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# Methodological Aspects of Assessment and Optimization of the Reliability of Electrical Installations of the Railway Self-Propelled Rolling Stock

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**ABSTRACT:** Analysis and evaluation of the reliability of electrical installations and the choice of technical solutions for their maintenance in operation of railway self-propelled rolling stock (SRS) are presented in the paper. An example of solving a practical problem using standard and special methods of the theory of reliability and optimal solution is considered. The problem of reliability of electrified railways in general, and non-traction units such as self-propelled rolling stock, in particular, becomes one of the main problems. There are many examples of identifying and eliminating the causes of unreliable operation of SRS, especially its electrical installations due to the shortcomings of their design development and operating modes.

**KEYWORDS:** self-propelled railway rolling stock, reliability assessment and optimization, electrical installations.

## I.INTRODUCTION

Considering the reliability indices of special self-propelled rolling stock (SSRS) it is necessary to take into account the conditions of its performance in case of failure of individual functional units and the effect of internal and external influences, when realizing all these functions or a part of them. An account of these features of the reliability indices of the SSRS during its operation by static simulation of the random process of a unit transition from one state to another is an urgent task. This approach makes it possible to solve the following practical problems [1]:

- static analysis and reliability assessment based on the results of long-term observations of existing installation;
- prediction and rationing of optimal reliability;
- rational choice of technical solutions in design, their creation and operation.

The features of the analysis and evaluation of SSRS reliability are:

- unlike conventional objects of statistical information, it is advisable to start the assessment of the object after the first overhaul, since the SRS has a special design and a special mode of operation;
- the minimum number of observed objects *N* to check the required probability *P (t)* of reliability (failure-free work) based on the exponential law of probability distribution is advisable to determine by the formula [2]:

$$\delta_{+1} = \frac{2N}{\chi^2(1-\beta;2N)}, \quad (1)$$

where $\chi 2$ (1-$\beta$; 2N) is the quintile of distribution, $x$ is the square of the number of the degrees of freedom N; $\beta$ is the used confidence probability within 0.90 ... 0.95; $\delta$ is the relative error, defined as $\delta = \frac{t^B - t_{cp}}{t_{cp}}$, $t^B$, $t_{cp}$ are the upper single-sided confidence limit and the average value of a random variable or parameter, respectively;

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- at an unknown $t^B$ distribution law of a random variable, the minimum number N to determine the probability P (t) of the failure-free operation of SRS for a given time $t$ with a confidence probability $\beta$ is calculated by the following formula:

$$N = \frac{\ln(1-\beta)}{\ln P(t)} \qquad (2)$$

- an important feature is the need to combine statistical data collected from different regions to more accurately determine the reliability indices and to establish the type of distribution law for random variables.

Taking into account the above circumstances when collecting a priori information to study the SRS reliability, a multivariate dispersion analysis is used, that is, the influence of several variables on any one random variable is taken into account; this makes it possible to determine the influence of the level and mode of operation, and the meteorological conditions of the regions, on the reliability indices of SSRS and the effectiveness of further technical maintenance.

It is known that multivariate dispersion analysis from an engineering point of view is advisable to determine in the form of regression analysis [2].
Due to the fact that SRS is a complex multi-element dynamic system that has interdependent input and output quantities of metal of constructional, hydraulic and electromechanical installations operating in difficult conditions, the reliability of SRS as a whole or of its individual installations is a difficult task.

Therefore, to analyze the reliability of SRS, (from an engineering point of view) we use statistical method of multiple regression, which makes it possible to determine the polynomial coefficients as regression coefficients, connecting the output parameters Y and the set of input parameters X.

