SYSTEM APPROACH TO ENSURE PERFORMANCE OF MARINE AND COASTAL ELECTRICAL SYSTEMS DURING OPERATION

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Abstract. The long service lifetime of marine and coastal electrical systems resulted in the increased number of gradual failures of their elements. Parametric instability has become one of the main reasons for quality decline of electrical systems during their operation. The paper considers the strategy and tasks of managing the state of marine and coastal electrical systems at various stages of their life cycle. To solve these problems, information about the performance boundary is required. A performance limit assessment of the system is required to ensure the operability of these systems. An assessment of performance limit is carried out and two methods that make it possible to calculate the performance limit of electrical system during its operation are proposed. The method of adaptive matrix search is aimed to estimate the condition of a system taking into account the fact that the performance region is approximated by linear hypersurfaces. The method of converging regions is applicable for any electrical system with predetermined performance conditions; however, it is more labor-consuming. In case of a large number of diagnostic parameters and the necessity to refine the obtained results, special algorithms have been developed to calculate the performance limit. The methods and algorithms considered in the paper were successfully tested during the study of marine and coastal electrical systems for various purposes.

1. Introduction

The Development Strategy of Inland Water Transport of the Russian Federation until 2030 is focused on comprehensive modernization and reconstruction as well as technical upgrade of existing shipbuilding capacities; increase in the output of shipbuilding products using modern technologies; fleet and shipping equipment renewal in river harbors; competitiveness of inland water transport in relation to other types of transport.

A prerequisite for solving these problems is high reliability of marine and coastal electrical systems (ES). At the same time, the achieved level of reliability does not fully meet modern requirements. For example, in recent years, the total costs for maintenance of ships, machines and mechanisms of onshore facilities during their service life has become two or three times higher compared to their
construction cost and the cost of repair of ships reached half of the sum spent for the construction of a new fleet. This is due to the specific characteristics of the ES operation of water transport facilities which attribute changing and complex operating conditions, great circuit diversity, lack of statistical information on their condition, and the autonomy of operation [1]. The long service life of these systems led to the growth of gradual (parametric) failures. Parametric instability of the ES has become one of the main reasons for their quality decline during their operation. It became obvious that mandatory parametric reliability must be taken into account when developing, manufacturing, setting up marine and coastal ES and their elements.

Both domestic and international experience regarding operation of the ES show that most failures are gradual failures, and statistical information on the laws of changing their parameters is limited. This circumstance has facilitated the development of functional and parametric direction in the reliability theory, which provides for the management of operational reliability of the ES, taking into account the determination of their technical state in the conditions of limited information or its absence [2].

In the framework of this direction, a strategy is proposed in paper [3], which is aimed at determining and ensuring the ES performance limit at all stages of their life cycle. This strategy involves the use of automated information systems that provide analysis of a priori information and the accumulation of statistical data on the parameters and quality indicators of the ES throughout their life cycle. At the design stage, the state management is reduced to the structural and parametric synthesis of the ES, which provides given or maximum possible performance limit. Nowadays the methods, algorithms and technical means have been developed that make it possible to solve the synthesis problem for complex, multiparameter systems [4, 5]. The tasks of setting and monitoring the state of the ES are being solved at the stage of adjustment. The most important task at the stage of operation is to assess the ES performance limit.

To solve the problems of structural and parametric synthesis of the ES under their parametric instability, as well as to solve the problems of the ES analysis, including the tasks of technical diagnostics, it is necessary to obtain information on the boundary of the system’s performance [6]. The construction and analysis of the performance region is important for the design and operation of various ES and their elements. The solution of this problem allows to estimate the performance limit for a chosen system structure and to compare opportunities of different structures, to implement the assignment of tolerances and the choice of nominal values for the parameters of elements of the designed ES. Information about the performance boundary allows successfully solving the issues of determining and forecasting technical state of the ES. Its variety is the task aimed at designing the areas of permissible variation of parameters, regions of stability and quality (which is widespread in the theory of automatic control), as well as reachability regions [7-10].

