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EFFICIENCY OF ADAPTIVE ALGORITHMS FOR CONTROLLING THE PARAMETERS OF INTERBLOCK ELECTRICAL CONNECTIONS

The article discusses the current challenges associated with the control of the parameters of cable and wire products, especially in the context of interconnection electrical connections. It is noted that traditional methods of control often do not correspond to dynamic changes in operating conditions, which leads to an increased level of defects. Given these limitations, the study focuses on the need to implement adaptive algorithms that not only improve measurement accuracy but also provide immunity to external interference. The literature review shows the active use of automated control systems, but the emphasis is on insufficient attention to adaptive algorithms that could significantly improve the quality of control. Among the methods considered, adaptive algorithms such as Adam, Levenberg-Marquardt, LMS, and RLS prove to be effective tools for improving the objectivity and performance of control systems. Their implementation allows systems to respond faster to changes in production conditions, increasing the reliability and stability of production processes. An important aspect is the integration of adaptive technologies into specialized software of automated control systems, which expands the capabilities of existing methods and can significantly reduce the negative consequences of self-heating during measurement.

Thus, the studies carried out demonstrate that an adaptive approach to parameter control not only improves the accuracy and stability of products, but also brings modern production systems closer to high quality standards. This allows you to ensure the reliability of the electrical infrastructure, which is critical for the successful functioning of various electrical systems.

Key words: *electrical systems, production process, interblock electrical connections, parameter control, performance, accuracy, reliability, efficiency, stability, testing, control methods, automated control system, adaptive algorithms, optimization.*

Problem Statement. In today's production environment, which requires continuous quality control and product stability, especially in sectors where interconnect electrical connections are used, the challenge is to improve the accuracy and reliability of parameter control systems. Existing methods are often not able to quickly adapt to dynamic changes in operating conditions, which leads to an increased level of defects and constant fluctuations in product quality.

Taking into account the above factors, there is a problem of development and implementation of improved adaptive methods of parameter control. This implies not only improving the accuracy of measurements, but also increasing immunity to external interference and internal nonlinearities. This approach should ensure the speed of response to changing conditions and continuous self-improvement of systems, which is important for maintaining high quality standards in the production of cable and wire products. Thus, the key task is the integration of new adaptive technologies that are able to provide the necessary accuracy, stability and efficiency in the processes of controlling production parameters.

Analysis of the latest research. Analysis of existing research in the field of control of parameters of interblock electrical connections of cable and wire products indicates the active use of automated control systems. In King, M. S. [1] and Ng, F. M. [2] article discussed the general issues of control of the parameters of interconnected electrical connections, emphasizing the importance of increasing the speed and accuracy of control of insulation parameters. Works by Khouri, P. M. P. [3] and Hershberger, D. [4] solve the problem of automating the process of testing electrical connections by describing the developed systems and test methods that can be useful for production processes. Research by Ng, F. M. [5] and Kakkeri, R. B. [6] are dedicated to solving the problems of error protection in insulation resistance control systems, emphasizing the importance of checking the key parameters of cable products. The work of Bodyansky E. V. [10] is devoted to the study of adaptive control of computer network security on the basis of fuzzy logic. This approach is useful for the development of systems for controling the parameters of interblock electrical connections using adaptive algorithms.

Thus, a review of the literature on the control of parameters of interblock electrical connections shows that today insufficient attention is paid to the development and implementation of adaptive algorithms in the relevant control systems. Existing studies do not fully reveal the influence of changing product characteristics and production conditions on measurement accuracy.

It is obvious that the introduction of adaptive algorithms in the systems for monitoring the parameters of interblock electrical connections is an urgent task that will increase the accuracy of parameter measurement, reduce control time, increase control reliability and increase production productivity.

Further research in this direction should be aimed at the introduction of adaptive algorithms in systems for controlling the parameters of interblock electrical connections, taking into account the changing characteristics of products and production conditions.

