АВТОМАТИЗАЦІЯ ТА ІНТЕЛЕКТУАЛІЗАЦІЯ ПРИЛАДОБУДУВАННЯ

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STUDY OF THE EFFECTIVENESS OF USING ADAPTIVE ALGORITHMS FOR PROCESSING MEASUREMENT DATA IN AN AUTOMATED SYSTEM FOR CONTROLLING PARAMETERS OF INTERBLOCK ELECTRICAL CONNECTIONS

Bukovskyi O. M., Vysloukh S. P.
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine
E-mail: olbukovskiy@gmail.com, vsp1@ukr.net

This article addresses the problem of comparative evaluation of algorithms for processing measurement data in an automated system for monitoring the parameters of inter-block electrical connections, designed for testing cable and harness products under production conditions. The relevance of the research is determined by the need to simultaneously ensure high accuracy in determining electrical parameters, immunity to interference, repeatability of results, control speed, and reliable detection of defective conditions. When using a direct threshold approach without adaptive refinement of estimates, the effectiveness of the control decreases due to noise in the measurement path, contact instability, parasitic connections, and the technological variation of product parameters.

The aim of this work is a comparative evaluation of measurement data processing algorithms to determine the most appropriate approach in terms of accuracy, repeatability, speed, sensitivity to defects, and stability of results in an automated system for monitoring the parameters of inter-block electrical connections. To achieve this objective, an experimental comparison of four algorithmic variants was performed: the baseline mode without adaptive estimation refinement, recursive least squares (RLS) estimation, iterative parameter optimization using the Adam method, and nonlinear parametric identification based on the Levenberg-Marquardt method. The research was conducted on a single hardware platform for power, signal, and combined harnesses in a series of controlled tests with various types of defects.

The results of the study established that adaptive processing of measurement data provides a significant improvement in the system's metrological and operational characteristics compared to the baseline mode. For power harnesses, the RLS algorithm proved to be the most suitable, providing the best repeatability and the highest overall performance index. For signal and combined harnesses, the Levenberg–Marquardt algorithm demonstrated the best results across a set of criteria. The Adam algorithm confirmed the feasibility of using an accelerated mode, especially for combined products, where it is important to minimize the duration of the inspection cycle. The practical significance of this work lies in the justification of algorithmic profiling of an automated inspection system depending on the product type and the nature of dominant defects.

***Keywords**: interblock electrical connections, automated inspection, adaptive algorithms, defect detection, accuracy.*

Problem Statement

Inspection of the parameters of interblock electrical connections is one of the critically important stages in the manufacture and testing of cable and harness products, since the operational capability of the final product depends precisely on the correctness of electrical connections, the integrity of conductors, the condition of insulation, and the absence of parasitic short circuits. In modern instrumentation, aviation technology, transportation, and specialized electrical systems, such connections are subject to heightened reliability requirements, and therefore the inspection procedure must ensure not only the detection of obvious defects but also the reliable identification of subtle deviations, which in the early stages may not lead to complete failure but significantly reduce the operational reliability of the product.

Traditional approaches to inspecting the electrical parameters of interblock connections are primarily focused on verifying the compliance of the connection diagram, measuring individual electrical parameters, and subsequently comparing the obtained values with permissible limits. However, in real-world production conditions, the results of such measurements are subject to the influence of noise, instability of contact junctions, manufacturing variations in parameters, temperature factors, and parasitic connections in the measurement path. Under these conditions, direct processing of measurement data without the use of special filtering algorithms and adaptive estimation can lead to reduced accuracy, degraded repeatability of results, and an increased likelihood of false decisions during defect detection.

This problem is particularly relevant in automated control systems, where it is necessary to simultaneously ensure high speed, metrological reliability, and resistance to random and systematic disturbances. Given the large number of controlled circuits and diverse measurement modes, the effectiveness of the entire system is largely determined not only by the characteristics of the hardware but also by the quality of the algorithms for processing measurement data. This is precisely why there is a scientific and practical need to conduct a comparative evaluation of algorithms capable of increasing the accuracy of determining the parameters of interblock electrical connections, reducing the variability of results, and improving the quality of diagnosing defective conditions in production environments.

In this regard, it is advisable to investigate the possibilities of applying adaptive data processing algorithms within an automated system for monitoring the parameters of interblock electrical connections and to determine their advantages compared to the baseline approach, which does not provide for adaptive correction of measurement results.

Literature Review and Problem Formulation

In research studies on the automation of testing for cable and harness products, the primary focus has been on developing flexible hardware-software testing tools, system modularity, and ensuring the verification of electrical integrity of connections. In particular, the work by Z. Bi and co-authors [1] demonstrates the feasibility of automated testing of electrical cable harnesses using a modular approach to hardware and software design, which allows the system to be adapted to various types of products. At the same time, these studies focus primarily on the architecture of the test system and general automation strategies, while the issue of in-depth algorithmic processing of measurement data to improve diagnostic accuracy is considered in less detail.

An important area of research concerns the metrological support for the control of electrical parameters [2]–[4]. The development of correct decisions in such systems must take into account the requirements for evaluating measurement uncertainty, as well as regulatory constraints regarding the determination of conductor resistance and insulation resistance. To this end, international practice employs the provisions of the GUM [2] regarding the presentation of measurement uncertainty, the IEC 60228 standard [3] regarding conductor characteristics and resistance, and IEC 61557-2 [4] regarding means of measuring insulation resistance in a de-energized state. However, regulatory documents primarily govern the requirements for measurement results and conditions, but do not specify the selection of effective digital data processing algorithms within an automated control system.

A separate group of sources consists of works on adaptive signal processing and parametric identification. LMS and RLS algorithms are widely used in adaptive filtering and sequential parameter estimation tasks, with RLS typically providing faster convergence and higher accuracy, while LMS is characterized by simpler implementation and lower computational costs [5]. For optimization problems involving noisy or non-stationary data, the Adam algorithm has gained widespread use, combining computational efficiency with low memory requirements [6]. Recent studies also explore the use of the Levenberg-Marquardt algorithm for nonlinear parameter identification and to mitigate the impact of disturbances during the processing of measurement data [7].

