Optimization of algorithms for diagnostics of electrical systems

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***Abstract* — The process of optimization of algorithms for diagnostics of electrical systems is examined in the paper. The mathematical description of the diagnostic process in different ways of presenting the test results is presented. A heuristic optimization method is considered, and its action for determining the number and sequence of tests is presented.**

Keywords — diagnostic process, optimization, information entropy, test, testing sequence

I. INTRODUCTION

The operation of electrical equipment in various sectors of industry is accompanied by high costs for maintaining its working condition throughout the service life of the respective electrical equipment. The maintenance of the working condition of the machines is ensured by performing planned and preventive maintenance and repair activities, as well as unplanned repairs performed in order to eliminate faults and malfunctions occurring during the operation periods [1, 2].

To increase the efficiency of the usage of electrical equipment, diagnostic methods and tools have been developed. These methods are used both during maintenance and repairs, and as an independent process. The diagnostics provides an opportunity to increase the availability of the machines, to reduce the complexity of repairs, and to reduce annual costs for operation of the electrical equipment and to increase its maintainability.

The optimization problems concerning the diagnostic processes of the electrical equipment are very varied, since the objective functions used depend on the chosen optimization criterion and the restrictions for the specific problem on one hand, and the stage of the system life cycle in which the optimization problem is solved on the other hand. This requires a division of the consideration of the optimization tasks depending on the stage of operation in which the task is solved.

Due to the fact that diagnostic processes are a key tool in the system for control of the technical condition of machines, the design of optimal diagnostic systems and optimization of existing ones leads to a reduction in the volume of maintenance and repair activities to levels corresponding to real needs.

The diagnostic algorithm determines the set of test (elementary checks), the sequence (or sequences) of their execution and the rules for processing the results of the performed elementary checks, in order to obtain the results of the diagnostics [3].

The diagnostic algorithm, built on the basis of a multi-step procedure satisfying a given objective function (cost, time, consumption of human resoureses, completeness of diagnosis), is called optimized [4, 9].

Optimized algorithms whose objective function is the number of test and its extremum is the minimum of test checks are called minimal algorithms. The concept of a minimum diagnostic algorithm is similar to the concept of an optimized algorithm, taking into account the set objective function.

II. MATHEMATICAL DESCRIPTION OF THE DIAGNOSTIC PROCESSES

Modern electrical systems are often a complex combination of subsystems and elements of different types, which can have both discrete (digital) and continuous (analog) nature. This feature is reflected in the methods for mathematical description of diagnostic algorithms mainly through the way of presenting the test results [8].

A. Mathematical description of diagnostic algorithms in binary presentation of test results

The most suitable method for the description and development of conditional diagnostic algorithms is the mathematical apparatus of the theory of questionnaires.

Consideration are made for the set of technical states E that has N elements e_i, each element $e_i \in E$ being called an event. A weighting factor $w(e_i)$ is assigned to each event. The question set $T = \{t_j\}$, the elements of which are called questions, is also considered.

The number $a(t)$ is intoduced, which can take values in the interval $2 \le a(t) \le N$, based on this number the set of technical states E is divided into subsets (classes) $E_{\gamma(t)}; \gamma(t) = 1, 2, ..., a(t)$. The coefficient $a(t)$ thus introduced is called the basis of the question. The signs by which the classes of events $E_{\gamma(t)}$ with $t \in T$ are distinguished are called answers (or results) from the question t.

In order to ensure greater completeness of the description of the diagnostic process, coefficients are assigned to each question $t \in T$ - criteria for describing the test $c(t)$.

A question $t_1 \in T$ is asked leading to the division of the set of technical states E into $a(t)$ classes $E_{\gamma(t)}$. For most of the classes obtained, one can also ask a question $(t_k \ne t_1) \in T$ and obtain the corresponding division classes, and so on. The purpose of the questions is to recognize (identify, isolate) the

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subset E_μ to which the actual technical condition e^* of the system belongs.

The first question is always asked about the set E. The second and subsequent questions are in relation to the assessments obtained as a result of the previous questions. The questions stop after all the received classes consist of only one element. When the identification is complete, the different events correspond to different in number, composition, or number and composition series of questions (test sequences) and answers [6].

Depending on the depth of diagnosis, the processes of searching for the failed element can be incomplete - the failed subsystem is determined (a non-oneelement class of the set E) and complete - the exact element that caused the failure is determined (oneelement class of the set E).

The set of questions $Q \subseteq T$ and the sequence in which these questions must be asked for complete (or incomplete) identification of N events from the set E are called a questionnaire.

