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Construction of verification and diagnostic tests for the functional diagram of the object of the diagnosis

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Abstract. This article is devoted to the problem of technical diagnostics in urban electric transport and electrical facilities. To find the solution to this problem, it is necessary to transfer the qualitative determination of the Vehicle into some quantitative basis. The formalization of qualitative definitions is essential to the construction of formal (computable) diagnostic procedures.

1. Introduction

The problem of a reliability evaluation and a predicting of the electrical system of the rolling stock per formability in cludes solving the following tasks:

- advanced arranging of the diagnostics and control of the electric brush's technical condition;
- assessment and prediction of the reliability of the electric brush while in operation;
- optimization of terms, determination of the volume and choice of a rational strategy, and planning for maintenance and repair of the electric brush considering its technical condition.

2. Tasks evaluation of the engines operating resource

Analysis of the features of continuous transport systems of urban electric transport and the railway automations, telemechanics and communications (RATC) allow to give preference to logical models. The use of logical models is associated with tolerance control methods, which are characterized by the fact that the conclusion about the item related state is issued by the results of the evaluation of signal values at control points (values of the test parameters of the object). In this case the results of parameter control are reduced to the following estimates: «within in tolerance – out of tolerance», «normal – not normal», in other words, to estimates of the two-digit type (zero or one). It follows as a logical consequence that in these cases it is convenient to use logical type models and various logical methods.

At the first stage of the logical model construction, the individual functional elements, which inputs and outputs are available for measurement, shall be identified in the system [1].

At the second stage of the model construction, a functional diagram of the system as an object of the diagnosis is drawn up, wherein all selected elements and the connections between them are indicated.

A functional diagram of the object of the diagnosis (figure 1) contains eight elements — *E1* — *E8,* has four external input influences — $x_1 – x_4$, and forms four output reactions — y_5, y_6, y_7, y_8. Each element forms its own output reaction y_i, moreover, the output reactions of the elements *E5, E6, E7, E8* coincide with the output reactions of the circuit. Along with this, x_i=1 and y_i=1, if *i*-e input action or output response of the *j-th* element is valid; otherwise x_i = 0 and y_i = 0.

For brevity, we can consider only single faults, thereupon the system has nine states:

$$S_0=11111111,\ S_1=01111111, S_2=10111111, \tag{1.1}$$

$$S_3=11011111,\ S_4=11101111, S_5=11110111, \tag{1.2}$$

$$S_6=11111011,\ S_7=11111101\ S_8=11111110. \tag{1.3}$$

When working with the logical model, it is assumed that the input of the object receives a single input action, determined by the permissible values of all input signals [2].

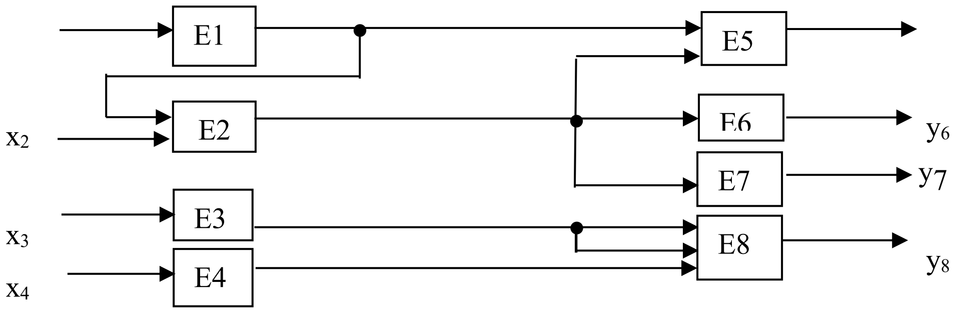

Figure1. A functional diagram of the object of the diagnosis

Therefore, possible elementary checks differ only in the sets of control points at which the measurement is carried out. In this case, the task of constructing a diagnosis algorithm is reduced to choosing a set of control points sufficient to solve a specific diagnosis problem. Since there is no access to the outputs of some elements, in practice, a large number of checks cannot be carried out; it is impossible to connect directly to the outputs of several elements, etc.

