Software complex for automated diagnostics of internal parameters of technical systems

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Abstract. We offer an information technology for diagnosing technical systems by monitoring the values of their internal parameters and comparing with the maximum allowable values. Diagnosed parameters of the internal elements of the technical system are determined by the mathematical calculations based on the well-known mathematical model of the system and the measured values of its output characteristics. Optimization methods are used for calculating the values of the internal parameters of the system.

Keywords: diagnostics, technical system, output characteristics, internal parameter, permissible value, optimization

1 Introduction

The reliability of any technical device is determined by the quality of its development, is ensured in the manufacturing process and maintained during operation. The impossibility of creating absolutely reliable products makes relevant the research, development and applying of principles, ways, methods and means, which increase reliability by timely detection and elimination of equipment failures. The main ways to prevent the failure of technical systems include the effective monitoring and diagnosis of their technical condition. Timely detection and elimination of defects increases the probability of failure-free operation, and also reduces the cost of operating controlled objects. The time spent on device diagnostics can be significantly reduced by automation of the diagnosis and using rational diagnostic procedures. There are different variants of the strategy of finding defects for both automated and non-automated diagnostics [1-5].

Failures occurring in the system due to strong changes in the values of its internal parameters are easier to detect because they lead to significant changes in the output characteristics. At the same time, the drift of the parameters of the system elements, for example, in the course of its operation under the influence of ageing and external factors, leads to small variations in the output characteristics with a slow deterioration of the properties. In addition, it is not always the overrange of the parameter of the internal element of the system beyond the permissible limits that leads to an unacceptable deviation of the controlled output characteristic. However, this may change for the worse the modes of operation of the system elements, which after a certain period of time will lead to an even greater change in the parameters and, as a result, to a defect. Such deviations of the internal parameters of the system are called latent defects, and they, as a rule, require the development of special diagnostic methods, since they are not detected by traditional methods. Also, during the operation of the system, there is a need not only to respond on the fly to its failures, but also to monitor the status of parameters and modes of operation of its elements and analyze trends in their work. This will allow not only to anticipate failures, but also to issue recommendations for their prevention by assessing the approximation of monitored parameters to their maximum allowable values, which can also vary depending on the time of operation, the effect of temperature and other external factors.

These tasks can be effectively solved by automated determination of the values of parameters and modes of operation of system elements based on stimulating input actions and experimentally obtained output characteristics.

2 Formal problem statement

The mathematical model should allow to determine the values of the parameters of the internal elements of the system being diagnosed from its known (measured) output characteristics.

In practice, there is only access to a limited number of circuit nodes, to which stimulated signals can be sent and output characteristics can be recorded. In addition, the number of internal circuit parameters is much greater than the number of obtainable nodes. Therefore, to determine the values of the parameters of internal elements from the measured output characteristics it is proposed to apply the optimization method. In the optimization process, the values of internal parameters are optimized so as to maximally bring the calculated values of the output characteristics of the system under diagnosis to the measured values.

As a criterion for the correspondence of the calculated values of the output characteristics to the measured values, we use the criterion of the minimum of the root-mean-square error (1):

$$f(q) = \sum_{j=1}^{M} \sum_{i=1}^{N} \nu_{ji} \left[1 - \frac{Y_{ji\ calc}(q)}{Y_{ji\ meas}(q)} \right]^2 \Rightarrow \min, \tag{1}$$

where $Y_{ji\,calc}(q)$, $Y_{ji\,meas}(q)$ are respectively the calculated and measured value of the j-th output characteristic at the i-th point, which depends on the vector of parameters of the elements of the scheme q; ν_{ji} are weighting indices of measurement accuracy of the j-th characteristic at the i-th point, which are calculated

$$\nu_{ji} = \frac{1 - \gamma_{jicalc}}{\sum_{j=1}^{M} \sum_{i=1}^{N} (1 - \gamma_{jimeas})}, \tag{2}$$

where γ_{jimeas} is the relative measurement error of the *i*-th sample on the *j*-th output characteristic.

3 Literature review

To minimize the mean-square error function, an optimization method is used.

