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MATHEMATICAL MODEL OF THE PROCESS OF CONTROLLING THE PARAMETERS OF INTERBLOCK ELECTRICAL CONNECTIONS

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Abstract. *The article discusses the issues of technological control of the insulation state of interblock electrical connections at the final stage of production. Due to the growing requirements for reliability and safe use of electrical systems, special attention is paid to the impact of temperature changes, electrical loads and higher harmonics on the quality of insulation materials.*

A key element of the work is the development of a mathematical model that allows you to evaluate the electrical resistance and thermal characteristics of the insulation. The model takes into account a variety of factors affecting the aging of materials and allows you to accurately predict their condition under the influence of external conditions.

The study highlights the importance of the mathematical model for identifying and evaluating possible degradation processes in insulating materials that can lead to a decrease in the reliability of electrical connections. The results obtained stimulate the further implementation of the appropriate automated control system using a mathematical model of the parameters of electrical connections at the final stage of cable production, increasing the overall level of product quality and safety.

Keywords: *Cable and wire products, interblock electrical connections, insulation condition, quality control, reliability, load currents, higher harmonics, power, integrity of the electrical circuit, electrical losses, temperature regimes, mathematical models.*

Introduction.

Modern electrical systems increasingly require high reliability and efficiency, as increasing demands on energy resources and process automation lead to increased component density and more complex designs. In such conditions, it becomes especially important to control the insulation condition of interblock electrical connections, since the quality of insulation materials directly affects the safety and efficiency of electrical devices.

The problem is compounded by the influence of various factors, such as temperature changes, the flow of load currents, as well as the presence of higher harmonics, which can cause significant thermal loads on insulating materials. Such factors can lead to degradation of insulation, a decrease in its electrical characteristics and, ultimately, to the failure of electrical connections.

Scientific studies demonstrate that traditional control methods, which are mainly based on manual measurements, are not always able to quickly and accurately detect problems related to the state of isolation. This increases the risk of defects and can lead to significant financial costs due to system failures. There is a need to introduce automated control systems that are able to adapt to changes in operating conditions and ensure timely detection of anomalies.

Therefore, the problem requires a holistic approach that combines materials science, electrical engineering and computer science to create an adaptive control system capable of integrating the latest technologies and algorithms. This will not only improve the quality of cable and wire products, but also ensure the safety of electrical systems in the conditions of modern industrial operation.

The work of Li, Zhang, Grzybowski and Liu (2012) investigates the characteristics of moisture diffusion in oil-paper insulation, which is important for understanding the terministic properties of insulating materials [1]. The results of this study help to assess the effect of humidity on electrical performance, which, in turn, affects the reliability of connections.

Lundgaard, Lillevik and Liland (2007) focus on the verification of the state of paper in transformers, which indicates the importance of material control in electrical systems [2]. This study highlights the need for regular inspections of the condition of insulation materials to ensure their durability.

Ahmed E.B. Abu-Elanien & Salama M.M.A. (2010) present asset management techniques for transformers, emphasizing the importance of a systematic approach to condition monitoring [3]. They note how timely diagnosis and maintenance can reduce the risks of defects.

A study conducted by Wang C., Bi Z.M. and Xu L.D. (2014) that analyzes the role of IoT and cloud technologies in design automation proves that the integration of the latest technologies can significantly increase the efficiency of production processes [4]. These technologies are already being used to improve monitoring of transformer parameters.

A study by Bi et al. (2017) in the context of IoT systems for communication by robotic teams highlights the need to integrate adaptive algorithms into industry [5]. This further defines the role of automated systems in managing workflows.

Further research by Bi et al. (2014) on IoT in modern manufacturing enterprises demonstrates how modern technologies can affect product quality due to the implementation of adaptive control systems [6].

The article by Bi Z.M., Pomalaza-Ráez C. and others (2014) discusses the implementation of adaptive machines to achieve systemic adaptability, which is essential for improving production techniques through the integration of new algorithms [7].

Cochran et al. (2017) analyze the design structure of production systems, proving that methods based on adaptive approaches can improve production results [8].