The paper considers one of the most important tasks of controlling the state of the ES at the operational stage, i.e. the condition assessment of a system, which involves calculating its performance limit. In this case it is assumed that the performance conditions are set for the ES.

2. Methods and materials

According to paper [11], the ES will be understood as a technical system designed for obtaining, distributing, transforming and using the electric power, as well as controlling these processes. The elements of the ES are electrical devices. These can be amplifiers, converters, filters, correction devices, etc., which are the ES elements or the elements of its subsystem, for example, a pulse-phase control system for an electric drive or a load sharing system between generators for a ship’s power supply system.

Under the performance limit we will understand the degree of approximation of the vector \( \mathbf{X}_t \) of the ES actual state to its maximum permissible value \( \mathbf{X}_{\text{lim}} \). The set of maximum permissible values of the vector \( \mathbf{X}_{\text{lim}} \) is determined by the performance boundary of the ES. The degree of approximation of a vector \( \mathbf{X}_t \) is specified by the distance from its end to the nearest boundary point.
Let us denote a point on the performance boundary by \( \mathbf{b} = [b_1, b_2, \ldots, b_h] \). The minimum distance of the vector of primary parameters from the vector \( \mathbf{X} = [X_1, X_2, \ldots, X_n] \) over all values of boundary points will determine the ES performance limit. If the nominal values of the primary parameters are determined \( \mathbf{X}_{\text{nom}} = [X_{1\text{nom}}, X_{2\text{nom}}, \ldots, X_{n\text{nom}}] \), then the nominal performance limit \( \rho_{\text{nom}} \) can be determined, which in this case is conveniently expressed in relative units \( \lambda(X) \):

\[
\rho = \min_{X_i} \left[ \sum_{i=1}^{n} (X_i - b_i)^2 \right]^{1/2}, \rho_{\text{nom}} = \min_{X_i} \left[ \sum_{i=1}^{n} (X_{i\text{nom}} - X_{i\text{br}})^2 \right]^{1/2}, \lambda(X) = \rho / \rho_{\text{nom}}.
\]

This estimation of the performance limit allows us to take into account both external and internal conditions of the system's performance [4, 6].

If the performance region is convex and the statistical data characterizing the technological spread of parameters of the ES components during the production and the data on the change of these parameters during their operation are known, the performance limit for one primary parameter \( X_i \) can be calculated by the following formula:

\[
\lambda_i(X) = \frac{(X_{i\text{nom}} - X_{i\text{lim}})}{\delta_i(X)} - 1, \quad i = 1, n,
\]

where \( X_{i\text{lim}} \) is the maximum (maximum \( X_{i\text{max}} \) or minimum \( X_{i\text{min}} \)) permissible value of the \( i \)-th primary parameter; \( \delta_i(X) \) is the rate setting parameter characterizing the parameter scattering \( X_i \).

The rate setting parameter \( \delta_i(X) \) can be set through the characteristics of scattering of primary parameters, which specify their possible losses:

\[
\delta_i(X) = X_{i\text{nom}} - X_{P_i}, \quad \delta_i(X) > 0, \quad i = 1, n,
\]

where \( X_{P_i} \) is the quantile of the distribution level \( P = 0 \) of the \( i \)-th primary parameter, i.e. \( P = P\{X_i(t) \leq X_{P_i}\} = \int_{-\infty}^{X_{P_i}} \Phi_i(X) dX \), and \( \Phi_i(X) \) is the distribution density of this parameter.

The performance region \( G \) is formed in the space of the internal parameters of the ES. The internal parameters are parameters of the ES elements that characterize the state and properties of the system itself. When solving synthesis problems, they determine the vector \( \mathbf{X} \) of the controlled parameters. These include, for example, the gain ratio, time constants, elastic coupling stiffness, resistor resistance, coil inductance, and so on. The mathematical functional model of the ES is an algorithm for calculating the vector of the output parameters \( \mathbf{Y} \) for given vectors of the internal parameter \( \mathbf{X} \) and the external parameters \( \mathbf{V} \).

The external parameters characterize the properties of the external medium relative to the ES and influence its functioning. The output parameters characterize the properties of the ES, which the consumer is interested in. They are the parameters and functionals, i.e. functional dependences of phase variables \( \mathbf{Z} \) and the parameters that are boundary values of ranges of external variables within which the ES preserves its performance.