The methods used to solve optimization issues are rather numerous [6–8]. Among them, there is no universal method that would be the best in all or most cases. Choosing a method conforming to the special features of a particular task increases the probability of its successful solution with minimal expences. At the heart of the diagnostic model is a convex functional that is a composition of convex functions. For such functions, gradient methods of the second order, for example, the Newton method, are the best in terms of the rate of convergence and stability. However, this method requires the calculation of the Hessian matrix of the second partial derivatives and its inversion [6].

It is most expedient to use the Davidon-Fletcher-Powell method [6], which does not require the calculation of the inverse Hessian $G^{-1}(q_i)$ at every step, because the search direction at step i is the direction $-H_i\, g(q_i)$, where H_i is positively defined symmetric matrix, which is updated at every step. At the boundary, the matrix H becomes equal to the inverse Hessian. This method combines both the ideas of Newton's method and the property of conjugate gradients, and when applied to the minimization of convex quadratic functions l variables converge in no more than n iterations. It, like Newton's method, is based on the correlation

$$q_{i+1} = q_i - \lambda_i G^{-1}(q_i)\, g(q_i), \tag{3}$$

where q is the vector of the diagnosed parameters; i is the iteration number of optimization; λ is an optimization step parameter; g is the vector of the sensitivity functions of the target function to a change in the parameter values (gradient); G is the matrix of sensitivity functions of the second order, the so-called Hessian matrix.

The search for the minimum of the objective function (1) begins at the starting point q_0 (usually, the nominal values of the diagnosed parameters), and the initial matrix H_0 is taken as the indentity one. The iterative procedure can be represented as follows:

1. At step i, there is a point q_i and the symmetric matrix H_i is positive defined.
2. As direction of the search, to take a direction $d_i = -H_i g_i$.
3. To find the function λ_i, which minimizes the function $f(q_i+\lambda_i d_i)$, to do a one-dimensional search along the straight line $q_i+\lambda_i\ d_i$.
4. To calculate the increase in the parameters $v_i = \lambda_i d_i$.
5. To calculate the new values of the parameters $q_{i+1} = q_i + v_i$.
6. To calculate the new values of the objective function $f(q_{i+1})$ and its gradient g_{i+1} for the values of the parameters q_{i+1}. If the values of $|g_{i+1}|$ or $|v_i|$ small enough, complete the optimization, otherwise continue.
7. To calculate the increase in the gradient $u_i = g_{i+1} - g_i$.
8. To calculate the matrix A_i

$$A_i = \frac{\mathrm{v}_i \cdot \mathrm{v}_i^T}{\mathrm{v}_i^T \cdot u_i},$$

where v_i is the vector of increment of parameter values, v_i^T is the transposed vector of increment of parameter values, u_i is the vector of increment of the gradient of the objective function.

9. To calculate the matrix $B_i = -H_i u_i u_i^T H_i / (u_i^T H_i u_i)$,

where H_i is the matrix H at the i-th iteration, u_i is the gradient increment vector, u_i^T is the transposed gradient increment vector.

10. To update the matrix H in the following way: $H_{i+1} = H_i + A_i + B_i$,

where H_{i+1} is the matrix H at the i+1-st iteration, H_i is the matrix H at the i-th iteration, A_i is the matrix A at the i-th iteration, B_i is the matrix B at the i-th iteration.

11. To increase i by one and to go back to step 2.

4 Requirements for the software complex

Functional capabilities and organization of software determine the basic requirements for the software system under development for automated diagnostics of the parameters of elements of technical systems.

The requirements to the functional capabilities of the complex can be formulated as follows.

The complex should allow:

- to analyze the characteristics of the technical system at the design stage;
- to obtain, according to the results of the analysis, the necessary test input effects and measurement points of the controlled output characteristics;
- by measured output characteristics to determine the actual values of the parameters of the elements of the system;
- automatically form the boundaries of the rejection tolerances for the parameters of the elements of the system, taking into account its lifetime, temperature and other external factors;
- by comparing the actual values of the parameters of the elements with the maximum permissible values, give information about the causes of system malfunction to the element level.

The practical implementation of the functions of constructing a mathematical model of the system being diagnosed and calculating its output characteristics can be performed using the methods and algorithms described in [9-11].

To implement the functions of calculating the values of the internal parameters of the system from the known values of its output characteristics, the additional use of the diagnostic model of the system [12] is necessary, on the basis of the objective function (1).