Thus, an analysis of the published works [1]–[7] shows that the issues of designing automated test systems, regulatory support for electrical measurements, and the application of specific adaptive algorithms in related problems – particularly in adaptive filtering, recursive parameter estimation, stochastic optimization, and nonlinear identification. At the same time, the issue of their direct comparison within the framework of the automated system used to monitor the parameters of interblock electrical connections based on a set of criteria of practical significance for production—namely, estimation accuracy, stability of results, duration of monitoring, and reliability of defect detection—remains insufficiently studied. It is precisely this circumstance that justifies the need for further research in the chosen direction.

Objective

The objective of this work is to conduct a comparative evaluation of algorithms for processing measurement data in an automated system for monitoring the parameters of interblock electrical connections; to determine the most appropriate approach in terms of the accuracy of electrical parameter estimation, stability of results, control speed, and quality of defect detection.

To achieve this objective, the following tasks are formulated in this work:

- to analyze the characteristics of the generation and processing of measurement data during the monitoring of inter-block electrical connection parameters in an automated system;
- to determine the set of data processing algorithms suitable for comparative evaluation within the selected software implementation of the control system;
- to investigate the basic algorithm for processing measurement data without adaptive correction, as well as the RLS, Adam, and Levenberg-Marquardt algorithms;

- conduct an experimental comparison of the aforementioned algorithms in terms of accuracy, repeatability, speed, sensitivity to defects, and stability of results;
- identify the advantages and limitations of each of the algorithms under study with regard to their application for the inspection of power, signal, and combined cable harnesses;
- justify the selection of the most effective algorithms for practical use in an automated inspection system for cable and wire products.

Research Results

The experimental part of this work is structured as a comprehensive comparison of modes for processing measurement data in an automated system for monitoring the parameters of inter-block electrical connections. Four algorithmic variants were compared: the baseline mode without adaptive estimation refinement, RLS recursive quadratic estimation, iterative parameter optimization using the Adam method, and nonlinear parametric identification based on Levenberg-Marquardt. Unlike these four modes, the LMS algorithm in the structure of the developed system performs the auxiliary function of preliminary smoothing of measurement series and was therefore not considered as a separate decision-making option in this series of tests. This approach allows for the evaluation of precisely those algorithms that directly determine the final values of the controlled parameters and form a conclusion about the technical condition of the product.

To ensure the validity of the comparison, all algorithms ran on the exact same hardware platform, used the same wiring diagram, the same switching modes, and the same control thresholds. This eliminates the influence of extraneous factors, including differences in hardware configuration, connection schemes, switching modes, and decision-making criteria, and allows the differences in the obtained results to be interpreted as a consequence of the algorithmic approach itself. Methodologically, this approach is consistent with current work in the field of automated cable harness testing [1], with requirements for metrological reliability of measurements [2], and with regulatory provisions regarding the testing of conductor and insulation parameters [3], [4].

Experimental setup and research objects

The tests were performed on an automated test bench, which consisted of a control PC, a tester unit with 96 measurement channels, a power supply, a network switch, and individual adapters for connecting specific devices [8], [9]. The tester unit supported three operating modes: “27 V – conductor resistance,” “27 V – short-circuit resistance,” and “100 V – insulation resistance.” In the 27 V modes, a stabilized test current in the range of 0.1–10 mA was used, while in the 100 V mode, a high-voltage mode was established to evaluate insulation resistance and associated leakage processes. The CableTester software suite performed channel addressing, switching control, collection of measurement series, execution of a specific evaluation algorithm, and generation of the final result. This architecture corresponds to the general concept of building an automated control system, as substantiated in previous studies [8], [9].

To ensure that the results are of practical value not only for a single sample but for a broader class of cable and wire products, the tests included three test specimens representing different electrical and design characteristics: power, signal, and combined harnesses. The power harness consisted mainly of power supply and return circuits, the signal harness consisted of low-current signal and shielded lines, and the combined harness combined power, signal, and service circuits within a single product. The generalized characteristics of the test harnesses are presented in Table 1.

Table 1. General characteristics of the tested cable harnesses

Harness type	**No. of circuits**	**Critical features**	**Main control threshold conditions**
Power	22	Low-impedance power supply circuits, high sensitivity to increases in contact contact resistance	$R_{in} \leq 0.80$ Ω; $R_{out} \geq 100$ MΩ; abnormal conductive contact was detected at $R < 10$ Ω; an increase in contact resistance of more than 25% relative to the reference value was additionally monitored
Signal	29	Low-current circuits, shielded branches, influence of parasitic connections and chassis connections	$R_j \leq 1.20$ Ω; $R_{iz} \geq 150$ MΩ; abnormal contact was detected at $R < 20$ Ω; shield-to-case resistance ≤ 1 Ω
Combined	41	Combination of power, signal, auxiliary, and shield-to-housing circuits; non-uniformity of lengths and cross-sections	For power branches, $R_j \leq 0.90$ Ω; for signal branches, ≤ 1.50 Ω; $R_{iz} \geq 120$ MΩ; the resistance of shield-to-housing transitions was checked separately and found to be ≤ 1 Ω

The test program was identical for all algorithms. For each type of harness, 50 cycles were performed per algorithm: 10 cycles without defects, 10 with an open circuit, 10 with an inter-circuit short circuit, 10 with reduced insulation resistance, and 10 with increased connection resistance. As a result, the total scope of the experiment amounted to 600 complete test cycles. Defects were introduced in a controlled manner: an open circuit was simulated by disconnecting one branch, a short circuit by connecting a low-resistance shunt between independent lines, reduced insulation by creating a high-resistance leakage path to the housing or an adjacent conductor, and increased contact resistance – by introducing an additional series component into the contact node. This scheme made it possible to investigate both gross and subtle defects, for which the algorithm is required not merely to record the fact of non-conformity, but to correctly identify a weak informative signal against the background of noise and variations in the measurement path.