In the case under study, we assume that only those verifications are possible that consist in measuring the reaction at the output of one of the elements of the system, and the outputs of all elements are available for measurement. Denote the elementary verification as π_i – the reaction control at the output of the *i-th* element ($i \in \{1, 2, \ldots, 7\}$).

Table 1 shows the FaultsFunction Table (FFT) compiled for the system (see figure 1) [3].

Table 1 The Faults Function Table (FFT)

Verification	R verification result for the system in the state of								
	S_0	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
π_1	1	0	1	1	1	1	1	1	1
π_2	1	0	0	1	1	1	1	1	1
π_3	1	1	1	0	1	1	1	1	1
π_4	1	1	1	1	0	1	1	1	1
π_5	1	0	0	1	1	0	1	1	1
π_6	1	0	0	1	1	1	0	1	1
π_7	1	0	0	0	1	1	1	0	1
π_8	1	1	1	0	0	1	1	1	0

When the system is properly operating (S_0 state), the outputs of all elements have valid signal values. The failure of any element causes the appearance of an invalid signal value at its output and at the outputs of all associated elements.

This FFT contains all the necessary information for the construction of the verification and diagnostic tests. Each FFT column determines a function defined on a set of verifications. The function is equal to one if the Verification gives a valid result. Denote F as the function of the properly operating object; f_i– is a function of the *i-th* state of a faulty object or function of the *i-th* fault. For example, we have:

$$F = \pi_1 \vee \pi_2 \vee \pi_3 \vee \pi_4 \vee \pi_5 \vee \pi_6 \vee \pi_7 \vee \pi_8, \tag{2.1}$$

$$f_1 = \pi_3 \vee \pi_4 \vee \pi_8,\ f_2 = \pi_1 \vee \pi_3 \vee \pi_4 \vee \pi_8, \tag{2.2}$$

$$f_3 = \pi_1 \vee \pi_2 \vee \pi_4 \vee \pi_5 \vee \pi_6, f_4 = \pi_1 \vee \pi_2 \vee \pi_3 \vee \pi_5 \vee \pi_6 \vee \pi_7, \tag{2.3}$$

$$f_5 = \pi_1 \vee \pi_2 \vee \pi_3 \vee \pi_6 \vee \pi_7 \vee \pi_8, \tag{2.4}$$

$$f_6 = \pi_1 \vee \pi_2 \vee \pi_3 \vee \pi_4 \vee \pi_5 \vee \pi_7 \vee \pi_8,\ f_7 = \pi_1 \vee \pi_2 \vee \pi_3 \vee \pi_4 \vee \pi_5 \vee \pi_6 \vee \pi_8, \tag{2.5}$$

$$f_8 = \pi_1 \vee \pi_2 \vee \pi_3 \vee \pi_4 \vee \pi_5 \vee \pi_6 \vee \pi_7 \tag{2.6}$$

When constructing the $T_п$ test, for each fault, a verification function is calculated to the formula (3):

$$\varphi_i = F \oplus f_i \tag{3}$$

The function $\varphi_i = 1$ only in those tests in which the test results are different for a properly operating diagram and for a diagram with an *i-th* fault. In other words, it combines those verifications on which the *i-th* fault is being detected [4].

Fault-detection test

$$T_п = \varphi_1\ \varphi_2,\ \ldots,\ \varphi_n \tag{4}$$

where n – number of faults.

In this case n = 8.

To findφ_i add the obtained values according to the formula (1.1 – 1.3) and get:

$$\varphi_1 = \pi_1 \vee \pi_2 \vee \pi_5 \vee \pi_6 \vee \pi_7,\ \varphi_2 = \pi_2 \vee \pi_5 \vee \pi_6 \vee \pi_7, \tag{5.1}$$

$$\varphi_3 = \pi_3 \vee \pi_7 \vee \pi_8,\ \varphi_4 = \pi_4 \vee \pi_8, \tag{5.2}$$

$$\varphi_5 = \pi_5,\ \varphi_6 = \pi_6,\ \varphi_7 = \pi_7,\ \varphi_8 = \pi_8 \tag{5.3}$$