From the point of view of software organization, the complex should meet the following requirements:

- have a block-modular structure that allows you to effectively complement the complex with other functional blocks and software patterns that extend its functional capabilities;
- to be able to function as part of an integrated CAD-system used in the design of the system being diagnosed;
- be open to the emergence of new numerical analysis methods used in the operation of the complex in order to increase the efficiency of its application in the process of diagnosing technical systems;
- to incorporate a database of maximum permissible values of parameters of system elements.

5 The structure and algorithm of the software complex functioning

The structure of the developed software complex is shown in Figure 1 [13], where the dotted line outlines the software modules that are part of the CAD for designing the diagnosed system and are used by the developed software complex. The arrows in the diagram show the direction of data transfer between the modules.

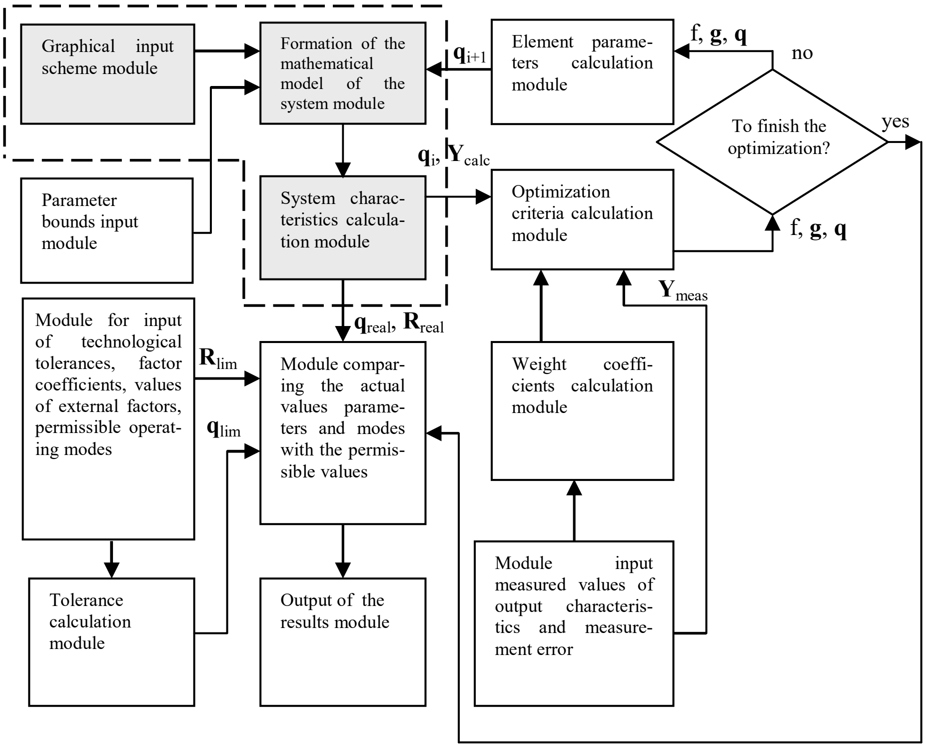

Fig. 1. The structure of the software complex for automated diagnosis of parameters of technical systems elements

Another important task of developing an automated diagnostics software complex is the development of an algorithm for its functioning. The algorithm of functioning of the complex is implemented by the managing program, which coordinates the interaction of program modules and ensures the implementation of certain procedures.

The algorithm of functioning of the complex, the block diagram of which is shown in Figure 2, is based on the method presented in Section 3, the requirements for the program complex and the structure of the complex presented above.

Block 1. The start of the algorithm of the software complex functioning.

Block 2. Introduction of the necessary source data: a basic diagram, technological tolerances on the parameters of elements, factor coefficients, maximum allowable modes of operation of elements, values of external factors, the parameter value of the calculation process cessation, the choice of diagnosable parameters and restrictions on them.

Block 3. Set of the input effects, measurement points and measurable values of the output characteristics.

Block 4. Formation of a mathematical model of the system being diagnosed with the data inserted.

Block 5. Calculation of output characteristics and functions of parametric sensitivity of output characteristics to changes in the values of the parameters of the elements.

Block 6. On the basis of the parametric sensitivity functions of the output characteristics, the formation of a test matrix with respect to the diagnosed parameters and the calculation of the rank of the matrix ρ.