Formalization of the measurement procedure and algorithmic modes

Within each test cycle, the electrical connection diagram was used as a reference for topological compliance, and the measurement results were converted into estimates of the parameters under test. For the "27 V – wire resistance" mode, the resistance of the conductive path was determined based on the average value of the measured voltage and a stabilized test current. For the “27 V – short-circuit resistance” mode, a similar relationship was applied to the abnormal conductive path between lines, and in the “100 V – insulation resistance” mode, the evaluation was performed either based on the steady-state leakage current or on the transient process parameters. It is precisely the difference in the physical nature of these measurement modes that explains why the same algorithm cannot demonstrate equal effectiveness for all types of objects. The calculated ratios for the basic test mode are as follows [2]:

$$\widehat{R_{ins}} = \overline{U_{27}} / I_{\mathrm{st}}, \tag{1}$$

$$\widehat{R_{\mathrm{sc}}} = \overline{U_{27}} / \overline{I_l}, \tag{2}$$

$$I\left(t_k\right) = \frac{U_{100}}{R_{\mathrm{ins}}} + A \cdot \exp\left(\frac{-t_k}{\tau}\right) + \varepsilon_k. \tag{3}$$

Where, $\widehat{R_{ins}}$ – estimated conductor resistance, Ω; $\overline{U_{27}}$ – average value of the measured voltage in the 27 V mode, V; I_{st} – stabilized test current, A; $\widehat{R_{\mathrm{sc}}}$ – estimated short-circuit resistance between conductors, Ω; $\overline{I_l}$ – average leakage current, A; $I\left(t_k\right)$ – instantaneous value of leakage current at time t_k, A; U_{100} – test voltage in insulation resistance measurement mode, V; R_{ins} – insulation resistance, Ω or MΩ; A – amplitude of the transient current component, A; t_k – time elapsed since the start of measurement, s; τ – time constant of the transient process, s; ε_k – random error or measurement noise, A.

In the basic mode, after calculating the values (1)–(3), the decision was made without recursive or iterative refinement of the estimate, i.e., according to a fixed comparison rule with the permissible limits. This mode should be considered the baseline, as it reflects the simplest practical control scheme but does not compensate for the effects of serial noise, drift, or the nonlinearity of transient processes.

The RLS algorithm was applied to a series of measurement readings as a recursive procedure for refining model parameters. Its advantage lies in the fact that each new measurement is not simply averaged with the previous ones, but modifies the estimate taking into account the information weight of the current reading. This is particularly important for low-impedance power circuits, where a relatively small absolute increase in resistance can have significant diagnostic value. The model parameter refinement algorithm is implemented as the following calculations [5]:

$$K_k = \frac{P_{k-1}\varphi_k}{\left(\lambda + \varphi_k^T P_{k-1}\varphi_k\right)}, \tag{4}$$

$$\theta_k = \theta_{k-1} + K_k \cdot \left(y_k - \varphi_k^T \theta_{k-1}\right), \tag{5}$$

$$P_k = \lambda^{-1} \cdot \left(P_{k-1} - K_k \varphi_k^T P_{k-1}\right). \tag{6}$$

Where, K_k is the vector of RLS algorithm gain coefficients, whose dimension corresponds to the chosen model parameterization; φ_k – vector of regressors formed from current measured readings and control parameters; λ – forgetting coefficient, a dimensionless quantity; θ_k – vector of estimated parameters at the k-th step; θ_{k-1} – vector of parameters at the previous step; y_k – measured system response at the k-th step, V, A, or a dimensionless normalized quantity depending on the control mode; φ_k^T – predicted value of the measured response in the same units as y_k; P_k – updated covariance matrix of the parameter estimate; P_{k-1} – the covariance matrix from the previous step; λ^{-1} – the inverse of the forgetting rate, a dimensionless quantity.

The Adam algorithm was used as a numerical optimization procedure for tuning evaluation parameters in cases where not only accuracy but also computational speed is critical. In this study, this algorithm is considered not as a machine learning method in the classical sense, but as an iterative mechanism for adjusting the parameter vector used in processing measurement data. Thanks to the separate accumulation of first- and second-order gradient estimates, Adam performs well under conditions of non-uniform parameter sensitivity and demonstrates high speed during successive control cycles. Parameter updates using the Adam method are determined by the following equations [6]:

$$m_k = \beta_1 m_{k-1} + \left(1-\beta_1\right) g_k; \tag{7}$$

$$v_k = \beta_2 v_{k-1} + \left(1-\beta_2\right) g_k^2; \tag{8}$$

$$\theta_k = \theta_{k-1} - \alpha \cdot \frac{\widehat{m_k}}{\left(\sqrt{\widehat{v_k}} + \varepsilon\right)}. \tag{9}$$

Where, m_k is the estimate of the first gradient moment; v_k is the estimate of the second gradient moment; β_1, β_2 are exponential smoothing coefficients, dimensionless quantities; g_k is the gradient of the objective function with respect to the parameter vector, whose units are defined by the ratio of the units of the objective function to the units of the parameters; θ_k is the vector of parameters being optimized; α – optimization step; m_{k-1}, v_{k-1} – adjusted estimates of gradient moments; ε – small regularization term, a dimensionless quantity or the scale factor of numerical stabilization.