Bi Z.M. & Zhang W.J. (2000; 2001) deserve attention because of their contributions to the development of modular robotic configurations and modularity technology in industry, further illustrating the importance of adaptive methods in enabling manufacturing flexibility [9].

All the above studies indicate the need to develop automated control systems using mathematical models and adaptive algorithms to increase the parameters of safety and reliability of electrical connections, especially under the influence of variable temperatures and electrical loads.

The article is aimed at modeling the parameters of inter-unit electrical connections and developing on this basis an adaptive control process system that provides accurate monitoring of the insulation condition, taking into account the influence of temperature conditions and electrical loads.

In accordance with the set goal, a number of tasks have been identified that will be implemented:

- to perform a study of the influence of temperature changes on the process of heating insulating materials under the influence of electric currents;
- to analyze the problems associated with the flow of currents of higher harmonics and their impact on the electrical characteristics of cables;
- to develop a mathematical model for determining the electrical resistance of

interblock electrical connections.

Main text.

Monitoring the insulation condition of inter-unit electrical connections is a critical element in ensuring the reliability and safety of modern electrical systems. Therefore, the article discusses the determining factors that affect the quality of insulation materials, in particular temperature conditions and electrical loads.

One of the main problems is the influence of higher harmonics and load currents, which can cause overheating of the insulation and, as a result, its degradation. To study the thermal process, which is of a random nature, the analysis of statistical data of various heating factors was carried out: load current, reverse sequence current of the fundamental frequency, currents of higher harmonic components, smoothed over the time interval $\Delta t = 4 \cdot T_\theta$ during the observation period.

The appearance of currents of higher harmonics is due to the connection of electric receivers with a nonlinear volt-ampere characteristic of its own conductivity, as well as the presence of higher harmonics of the supply voltage in the connection points of the linear load.

Most of the electrical receivers of the low-voltage network, including non-linear ones, are single-phase load, and the network is made three-phase with a neutral wire. Thus, currents of all higher zero-sequence harmonics will flow in the neutral wire, the peculiarity of which is the absence of phase shift, as well as forward and reverse sequence currents caused by the uneven load of phase conductors when single-phase nonlinear electric receivers are connected to them.

As a result, in addition to heat proportional to the amount of active power losses and released in the case of flow of the fundamental frequency current through interblock electrical connections, heat is also released due to losses from currents of higher harmonic components in phase conductors, and heat from the flow of current through the neutral wire, which occurs due to currents of higher harmonics of zero sequence.

In the case of alternating current, there are losses both in the conductor where the current flows and in the insulation and in the protective metal sheaths. Additional losses in the conductors of interblock electrical connections at alternating current are explained by the surface effect. In connections with a large number of cores, there is an additional increase in resistance compared to DC resistance due to the proximity effect due to the influence of the cores on each other.

The electrical resistance of the conductor per unit length of the interblock electrical connection at alternating current is determined according to the formula that takes into account the surface effect and the effect of proximity [11]:

$$R_{жc\approx} = R_{жc\text{-}} \cdot \left(1 + y_n + y_\delta\right), \tag{1}$$

where y_n is the coefficient that takes into account the surface effect; y_δ — a coefficient that takes into account the effect of proximity; $R_{жc}$ is the value of the resistance of the conductor during the flow of direct current.

The value of the electrical resistance of the core per unit length of the cable during the flow of direct current is determined by the formula [12] in ohms:

$$R_{жc\text{-}} = \frac{\left(1 + k_0\right) \cdot l \cdot \rho_{20}}{S_{жc}} \cdot \left(1 + a_{20}\left(T_{жc} - 20\right)\right), \tag{2}$$

where ρ_{20} is the value of the electrical resistivity of the core material at 200°C; l - length of the core; $S_{жc}$ — cross-sectional area of the core, mm2; α_{20} — temperature coefficient, which takes into account the increase in the resistance of the core material; $T_{жc}$ - the maximum value of the operating temperature of the cable core; k_0 is the twisting coefficient, which takes into account the length of the wires from which the core is twisted (usually it is 0.03–0.05).

