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Reliability And Resource Evaluation Of The Traction Asynchronous Motor Control System

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ABSTRACT

The reliability of the control system for electric rolling stock is considered using probabilities without failure of the power traction transformer of a controlled rectifier, an autonomous inverter and a traction asynchronous electric motor presented in the form of blocks, in which the failure of the entire system, which in the theory of reliability is called a series connection of elements.

An example is given of determining the probability of normal operation of an object using the method of obtaining moments from the characteristics of blocks and a given function by sequentially calculating the mathematical expectation, standard deviation, third and fourth central moments with their expansion in a Taylor series. The probabilities of not exceeding the specified values are estimated under the assumption that the characteristics of individual blocks are independent.

KEYWORDS

Electric motor, mathematical expectation, power transformer, input controlled rectifier, autonomous, feedback blocks, electric locomotives.

INTRODUCTION

The most important quality characteristic of the automatic control system (ACS) of the traction drive of an induction motor is its reliability, determined by the preservation in time of the value of the established performance indicators within the specified limits, corresponding to the established modes, conditions for the use of maintenance, repairs and storage in compliance with the schedule and ensuring the safety of the electric locomotive [1].

A traction three-phase asynchronous motor TAEM with a squirrel-cage rotor is controlled by an automatic control system, which consists of interconnected and feedback blocks: a power transformer, a four-quadrant converter 4QS –

A controlled input rectifier and an autonomous inverter that converts direct current into three-phase alternating current based on the pulse-width modulation principle (PWM) [2].

During the operation of electric rolling stock, it is often necessary to identify the cause of the TAEM failure, conditions and factors that depend on changes in the input and output values, mode parameters and external influences of each block of the control system. One of the most expedient methods for determining and assessing the reliability indicators of assembly units of EPS is the analogy method based on the application of the structural-logical reliability scheme [3,4].

THE MAIN FINDINGS AND RESULTS

From the viewpoint of reliability, a set of blocks of a control system is a system in which the failure of one element causes a failure of the whole system, but does not change the reliability of other blocks. Such a structure in the theory of reliability is called a system with a series connection of elements [5]. Thuswise, the probability of failure-free operation of the TAEM control system over time is represented in the form:

$$P(t) = P_{Tr}(t) \cdot P_{\mathrm{ICR}}(t) \cdot P_{AI}(t) \cdot P_{TAEM}(t)\,, \qquad (1)$$

where $P_{Tr}(t), P_{\mathrm{ICR}}(t), P_{AI}(t), P_{TAEM}(t)$ – accordingly, the probability of failure-free operation of the power transformer, input controlled rectifier, autonomous inverter and traction asynchronous electric motor. If we express $P_i(t)$ in terms of the failure rates [5]

$$P(t) = \exp\left[-\sum_{i=1}^{4} \int_0^t \lambda_i(x)dx\right], \qquad (2)$$

then the total failure rate of the whole system is defined as

$$\lambda(t) = \sum_{i=1}^{4} \lambda_i(t) = \lambda_{Tr}(t) + \lambda_{ICR}(t) + \lambda_{AI}(t) + \lambda_{TIEM}(t), \qquad (3)$$

where λ_i – the failure rates of the above units.

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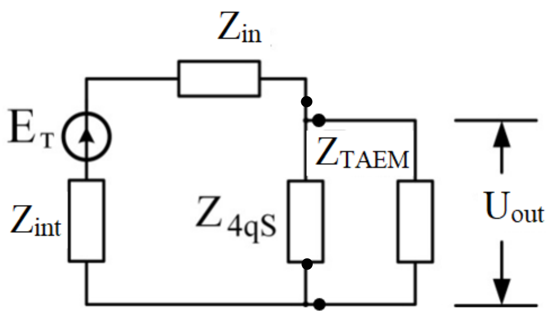
Therefore, the reliability of the object can be calculated by analogy with the schemes shown in Fig. 1 and Fig. 2.