In this paper, statistical data are selected from a variety of observations during the eight-year operation of various modifications of SSRS in “Uzbekistan Temir Yollari” regions, taking into account the rules for constructing optimal plans for full and fractional factor elements (Table 1). These rules allow reducing the mean square error of the estimates obtained using the regression polynomial and reducing the number of experiments [2].
For electromechanical installation of SRS, the factor experiment with three factors has a planning matrix in the form:

Table 1

| k | $X_0$ | $X_1$ | $X_2$ | $X_3$ | $X_1X_2$ | $X_2X_3$ | $X_1X_3$ | $X_2X_3$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 6 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 7 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 8 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

here k is the number of lines or tests, in our case it is an observation; for failures and faults -1 - is the upper level of the influence of the value or parameter (factors), and +1 – is the lower one, which enables the estimation of the polynomial coefficients

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{123}x_1x_2x_3 \qquad (3)$$

Where $b_i$ is defined by the formula:

$$b_i = \frac{1}{8}\sum_{k=1}^{8} x_i \cdot y_k ; b_{ij} = \frac{1}{8} x_i x_j y_k ; b_{ijs} = \frac{1}{8} x_i \cdot x_j \cdot x_s \cdot y_k \qquad (4)$$

with dispersion coefficient

$$\sigma^2(b_i) = \frac{1}{8}\sigma^2(y) \qquad (5)$$

where $\delta^2$ *(y)* is the dispersion of the estimate, *y* is the corresponding parameters, in each of eight experiments.

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The above multi-factor experiment gives a numerical estimate of each exposure quantity *x* on the controlled parameter *y*. Rejecting the terms of the second-order polynomial of smallness, we can obtain a confidence model of the object under study.

Based on the above statements, consider the prediction of the failure rate parameter for a synchronous generator (SG) of the SECC 62-4U2 type installed on the rail service car to power the actuating motors of the turning mechanism on the assembly site, hydraulic pump, crane turning mechanism and electro-hydraulic tappet.

Operational reliability of the SG is determined by the following factors of influence [3]:

1. Electric strength of stator winding insulation with regard to dirt accumulation. The upper level corresponds to a multiple electrical strength equal to 2, the lower level to 1.3;
2. Maximum current of short circuit. The upper level is 100% of the cut-off current limit; the lower level is 50%;
3. Impermissible maximum temperature. The upper level is 86°C for 24 hours; the lower level is 20°C;
4. Permissible eccentricity of the rotor. The maximum deflection of the rotor in the middle of the rotor is 0.5 cm; the minimum deflection is 0.3 cm;
5. Shutdown of the SG due to a short circuit of the actuating electric motors within a year; the upper level is 10 short circuits and more; the lower level is about 3 short circuits;
6. The number of the SG stops due to the failures of bearings. The upper level is 5 shutdowns, the lower level is 1.

Table 2.

Characteristics of a factor experiment

| Number of tests, к | Number of failures, m | Total operating time, days | Unbiased failure rate, λ = m/S | Biased operating time ΔS | Biased failure rate λ = m/(S-Δ S) |
|---|---|---|---|---|---|
| 1 | 5 | 232 | 0,0215 | 207 | 0,0241 |
| 2 | 11 | 402 | 0,0277 | 362 | 0,0304 |
| 3 | 7 | 133 | 0,0526 | 119 | 0,0588 |
| 4 | 3 | 121 | 0,0248 | 109 | 0,0275 |
| 5 | 1 | 132 | 0,0076 | 118 | 0,0084 |
| 6 | 9 | 374 | 0,0241 | 337 | 0,0267 |
| 7 | 1 | 196 | 0,0051 | 176 | 0,0057 |
| 8 | 3 | 98 | 0,306 | 88 | 0,0341 |

Classifying the operational statistics data for a synchronous generator according to the plan of a fractional factor experiment and Table 2, and assuming that the interrelation of the factors listed above does not affect the average parameter of the failure rate, the following result is obtained:

$$\overline{\lambda} = 0{,}0324 - 0{,}005 \cdot x_3 + 0{,}0061 \cdot x_4 + 0{,}0111 \cdot x_5 \qquad (6)$$

Based on the average parameter of the failure rate and using a polynomial, it can be shown that the reliability of comparison of the obtained value and the table one, based on the Fisher criterion, is 95%.

$$F_{табл} < F_{факт} = \frac{\Sigma(\hat{y} - \overline{y})^2 / m}{\Sigma(y - \hat{y})^2 / (n - m - 1)},$$

where *m* is the number of parameters at factor *x; n – 8* is the number of observations; *y, g* are the estimates. At that, $\overline{\lambda}$ gives an adequate description of the effect of exposure factors. According to the data obtained, we can assume that the parameter of the failure rate (6) in operation of the ESS-62-4U2 generator, installed on the ADM-1 rail service car, is determined by the following factors, in decreasing order of influence: by the number of short circuits of current lines of actuating motors $x_5$ (since the observations show a significant influence of the turning mechanism and the hydraulics pump), overheating of the stator winding due to overload ($x_4$), and shutdown of the SG due to malfunctions in actuating electric motors - ($x_3$).