The Levenberg-Marquardt algorithm has been applied to problems where the parameter of interest is related to a nonlinear model, particularly in estimating insulation resistance and transient leakage components. Compared to linear recursive procedures, it is more time-consuming, but it provides an effective approximation of the measured curve to the model and reduces the systematic bias of the estimate in complex signal and combined structures. In this case, the iterative refinement of the parameters was performed according to the relation [7]:

$$\theta_{k+1} = \theta_k - \left(J_k^T J_k + \mu_k I\right)^{-1} J_k^T r_k. \tag{10}$$

Where, θ_{k+1} – vector of parameters after the current iteration; θ_k – vector of parameters at the current iteration; J_k – Jacobian matrix formed according to the nonlinear model of the measurement process; μ_k – damping parameter, a dimensionless quantity; I – identity matrix; r_k – vector of discrepancies between measured and model values, B, A, or normalized units depending on the control mode.

Thus, within a single hardware system, four different strategies were compared: direct threshold estimation, recursive refinement, accelerated optimization, and nonlinear parametric identification. This combination of algorithms is sufficiently representative for industrial control tasks involving interblock electrical connections, as it covers various methods of handling measurement series and different trade-offs between accuracy and speed [5]–[7].

Comparative Evaluation Metrics

Since the technical value of the algorithm in this task cannot be reduced to a single metric, the evaluation was performed based on five groups of criteria: accuracy, repeatability, speed, sensitivity to defects, and robustness to changes in inspection conditions. Accuracy was characterized by the relative error in determining the controlled parameter $\Delta\varepsilon$; repeatability by the coefficient of variation CV in a series of repeated measurements; defect sensitivity by the Precision, Recall, and F1-score metrics; stability – by a combination of metric drift δ_{st} and stability of the final classification decision P_{st} under external influences. The corresponding calculation relationships are given in the following formulas [3, 4]:

$$\delta_{\text{rel}} = \frac{\left|x_{\text{est}} - x_{\text{ref}}\right|}{x_{\text{ref}}} \cdot 100\%, \tag{11}$$

$$V = \frac{s}{\overline{x}} \cdot 100\%, \tag{12}$$

$$\text{Precision} = \frac{T_P}{T_P + F_P}, \quad \text{Recall} = \frac{T_P}{T_P + F_N}, \tag{13}$$

$$F1 = 2 \cdot \text{Precision} \cdot \frac{\text{Recall}}{\left(\text{Precision} + \text{Recall}\right)}, \tag{14}$$

$$\delta_{\text{st}} = \frac{\left|x_{\text{cond}} - x_{\text{nom}}\right|}{x_{\text{nom}}} \cdot 100\%, \quad P_{\text{st}} = \frac{N_{\text{corr}}}{N_{\Sigma}} \cdot 100\%. \tag{15}$$

Where, δ_{rel} – relative error in determining the parameter, %; x_{est} – estimated value of the measured parameter, in ohms, kiloohms, megaohms, or another unit depending on the type of parameter; x_{ref} – standard or reference value of the same parameter in the same units; V – coefficient of variation, %; s – standard deviation of repeated measurements, in the same units as the controlled parameter; $\overline{x}$ – mean value of the measurement series, in the same units; Precision – classification accuracy, dimensionless quantity; Recall – defect detection rate, dimensionless quantity; $F1$ – harmonic mean between Precision and Recall, dimensionless quantity; T_P – number of correctly detected defective states; F_P – number of false-positive decisions; F_N – number of false-negative decisions; δ_{st} – metric drift indicator or deviation under changed control conditions, %; x_{cond} – parameter value under changed conditions, in the same units as x_{nom}; x_{nom} – nominal or base value of the parameter, ohms, kiloohms, megaohms, etc.; P_{st} – the proportion of correct decisions under external influences, %; N_{corr} – the number of correct classification decisions; N_{Σ} – the total number of tests.

To arrive at a final recommendation, individual criteria were normalized and then aggregated into a single performance indicator. Unlike subjective expert ranking, this procedure allows for the use of diverse indicators on a single dimensionless scale. In this paper, equal weighting was adopted, meaning that each of the five criteria was assigned an equal weighting factor of 0.20. This approach does not establish a rigid, universal framework for all practical problems; however, it is justified specifically for scientific comparison, where no single criterion should a priori dominate the others. The integral efficiency index was determined using the formula [4]:

$$E_j = \sum w_i \cdot k_{ij}, \quad \sum w_i = 1, \quad w_i = 0,20. \qquad (16)$$

Where, E_j is the integral performance index of the j-th algorithm, a dimensionless quantity; w_i is the weighting coefficient of the *i*-th criterion, a dimensionless quantity; k_{ij} is the normalized value of the *i*-th criterion for the *j*-th algorithm, a dimensionless quantity.

It is precisely the system of indicators (11)–(16) that was subsequently used for the analytical comparison of algorithms. Its advantage lies in the fact that it allows one to separately demonstrate the nature of an algorithm's advantage, rather than merely its overall ranking position. For example, one algorithm may be inferior in terms of accuracy but superior in terms of speed, while another may have the best temperature stability but not be optimal according to classification metrics. For industrial control systems, this type of multi-criteria analysis is the most useful.

Results of the comparative evaluation of algorithms

The results presented below were obtained for three test harnesses: a power harness (22 circuits), a signal harness (29 circuits), and a combined harness (41 circuits). The comparison was performed based on test data in the modes of conductor resistance, short-circuit resistance, and insulation resistance under defect-free conditions and with the controlled introduction of typical defects.

It is advisable to consider the comparative evaluation sequentially: first by metric characteristics, then by temporal and classification features, and finally as a generalized integrated conclusion. This logic allows preserving the physical meaning of each group of indicators while simultaneously forming a practical recommendation regarding the selection of a testing mode for a specific type of harness.

The data in Fig. 1 and Fig. 2 confirm that the transition from the baseline mode to adaptive processing improves not only the accuracy but also the stability of the serial estimates. For the power harness, the relative error decreased from 3.50 % in the baseline mode to 1.21 % for RLS, 1.62 % for Adam, and 0.94 % for LM. In terms of the coefficient of variation, RLS even outperformed LM: 1.46 % versus 1.60 %, which is explained by the recursive nature of parameter refinement on low-resolved measurements. Thus, for a power system, it is important to distinguish between absolute accuracy and repeatability: LM minimizes the bias of the estimate, while RLS minimizes the variance of the series of results.