Let's calculate the coefficient that takes into account the surface effect using the formula [12]:

$$y_n = \frac{x_n^4}{192 + 0.8 x_n^4}, \tag{3}$$

where $x_n^2 = \dfrac{8 \cdot \pi \cdot f}{R_{жc-}} \cdot 10^{-7} \cdot k_n$, f is the frequency of alternating current,

k_n is a coefficient that depends on the design of the conductive core and is determined according to [13].

Formula (3) can be used if the surface effect is weakly expressed. Its criterion is $x_n < 2.8$. The value y_δ for the number of cores in cables equal to three or four is determined by the formula:

$$y_\delta = \frac{x_\delta^4}{192 + 0.8x_\delta^4} \cdot \left(\frac{d_{жс}}{h}\right)^2 \left[\frac{1,18}{\frac{x_\delta^4}{192 + 0,8x_\delta^4} + 0,27} + 0,312\left(\frac{d_{жс}}{h}\right)^2\right], \tag{4}$$

where h is the value of the distance between the axes of the conductors, $d_{жс}$ is the diameter of the conductor.

$$x_\delta^2 = \frac{8 \cdot \pi \cdot f}{R_{жс-}} \cdot 10^{-7} \cdot k_\delta, \tag{5}$$

Formula (5) can be used if the effect of proximity is weakly expressed, i.e., when $x_\delta < 2,8$

Let's determine the value of the active resistance of the conductor of the interblock electrical connection to the currents on the $n - iй$ harmonic (R_n) at according $n \geq 3$ to the formula [13]:

$$R_n = R_{жс\approx} \cdot \left(0,187 + 0,532 \cdot \sqrt{n}\right), \tag{6}$$

where $R_{жс\approx}$ is the value of the resistance of the conductor of the interblock electrical connection to the currents at the fundamental frequency, n is the harmonic number.

Let's determine the value of the released heat that occurs when non-sinusoidal currents flow through the phase conductors according to the formula:

$$\sum p_{фазн} = I_1^2 \cdot R_1 + \sum_{n=2}^{40} I_n^2 \cdot R_n, , \tag{7}$$

where I_1, I_n are the currents of the fundamental frequency and higher harmonics, $R_1\, i\, R_n$ are the values of active resistances at the fundamental frequency and higher harmonics of the current.

In the case of a nonlinear symmetrical load, currents of higher harmonics flow in the neutral conductor, which are multiples of three. The amount of heat that is released in this case is:

$$\sum p_{нул} = 3 \cdot \sum\nolimits_{n=3,9,15\ldots} I_n^2 \cdot R_n, \tag{8}$$

where I_n is the magnitude of the phase current that is created by harmonics in multiples of three.

For the case of a nonlinear and asymmetric load, when calculating the value of active power losses in the neutral wire, it is increased by three times the value of the square of the zero sequence current multiplied by the value of the zero sequence resistance.

Let's determine the total active power losses in the core of each phase $\left(\sum^{p^{фазн}}\right)$ as the total losses at the fundamental frequency and at higher harmonics:

$$\sum^{p^{фазн}} = P_1^{фазн} + \sum\nolimits_{n=2}^{40} p_n^{фазн} = I_1^2 \cdot R_1 + \sum\nolimits_{n=2}^{40} I_n^2 \cdot R_n \tag{9}$$

where is the harmonic number.n

To calculate the amount of active power loss at higher harmonics, harmonics from 2 to 40 are taken into account. For these voltage harmonics, normally permissible and maximum permissible values of the coefficients $n-x$ of harmonic components are set.

We will set the current at higher harmonics as a percentage relative to the fundamental frequency current. Let's denote this coefficient K_{In}.

Let's present the components of formula (9) using the coefficient K_{In} and values R_n according to [14]. We get:

$$\sum^{p^{фазн}} = I_1^2 \cdot R_1 + \sum_{n=2}^{40} \left(K_{I_n} \cdot I_1\right)^2 \cdot R_1 \cdot \left(0,187 + 0,532 \cdot \sqrt{n}\right). \tag{10}$$

Let's perform the necessary transformations so that the expression (10) takes the form:

$$\sum^{p^{фазн}} = I_1^2 \cdot R_1 \left(1 + \sum_{n=2}^{40} \left(K_{I_n}\right)^2 \cdot A_n\right) \tag{11}$$

where $A_n = 0,187 + 0,532 \cdot \sqrt{n}$.