The performance region \( G = D_{\mathbf{X}} \cap M_{\mathbf{Z}} \cap M_{\mathbf{Y}} \) is determined by the conditions of efficiency of the ES, which generally are presented as follows:

\[
Y_{j\text{min}} \leq Y_j = F_j(X) \leq Y_{j\text{max}}, \quad j = 1, m;
\]
\[
Z_{j\text{min}} \leq Z_j = F_{j\text{v}}(X) = Z_{j\text{max}}, \quad j = 1, h;
\]
\[
X_{i\text{min}} \leq X_i \leq X_{i\text{max}}, \quad i = 1, n.
\]

where the first, second and third inequalities define the tolerance regions \( M_Y, M_Z, D_X \), respectively.

The diagnostic parameters in this work are the primary parameters of \( \mathbf{X} \). This is due to the fact that it is the primary parameters that ultimately determine the state of the ES. In addition, only in the parameter space \( \mathbf{X} \) is it possible to determine the most important indicator of the ES, i.e. the
performance limit which is understood as the degree of approximation of the vector of the actual state of the system to its maximum permissible value. Methods for assessing the state of the ES in the space of measured characteristics based on the use of information about the performance boundary were considered in paper [12].

To assess the state of the ES in the space of primary parameters, it is required to establish whether the measured values of the parameters $X$ are in the performance region. The performance region can be defined as a set of boundary points or as a hypersurface that limits the range of permissible values of the primary parameters. To define the performance region by an array of boundary points, methods and algorithms were developed based on a discrete and continuous search for the coordinates of these points [6]. For the technical implementation of the methods of searching and storing the boundary points, a fairly large amount of memory is required. At the same time, the calculation capabilities of modern computers make it possible to implement the developed algorithms for finding the boundary points for a sufficiently large number of primary parameters. An exact solution of the problem of describing the region of performance by a hypersurface is possible only for the simplest systems with a small number of parameters [6].

When developing methods for assessing the state of the ES, it is necessary to take into account the initial data, the dimension of the system and a priori information on the form and task of the performance region. It is assumed that the coordinates of the diagnosed parameters $X_t$ that determine the point $R_t$ in their space are known. Such information is usually obtained experimentally based on the use of known methods of identification of the ES. The methods for monitoring the status of the ES must have the criteria that allow to recognize the belonging of any arbitrary point $R_t$ of the performance region and to estimate the performance limit of the system. When monitoring the status of the ES by independent tolerances, the problem is solved very simply. The coordinates of the point $R_t$ are compared independently of each other with the tolerances (limit coordinates for each parameter) and when all inequalities are satisfied, a conclusion is made about the belonging of the point of the performance region and, as a consequence, about the performance of the ES. With the more accurate approximation of the performance and the transition to the dependent tolerances this rule cannot not be referred to.

3. Results

Let us consider two methods that are based on the use of information about the performance boundary and can be successfully used when assessing the state of the ES during operation.

4. Adaptive matrix method

The method assumes that each of the restriction functions of inequality (1): $Y_{j_{\text{max}}} - F_j(X) \geq 0$ and $F_j(X) - Y_{j_{\text{min}}} \geq 0$ is approximated by a finite set of linear hypersurfaces $f_j$, and the admissible region $M$ is given by the following system of inequalities:

$$\sum_{j=1}^{2m} f_j(X) \geq 0; \quad f_j(X) = b_{j0} + \sum_{i=1}^{n} b_{ji} X_i \geq 0.$$  

To form the rule of recognition of the ES state, we use the properties of logical $R$-functions, which include linear hypersurfaces $f_j(X)$ [13]. In this case, the performance region can be set by the following inequality:

$$((\varphi_1 \wedge_{\alpha_1} \varphi_2) \wedge_{\alpha_2} \varphi_3) \wedge_{\alpha_3} \ldots) \wedge_{\alpha(g-1)} \varphi_d = \bigwedge_{g=1}^{d} \varphi_g \geq 0, \quad (2)$$

where $\bigwedge_{\alpha(g)}$ is the $R$-conjunction of the $R$-functions $\varphi_g$, which makes it possible to take $k$ derivatives; $\alpha(g), g = 1, d$ are the quantities belonging to the interval $(g) \in [-1; 1]$. 