For the signal harness, the dominant advantage shifts to Levenberg–Marquardt. The relative error decreases from 8.08 % in the baseline mode to 3.19 % for RLS, 2.34 % for Adam, and 1.38 % for LM; the coefficient of variation is 5.70, 3.19, 2.70, and 1.89 %, respectively. This means that in signal and multichannel circuits , the nonlinear algorithm better accounts for the behavior of weak currents, parasitic couplings, and shield branches. For the combined harness, the trend persists: LM again provides the minimum error (1.25 %) and the best repeatability (2.01 %), but Adam forms an alternative mode of comparable quality, which becomes significant during performance analysis.

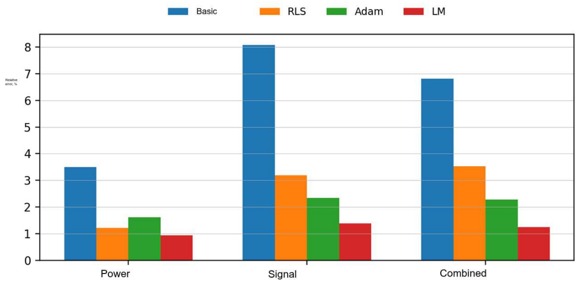

Fig. 1. Comparison of the relative error in determining the control parameter

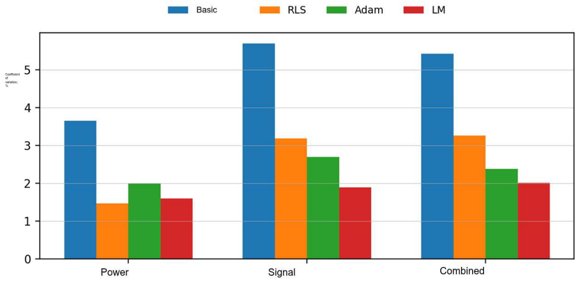

Fig. 2. Comparison of the coefficient of variation of results in measurement series

The results obtained are of fundamental importance for practical applications. If one were to focus solely on the average value of the controlled parameter, one might conclude that LM has an unconditional advantage.

However, for production control, the narrowness of the distribution of repeated results is equally important. This is precisely why the power harness demonstrates a different selection logic than the signal harness: in it, a slight drift in low-resistance measurement can be more critical than a small difference in the mean error. In this sense, RLS is not a worse algorithm, but a functionally more appropriate one for the corresponding class of products. A comparison of the average full-cycle control time for different algorithms and harness types is shown in Fig. 3.

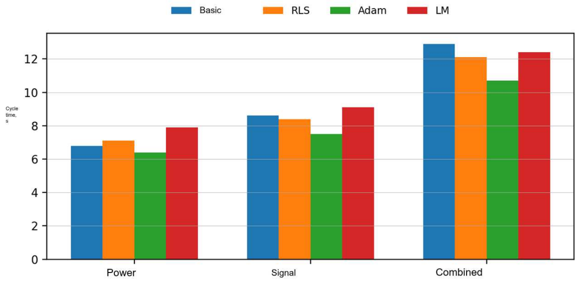

Fig. 3. Comparison of the average full control cycle time

As shown in Fig. 3, Adam provides the shortest cycle time: 6.4 s for the power harness, 7.5 s for the signal harness, and 10.7 s for the combined harness. Compared to the baseline mode, this corresponds to a cycle time reduction of 5.9%, 12.8%, and 17.1%, respectively. RLS is only slightly slower than Adam in terms of speed, while Levenberg–Marquardt is the slowest among the adaptive options due to the need for an iterative solution to a nonlinear problem. At the same time, even the baseline implementation of the developed system outperforms manual inspection and the semi-automatic CableEye M4 tester in terms of time, confirming the overall feasibility of the automated approach. A comparison of the time requirements for the developed system and traditional inspection methods is presented in Table 2.

Table 2. Comparison of time expenditures of the developed system with traditional control methods

Harness type	**No. of circuits**	**Manual control, with**	**CableEye M4, with**	**Developed system, basic mode, with**	**Developed system, Adam, c**
Power	22	13.3	8.7	6.8	6.4
Signal	29	15.2	9.6	8.6	7.5
Combined	41	22.3	14.9	12.9	10.7

A comparison with traditional methods shows that for the force sample, the cycle in the developed system is approximately 2.1 times shorter than manual inspection and 1.36 times shorter than CableEye M4. For signal and combined samples, these ratios remain at a similar level. Thus, even when the priority is not maximum metrological accuracy but rather the throughput of the workstation, the Adam algorithm transforms the automated system into a tool for accelerated screening without losing its core diagnostic functionality. A comparison of F1-scores for different algorithms and harness types is shown in Fig. 4, and the stability of the classification decision under varying test conditions is shown in Fig. 5.

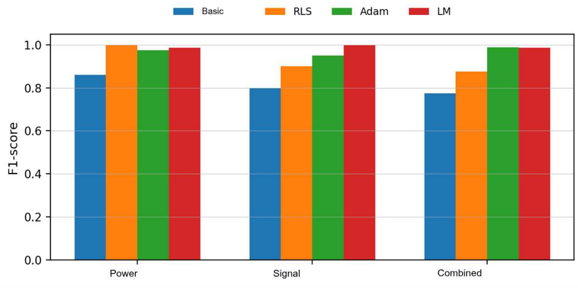

Fig. 4. Comparison of F1-scores for different algorithms and harness types

The classification results show that adaptive algorithms perform best precisely in situations where the defect does not cause a major break or a severe short circuit. For the power harness, the baseline model yielded an F1-score of 0.860, while RLS achieved 1.000, Adam – 0.975, and LM – 0.987. Analysis of specific defects revealed that the most challenging condition to detect in a power environment is elevated contact resistance. It is here that RLS's recursive refinement proved most effective, as it better distinguishes the true trend of resistance increase from random measurement noise.