Then

$$T_п = \varphi_1\varphi_2\varphi_3\varphi_4\varphi_5\varphi_6\varphi_7\varphi_8 = (\pi_1 \vee \pi_2 \vee \pi_5 \vee \pi_6 \vee \pi_7)\ (\pi_2 \vee \pi_5 \vee \pi_6 \vee \pi_7)\ (\pi_3 \vee \pi_7 \vee \pi_8)\ (\pi_4 \vee \pi_8)\ \pi_5\pi_6\pi_7\pi_8 \tag{6}$$

Formula (2.1 – 2.6) can be simplified based on the absorption law, which is characterized by the following equalities:

$$a(a \vee b) = aa \vee ab = a \vee ab = a(1 \vee b) = a \times 1 = a,\ (a \vee b)\ (a \vee b \vee c) = a \vee b \tag{7}$$

or in general

$$(G_1 \vee G_2)\ (G_1 \vee G_3) = G_1, \tag{8}$$

whereG_1, G_2, G_3 – are any logical functions.

By manipulations:

$$
\begin{aligned}
&1)(\pi_6)\times(\pi_6+\pi_7)=\pi_6\times\pi_6+\pi_6\times\pi_7=\pi_6\times(1+\pi_7)=\pi_6\\
&2)(\pi_6)\times(\pi_6+\pi_8)=\pi_6\times\pi_6+\pi_6\times\pi_8=\pi_6\times(1+\pi_8)=\pi_6\\
&3)(\pi_6)\times(\pi_4+\pi_6)=\pi_6\times\pi_4+\pi_6\times\pi_6=\pi_6\times(1+\pi_4)=\pi_6\\
&4)(\pi_1+\pi_5)\times(\pi_1+\pi_5)=\pi_1+\pi_5\\
&5)(\pi_1+\pi_5)\times(\pi_1+\pi_2+\pi_5)=\pi_1\times(\pi_1+\pi_2+\pi_5)+\pi_5\times(\pi_1+\pi_2+\pi_5)=\pi_1\times(1+\pi_2+\pi_5)+\pi_5\times(1+\pi_2+\pi_5)=\pi
\end{aligned}
\tag{9}
$$

As a result, 2 verification tests have been obtained:

$$
\begin{aligned}
T_{П1}&=\pi_6\times\pi_1\\
T_{П2}&=\pi_6\times\pi
\end{aligned}
\tag{10}
$$

as follows from equation, for a complete system verification it is necessary and sufficient to simultaneously apply permissible influences to the external inputs of elements 1 and 6 or 6 and 5 and measure the response at the output. If the system is properly operating, then at the output of the element there will be a valid signal, if it is faulty, then at the output of the element there will be an invalid signal [5].

In general case, to verify the serviceability or operability of an object, it is enough to check all its external outputs. However, the logical model and the FFT allow one to find such a minimal set of checks that will not include the external outputs of the object, which are also the inputs of the model blocks.

When solving the problem of finding a faulty element, a diagnostic *Tд* test has been built. For each pair of faults (with numbers *i* and *j*), a discriminating function has been calculated to the formula (11):

$$\varphi_{i,j}= f_i\oplus f_j \tag{11}$$

The distinguishing function obtained by formula (7) is equal to unity only in those tests in which the test results are different for the diagram with the *i-th* fault and for the diagram with the *j-th* fault. Alternately stated, it combines those verifications on which the *i-th* and *j-th* faults differ from each other.

Measurements and their analysis are carried out with a given frequency and compose a database of measurements and results of comparing the amplitudes at characteristic frequencies with the signal value at a frequency of zero hertz, by which the development of damage over time is monitors and the limited operation life of the equipment is predicted.

Harmonic components in the vibration spectrum corresponding to different types of faults differ from each other. Therefore, the detection in the spectrum of typical harmonics allows you to uniquely identify the electrical and mechanical faults of the electric motor. All necessary measurements shall be carried out on the operating equipment (its shutdown is not required).