Taking into account the assumption that the load is symmetrical, and the harmonic spectrum in each of the conductors is the same, currents of higher harmonic components of order $(n=6k-3)$, as well as a constant component of the current, which can be neglected, will flow through the neutral conductor. It should also be noted that the value of these currents in the neutral wire will be 3 times higher compared to the values of the currents of the higher harmonic components for similar orders in the phase conductors. These currents are the cause of active power losses in neutral wire, which are equal to:

$$\sum^{p^{нул}} = \sum_{\substack{n=6k-3 \\ n=3,9,15...}}^{40} (3 \cdot I_n)^2 \cdot R_n^{нул}, \tag{12}$$

where $R_n^{нул}$ is the value of the active resistance of the neutral core at higher harmonics of the current.

Taking into account the accepted notations, the formula (12) will take the form

$$\sum^{p^{нул}} = 9 \cdot \sum_{\substack{n=6k-3 \\ n=3,9,15...}}^{40} \left(K_{I_n} \cdot I_1\right)^2 \cdot R_1^{нул} \cdot A_n = 9 \cdot I_1^2 \cdot R_1^{нул} \cdot \sum_{\substack{n=6k-3 \\ n=3,9,15...}}^{40} \left(K_{I_n}\right)^2 \cdot A_n \tag{13}$$

where $R_1^{нул}$ is the value of the active resistance of the zero core at the fundamental frequency.

Let's determine the total active power losses in the zero and phase conductors using the formulas:

$$P_\Sigma = 3 \cdot P_\Sigma^{фазн} + P_\Sigma^{нул} = 3 \cdot I_1^2 \cdot R_1 \left(1 + \sum_{n=2}^{40} \left(K_{I_n}\right)^2 \cdot A_n\right) + 9 \cdot I_1^2 \cdot R_1^{нул} \cdot \sum_{\substack{n=6k-3 \\ n=3,9,15..}}^{40}$$

$$= 3 \cdot I_1^2 \cdot R_1 \left(1 + \sum_{n=2}^{40} \left(K_{I_n}\right)^2 \cdot A_n + 3 \cdot \frac{R_1^{нул}}{R_1} \sum_{\substack{n=6k-3 \\ n=3,9,15...}}^{40} \left(K_{I_n}\right)^2 \cdot A_n\right) = 3 \cdot I_1^2 \cdot R_1 \cdot K_{д\epsilon} \tag{14}$$

To determine the insulation temperature of the cable cores, we will bring the thermal problem to the electrical problem and perform further calculations for the electrical circuit. Let's write down the law that describes the process of heat transfer ("Ohm's thermal law") [15]:

$$\varDelta T = P \cdot S, \tag{15}$$

where $\varDelta T$ is the temperature difference between the points of the isothermal surfaces of the cable or the environment; P — the value of the heat flux passing through the isothermal surface, W; S is the value of the thermal resistance of the cable element and the environment, K/W.

To determine the temperature, it is necessary to identify the heat sources in the cable, as well as the values of the thermal resistances of structural elements.

To determine the correction factor, we use an analytical method based on the concept of equivalent current, which is the reduction of four heat sources (3 phase cores and zero) to three phase cores [15].

Based on the sufficient accuracy of the equivalent conversion, we will use the expressions to calculate thermal resistance for three-phase cables with sector conductors and belt insulation [16].

The value of the thermal resistance between the core and the sheath (S_1) for three-core cables with sector cores and belt insulation is determined according to the formula:

$$S_1 = \frac{\rho_T}{2\pi} \cdot 3 \cdot \left(1 + \frac{3 \cdot t}{2\pi \cdot \left(d_x + t \right) - t} \right) \cdot ln\left(\frac{d_a}{2 \cdot r_1} \right), \tag{16}$$

where ρ_T is the value of the thermal resistivity of the insulation, K·m/W; d_a — core diameter, mm; r_1 — radius of the circumference described around the cores, mm; d_x — diameter of the round core with the same cross-sectional area and degree of compaction as the shaped core, mm; t — thickness of insulation between the core and the sheath, mm.