Summary of the main material. One of the main directions of implementation of adaptive algorithms in the direction of parameter control is to clarify the characteristics of controlled signals [1]. The use of such algorithms is aimed at improving the productivity and accuracy of the parameter control process, which is critical in today's production environment. Accordingly, production systems, especially those that work with cable and wire products, require reliable and efficient control methods to ensure high quality and product stability. In this context, it is important to consider the possibilities and advantages of using adaptive algorithms to improve the process of controlling the parameters of interblock electrical connections in modern production. The Levenberg-Marquardt (LM) algorithm is an efficient nonlinear optimization method used to solve nonlinear minimization problems [2]. It is used in a wide range of areas, including optimizing model parameters, approximating functions, and more. The algorithm is based on a combination of gradient descent methods and Newton's method [3]. Unlike Newton's method, which can fail in the case of a non-inverted Hesse matrix, LM uses a quasi-Newtonian update of the Hesse matrix to ensure stability and convergence. This algorithm is effective in solving optimization problems that include minimizing error functions, which can be useful for analyzing the electrical parameters of cables and selecting optimal settings.

Mathematically, the Levenberg-Marquardt algorithm can be represented in the following sequence of actions:

1) The error gradient $\mathrm{J(p)}$ is calculated according to the model p parameters.

$$\nabla \mathrm{J(p)} = \frac{\partial \mathrm{J(p)}}{\partial \mathrm{p}}, \qquad (1)$$

2) The parameters of the model are updated according to the formula:

$$\mathrm{p_{k+1}} = \mathrm{p_k} - (\mathrm{H} + \lambda \mathrm{I})^{-1} \nabla \mathrm{J(p)}, \qquad (2)$$

where H is the Hesse matrix (the matrix of the second derivatives of the error function); λ – regularization parameter; I - a unit matrix.

3) The new value of the error function is evaluated $J(p_{k+1})$.

4) If the new value of the error function is less than the previous one, the parameter λ is reduced and the transition to the next iteration is performed. If the new value is larger, λ is increased and iteration is repeated.

5) Steps 1-4 are repeated until the specified accuracy or maximum number of iterations is reached.

It is advisable to use the LM algorithm to optimize the parameters of models used to analyze electrical connections in the control system. It allows you to quickly and efficiently adapt models to changing conditions and provides resistance to noise and nonlinearity. Also, the Levenberg-Marquardt method provides rapid convergence and reliability of solving optimization problems, which will allow to effectively adapt the parameters of the control system. The use of this adaptive algorithm will improve the efficiency of cable control by optimizing system performance and adapting to changing conditions.

The adaptive algorithm "Adam" (Adaptive Moment Estimation), which can also be effective for use in the system for controlling the parameters of interblock electrical connections, combines the ideas of adaptive learning speed and gradient moment [4, 5]. It uses exponentially smoothed gradient and gradient square estimates to adapt parameter updates. This algorithm can be used to optimize the parameters of models that analyze the electrical parameters of cables. It allows you to effectively train models, taking into account different scales of gradients, and adapt to changing production conditions.

Parameter update formulas are presented as follows:

$$\mathrm{m_{k+1}} = \beta_1 \mathrm{m_k} + (1 - \beta_1) \nabla \mathrm{J(w_k)}, \qquad (3)$$

$$\mathrm{s_{k+1}} = \beta_2 \mathrm{s_k} + (1 - \beta_2) \left(\nabla \mathrm{J(w_k)}\right)^2, \qquad (4)$$

$$\mathrm{m_{k+1}} = \frac{\mathrm{m_{k+1}}}{1 - \beta_1^{k+1}}, \qquad (5)$$

$$\mathrm{s_{k+1}} = \frac{\mathrm{s_{k+1}}}{1 - \beta_2^{k+1}}, \qquad (6)$$

$$\mathrm{w_{k+1}} = \mathrm{w_k} - \frac{\alpha}{\sqrt{\hat{\mathrm{s}}_{k+1}} + \varepsilon} \cdot \hat{\mathrm{m}}_{k+1}, \qquad (7)$$

where m_k and s_k are exponentially smoothed estimates of the first and second moments of the gradient, respectively; β_1 and β_2– exponential smoothing parameters; α – learning step; ε is an additional parameter for numerical stability.

