{\max} f = \sup Mf. \qquad (8)$$

The choice of indicators and the required boundary of the evaluation interval is a purely technical task.

For example, an experimental study during the technological cycle of the breakdown voltage U of insulation of the wire with a nominal diameter of 0.56 mm indicates that during different technological periods the dynamics of the diametrical thickness t of the enamel can vary significantly (Fig. 1).

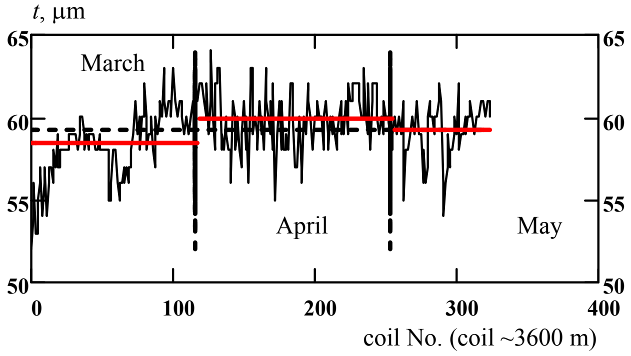

Fig. 1. Dynamics of diametrical thickness t change of enamel of wire with nominal diameter of 0.56 mm during different technological periods

One of the main indicators of the quality of the enameled wire is the breakdown voltage U. Therefore, the evaluation of the effect of this change in the diametrical thickness t of the enamel on the breakdown voltage is crucial in selecting the control parameters and the required boundaries of the evaluation interval and is of great practical importance in the production conditions.

For the breakdown voltage the vector is the primary feature is $\boldsymbol{\chi} = \{U_1,\ \dots\ ,\ U_r\}$, the vector of the secondary feature: $\boldsymbol{f} = \{fU_1, \dots, fU_r\}$, where $fU_i = [(U_{i+1} - U_i)/U_{i+1}]^2 = \delta_i$ from point of view of the need to center the feature and technically feasible restriction on top.

It also solves the problem of comparing the results of measuring various control parameters.

By (6) the average value of the secondary feature of the array $\boldsymbol{\chi}$ is the scalar product of the vectors $\boldsymbol{f}$ and $\boldsymbol{P}$:

$$Mf = \sum \delta_i \cdot p_i,\ \text{where}\ i = 2, \dots, r, \qquad (9)$$

and for the purpose of determining p_i we used of a normal law of distribution of probabilities, the suitability of which in this case is illustrated by Fig. 2, the suitability test on condition (7) is illustrated by Fig. 3, where the experimental points of the relative dispersion of the breakdown voltage are plotted on the derivative of the normal distribution function.

Condition (7) (Fig. 3) is approximated, which further indicates the necessity of using interval estimates in the monitoring of technical parameters. In the example given, condition (7) is reliably executed for $r \geq 17$, so r can not be arbitrarily selected, but must be chosen as $r = \inf r\ (\sum p_i = 1)$.

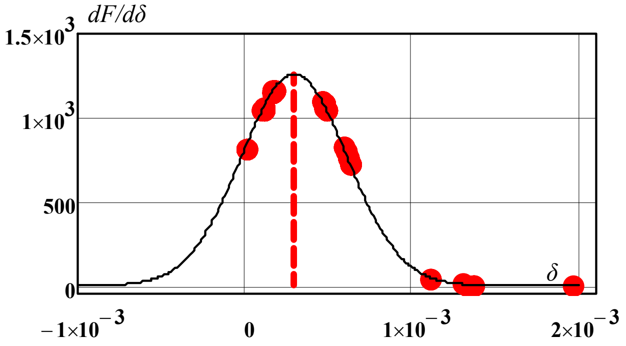

Fig. 2. Comparison of the theoretical density of normal distribution (solid curve) and approximation of the distribution density of experimentally determined values of δ_i by normal distribution (324 experimental values)

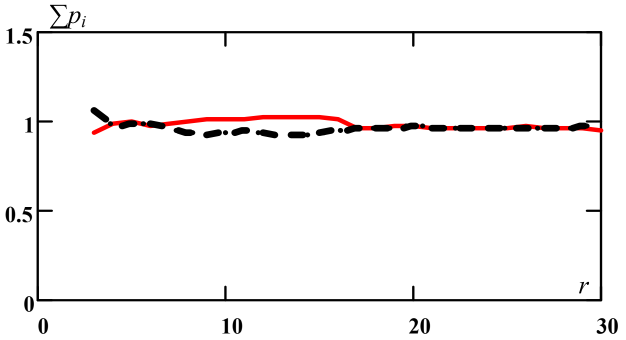

Fig. 3. On checking the fulfillment of condition (7) for the interval estimation of the relative breakdown voltage dispersion of the wire with nominal diameter of 0.56 mm

The average values of the secondary features for the data arrays at $r = 30$ determined by (8) in different technological periods are shown in Fig. 3, which confirms that condition (7) is reliably executed for $r \geq 17$.