Regular measurements (monitoring) of the electric motor make it possible to identify fault sat an early stage of occurrence, to monitor the dynamics of their development, to determine the residual resource of nodes and to plan rational terms for repairs. [6].

Assessment of the measurement results has been carried out by the probabilistic-statistical method. When assessing the measurement results, we analyzed the vibration spectra in the range of vibration frequencies from 0 to 1000 Hz (400 readings) (Figure 2) with a nominal speed of *n* = 750 rpm.

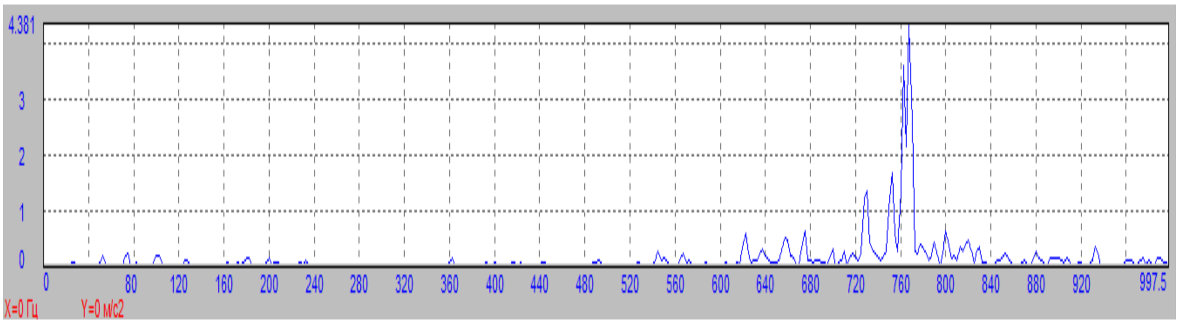

Figure2. Frequency response of the vibration spectrum of the electric motor in the presence of defects in the brush-collector assembly

Figure 3 shows the frequency response of the vibration spectrum of the electric motor in the frequency range from 0 to 1 kHz in the presence of faults in the brush-collector assembly (red) and on the bearings (blue), containing frequency characteristics, the letter *"f"* indicates the characteristic frequencies corresponding to the diagnosed fault. The amplitudes of the signals are plotted vertically, the frequencies - horizontally.

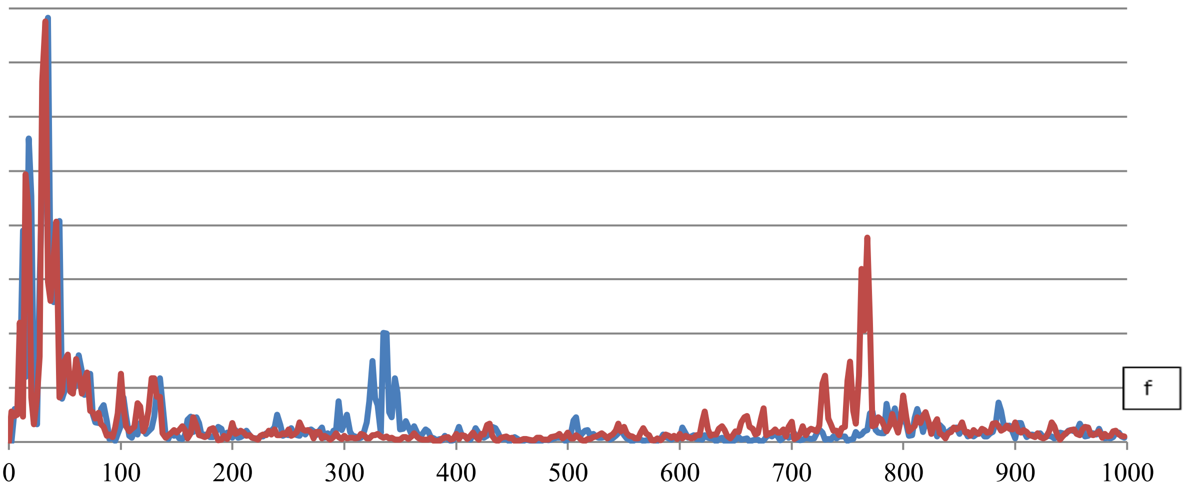

Figure 3. The obtained curves of the vibration spectrum of a D.C. motor: Blue - defects on bearings, red - defects on a brush-collector assembly.