Each questionnaire can be represented through a directed graph $G = (Z, \Gamma)$ that includes Z vertices (answers) and Γ arcs (questions) [10]:

$$\begin{aligned} &Z = \{z / z \in Q \cup E\}, \\ &z = e \in E \rightarrow |\Gamma e| = 0, \\ &z = x \in Q \rightarrow |\Gamma x| = a(t) \end{aligned} \quad (1)$$

with a single root $x_0 \in Q$ for which $\left|\Gamma^{-1} x_0\right| = 0$.

The set of vertices of the graph G consists of the two intersecting subsets Q and E. A weight factor $w(e_i)$ is assingned to the vertices of the subset E of the graph G, and the price of the question $c(x)$ to the vertices of the subset Q.

The graph G describes the questionnaire for the set of technical conditions E. The graph G contains N vertices with zero degree of freedom of the result and these vertices are called top vertices or events. Each vertex $x \in Q; x \neq x_0$ is an inner vertex or question, and $x_0 \in Q$ is the root of the graph or first question.

For each of the vertices $z \in Z$ of the graph, the following sets of questions can be distinguished: $\hat{\Gamma} z \setminus z = \Gamma z \cup \Gamma(\Gamma z) \cup ...$ - a set of subsequent questions, and $\hat{\Gamma}^{-1} z \setminus z = \Gamma^{-1} z \cup \Gamma^{-1}(\Gamma^{-1} z) \cup ...$ - a set of previous questions.

The cost of the path from the root x_0 of the graph to the top vertex $z \in Z$ is the sum of the prices of the previous questions:

$$c(x_0, z) = \sum_{x \in \Gamma^{-1} z \setminus z} c(x). \quad (2)$$

The costs required to determine the technical condition are minimal when the path leading to each $e_i \in E$ event is unique and there are no closed loops in the graph. Therefore, the questionnaire E for event identification with minimum costs corresponds to a tree type graph with root x_0.

B. Mathematical description of diagnostic algorithms for the multi-valued presentation of test results

Currently, the most widespread in the field is the optimization of model-based diagnostic algorithms. Many studies have been conducted in this direction, but most of the current studies are based on a binary presentation of the results of elementary checks, but in fact, there are many tests with a multi-valued result. Moreover, most of the existing methods for optimizing diagnostic algorithms consider only one part of the problem - the cost of the diagnostic process or maintaining the reliability of the system, but ignore the problem of diagnostic accuracy, which should be the main consideration at the stage of work (fault detection). In fact, it is difficult to obtain completely reliable test results, so the accuracy of the diagnosis cannot be neglected when designing diagnostic algorithms [7, 8].

The process of detecting damaged or failed elements using tests with miulti-valued results can be described using a combination of sets and correlation matrices. These are the set of faulty states of the system $F = \{f_1, f_2, ..., f_n\}$, the set of the probability of occurrence of the respective fault $P = \{p(f_1), p(f_2), ..., p(f_n)\}$, the set of possible (realizable) tests $T = \{t_1, t_2, ..., t_m\}$ and the set of the cost of the checks $C = \{c_1, c_2, ..., c_m\}$. The main difference in the mathematical description of diagnostic processes using tests with binary and multi-valued representation of the results is the correlation matrix $D = \left| d_{ij} \right|_{(n+1)\,m}$.

In binary representation of the results, the correlation matrix is composed of ones (passed test) and zeros (fault). In multi-valued result from the tests, the elements of the correlation matrix can be any number.

From the above it is clear that it is necessary to introduce the concept of entropy of information. The greater the amount of information provided by a given inspection or test, the more effective it is in using it to detect and isolate faults. According to the principles of organization of diagnostic processes in the construction of the diagnostic tree, priority should be given to inspections that ensure the receipt of a large amount of information.

Typically, the optimization of diagnostic algorithms using multi-valued representation of test results is performed by heuristic optimization methods.

III. Heuristic Optimization Method Based on the Entropy of Information

The possibility of detecting and isolating faults, the accuracy of the test, and the cost of te test are thoroughly considered and combined into a heuristic function to assess the effectiveness of the inspection [5].

The basis of the heuristic optimization method is obtaining the value of the heuristic function to evaluate the effectiveness of the test. For this purpose, the increase of the information entropy (information function) of all possible (available) tests is calculated, after which the value of the heuristic function for the specific optimization parameter (cost of diagnostics, duration of the diagnostic process, consumption of human resources ect.) is determined.

Assuming that the possible set of system tests is $T = \{t_1, t_2, ..., t_m\}$. According to the results from the test t_j, which has L_j possible states, the set of faulty technical states of the considered system can be divided into k subsets $F_{j0}, F_{j1}, ..., F_{j(k-1)}$. However, the amount of information obtained from this test (information function) can be determined by

$$I(F, t_j) = -\sum_{k=1}^{L_j} \frac{P(F_{jk})}{P(F)} \log_2 \frac{P(F_{jk})}{P(F)}, \quad (3)$$

where: F_{jk} is the set of possible conclusions from the diagnostics (faults) in case an output signal l_{jk} is received during the test t_j;

P_{ij} - the probability (accuracy) of detecting the *i-th* state f_i during the *j-th* test t_j.