Estimates $Mf_{\max} = \sup(Mf_i)$ for $r = 30$ indicate that in the various technological periods (see Fig. 1), the upper average relative dispersions of the breakdown voltage are different:

$Mf_{\max}1\ (i = 1, \dots, 117) = \sup(Mf_i(i = 1, \dots, 117)) = 4.2 \cdot 10^{-4}$;

$Mf_{\max}2\ (i = 118, \dots, 255) = \sup(Mf_i(i = 118, \dots, 255)) = 4.3 \cdot 10^{-4}$;

$Mf_{\max}3\ (i = 256, \dots, 324) = \sup(Mf_i(i = 256, \dots, 324)) = 4.0 \cdot 10^{-4}$.

The dependence $Mf(\delta)$ for $r = 30$ over a long-term technological period is presented in Fig. 4, which shows a stable decrease in the relative dispersion of the breakdown voltage for $i = 148, \dots, 255$, that is, during a period with a higher average thickness of the insulation (see Fig. 1). Fig. 4 is an image of the control card of the relative dispersion of the breakdown voltage, on which the rigid boundaries of regulation based on normal distribution [12], corresponding to the range $M[\delta] \pm \sigma[\delta]$, which is up to 30 % of the values, are applied. For technical reasons, the relative dispersion should be limited only to the maximum allowable value.

Fig. 4 shows that $Mf_{\max} < M[\delta] + 3\ \sigma[\delta]$, in normal distribution, that is, corresponds to the known criterion of maximum product homogeneity [12].

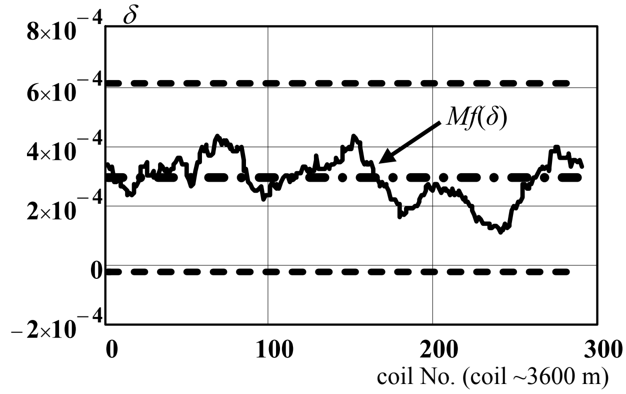

Fig. 4. Statistical control card of the dependence $Mf(\delta)$ for $r = 30$, which shows a stable decrease in the relative dispersion δ of the breakdown voltage during April (Fig. 1) when there was a tendency to decrease the thickness of the enamel

Conclusions.

1. To obtain reliable (reliable probability equal to one) numerical estimates of the relative dispersion of the parameter on the basis of the use of interval statistical models, a unified statistical control card of the relative disperse of the parameter, applicable to the whole set of parameters that are controlled during the manufacture of the enameled wire, has been developed. The verification of its applicability in the production conditions is carried out on the example of the monitoring of breakdown voltage U of the wire with two-layer poliimide insulation with nominal diameter of 0.56 mm. Using the unified control card of the relative dispersion of the parameter in the system of ensuring homogeneity of the enterprise products will significantly reduce the amount of processing procedures for technological control data (more than 10 parameters).

2. For three months, the relative dispersion of the breakdown voltage of the wire did not exceed 0.05 % (reliability of the estimation is equal to one), which testifies, firstly, to the stability of the technological process in relation to the electrical strength of the enamel of insulation, and, secondly, on the appropriateness of the use of interval statistical models in the analysis of technological control results.

3. Centering the feature and technically expedient upper restriction for it allow to solve the problem of comparing the results of measurement of various control parameters.

4. Estimates of the maximum average $Mf_{\max}$ of the relative dispersion δ of the breakdown voltage U of the wire over a long-term period in the conditions of production and comparison of these estimates with the dynamics of diametrical thickness of the enamel wire t change showed that one of the reasons for the growth of the dispersion of the breakdown voltage is an increase in the thickness of the enamel of insulation.

5. The use of interval statistical models to obtain reliable (reliable probability equal to one) numerical estimates, even for individual series with a small number of measurements (a multiple sample of 30), which are not subject to either statistical stability or mutual independence, is a promising method of analysis the results of technological monitoring in the conditions of the current production.

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