The thermal resistance between the shell and the armor is defined as:

$$S_2 = \frac{\rho_T}{2\pi} \cdot ln\left(1 + \frac{2 \cdot t_2}{D_s} \right), \tag{17}$$

where t_2 is the thickness of the pillow under the armor, mm; D_s is the value of the outer diameter of the shell, mm.

The thermal resistance of the outer protective coating is:

$$S_3 = \frac{\rho_T}{2\pi} \cdot ln\left(1 + \frac{2 \cdot t_3}{D_a^{'}}\right), \tag{18}$$

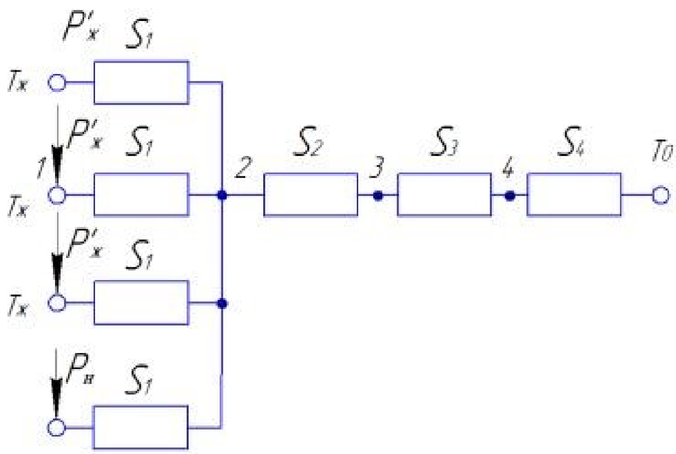
where t_3 is the thickness of the protective coating, mm; $D_a^{'}$ — outer diameter of armor (for unarmored cables, the outer diameter of the element, which is usually located directly under the armor, i.e. sheath, shield or pillow), mm.

To calculate the thermal resistance of the environment for an insulated cable, we use the dependence:

$$S_4 = \frac{\rho_T}{2\pi} \cdot ln\left(\frac{2 \cdot L}{D_e} + \sqrt{\left(\frac{2 \cdot L}{D_e}\right)^2 - 1}\right), \tag{19}$$

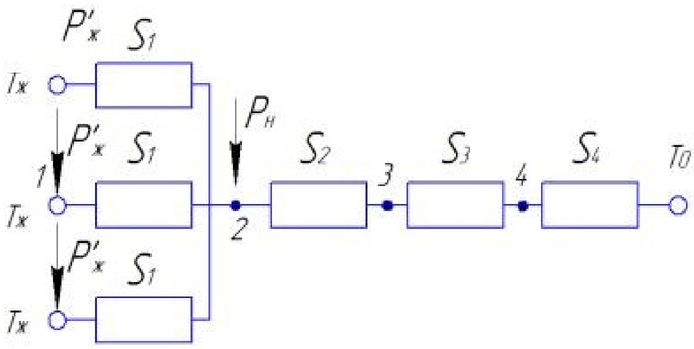
where L is the distance from the surface of the product to the cable axis, mm; D_e — outer diameter of the cable, mm.

Let's draw up a thermal substitution scheme, according to which we will calculate for a four-core cable (Figure 1).



Rice. 1. Thermal diagram of a four-core cable

For a three-core cable with a neutral wire, made along the cable sheath, it is not necessary to make significant changes to the thermal circuit (Figure 2). Let's add at point 2 the component of active power losses in the cable sheath. The heat release power in the phase core is proportional not to the square of the equivalent current, but to the square of the RMS value of the flowing phase current.