Block 7. Determination of the degree of the possibility of a solution with respect to the diagnosable parameters $\mu = n_q - \rho$, where n_q is the number of diagnosable parameters. If the condition of diagnosability $\mu \leq 0$ is fulfilled, then the weighting factors are calculated (block 8). If the condition $\mu \leq 0$ is not fulfilled, then additional input actions and control points of measurement are needed, that is, a return to the fulfilment of block 3.

Block 8. The calculation of the weighting coefficients of the objective function on the basis of the measurement accuracy of the corresponding output characteristics.

Block 9. The calculation of the objective function to determine diagnosable parameters.

Block 10. Calculation of the gradient of the objective function.

Block 11. Checking the completion of the process of optimizing the values of diagnosable parameters.

Block 12. The inclusion of additional controlled characteristics.

Block 13. Calculation of parameters and modes of operation of the elements of the system being diagnosed.

Block 14. Calculation of the maximum permissible values of the parameters of the elements, taking into account the temperature and time of operation.

Block 15. Comparison of the calculated values of parameters and modes of operation of the elements of the system being diagnosed with the maximum allowable values.

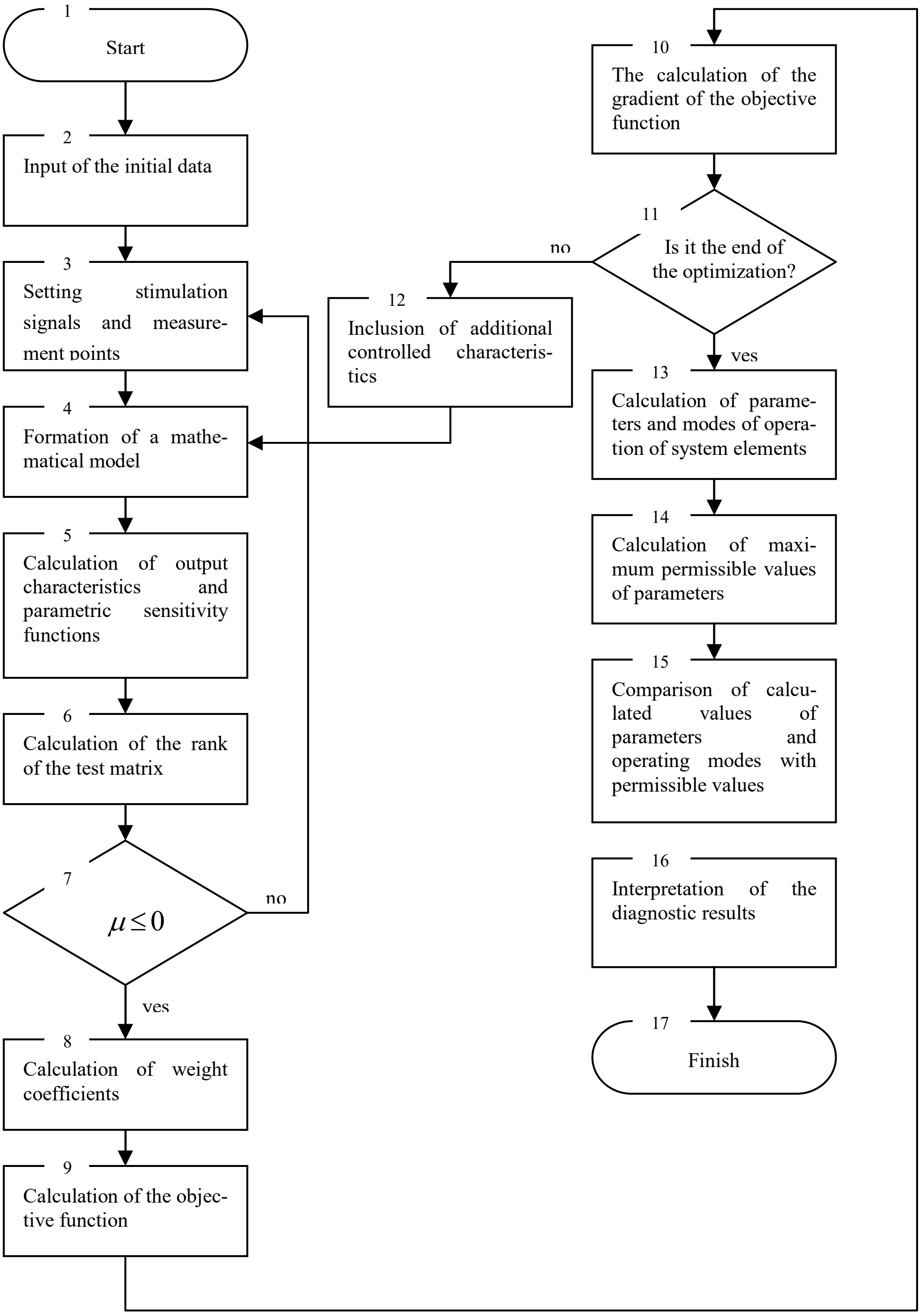

Fig. 2. Algorithm of the software complex for automated diagnosis of the parameters of the technical systems

Block 16. Interpretation of the results of calculations and diagnostics, that is, the derivation of the calculated values of the parameters and modes of operation of the elements and the results of their comparison with the maximum allowable values of the classification of the technical state of the system being diagnosed.

Block 17. The end of the algorithm of the software complex functioning.

If according to the results of diagnosing any one or several internal parameters of the system go beyond their maximum permissible limits, the presence of a defect is ascertained. If any internal parameter of the system has not reached its maximum permissible value, but is close to it, we can speak of a possible defect in the near future. In this case, it is necessary to predict the behavior of the parameter [14] in order to take action in advance without allowing the parameter to go beyond the tolerances.

6 Experiments and results