Adam's algorithm adaptively updates the parameters taking into account the first and second moments of the gradient, which allows you to work efficiently at the learning rate and store information about the gradient [6]. Adaptive adjustment of the learning rate for each parameter allows for faster training coincidence and avoids gradient attenuation or impulsive growth.

For signal noise filtering and parameter analysis, it is advisable to use filters based on the recursive adaptive least-squares algorithm (RLS) [7]. The use of adaptive filtering will help to improve the accuracy of measurements and ensure reliable control of cable parameters in various operating conditions. In the case of a signal received, one or more implementations of this process must be processed. To do this, you need to find the filter coefficients w, which minimize the error rate (8) of signal reproduction [8].

$$\mathrm{J(w)} = \sum_{\mathrm{t=0}}^{\mathrm{T-1}} |\mathrm{e(t)}|^2 \to \min, \tag{8}$$

If we continue the matrix notation of the t-coordinate, we get the formulas for the column vector of the output signal a (9) and the error of reproduction of the input signal e (10) [7].

$$\mathrm{a} = \mathrm{U^T w} \tag{9}$$

$$\mathrm{e} = \mathrm{m} - \mathrm{U^T w}, \tag{10}$$

where m is the vector-column of sampling signal counts; $\mathrm{U} = [\mathrm{u}(0), \mathrm{u}(1), \ldots, \mathrm{u}(\mathrm{T}-1)]$ is a matrix, whose columns display the contents of the delay line at different cycles.

The error rate expression (8) can be rewritten with the representation a in matrix form as follows

$$\mathrm{J(w)} = \mathrm{e^T e} \to \min. \tag{11}$$

Substituting (9) and (10) for (11), we get (12)

$$\mathrm{J(w)} = \left(\mathrm{m} - \mathrm{U^T w}\right)^{\mathrm{T}}\left(\mathrm{m} - \mathrm{U^T w}\right) = \mathrm{m^T m} - \mathrm{w^T U m} - \mathrm{m^T U^T w} + \mathrm{w U U^T w}. \tag{12}$$

To determine the minimum value of the objective function, it is necessary to calculate the gradient of this function and equate the resulting value to zero (13).

$$\mathrm{gradJ(w)} = -2\mathrm{Um} + 2\mathrm{UU^T w} = 0, \tag{13}$$

Thus, the optimal solution is:

$$\mathrm{w} = \left(\mathrm{UU^T}\right)^{-1}\mathrm{Um}, \tag{14}$$

In the process of receiving the signal, the filter coefficients can be directly calculated according to equation (14) at each subsequent step. At the same time, the size of the matrix U continues to increase, and the inverse matrix $\left(\mathrm{UU^T}\right)^{-1}$ needs to be recalculated each time. However, the computation costs can be reduced if you consider that each step only requires the addition of a new column to the matrix U and a new element to the vector m so that the value can be calculated recursively. The use of the adaptive RLS algorithm will provide the ability to obtain useful signals in the process of monitoring the connection almost without distortion [9]. The ability of filters to adapt to changing environmental conditions and respond quickly to changes will allow you to effectively detect anomalies and ensure stability in parameter control. Another effective means of filtering signals is the adaptive least-squares algorithm (LMS), which is a simple and effective method of adaptive filtering used to process signals in various systems [10]. Its main task is to find the optimal filter parameters that help minimize the deviation between the output and expected signals. Let's consider the mathematical implementation of this algorithm. Let the input discrete random signal $n(t)$ be processed by a non-recursive discrete order filter N, whose coefficients can be represented by a column vector $\mathrm{w} = [\mathrm{w_0}, \mathrm{w_1}, \ldots, \mathrm{w_N}]^{\mathrm{T}}$, then the output signal of the filter is:

$$\mathrm{a(t)} = \mathrm{u^T(t) w}, \tag{15}$$

where $\mathrm{u(t)} = [\mathrm{x(t)}, \mathrm{x(t-1)}, \ldots, \mathrm{x(t-N)}]^{\mathrm{T}}$ is the column vector of the content of the filter delay line in the t-th step.