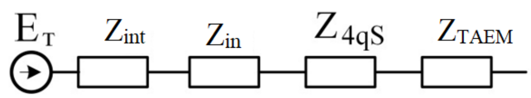


Fig. 1 Block wiring diagram

Fig. 2. Block diagram of the TAEM reliability

E_T – transformer voltage; Z_{int} – equivalent internal resistance of the transformer; Z_{4qs} – equivalent input impedance of 4qS; Z_{TAEM} – equivalent input impedance of TAEM .

The purpose of the circuit in Fig. 1. is the creation at the input of the TAEM voltage U_{out}, and voltage drops on the elements Z_{int}, Z_{in}, Z_{4qS}. According to Ohm's law, the voltage at the TAEM terminals:

$$U_{\text{вых}} = E_{\text{т}} - \frac{E_{\text{т}}(Z_{int}+Z_{in})}{Z_{int}+Z_{in}+Z_{4qS}Z_{TEAM}/(Z_{4qS}+Z_{TEAM})} \qquad (4)$$

The diagram in Fig. 1 shows that the TAEM voltage depends on changes in the parameters of the circuit elements, which can be determined by differentiating in parts:

$$\Delta U_{\text{вых}} = \frac{\partial U_{out}}{\partial E_T}\cdot \Delta E_T + \frac{\partial U_{out}}{\partial Z_{in}}\cdot \Delta Z_{in} + \frac{\partial U_{out}}{\partial Z_{4qS}}\cdot \Delta Z_{4qS} + \frac{\partial U_{out}}{\partial Z_{int}}\cdot \Delta Z_{int} +$$

$$+\frac{\partial U_{out}}{\partial Z_{TEAM}}\cdot \Delta Z_{TEAM} (5)$$

Consequently $\frac{\partial U_{out}}{\partial E_T} = 1 - \frac{A}{Z}$,

where $A = Z_{int} + Z_{in}$; $Z = Z_{int} + Z_{in} + Z_{4qS}Z_{TEAM}/(Z_{4qS} + Z_{TEAM})$ – equivalent input impedance at terminals 4qS (Fig.1).

$$\frac{\partial U_{out}}{\partial Z_{int}} = E_T\frac{A}{Z^2}; \qquad (6)$$

$$\frac{\partial U_{out}}{\partial Z_{4qS}} = \frac{E_T A Z_{TEAM}^2}{(Z_{4qS}+Z_{TEAM})^2 Z^2} \qquad (7)$$

$$\frac{\partial U_{out}}{\partial Z_{in}} = \frac{E_T(A-Z)}{Z^2}; \qquad (8)$$

$$\frac{\partial U_{out}}{\partial Z_{TEAM}} = \frac{E_T \cdot A \cdot Z_{4qS}}{(Z_{4qS}+Z_{TEAM})^2 Z^2}. \qquad (9)$$

If the changes in the parameters of each unit are known ($\Delta E_T, \Delta Z_{int}, \Delta Z_{in}, \Delta Z_{4qS}, \Delta Z_{TEAM}$), then we can calculate the values of deviations 〖$\Delta U_{ТАД}$ beyond the permissible limits, which are determined by the probability of failure of the operation of the TAEM control system.

For the initial data [2] given in the following table 1, we determine the probability of normal operation of the object under consideration, with the deviation of the primary parameters distributed according to the Gaussian law.

Parameters of control system units of the TAEM drive

Table 1

	Blocks				
	E_T, В	Z_{int}, Ом	Z_{in}, Ом	Z_{4qS},Ом	Z_{TEAM},Ом
mean equivalent value / mean square deviation	1000/10	0,2/0,04	5,01/0,0625	6,02/0,075	10/0,04

We solve the problem by the method of obtaining the moments of the system [3], according to the characteristics of the blocks and a given function, by sequentially calculating the mathematical expectation, the standard deviation, the third and fourth central moments. Having the numerical values of all the listed moments on the Pearson distribution, we estimate the probabilities of not exceeding the specified permissible values, assuming the independence of the characteristics of individual elements. To calculate the above moments, we use the Taylor series expansion [6].