To test and confirm the practical application of the developed diagnostic method, we conduct the experimental studies of simple technical systems representing basic analog electrical circuits.

The passive RC low-pass filter was taken as the simplest test case [12]. Its basic electrical circuit diagram is shown in Figure 3.

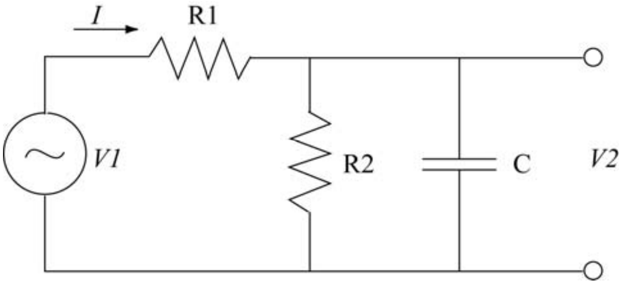

Fig. 3. The basic electrical circuit of the filter

The electrical parameters of the device are the resistance of resistors R1, R2 and the capacitance of capacitor C. Their nominal values:

C1 = 100 pF, R1 = 10 kΩ, R2 = 10 kΩ.

To ensure the diagnosability of the filter, it is necessary to select input influences and output characteristics sufficient for unambiguous determination of the parameters of the filter elements. Such a linear frequency-dependent device is advisable to diagnose in the frequency domain. If the stimulating signal is the input harmonic voltage *V1*, and the output controlled characteristic is *V2*, then in accordance with section 5 the test diagnostic matrix will have a rank of 1. Thus, when monitoring the voltage *V2*, it is impossible to ensure the diagnosability of three circuit parameters. In this case, the scheme can be diagnosed only with a single fault. If the input action is voltage *V1*, and the output controlled characteristic is alternating current *I*, then the test matrix will also have a rank equal to 1. If the output controlled characteristics are current *I* and voltage *V2*, then the rank of the resulting matrix is three, and the scheme will be diagnosed over all parameters. Therefore, the amplitude-frequency dependences of the output voltage *V2* and the input current *I* are used as output characteristics. The test input is a harmonic voltage with amplitude of 1V and a frequency of 0, 100 kHz, 200 kHz, 300 kHz, 400 kHz, 500 kHz.

First, using CAD MAES-P [12] according to the specified scheme, parameter values and test input effects, the selected output characteristics were calculated. Then, using the diagnostic program, these parameters were used to calculate the values of the parameters of the elements, which were compared with their previously specified values. Thus, verification of the accuracy of identification of parameter values was carried out on the calculated output characteristics, which were taken as measured and corresponded to the values of the parameters of the elements, both within tolerances and beyond their limits [13]. The results of the calculation of the parameters of the filter elements are shown in Table 1.