As a result of numerous experiments, it was found that there is a correlation between the theoretical electric motor *x* and the defective brush-collector unit *y*:

$$\left(y-\overline{y}\right)=r\frac{\sigma_y}{\sigma_x}\left(x-\overline{x}\right) \tag{12}$$

where $\overline{y}, \overline{x}$ - arithmetic mean values of the parameters of a theoretical electric motor and a defective brush-collector assembly;
σ_x, σ_y - a standard deviations of the parameters of a theoretical electric motor and a defective brush-collector assembly;
r - correlation parameter.

The indicated parameters and deviations are determined by the formulas (14 – 17):

$$\bar{x} = A_x + h_x \frac{\sum m_x \Delta x}{N} \tag{13}$$

$$\bar{y} = A_y + h_y \frac{\sum m_y \Delta y}{N} \tag{14}$$

$$\sigma_x = \left[\frac{\sum m_x \Delta x^2}{N} - \left(\frac{\sum m_x \Delta x}{N} \right)^2 \right] h_x \tag{15}$$

$$\sigma_y = \left[\frac{\sum m_y \Delta y^2}{N} - \left(\frac{\sum m_y \Delta y}{N} \right)^2 \right] h_y \tag{16}$$

$$\Delta x=(x-A_x)/h_x,\ \Delta y=(y-A_y)/h_y \tag{17}$$

where 2Δx, Δy– given values of a theoretical electric motor and a defective brush-collector assembly;
A_x, A_y – values of a theoretical electric motor and defective brush-collector assembly having the highest failure rate;
h_x, h_y – time intervals for measuring the parameters of a theoretical electric motor and a defective brush-collector assembly.
Correlation coefficient r between parameters x and y is determined from the formula (18)

$$r = \frac{\sum m_{xy} \Delta x \Delta y - \dfrac{\sum m_x \Delta x \sum m_y \Delta y}{N}}{N \sigma_x^1 \sigma_y^1} \tag{18}$$

Grading of the products is carried out depending on the results of comparing the theoretical (standard) and current spectra of electric motors according to the values of the objective comparison functions [7]:

- a correlation coefficient;
- the Spearman rank-order correlation coefficient;
- the Fisher Sign Statistics.

For each electric motor, its own set of informative (characteristic) frequencies is calculated.The composition of this set is determined by the type of electric motor, the characteristics of the bearings and the type of electric brushes used. To determine the characteristic frequencies of some faults and their diagnostics, the frequency of rotation of the electric motors, the number of teeth of the armature and collector plates shall be additionally determined.

Conclusion

The problem of technical diagnostics on urban electric transport and electrical equipment has been considered. To find the solution to this problem, it is necessary to transfer the qualitative determination of the Vehicle into some quantitative basis. The formalization of qualitative definitions is essential to the construction of formal (computable) diagnostic procedures.

Thus, when implementing the proposed method for monitoring the vibration of brush-collector assemblies of D.C. motors, an increase in the accuracy of signal measurement is achieved due to the exclusion of sensors mounted in the motor housing and introducing additional errors, and a standard analyzer sensor is used, which is used to obtain a spectrum, which is the measured signals that are converted into reference and real spectra, when compared, defects are detected and their development is predicted. The proposed method is applicable for the diagnosis of engines of various types having a rotating shaft and a standard vibration sensor cinematically connected with this shaft and generating a spectrum during rotation and the class of detected defects is determined by emerging vibrations that affect the spectral composition of the generated spectrum.

It can conclude that there is a motor fault itself, if the amplitude at the characteristic frequencies coincides, then the studied motor is in good technical condition, and if the indicated difference between the amplitudes is present, then conclusions shall be made on the presence of damage corresponding to this characteristic frequency.

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