The mathematical expectation of the system function obtained above is calculated by the formula [4]:

$$\mathcal{M} = f[\mathcal{M}(x_1)\ldots\mathcal{M}(x_n)] + \frac{1}{2}\sum_1^n \frac{\partial^2 f[\mathcal{M}(x_1)\ldots\mathcal{M}(x_n)]}{\partial x_i^2} \cdot \mathcal{G}^2(x_i), \qquad (10)$$

where $f[\mathcal{M}(x_1)\ldots\mathcal{M}(x_n)]$ – given function of the object (4), when substituting the values of the parameters equal to their mathematical expectations; $\frac{\partial^2 f[\mathcal{M}(x_1)\ldots\mathcal{M}(x_n)]}{\partial x^2}$ – derivative values $\frac{\partial^2 f}{\partial x^2}$ at the point, the parameters of which are respectively equal to the mathematical expectations.

Using the first partial derivatives (6), (7), (8), (9), we calculate the second partial derivatives:

$$\frac{\partial^2 U_{out}}{\partial {E_T}^2} = 0, \frac{\partial^2 U_{out}}{\partial {Z_{int}}^2} = \frac{2E_T(Z-A)}{{Z_{int}}^3}; \frac{\partial^2 U_{out}}{\partial {Z_{in}}^2} = \frac{2E_T(Z-A)}{{Z_{in}}^3}; \qquad (11)$$

$$\frac{\partial^2 U_{out}}{\partial {Z_{4qS}}^2} = -2E_T A Z_{TEAM}^2 \frac{Z(Z_{4qS}+Z_{TEAM})+Z_{TEAM}^2}{(Z_{4qS}+Z_{TEAM})^4 Z^3}; \qquad (12)$$

$$\frac{\partial^2 U_{out}}{\partial {Z_{TEAM}}^2} = -2E_T A Z_{TEAM}^2 \frac{Z(Z_{4qS}+Z_{TEAM})}{(Z_{4qS}+Z_{TEAM})^4 Z^3}. \qquad (13)$$

Substitute the numerical values from the above table 1.

$$A = Z_{int} + Z_{in} = 0{,}2 + 5{,}01 = 5{,}21 \text{ Ом};$$

$$Z = Z_{int} + Z_{in} + Z_{4qS} Z_{TEAM}(Z_{4qS} + Z_{TEAM}) = 0{,}2 + 5{,}01 + 6{,}0 \cdot 10{,}0(6{,}0 + 10{,}0) = 5{,}2 + 3{,}75 = 8{,}95 \text{ Ом};$$

$$\frac{\partial^2 U_{out}}{\partial {Z_{int}}^2} = \frac{2E_T(Z-A)}{Z^3} = \frac{2 \cdot 1000(8{,}95 - 5{,}2)}{8{,}95^3} = \frac{7500}{716{,}91} = 10{,}461\ {}^{V}\!/_{Ohm^2};$$

$$\frac{\partial^2 U_{out}}{\partial Z_{in}^2} = 10{,}461\ {}^{\text{В}}\!/_{\text{Ом}^2};$$

$$\frac{\partial^2 U_{out}}{\partial {Z_{4qS}}^2} = -2 \cdot 1000 \cdot 5{,}2 \cdot 10^2 \frac{8{,}95(6{,}0 + 10{,}0) + 10{,}0^2}{(6{,}0 + 10{,}0)^4 8{,}95^3} == -5{,}44\ {}^{V}\!/_{Ohm^2};$$

$$\frac{\partial^2 U_{out}}{\partial {Z_{TEAM}}^2} = -2 \cdot 1000 \cdot 5{,}2 \cdot 6^2 \frac{8{,}95(6{,}0 + 10{,}0) + 6^2}{(6{,}0 + 10{,}0)^4 8{,}95^3} = -1{,}44\ {}^{V}\!/_{Ohm^2};$$