The reproduction error (16) of the sample signal $\mathrm{m(t)}$ is accordingly defined as:

$$\mathrm{e(t)} = \mathrm{m(t)} - \mathrm{a(t)} = \mathrm{m(t)} - \mathrm{u^T(t) w}, \tag{16}$$

The adaptive algorithm needs to find such filter w coefficients that ensure the maximum proximity of the input signal $a(t)$ to the reference one $m(t)$, i.e. minimize the error $e(t)$. Since $e(t)$ is also a random process, it is reasonable to take the RMS value as a measure of its magnitude, then the function to be optimized (17) can be defined as:

$$\mathrm{J(w)} = \overline{\mathrm{e^2(t)}} \to \min, \tag{17}$$

$$e^2(t) = \left(m(t) - u^T(t)w\right)^2 = m^2(t) - 2m(t)u^T(t)w + w^T u(t)u^T(t)w. \quad (18)$$

Statistically averaging the expression (18), we get (19)

$$J(w) = \overline{e^2(t)} = \overline{m^2(t)} - \overline{2m(t)u^T(t)w} + w^T\overline{u(t)u^T(t)w}, \quad (19)$$

where $\overline{m^2(t)} = \sigma_d^2$ is the middle square of the reference signal; $\overline{m(t)u^T(t)} = p^T$ – transposed column vector of mutual correlations p between the t-th sample signal and the content of the filter delay line u; $\overline{u(t)u^T(t)} = R$ is a correlation matrix of a signal having the size of $(N+1) \times (N+1)$.

The method of fastest descent, based on the search for the minimum of the objective function (19), is the main criterion for adapting the least-squares algorithm. When using this optimization method, the coefficient vector w should be recursively updated as follows (20)

$$w(t+1) = w(t) - \frac{\mu}{2}\text{grad}J\left(w(t)\right) = w(t) + \mu \cdot p - \mu R w(t), \quad (20)$$

where μ is the size of the gradient descent step; p – column vector of mutual correlations between t-th reference of the sample signal and the content of the filter delay line; R is a correlation matrix of a signal having the size of $(N+1) \times (N+1)$.

The algorithm converges if $0 < \mu < 2/\lambda_{max}$, where λ_{max} is the maximum eigenvalue of the correlation matrix R, but to calculate the gradient you need to know the values of the matrix R and the vector p. In practice, only estimates of these values derived from input data may be available. The simplest estimates are the instantaneous values of the correlation matrix (21) and the mutual correlation vector (22), which are obtained without any averaging:

$$R(t) = u(t)u^T(t); \quad (21)$$

$$p(t) = m(t)u(t). \quad (22)$$

When using these estimates, formula (20) takes the form (23)

$$w(t+1) = w(t) + \mu u(t)\left(m(t) - u^T(t)w(t)\right), \quad (23)$$

The expression in parentheses, according to (16) represents the filtering error $e(t)$, taking this into account, the expression for the recursive update of the filter coefficients is (24)

$$w(t+1) = w(t) + \mu e(t)u(t). \quad (24)$$

The main advantage of the LMS algorithm is its extreme computational simplicity – to adjust the filter coefficients at each step, you need to perform $N+1$ multiplication-addition operations [11]. The consequence of this is slow convergence and increased error variance in the steady-state mode – the filter coefficients always fluctuate around the optimal values, which increases the level of output noise.