The probability $P(F_{jk})$ for occurrence of the *i-th* fault and its detection upon receipt of the *k-th* result of the *j-th* elementary check is determined by using the following dependance

$$P(F_{jk}) = \sum_{i=0}^{Lj} P_{ijk} . p(f_i). \quad (4)$$

The objective function for optimizing the testing sequence is obtained on the basis of the ratio between the information function and the cost of the test. The general equation that describes the optimization problem is:

$$k^* = \max\left(\frac{I(F, t_j)}{c_j}\right). \quad (5)$$

The main steps for solving the thus defined optimization problem are:

1. The faulty states of the system F and the set of the possible tests T for the system are set;
2. The amount of information obtained from each of the available tests t_j is calculated by using the dependency (3);
3. The test t_α that provides the maximum value of the heuristic function k^* is selected from the set of available tests T;
4. After performing the test, the set of faulty states is divided into subsets, and for each subset the possible tests are determined by excluding the test t_α from the set of available tests. Then the procedures from points 2 and 3 are repeated until the number of elements in each of resultant subsets is equal to one.

The solution of the optimization problem is performed by means of a computer program developed in the software product Matlab R2019b.

IV. Example of Application of the Heuristic Optimization Method

The problem of determining the optimal number and sequence of performing tests for a system in which there is possibility for occurence of eight faulty states $F = \{f_1, f_2, f_3, f_4, f_5, f_6, f_7, f_8\}$, is considered. The probability that the system is in a specific faulty state is determined by the set $P = \{0{,}21; 0{,}01; 0{,}04; 0{,}1; 0{,}14; 0{,}15; 0{,}08; 0{,}27\}$. The number of possible tests of the system is seven, as each test has maximum four possible results $\max(L_j) = 4$, and the costs of the individual tests are set with the set $C = \{1; 3; 8; 4; 6; 2; 5\}$. The correlation (diagnostics) matrix $D = \left|d_{ij}\right|_{n,m}$ presenting the ralationship between the values of the result from the tests and the presence of a given malfunction is shown in Table I.

The probability of detecting the *i-th* fault condition f_i by using the *j-th* test t_j is set by the probability matrix (diagnostic accuracy matrix), which is presented in Table II.

TABLE I. Correlation Table (Matrix)

Failure Mode	t1	t2	t3	t4	t5	t6	t7	Probability
f1	1	3	0	1	3	0	3	0,18
f2	0	2	3	2	2	3	0	0,03
f3	1	1	0	3	1	1	1	0,06
f4	0	2	2	0	0	2	3	0,12
f5	0	3	1	1	0	1	2	0,14
f6	0	2	2	2	1	3	0	0,16
f7	1	0	2	0	2	2	1	0,08
f8	0	1	1	0	3	0	1	0,23

TABLE II. Detection Probability Matrix

Pij	t1	t2	t3	t4	t5	t6	t7
f1	0,56	0,71	0	0,92	0,94	0	0,76
f2	0	0,95	0,91	0,93	0,97	0,86	0
f3	0,75	0,88	0	0,91	0,97	0,87	0,93
f4	0	0,93	0,96	0	0	0,91	0,89
f5	0	0,9	0,87	0,79	0	0,95	0,95
f6	0	0,86	0,92	0,95	0,64	0,87	0
f7	0,73	0	0,78	0	0,83	0,78	0,86
f8	0	0,91	0,84	0	0,92	0	0,82

A. First iteration

The results from the calculations of the probability of occurrence of the *i-th* fault and its detection upon receipt of the *k-th* result of the *j-th* test are shown in Table III.

TABLE III. RESULTS FOR THE PROBABILITY FOR DETECTION OF AN OCCURRED FAULT BY EVERY TEST

Pijk	t1	t2	t3	t4	t5	t6	t7
f1	0,101	0,1278	0	0,1656	0,1692	0	0,1368
f2	0	0,171	0,1638	0,1674	0,1746	0,1548	0
f3	0,135	0,1584	0	0,1638	0,1746	0,1566	0,1674
f4	0	0,1674	0,1728	0	0	0,1638	0,1602
f5	0	0,162	0,1566	0,1422	0	0,171	0,171
f6	0	0,1548	0,1656	0,171	0,1152	0,1566	0
f7	0,131	0	0,1404	0	0,1494	0,1404	0,1548
f8	0	0,1638	0,1512	0	0,1656	0	0,1476

Depending on the results from the test t_j, which has L_j possible results, the set of faulty technical states of the considered system can be divided into k subsets $F_{j0}, F_{j1},..., F_{j(Lj-1)}$. The probability $P(F_{jk})$ of occurrence of any subset is equal to the sum of the probabilities of the faults assigned to the respective subset. The results for the number and probabilities of occurrence of the subsets F_{jk} during the tests of the set T are shown in Table IV.