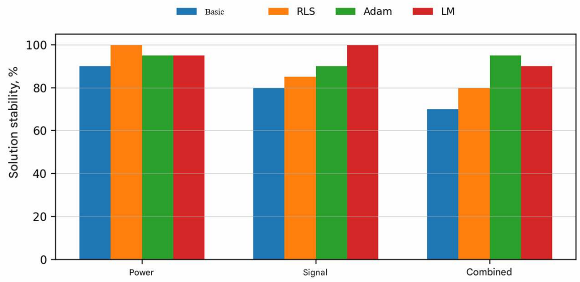

Fig. 5. Stability of the classification decision under varying control conditions

For the signal harness, Levenberg–Marquardt demonstrates a clear advantage: the F1-score for LM is 1.000, while for the baseline, RLS, and Adam, it is 0.800, 0.900, and 0.950, respectively. Physically, this is explained by the fact that in signal lines, defects involving a decrease in insulation resistance and states of increased connection resistance are more complex, as they have lower contrast and are more strongly distorted by parasitic couplings. In a combined harness, the best classification performance belongs to Adam and LM: 0.988 and 0.987, respectively. However, the nature of these advantages differs: Adam provides maximum detection completeness, while LM is more conservative and better at avoiding false positives.

The metrics shown in Fig. 5 further illustrate this picture in terms of resistance to external influences. In terms of the stability of the final solution, RLS is the clear leader for the power bundle (100 % correct solutions under of varying conditions), Levenberg-Marquardt for the signal bundle (100 %), and Adam for the combined bundle (95 %). However, if we analyze not only classification stability but also metric drift of the parameter, the picture becomes somewhat more complex: for the power bundle, RLS has the smallest relative deviation of 1.34 %, for the signal bundle, LM has 1.27 %, and for the combined LM – 1.69 %, whereas Adam, although inferior in terms of metric drift, better preserves the correctness of the final decision. This means that the concept of "stability" cannot be reduced to a single metric: an algorithm may be more metrically accurate but less stable regarding the final PASS/FAIL decision under perturbed conditions.

From a practical standpoint, it is the combination of the F1-score and decision stability that determines an algorithm's actual suitability for production use. In the context of mass production quality control, what matters to the operator is not only the average error but also the absence of fluctuations in the decision threshold. Therefore, power harnesses naturally "lean" toward RLS, signal harnesses toward LM, and combined harnesses allow for two working strategies: a universal-quality strategy based on LM or an accelerated strategy based on Adam. The integrated indicator of the comparative effectiveness of the algorithms is shown in Fig. 6.

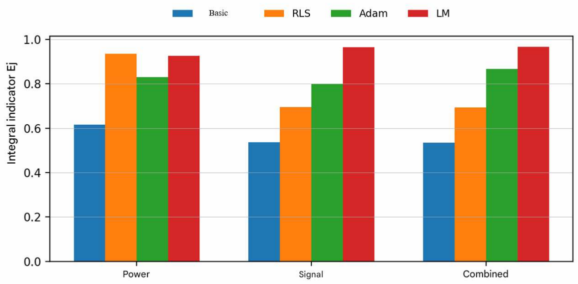

Fig. 6. Integrated indicator of comparative algorithm performance

The summary normalization of criteria (Fig. 6) generalizes the previous results without losing their technical meaning. For the power harness, the maximum integral index was obtained for RLS (E_j= 0.936), while Levenberg–Marquardt has almost the same result (0.927) but demonstrates its advantage based on other criteria. This means that in power circuits, RLS is not merely statistically superior but functionally better suited to the nature of defects and the behavior of low-impedance measurement data.

For the signal and combined datasets, the highest values of the integral metric belong to Levenberg–Marquardt—0.965 and 0.967, respectively. In the signal dataset, this advantage is indisputable, as LM simultaneously provides the smallest relative error, the best repeatability, the highest sensitivity, and the greatest solution stability. In the mixed harness, competition with Adam is fiercer: Adam has better speed and is on par in terms of F1-score, but falls short in accuracy, repeatability, and metric stability. That is why, for mixed products, LM should be considered the primary mode, and Adam—as an operational alternative.

An important implication of this study is that it did not identify a universal leader for all products. On the contrary, the results demonstrate the need for a differentiated choice of algorithm depending on the electrical nature of the harness, the nature of the dominant defect, and production constraints regarding cycle time. This conclusion is of fundamental importance for practical implementation: instead of a rigidly fixed mode, it is advisable to use types of algorithms that are activated according to the product type or the inspection scenario (Table 3).

Table 3. Recommendations for algorithm selection for different types of cable harnesses

Harness type	**Recommended algorithm**	**Alternative algorithm**	**Explanation of selection**
Power	RLS	LM	RLS has the maximum integral index E_j = 0.936 due to the best repeatability, full sensitivity to defects, and the highest stability; LM is appropriate when minimizing error is the priority
Signal	LM	Adam	LM has E_j = 0.965 and leads in accuracy, repeatability, sensitivity, and stability; Adam can be used as a fast mode with some compromise on quality
Combined	LM	Adam	LM has a maximum E_j = 0.967 due to the balance of all criteria; Adam is a practically viable alternative when the requirement for minimum cycle time dominates

From a methodological standpoint, the results also indicate that evaluating algorithms based on a single criterion can lead to a wrong choice. If one focuses solely on minimum error, the power harness would be best served by Levenberg–Marquardt. If cycle time is the only consideration, Adam would be the best choice for all product types. However, real-world production control requires simultaneous assurance of reproducibility, classification sensitivity, and decision robustness; therefore, a multi-criteria approach is not merely an additional but a necessary element of a correct technical evaluation.