The selected adaptive Adam algorithms, adaptive filtering (LMS or RLS) and adaptive Levenberg-Marquardt algorithm, are the most appropriate for the system for monitoring the parameters of interconnect electrical connections in the production of cables. They allow you to effectively adapt to changing operating conditions and provide fast convergence and reliability in solving optimization problems. The LMS can be used for signal filtering and adaptive parameter control, while the RLS can be used to predict future cable parameter values and effectively respond to changes in operating conditions. The use of these algorithms will help improve the quality of cable parameter control, ensuring stable and reliable operation of the control system.

Conclusions. Studies have shown that effective control of the parameters of cable and wire products is a decisive factor for ensuring the quality and reliability of electrical infrastructure, which includes such important issues as the connection of power supplies to end consumers, the installation of electrical devices, as well as integration in distribution assemblies and internal power grids. The variety of types of cable and wire products requires a careful approach to the control of their parameters, which It is carried out using various automated methods, limited only by the capabilities of the equipment.

It has been found that under conditions of limited traditional methods, the use of adaptive algorithms in control systems provides a significant improvement in the control process, demonstrating high efficiency of adaptation to a rapidly changing environment and various production parameters. It has been proved that adaptive algorithms, such as Adam, Levenberg-Marquardt, as well as filtering using LMS and RLS algorithms, can significantly increase the objectivity and productivity of monitoring the parameters of interblock electrical connections.

Integration of these adaptive algorithms into specialized software for automated control systems not only increases the accuracy and reliability of measurements, but also allows you to efficiently use resources and expand the capabilities of existing systems. This approach helps to reduce almost all negative factors associated with self-heating during measurement, thereby improving the overall stability and quality of products.

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ЕФЕКТИВНІСТЬ АДАПТИВНИХ АЛГОРИТМІВ ДЛЯ КОНТРОЛЮ ПАРАМЕТРІВ МІЖБЛОКОВИХ З'ЄДНАНЬ КАБЕЛЬНО-ПРОВІДНИКОВОЇ ПРОДУКЦІЇ

У статті розглянуто сучасні виклики, пов'язані з контролем параметрів кабельно-провідникової продукції, особливо в контексті міжблокових електричних з'єднань. Відзначено, що традиційні методи контролю часто не відповідають динамічним змінам умов експлуатації, що призводить до підвищеного рівня дефектів. Враховуючи ці обмеження, дослідження зосереджено на необхідності впровадження адаптивних алгоритмів, які не лише підвищують точність вимірювань, але й забезпечують стійкість до зовнішніх перешкод. Проведений огляд літератури свідчить про активне використання автоматизованих систем контролю, але акцентується недостатня увага до адаптивних алгоритмів, що могли б суттєво покращити якість контролю. Серед розглянутих методів, адаптивні алгоритми, такі як Adam, Левенберга-Марквардта, LMS і RLS, виявляються ефективними інструментами для підвищення об'єктивності та продуктивності систем контролю. Їх впровадження дозволяє системам швидше реагувати на зміни виробничих умов, підвищуючи надійність і стабільність виробничих процесів. Важливим аспектом є інтеграція адаптивних технологій у спеціалізоване програмне забезпечення автоматизованих систем контролю, що розширює можливості існуючих методів і дозволяє значно зменшити негативні наслідки саморозігріву під час вимірювання.

Таким чином, виконані дослідження демонструють те, що адаптивний підхід до контролю параметрів не лише покращує точність і стабільність продукції, але й наближає сучасні виробничі системи до високих стандартів якості. Це дозволяє забезпечити надійність роботи електричної інфраструктури, що є критично важливим для успішного функціонування різноманітних електротехнічних систем.

Ключові слова: *електротехнічні системи, виробничий процес, міжблокові електричні з’єднання, контроль параметрів, продуктивність, точність, надійність, ефективність, стабільність,. тестування, методи контролю, автоматизована система контролю, адаптивні алгоритми, оптимізація.*