Rice. 2. Thermal diagram of a three-core cable

The heating of conductive conductors and other cable elements is proportional to the square of the current flowing through the cable. Therefore, a decrease in current by a certain amount causes a reduction in losses in the active resistances of the cable in proportion to the square root of the current decrease value, and in accordance with this value, there is a decrease in the temperature of all cable elements. I_t can be determined by the following formula:

$$I_t = K_н I_{дл.доп}, \tag{20}$$

where $K_н$ is the coefficient of current load reduction; $I_{дл.доп}$ is the long-term allowable current value for the cable in question. Based on this, let's transform the formula (14), it takes the form:

$$P_\Sigma = 3 \cdot \left(K_H \cdot I_1\right)^2 \cdot R_1 \cdot K_{доп} \tag{21}$$

The resulting formula provides a determination of losses taking into account the impact of cables laid in one place.

Let's determine the insulation temperature of the core for a four-core cable using the formula:

$$\tau_{жс} = P'_{жс} \cdot S_1 + 3 \cdot P'_{жс}\left(S_2 + S_3 + S_4\right) + \tau_{окр,\ ср} \tag{22}$$

Let's use the exponential Arrhenius equation to determine the decrease in service life ($V_{нс}$) due to thermal aging. This equation allows you to determine the amount of reduction in the standard service life of equipment ($V_{ном}$) in case of reaching a certain value of activation energy, which depends on temperature.

$$V_{нс} = V_{ном} \cdot exp\left(-K_a\left(\frac{1}{\theta_{ном}} - \frac{1}{\theta_{нс}}\right)\right), \quad (23)$$

where $\theta_{ном}$ is the value of the insulation temperature for the nominal mode, K; $\theta_{нс}$ – the value of the insulation temperature in the presence of higher harmonic components, K; K_a is a coefficient proportional to the activation energy, K.

Let's determine the coefficient that is proportional to the activation energy according to the formula:

$$K_a = \frac{E_a}{R}, \quad (24)$$

where E_a is the activation energy, J/mol; $R = 8{,}314$ J/(K·mol) is a universal gas constant.

For the operating temperature range, the expression (23) with a sufficient degree of accuracy should be approximated using the simpler Montsinger equation:

$$V_{нс} = V_{ном} \cdot e^{-\beta \cdot \Delta\tau}, \quad (25)$$

where $\Delta\tau = \theta - \theta_{довж.доп.}$ is the value of additional heating of the insulation, $\beta = \frac{ln\,2}{\Delta\tau}$ is the aging coefficient of the insulation.

At a temperature equal to the long-term permissible temperature, thermal wear should be considered normal for the most heated insulation point. If the permissible temperature is exceeded for a long time, then the thermal aging of the insulation will occur more intensively. At the same time, the higher the temperature relative to the long-term permissible temperature, the more the insulation will wear. If the temperature exceeds the maximum allowable, this leads to irreversible damage to the insulation, and then to its breakdown.

The maximum insulation temperature of power cables, taking into account the influence of currents of higher harmonic components, can be determined according to the compiled thermal substitution schemes and according to the calculation of the maximum core temperature according to the expression (19). To apply this method, information about the design features of the cable is required. It is also necessary to know the real values of the thermal conductivities of all elements.

If there is no information for the use of thermal replacement schemes, then when loading the cable in nominal mode and in the absence of higher harmonic components, the value of the most heated point equal to the long-term permissible temperature should be accepted, while the spectrum of current harmonics should be considered unchanged. Next, in the nominal cable loading mode and in the arbitrary non-sinusoidal mode according to the formula (19), we write down the system of equations:

$$\begin{cases} \Delta\tau_{ж}^{ном} = P_{ж}^{ном} \cdot \left(S_1 + 3 \cdot \left(S_2 + S_3 + S_4\right)\right), \\ \Delta\tau_{ж} = P_{ж}^{'} \cdot \left(S_1 + 3 \cdot \left(S_2 + S_3 + S_4\right)\right), \end{cases} \tag{26}$$

where $\Delta\tau_{ж}^{ном}$ and $\Delta\tau_{ж}$ is the value of the excess temperature of the cable core over the ambient temperature.