Overall, the main part of the experimental study confirmed the operational capability of the developed automated control system under conditions close to those of actual production and demonstrated that adaptive processing of measurement data significantly expands its functionality compared to the basic mode. Most importantly, the increase in efficiency is achieved without changing the technical components of the automated control system-solely through the rational selection of an algorithm that best matches the structure of the controlled object. It is precisely this circumstance that creates the practical prerequisites for the flexible use of the system during acceptance testing, technological screening, and in-depth diagnostics of cable products.

Analysis of defects critical for different algorithms

Integrated metrics alone do not indicate which specific technical conditions are problematic for a given algorithm. This is of fundamental importance in industrial practice, since the decision to apply a particular inspection mode is based not on an abstract F1-score, but on whether the system is capable of consistently detecting defects characteristic of a specific class of products. For this reason, we additionally analyzed the defects that were most frequently underdetected based on the results of the experimental program. The defects that were most difficult to detect across the algorithms are listed in Table 4.

Table 4. Defects Most Difficult to Detect by Algorithm

Harness type	Basic	RLS	Adam	LM
Power	Increased contact resistance – 8/10	All defects 10/10	Increased contact resistance – 9/10	Increased contact resistance – 9/10
Signal	Insulation loss / increased resistance – 7/10	Increased resistance – 8/10	Decreased insulation / increased resistance – 9/10	All defects 10/10
Combined	Insulation loss – 6/10	Insulation loss / increased resistance – 8/10	All defects 10/10	Increased resistance of the shield-to-case connection – 9/10

The data in Table 4 allow us to move from average numerical values to a technical interpretation. For the power harness, the most difficult fault to detect was not an open circuit or a short circuit, but rather increased contact resistance. This is logical: in such circuits, the defect does not violate topological integrity but manifests as a relatively small increase in an already low resistance value. Therefore, the basic threshold mode reacts to it inconsistently. RLS, on the other hand, thanks to recursive refinement of the estimate, best accumulates information about systematic deviations and has a clear advantage in the power environment.

For signal cables, insulation breakdown defects and high-resistance branch conditions proved to be critical. In this class of products, shielded lines, lower operating currents, and sensitivity to parasitic couplings are of great importance, so simple threshold processing results in the highest number of false alarms. Even RLS, which performs well in low-impedance power measurements, does not fully eliminate these issues in a signal environment. It is Levenberg–Marquardt, which correctly handles nonlinear models and allows for better separation of the informative component from the parasitic one, that provides complete detection of all fault conditions.

For the combined harness, the behavior of the Adam algorithm is most revealing. Unlike the signal case, where LM is the clear leader, in the mixed structure Adam achieves complete detection of all introduced defects. This indicates that accelerated parametric optimization works well in conditions where the object combines several types of circuits and the algorithm needs to adapt quickly to heterogeneous local regimes. At the same time, Levenberg-Marquardt still has an advantage in terms of stability and accuracy, so the practical choice between Adam and LM in combined products depends on what is considered more critical—cycle time or overall evaluation quality.

Interpretation of results for different control modes

Detailed experimental results show that the choice of algorithm is directly related to the physical nature of the controlled parameter. In the “27 V – wire resistance” mode, the key factors are accuracy when handling low-resistance values, as well as the algorithm’s ability to detect small increases in resistance, which are characteristic of contact node defects. Here, the advantage of RLS is most evident: it does not require a complete recalculation of the entire model after each new measurement and, at the same time, ensures a sequential convergence of the estimate toward the true value. For power harnesses, this means lower result variance and more reliable differentiation between a good and a degraded contact.

In the "100 V – insulation resistance" mode, a different pattern is observed. Not only is the steady-state leakage current value informative, but so is the shape of the transient process, which depends on the capacitive and resistive properties of the specific section. Therefore, the advantage of Levenberg-Marquardt is no coincidence: this algorithm allows for parameter estimation by minimizing the discrepancy between the experimental curve and the mathematical model. For signal and composite samples, where the influence of parasitic connections, shields, and non-uniform branches is stronger, this procedure yields the smallest estimation bias and the most reliable final result.

Adam occupies a distinct practical position within the scope of the methods considered. It cannot be viewed merely as a “simplified substitute” for more complex algorithms. Within the scope of this study, it demonstrated its own functional application profile: when the production process imposes strict requirements on minimum cycle time, Adam becomes the most efficient mode. This is particularly evident for the combined harness, where it simultaneously provided the shortest inspection time and was virtually on par with LM in terms of F1-score. Therefore, it is advisable not to contrast Adam with “more accurate” algorithms in the system, but rather to consider it as a standard accelerated mode for processing inspection results.

Another important consideration is that algorithm results should not be directly transferred from one product class to another. Power harnesses, signal harnesses, and combined samples exhibit different relationships between low-impedance, high-impedance, and parasitically coupled modes. That is why the conclusion regarding the superiority of a specific algorithm should be formulated not generally for “cable products,” but for a specific group of inter-block connections with similar circuit structures. This approach is of fundamental importance for industrial implementation, as it allows moving from a universal test mode to a customized configuration scheme.

In practice, this means that the control system software should include not just a single fixed processing mode, but a library of algorithmic profiles. For power products, it is advisable to use RLS as the base profile; for signal and multichannel products—Levenberg–Marquardt; for quick checks after reconnection, repair, or correction of technical equipment—Adam. Within a single production area, this allows the control mode to be adjusted to a specific product and process scenario without changing the hardware, while maintaining measurement traceability and the possibility of further statistical analysis.

It should also be emphasized that the results presented do not contradict the role of LMS in the overall system architecture. LMS was not included in the main set of four compared modes, but retains its significance as a preliminary stage of adaptive smoothing of the measurement series. This is important in cases where the measurement path operates in a noisy environment or when control is performed after switching operations that may temporarily increase the variation of instantaneous readings. Thus, the overall system concept is hierarchical: LMS can be used as a pre-filter, while RLS, Adam, or LM can serve as the primary mode for generating the final estimate.