The mathematical expectation of the voltage at the output of the ACS TAEM :

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$$\mathcal{M} = 1000 - \frac{1000(0{,}2+5{,}0)}{0{,}2+5{,}0+6{,}0\cdot\dfrac{10{,}0}{6+10}}$$
$$+\frac{1}{2}(0\cdot 100^2 + 10{,}461\cdot 0{,}04^2 + 10{,}461\cdot 0{,}625^2 - 5{,}44\cdot 0{,}75^2 - 1{,}44\cdot 0{,}42^2) =$$
$$= 581{,}005 + 0{,}5(0 + 0{,}016 + 4{,}086 - 3{,}060 - 0{,}23) = 581{,}411\ V.$$

The dispersion of the characteristics of the ACS TAEM can be calculated by the formula [2]:

$$\sigma^2 = \sum_{i=1}^{n}\left(\frac{\partial f[\mathcal{M}(x_1)\ldots\mathcal{M}(x_n)]}{\partial x_i}\right)^2\cdot\sigma^2(x), \qquad (14)$$

In accordance with (12), it is possible to determine the numerical values of the first derivatives (6), (7), (8), (9), substituting the data in Table 1 into them.

$$\frac{\partial U_{out}}{\partial E_T} = 1 - \frac{5{,}2}{8{,}95} = 0{,}418,$$

$$\frac{\partial U_{out}}{\partial Z_{int}} = 1000\frac{0{,}21-8{,}95}{8{,}95^2} = -0{,}1091\ \frac{V}{Ohm};$$

$$\frac{\partial U_{out}}{\partial Z_{int}} = 1000\frac{5{,}21-8{,}95}{8{,}95^2} = -46{,}81\ \frac{V}{Ohm};$$

$$\frac{\partial U_{out}}{\partial Z_{4qS}} = \frac{1000\cdot 5{,}2\cdot 10^2}{(6+10)^2 8{,}95^2} = 25{,}35\frac{V}{Ohm};$$

$$\frac{\partial U_{out}}{\partial Z_{TEAM}} = \frac{1000\cdot 5{,}2\cdot 6^2}{(6+10)^2 8{,}95^2} = 9{,}12\frac{V}{Ohm};$$

The variance of the voltage at the output of the ACS TAEM is:

$\sigma^2 = 0{,}418^2\cdot 10^2 + (-0{,}1091)^2\cdot 0{,}04^2 + (-46{,}81)^2\cdot 0{,}0625^2 + 25{,}35^2\cdot 0{,}075^2 + 9{,}12^2\cdot 0{,}04^2 =$ $16{,}545\ V$, i.e $\sigma = 4{,}067\ V$.

The third central point of the characteristics of the ACS TAEM is found by the formula [2]:

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$$\mathcal{M}_3 = \sum_{i=1}^{n} \left[\frac{\partial f[\mathcal{M}(x_1) \ldots \mathcal{M}(x_n)]}{\partial x_i}\right]^3 \cdot \mathcal{M}_3(x_i), \qquad (15)$$

where $\mathcal{M}_3(x_i)$ – the third central moment of the distribution of the parameters of the i-th block. Since, according to the conditions of the problem posed, the parameters of the blocks are subject to the Gauss law, then $\mathcal{M}_3(x_i) = 0$.

The fourth central moment, calculated above by the ACS TAEM , is found by the following formula [1,2]:

$$\mathcal{M}_4 = \sum_{i=1}^{n} \left[\frac{\partial f[\mathcal{M}(x_1) \ldots \mathcal{M}(x_n)]}{\partial x_i}\right]^4 \cdot \mathcal{M}_4(x_i) + 6 \sum_{i>j}^{n} \sum_{j=1}^{n} \left[\frac{\partial f[\mathcal{M}(x_1) \ldots \mathcal{M}(x_n)]}{\partial x_i}\right]^2 \cdot \left[\frac{\partial f[\mathcal{M}(x_1) \ldots \mathcal{M}(x_n)]}{\partial x_j}\right]^2 \cdot \sigma^2(x_i) \cdot \sigma^2(x_j), \qquad (16)$$

Where $\mathcal{M}(x_1)$ – the fourth central moment of the distribution of the parameters of the i-th block.