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The value of the exposure factor $x_5$ stimulates the need to develop and analyze a mathematical model of the SG failure for a deeper analysis of the reliability prediction process in order to gradually find the optimal preventive maintenance frequency.

The reliability of the SG protection and control system as one of the main functional devices largely determines the localization of failures and restoration of the normal SRS mode. To directly assess the probability of the SG failure-free operation, let us consider the simplest of models, which determines its current reliability, and formulate the conclusions regarding the conduct of its optimal prevention frequency.

Suppose that at time *t*, the probability of failure-free operation is represented as the product:

$$P(t) = P_0 \cdot P_1(t) \cdot P_2(t), \qquad (7)$$

where $P_0, P_1(t), P_2(t)$ are the probability of failure-free operation, sudden failures and the failures powered by electric motors due to a short circuit in the SG.

According to statistics, the probability of failure Q ($t_0$) of the SG at the initial stage of operation due to low manufacture quality is in the range of 0.001, ..., 0.006 [4]. Therefore, for the SG the probability of failure-free operation can be taken equal to $P_0$ = 0.999 ... 0.994. It is also known that the probability of the absence of sudden failures for electromechanical objects varies according to expression

$$P_1(t) = \exp(-\lambda t), \qquad (8)$$

where $\lambda$ is the failure rate determined with sufficient probability based on long-term operation.

In the SG, which feeds a set of actuating electric motors, resource working off is uneven, due to the nonlinearity of the electrical insulation strength, current-voltage characteristics and other wear parameters. Short circuits are possible on the SG due to various malfunctions and restarts of electric motors. The value of operating resource of the SG depends on the value of the current of short circuit, temperature and loading-reloading processes. The operation of the SG, which at each moment of time can be in any of a finite number of states, is denoted by $E_1$, $E_2$, …, $E_N$, and $E_0$ is the state of failure-free operation. An object can move into the state $E_{N-k}$ from any state $E_{N-k+1}$, $E_{N-k+2}$, …, $E_{N-k}$, $E_N$, and to move into the finite state from any state. The flow parameters of possible switching are denoted by $\lambda_1$, $\lambda_2$, …, $\lambda_N$. The graph of this random process is shown in Figure 1. Different values of $\lambda$ correspond to different transitions that reduce the life of the SG in different degrees. The number M denotes the initial resource of the SG. A reloading at $\lambda_1$ reduces the resource by 1/M-th, and the parameter $\lambda_2$ - by 2/M, and at $\lambda_M$ it immediately leads to a device failure.