TABLE IV. RESULTS FOR THE NUMBER OF OCCURRING SETS OF THE TECHNICAL CONDITION AND THE PROBABILITIES OF THEIR OCCURRENCE, THE INFORMATION FUNCTION, AND THE HEURISTIC FUNCTION.

	t1	t2	t3	t4	t5	t6	t7
Lj	2	4	4	4	4	4	4
P(j,k0)	0	0	0	0	0	0	0
P(j,k1)	0,367	0,322	0,308	0,308	0,290	0,328	0,470
P(j,k2)	-	0,493	0,479	0,338	0,324	0,304	0,171
P(j,k3)	-	0,326	0,164	0,164	0,335	0,311	0,297
I(F,tj)	0,244	0,743	0,646	0,589	0,664	0,662	0,642
k*	0,244	0,248	0,081	0,147	0,111	0,331	0,212

The results show that the maximum value of the heuretic function k^* is achieved by performing test - **t6**. After performing test **t6**, the set of fault states is divided into four subsets corresponding to the possible results from this test $F1 = \{f_1, f_8\}$, $F2 = \{f_2, f_6\}$, $F3 = \{f_3, f_5\}$ and $F4 = \{f_4, f_7\}$.

B. *Subsequent iterations*

In order to accurately determine the faulty state that has occurred, it is necessary to reduce the non-one-element sets to one-element sets by performing subsequent tests, excluding the already performed test **t6**. For this purpose, the obtained subsets are considered separately.

The results for the values of the information function and the heuristic function obtained when considering the individual subsets are shown in Table V.

From the presented results it is clear that in case of obtaining any of the subsets *F1*, *F3* or *F4* the test **t1** should be performed, while in case of obtaining the subset *F2* it is necessary to perform test **t2**.

TABLE V. RESULTS FOR THE INFORMATION FUNCTION, AND THE HEURISTIC FUNCTION.

Test	t1	t2	t3	t4	t5	t7
Subset F1						
I(F,tj)	0,261	0,698	0,380	0,351	-	0,690
k*	0,261	0,233	0,048	0,088	-	0,138
Subset F2						
I(F,tj)	-	0,722	0,509	0,731	0,224	-
k*	-	0,241	0,064	0,183	0,037	-
Subset F3						
I(F,tj)	0,296	0,711	0,378	0,691	0,344	0,731
k*	0,296	0,237	0,047	0,173	0,057	0,146
Subset F4						
I(F,tj)	0,330	0,455	-	-	0,355	0,808
k*	0,330	0,152	-	-	0,059	0,162

After performing any of the optimal tests, only one-element sets are obtained. It follows that the optimal diagnostic algorithm is realized by performing only three of the tests included in the set T. The diagnostic tree representing the obtained optimal diagnostic algorithm is shown in Fig.1.

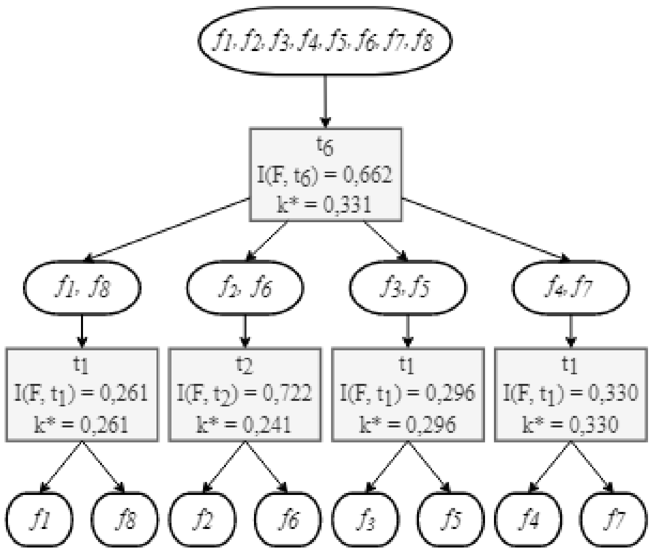

Fig. 1. Diagnostic tree for the optimal testing sequence

Applying the heuristic approach to determine the optimal test sequences significantly reduces the amount of requred computational power compared to the use of dynamic programming methods or the AND/OR algorithms (*AO* algorithms*).

V. CONCLUSION

The development of optimal diagnostic algorithms (test sequences) is one of the main optimization problems in the field of technical diagnostics, the solution of which can be performed at all stages of the life cycle of technical systems.

The use of the heuristic optimization method leads to a significant simplification of creating optimal test sequences with binary or multi-valued presentation of the test results. In addition, the heuristic optimization method can be easily adapted to solve multi-criterial problems related to diagnostic processes.

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