Practical implications for the implementation of an automated control system

The issue of implementing the obtained results into the actual production cycle takes on particular significance. The conducted study showed that an increase in control efficiency is achieved not so much by expanding hardware resources as by the correct combination of the existing hardware configuration and algorithmic mode. If the system remains unchanged and only the software approach to processing a series of measurements is modified, the enterprise gains the ability to adapt the control process to a specific class of products without further complicating the technical aspects.

Equally important is the fact that algorithmic profiling simplifies the interpretation of results for the operator. When the inspection mode is tied to a specific product type, it becomes possible to determine in advance which defects are critical for that scenario and which numerical indicators should be monitored most closely. This enhances not only the objectivity of the results but also the operational efficiency of the automated system.

In conclusion, it can be stated that the experimental comparison of algorithms fulfilled two interrelated functions. First, it quantitatively confirmed the advantage of adaptive data processing over the baseline mode. Second, it made it possible to formulate a logic for the differentiated selection of algorithms, which directly translates into practical recommendations for an automated system for monitoring the parameters of inter-block electrical connections. It is this logic that is subsequently used as the basis for drawing the generalized conclusions of the article.

Conclusions

This paper evaluates the effectiveness of four options for processing measurement data in an automated system for monitoring the parameters of inter-block electrical connections: the baseline algorithm, RLS, Adam, and Levenberg–Marquardt. The experiment was conducted on three types of cable harnesses – power, signal, and combined – using a unified test program that included 600 full control cycles and allowed for a comparison of the algorithms in terms of accuracy, repeatability, speed, and defect detection quality.

It was found that the use of adaptive algorithms significantly increases inspection efficiency compared to the baseline processing mode. The baseline algorithm proved capable of detecting gross violations but was inferior to adaptive approaches in terms of evaluation stability, sensitivity to subtle defects, and generalized classification metrics, especially for structurally complex signal and combined harnesses.

It was shown that the algorithm's effectiveness depends on the type of object under inspection. For power cable harnesses, the RLS algorithm is the most suitable, as it provided the best combination of repeatability, robustness, and sensitivity to low-contrast defects, particularly conditions with increased contact resistance. For signal and combined harnesses, the Levenberg-Marquardt algorithm demonstrated the best results, providing the highest overall performance, better metrological accuracy, and evaluation stability. The Adam algorithm should be considered a rational accelerated mode in cases where the minimum inspection cycle time is the determining criterion.

The results confirm that the selection of a measurement data processing algorithm in control systems for inter-block electrical connections must be made on a case-by-case basis, taking into account the electrical nature of the cable harness and the dominant technical priority. The practical significance of this work lies in the fact that the recommendations developed make it possible to improve the reliability and performance of automated monitoring without changing the overall system architecture, through the well-founded selection of an algorithmic mode.

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О. М. Буковський, С. П. Вислоух
Національний технічний університет України «Київський політехнічний інститут імені Ігоря сікорського», Київ, Україна

ДОСЛІДЖЕННЯ ЕФЕКТИВНОСТІ ВИКОРИСТАННЯ АДАПТИВНИХ АЛГОРИТМІВ ОБРОБЛЕННЯ ВИМІРЮВАЛЬНИХ ДАНИХ В АВТОМАТИЗОВАНІЙ СИСТЕМІ КОНТРОЛЮ ПАРАМЕТРІВ МІЖБЛОКОВИХ ЕЛЕКТРИЧНИХ З’ЄДНАНЬ

У статті розглянуто задачу порівняльного оцінювання алгоритмів оброблення вимірювальних даних в автоматизованій системі контролю параметрів міжблокових електричних з’єднань, призначеній для випробування кабельних і джгутових виробів у виробничих умовах. Актуальність дослідження зумовлена необхідністю одночасного забезпечення високої точності визначення електричних параметрів, стійкості до завад, повторюваності результатів, швидкодії контролю та достовірного виявлення дефектних станів. За використання прямого порогового підходу без адаптивного уточнення оцінок ефективність контролю знижується під впливом шумів вимірювального тракту, нестабільності контактів, паразитних зв’язків і технологічного розкиду параметрів виробів.

Метою роботи є порівняльне оцінювання алгоритмів оброблення вимірювальних даних для визначення найбільш доцільного підходу з погляду точності, повторюваності, швидкодії, чутливості до дефектів і стійкості результатів в автоматизованій системі контролю параметрів міжблокових електричних з’єднань. Для досягнення поставленої мети виконано експериментальне порівняння чотирьох алгоритмічних варіантів: базового режиму без адаптивного уточнення оцінок, рекурсивного квадратичного оцінювання RLS, ітераційної оптимізації параметрів за методом Adam та нелінійної параметричної ідентифікації на основі Levenberg–Marquardt. Дослідження проводили на єдиній апаратній платформі для силового, сигнального та комбінованого джгутів у серії контрольованих випробувань із різними типами дефектів.

За результатами дослідження встановлено, що адаптивне оброблення вимірювальних даних забезпечує істотне покращення метрологічних і експлуатаційних характеристик системи порівняно з базовим режимом. Для силових джгутів найбільш доцільним виявився алгоритм RLS, який забезпечив найкращу повторюваність і максимальний інтегральний показник ефективності. Для сигнальних і комбінованих джгутів найкращі результати за сукупністю критеріїв продемонстрував алгоритм Levenberg–Marquardt. Алгоритм Adam підтвердив доцільність використання як прискореного режиму, особливо для комбінованих виробів, коли важливо мінімізувати тривалість циклу контролю. Практичне значення роботи полягає в обґрунтуванні алгоритмічного профілювання автоматизованої системи контролю залежно від типу виробу та характеру домінувальних дефектів.

Ключові слова: міжблокові електричні з’єднання, автоматизований контроль, адаптивні алгоритми, виявлення дефектів, точність.

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