It is known [2] that if, according to the condition of the problem, the distribution of block parameters obey the Gauss law, then $\mathcal{M}_4(x_j) = 3\mathcal{M}_2^2$.

The numerical values of the fourth central moment calculated according to (16) of the function under consideration using the initial data of Table 1 and the values of the first derivatives of the functions is equal to $\mathcal{M}_4 = 7{,}23$ B.

We can determine the estimates of the desired voltage deviations by the formula:

$U_{\mathrm{TAEM}\ (\pm\%)} = \mathcal{M}(\pm n + 100)/100$, where ±n is the specified percentage of deviations

$$U_{\mathrm{TAEM}\ (-20\%)} = \frac{581{,}41(-10 + 100)}{100} = 523{,}26\ V$$

$$U_{\mathrm{TAEM}\ (+20\%)} = \frac{581{,}41(10 + 100)}{100} = 639{,}55\ V$$

We calculate the corresponding deviations of the stress distribution by the formula [2]:

$$K_\alpha = \left(U_{\mathrm{TAEM}\ (\pm 10\%)} - \mathcal{M}\right)/\sigma.$$

$$K_{\alpha(-10\%)} = \frac{(523{,}26 - 581{,}41)}{4{,}061} = -14{,}319$$

$$K_{\alpha(+10\%)} = \frac{(639{,}55 - 581{,}41)}{4{,}061} = 14{,}316$$

Determine the probabilities of non-exceedance permissible limits using the Pearson distribution tables [3]:

$$\mathrm{P}\left[U_{out} < U_{out(-20\%)}\right] = 0{,}026$$

$$\mathrm{P}\left[U_{out} < U_{out(-20\%)}\right] = 0{,}974$$

The probability that the voltage at the output of the ACS TAEM will go beyond the permissible limits and the circuit will fail will be:

$$Q = \mathrm{P}\left[U_{out} < U_{out(-20\%)}\right] + 1 - \mathrm{P}\left[U_{out} < U_{out(-20\%)}\right] = 0{,}026 + 1 - 0{,}974 = 0{,}052.$$

This value corresponds to the tolerance probability of the observing object failure.

Therefore, the system probability of failure-free operation or resource is P = 0.948. For a TAEM controlled by a four-quadrant 4qS converter, there is a superposition of two laws - exponential and normal Gaussian laws [3,4], due, respectively, to TAEM wear processes (aging of insulation, exposure to overvoltage peaks, humidification, heating, mechanical damage, etc.) and the presence of hidden defects in the manufacture of electronic control elements (Fig. 3).