If we divide the first equation of the system (26) by the second, we get the ratio of the excess temperature of the cable core in nominal and non-sinusoidal modes, which can be used to determine the temperature of the core in an arbitrary non-sinusoidal mode:

$$\tau_{ж} = k_{3,1}^{2} \cdot \frac{P_{ж}^{'}}{P_{ж}^{ном}} \cdot \Delta\tau_{ж}^{ном} + \tau_{окр.серед.}, \tag{27}$$

In the first component of the formula, (27) $\Delta\tau_{ж}^{ном}$ determines the excess of the conductor insulation temperature for the nominal mode, and the product $k_{3,1}^{2} \cdot \frac{P_{ж}^{'}}{P_{ж}^{ном}}$ is an increasing coefficient, indicating how much the temperature exceeds the nominal temperature in the presence of higher harmonic components in the current. With the help of this formula, it is possible to calculate the temperature of the cable core, and then, using the expressions (23–25), it is necessary to determine the service life of the insulation.

The study confirms that monitoring the insulation condition of inter-unit electrical connections is a complex task that requires an integrated approach. Taking into account the influence of temperature, higher harmonics and electrical loads on insulating materials is necessary to ensure their reliability and safety in operation. The mathematical models that are given in this article show a method for assessing thermal characteristics, which allows you to predict the wear of insulation and estimate its service life. The determination of maximum allowable temperatures and active losses clearly illustrates the need to integrate mathematical models and adaptive algorithms into control systems, which contributes to increasing the accuracy of monitoring and the ability to prevent defects. This, in turn, emphasizes the importance of developing an automated control system using mathematical models and adaptive algorithms to maintain the high quality of cable and wire products in modern production.

Conclusions.

A detailed analysis of the influence of temperature conditions and electrical characteristics on the insulation state of interblock electrical connections has been performed.

It has been determined that load currents, reverse sequence currents of the fundamental frequency and higher harmonics have a significant impact on the heating of insulating materials. Studies confirm that these factors can lead to insulation degradation, which, in turn, reduces the reliability of electrical systems.

It has been established that higher harmonics of harmonic currents cause additional losses of active power, which negatively affects the thermal regime of insulating materials. Mathematical models developed in the process of research make it possible to obtain an accurate estimate of the electrical resistance of insulating joints under conditions of altered loads and temperature fluctuations.

The importance of monitoring the integrity of electrical connections is confirmed by the correctness of the results obtained, which indicate the need to comply with established standards in production processes. It is recommended to more actively implement mathematical modeling and adaptive control methods, which will improve the quality of final products and reduce the likelihood of defects.

The results of the study indicate the need to integrate the latest modeling technologies and adaptive algorithms into insulation control systems for inter-unit electrical connections. Improving technological processes in this area has a potential impact on increasing the productivity and reliability of cable and wire products in modern production.

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Анотація. *У статті розглядаються питання технологічного контролю стану ізоляції міжблокових електричних з'єднань на завершальному етапі виробництва. У зв'язку зі зростаючими вимогами до надійності та безпечного використання електричних систем, особлива увага приділяється впливу температурних змін, електричних навантажень і вищих гармонік на якість ізоляційних матеріалів. Ключовим елементом роботи є розробка математичної моделі, яка дозволяє оцінити електричний опір та термічні характеристики ізоляції. Модель враховує різноманітні фактори, що впливають на старіння матеріалів, і дозволяє точно прогнозувати їхній стан під дією зовнішніх умов. У результаті дослідження* *підкреслюється важливість математичної моделі для виявлення та оцінки можливих деградаційних процесів у ізоляційних матеріалах, що можуть призводити до зниження надійності електричних з'єднань. Отримані результати стимулюють подальше впровадження відповідної автоматизованої системи контролю з використанням математичної моделі параметрів електричних з'єднань на завершальному етапі виготовлення кабелю, підвищуючи загальний рівень якості та безпеки продукції.*

Ключові слова: *Кабельно-провідникова продукція, міжблокові електричні з'єднання, стан ізоляції, контроль якості, надійність, струми навантаження, вищі гармоніки, потужність, цілісність електричного ланцюга, електричні втрати, температурні режими, математичні моделі.*

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