If all constraints (1) are two-sided, then $d = 2(m+n)$. In this case, for the constraint functions
$f_j(X): Y_{j_{\min}} - F_j(X) \geq 0$ and $F_j(X) - Y_{j_{\max}} \geq 0 - \varphi_g = f_j(X), \ g = j, \ j = \overline{1,2m}$ and for the
constraint functions $f_i(X): X_{i_{\max}} - X_i \geq 0$ and $X_i - X_{i_{\min}} \geq 0 - \varphi_g = f_i(X), \ g = i, \ i = \overline{1,2n}$. In
formula (2), parentheses can be omitted and the final result will not depend on the sequence of
convolution of the $R$-functions $\varphi_g$.

To build the $R$-conjunction, the following formula can be used [6]:
$$\varphi_1 \land \varphi_2 = 0.5(\varphi_1 + \varphi_2 - |\varphi_1 - \varphi_2|).$$

Equating the function $G(X)$ to zero we obtain the equation $G(X)=0$ which describes the boundary
of the ES peformance. Writing the function $G(X)$ as the $R$-conjunction of the functions $M(X)$ and
$P(X)$, which describe the regions $M$ and $P$ the following is obtained
$$G(X) = 0.5(M(X) + P(X) - |M(X) - P(X)|) \geq 0.$$

In papers [4, 14], an equation of the boundary of the region $G_\mu$ located equidistantly to the domain
$G$ and inside it is obtained. Moreover, the boundary points of the regions $G$ and $G_\mu$ are relative to one
another in the direction of gradient to the function $G(X)$ at the same distance $l$.

The evaluation of the state of the ES is carried out in the following manner. If the calculated value
of the function $G_1(X)$ is positive, then the ES is in good operating condition; if it is negative, the
system is inoperable. If the values of the parameters $X$ are expressed in relative units, then the
calculated value of the function will characterize the relative value of the ES performance limit
belonging to the interval $[-1; 1]$.

The method for performance limit determination involves sequential probing of the $R^k$ space of
diagnostic parameters $X$ of the ES. The directions of probing are determined by the given matrix $M(X)$
of coordinates of primary parameters and the deviation of experimental points from the initial value
$X$, depends on the results of previous experiments. The matrix $M(X)$ includes $N = 2^n + 2n$ of the search
directions. The choice of the number $N$ is determined by the fact that in the analytic description of
hypersurfaces that make up the ES performance region, in most cases the second-order polynomials
are used for the construction of which $N$ points constituting the nucleus and stellar points of the
second-order plans are used. In this case, the accuracy of approximation of the performance region
will be commensurable with the accuracy of the search for the amount of performance limit of the
ETS.

5. Method of convergent regions

The method of convergent regions is developed for solving the problem of parametric ES synthesis by
the criterion of the performance limit [4, 15]. The main advantage of this method is the fundamental
possibility of finding a global optimum for an arbitrary form of the performance region. The method
provides for a consistent convergence of the initial region of the performance region until it
degenerates to the point. For analytical description of the boundaries of the regions $G_1, G_2, \ldots, G_k, \ldots, G_t$
the mathematical apparatus of $R$-functions is used at each $k$-th step of the search [4]. The performance
limit of the ES $l_1, l_2, \ldots, l_k, \ldots, l_s$(in the relative units $\lambda_1, \lambda_2, \ldots, \lambda_k, \ldots, \lambda_s$) correspond to these regions.
For example, when $S=3$ for the subregions $G_1: \lambda_1 \in [0; l_1/l_0]$; $G_2: \lambda_2 \in [l_1/l_0; l_2/l_0]$;
$G_3: \lambda_3 \in [l_2/l_0; 1]$. To diagnose the state of the ES, it is sufficient to establish the belonging of the
actual state vector of the system $X$, determined by the coordinates of the point $R$, of a specific region
$G_t$ according to the criterion considered earlier.