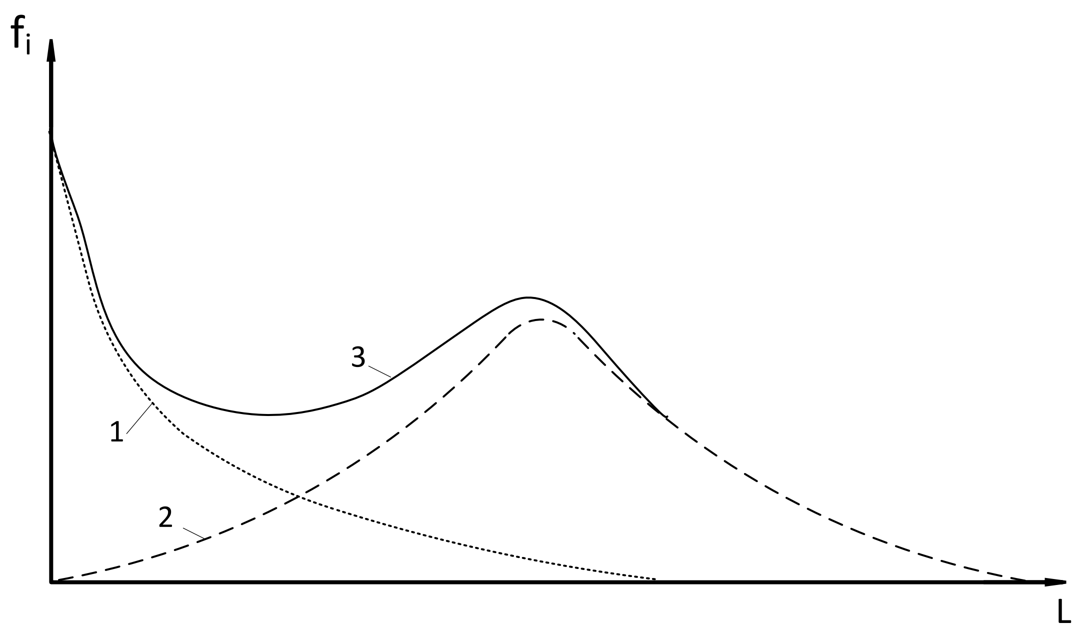

Fig. 3. The dependence of the density of probability distribution on the relative mileage $\Delta l = 100 \cdot 10^3$ km. 3 - superposition, 2 - exponential, 3 - normal Gaussian distribution laws

The estimation of the parameters of the average failure density of electric locomotives is defined as [3,4]:

$$\lambda = \frac{d}{\sum_{i=1}^{N} l_i + (N-d) l_0},$$

where N– is the number of observed electric locomotives; d - is the number of failed electric locomotives during the observation; $\sum_{i=1}^{N} l_i$ – total mileage of electric locomotives; $L_0 = 100 \cdot 10^3$km mileage during observations.

Average failure rate of type electric locomotives $\lambda = 0{,}625 \cdot 10^{-6} \frac{1}{km}$

The point estimate of the mean time to failure is [2]:

$$\lambda_{avg} = \frac{1}{\lambda} = \frac{1}{0{,}625 \cdot 10^{-6}} = 1600 \cdot 10^3\ km;$$

Lower and upper confidence limits of mean time to failure with confidence probability β = 0,9, having lower and upper values of failure rate $\lambda_{low} = 0{,}85 \cdot 10^{-6}$ и $\lambda_{up} = 2{,}5 \cdot 10^{-6}\text{км}^{-1}$[4].

$$L_{avg.low} = \frac{1}{\lambda_{up}} = 0{,}401 \cdot 10^6 km;$$

$$L_{avg.up} = \frac{1}{\lambda_{low}} = 1{,}176 \cdot 10^6 km$$

Accordingly, the two-sided boundaries of the 0,9th resource

$$L_{\gamma low} = \frac{1}{\lambda_{up}}(-ln0{,}9) = 42{,}5 \cdot 10^3 km;$$

$$L_{\gamma b} = \frac{1}{\lambda_{low}}(-ln0{,}9) = 123{,}2 \cdot 10^3 km.$$

CONCLUSION

The advantage of the method for calculating the moments for assessing reliability indicators is a relatively simple algorithm combined with the ability to assess the effect of each unit on the output voltage of the ACS TAEM . For a TAEM controlled by a four-quadrant 4qS converter, it is necessary to take into account the presence of a superposition of the exponential and normal distribution laws of the probability of operating time to failure.

A preliminary systematic analysis of statistical data shows the presence of a superposition not only of the exponential and normal Gaussian laws of the probability distribution of operating time to failure caused by the use of the 4qS converter and TAEM wear processes, but also the imposition of the Weibull-Gnedenko law, due to the use of electronic elements, which is an unambiguous consequence of vibration signals caused by defects in its bearings.

The boundaries of the sections of the indicated laws of the distribution of the probability of operating time to failure make it possible to adjust the timing of maintenance and repairs of the blocks of the TAEM control system.

Sequential monitoring of the output values of each block makes it possible to determine their numerical values of diagnostic signs as well as their residual life.

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