Table 1. Values of the diagnosed parameters (Modeling)

Parameter	Nominal Values		
	Set	Calculated	Error, %
R1, kΩ	10	9.990	0,01
R2, kΩ	10	9.999	0,01
C1, pF	100	99.998	0,002
	In the tolerance range		
	Set	Calculated	Error, %
R1, kΩ	9	8.999	0,011
R2, kΩ	11	10.999	0,009
C1, pF	90	89.999	0,001
	One parameters are out of tolerance		
	Set	Calculated	Error, %
R1, kΩ	15	14.999	0,007
R2, kΩ	10	9.999	0,01
C1, pF	100	99.992	0,008
	Two parameters are out of tolerance		
	Set	Calculated	Error, %
R1, kΩ	15	15.0009	0,006
R2, kΩ	15	15.0002	0,0013
C1, pF	100	99.993	0,07
	Three parameters are out of tolerance		
	Set	Calculated	Error, %
R1, kΩ	15	15.001	0,001
R2, kΩ	15	15.002	0,002
C1, pF	50	50.0005	0,001

From Table 1 it can be seen that in all cases, the parameters of the elements are uniquely identified with an error not exceeding 0.01%.

Then three filter layouts were assembled, the parameters of the elements were measured before installation. Elements with nominal values of parameters were installed in one layout, and elements with values outside tolerances were installed in other models. Test inputs were submitted and output characteristics measured.

Further, the measured values of the output characteristics of the filter using the diagnostic program were calculated values of the parameters of the elements. According to the results of their comparison with the maximum permissible values, defective elements were identified. The values of the parameters obtained as a result of the calculation, the measured values and the maximum permissible values are given in Table 2.

From Table 2 it can be seen that the error in calculating the parameter values does not exceed 0.3% for all three cases.

Table 2. Values of the diagnosed parameters (Experiment)

Parameter	Maximum permissible values		Mock-up 1 One parameters are out of tolerance		
	Lower	Upper	Calculated value	Measured value	Error, %
R1, kΩ	9	11	15.21	15.2114	0,0066
R2, kΩ	9	11	10.14	10.1095	0,3
C1, pF	80	120	103.6	103.385	0,2
			Mock-up 2 Two parameters are out of tolerance		
R1, kΩ	9	11	15.21	15.2112	0.0079
R2, kΩ	9	11	6.84	6.8464	0,094
C1, pF	80	120	103.6	103.75	0,144
			Mock-up 3 Three parameters are out of tolerance		
R1, kΩ	9	11	15.21	15.2102	0,013
R2, kΩ	9	11	6.84	6.84608	0,087
C1, pF	80	120	151.2	0,102	0,067

Thus, the accuracy of diagnosing the parameters of the elements is almost determined by the accuracy of the measuring devices.

For more complex schemes, the error in diagnosing, in addition to the accuracy of measuring devices, also depends on the accuracy of mathematical models of the systems being diagnosed.

7 Conclusion

Thus, in the course of automated diagnostics, the problem inverse to the system design problem is solved — the values of the internal parameters of its mathematical model are calculated from the known (measured) output characteristics of the system.

For a successful diagnosis, the main condition is the presence of an adequate (fairly accurate) mathematical model of the system being diagnosed because the higher the accuracy of the system model, the higher the accuracy of diagnosis. Therefore, it will be most effective to diagnose a system using CAD-systems that are used during its design.

At the same time, it makes no difference to which particular area the diagnosed system belongs. It can be of any nature, provided it has a sufficiently accurate mathematical model and the possibility to apply test stimuli and measure the output characteristics necessary for a successful diagnosis.

So, as it is not possible to determine the values of all the internal parameters of its model by the usually available small set of output characteristics of the system, the key point in the diagnosis is to find and select those input test influences and control points for measuring the output characteristics that would uniquely determine the values of all internal parameters of the system being diagnosed. That is, they would ensure the single-extremes of the objective function (1), at least in a certain range of possible values of the internal parameters (usually 2-3 times exceeding the allowable spread of the parameter values according to the system specification).

To speed up this procedure and increase its efficiency, it is advisable to use methods based on neural networks and artificial intelligence [15, 16]. At the same time, the constantly increasing processing power of modern computers allows increasing the complexity of diagnosable systems (and their mathematical models) and approaching the solution of real practical problems.

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