If the information about the boundaries of the regions $G_1, G_2, \ldots, G_k, \ldots, G_t$ is absent and there is
only an analytical description of the performance region, and each component of its hypersurface is
approximated by the hypersphere class [16], it is proposed to use the following algorithm for
estimating the state of the ES.
At the first stage the belonging or non-belonging of the point \( R_t \) to the performance area is determined. To do this, the coordinates of the point under study are applied to the formula for the analytic description of the performance region on the basis of logical \( R \)-functions. At the same time, as it was noted above, a positive result means that the point belongs to the region of performance and the electrical systems are in good operational conditions.

In the second stage, a hypersphere is determined, which is closest to the point \( R_t \). It was proved in paper [16] that for this purpose it is sufficient to compare the numerical values of the \( R \)-functions that define each hypersphere when they are applied to coordinate expressions of the point \( R_t \). A smaller value will determine the hypersphere remaining for further analysis.

The third stage determines the performance limit of the \( l \) ES. It can be seen that \( l = |R - L| \), where \( R \) is the radius of the hypersphere left for analysis; \( L \) is the distance between the point \( R_t \) and the center of the hypersphere.

The considered algorithm differs with its small time consumption and the possibility of practical implementation when the diagnostic parameters are presented in a large number. In case \( n > 10 \), its advantages are often decisive when choosing the ES control algorithm.

6. Discussion

The obtained results allow to determine the performance limit and evaluate the state for practically any ES for which the performance conditions (1) are given. In the event that the system performance region can be approximated by a finite set of linear hypersurfaces, an adaptive matrix search method should be used to solve the problem. In the most general case, one should use the method of converging regions. Therewith, in the case of a large number of diagnostic parameters, it is advisable to use an algorithm that assumes that the performance region is approximated by a regular figure in the form of hypersphere.

If you need to refine the obtained estimate of the performance limit, one should use the spiral scanning algorithm. In this case, the search step is determined by the required tolerance of calculation of the performance limit of the ES [4].

The spiral scanning algorithm was developed to solve the problem of finding the first boundary point belonging to the performance region when it was defined as a set of boundary points and described in paper [6].

The choice of points for the belonging analysis of their region \( G \) is carried out in a spiral way, starting from the points \( R'_1 \) and \( R'_2 \) and following the rule:

\[
R_v = 0.125 \Delta X_i \left[ 2v' + 1 + (-1)^{(v'-1)} \right] \left( -1 \right)^{(v'-1)} \left[ \left( -1 \right)^{(v'-1)} + 1 \right] + 0.125 \Delta X_i \left[ 2v' + 1 + (-1)^{(v'-1)} \right] \left( -1 \right)^{(v'-1)} \left[ \left( -1 \right)^{(v'-1)} + 1 \right];
\]

\[
v' = 0.5 \left( -1 \right)^{v'} + 1.5; \quad v' = E \left( 0.5v + 0.5 \right); \quad E = 1, 2, 3, \ldots
\]

The transition from coordinates \( 0X'_1X'_2 \) to coordinates \( 0X_1X_2 \) is carried out according to the known formulas [6] and for the angle of rotation between the axes \( X'_1 \) and \( X_1 \) equal to \( 0.25\pi \) one obtains \( X'_1 = (X_1 + X_2) / \sqrt{2} \) and \( X'_2 = (X_1 - X_2) / \sqrt{2} \).

The application of automated systems for the control of the ES state of onshore and marine installations under normal and emergency modes was considered in papers [3, 17].

7. Conclusion

The control of the state of the ES involves solving the whole complex of problems of analysis and synthesis, including the tasks of methodological support of this process, the tasks of structural and parametric synthesis, as well as monitoring and forecasting the state of the system. To solve these problems, information on the performance boundary of the system has to be in place. In this case, it is possible to parametrically optimize the ES accounting for the performance limit criterion and to
provide high reliability of control. For an analytical description of the performance regions with a low methodological error, a developed method based on the application of logical $R$-functions should be used. The methods considered in this paper were tested on the examples of synthesis and control of the state of various ES and their elements.

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