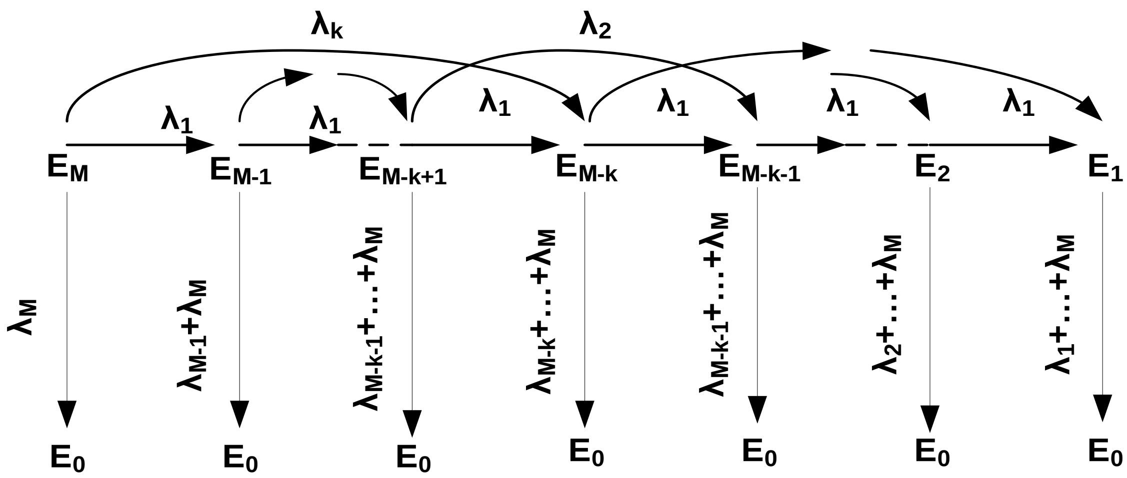


Fig. 1 Graph model of uneven wear

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When considering the probability of failure-free operation from the initial moment of time, the sum of the probabilities from the first state to the *M*-th state can be written

$$\mathrm{P(t)} = \sum_{i=1}^{M} P_i(t)\,. \tag{9}$$

The current *i*-th state is characterized by the remaining resource *i* and the spent resource M - *i*.

Differential equation for the probability of the current state can be written as [5]:

$$\mathrm{P_i^1(t)} = -\sum_{j=1}^{M} \lambda_j \cdot \mathrm{P_j(t)} + \sum_{j=1}^{M} \lambda_j \cdot \mathrm{P_{i+j}(t)}\,, \tag{10}$$

where *j* is the index of the parameter of working off flow of *j/M*-th part of initial resource.

In practice, it is necessary to consider the probability of failure-free operation from the time when the available resource is not equal to M, then (9) and (10) are transformed to

$$\mathrm{P(t)} = \sum_{i=1}^{n} P_i(t)\,,$$

$$\mathrm{P_i^1(t)} = -\sum_{i=1}^{N} \lambda_j \cdot \mathrm{P_j(t)} + \sum_{i=1}^{N-1} \lambda_j \cdot \mathrm{P_{i+j}(t)}\,, \tag{11}$$

where *n* is a worked off resource.

Solving (11) we get the formula for the probability $P_2(t)$ $n \le M$ [5]

$$P_2(t) = \frac{-\exp(-a1-a2-a3)\cdot \sum_{k=0}^{\le A_k}\cdot\sum_{k=0}^{\le A_p}\cdot\sum_{k=0}^{\le A_m}\cdot(a_5^k\cdot a_2^p\cdot a_1^m)}{k!\,p!\,m!}\,, \tag{12}$$

where $a_1 = \lambda_1 t;\quad a_2 = \lambda_2 t;\quad a_5 = \lambda_5 t;\ A_k = (n-1)/5;$

$$A_p = (n-1-5k)/2;\quad A_m = n-5k-2p\,.$$

where k is the part of the resource with permissible continuous operation.

Figure 2 shows the probability curves of failure-free operation on the worked off resource of the SG with uneven and uniform wear, calculated by formulas (9) - (12).

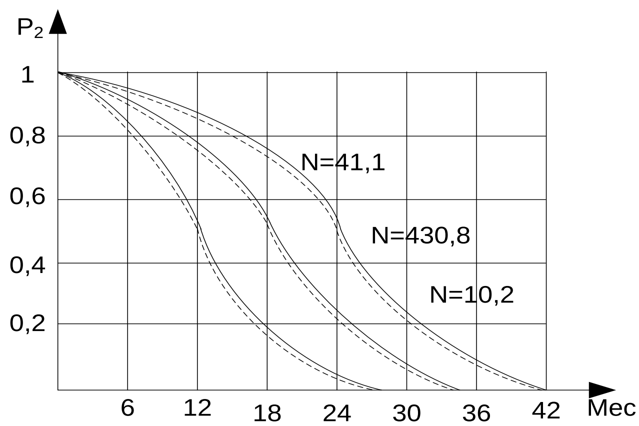


Fig. 2. The dependence of the probability of failure-free operation on the worked off resource;
(Solid curves – uneven wear; dashed curves - uniform wear).

The analysis of the curves in Figure 2 shows that the curve corresponding to the model of probability of failure-free operation with uneven working off of resource, constructed by formula (12) for different combinations of value $\lambda$ is more acceptable compared to the model [6] of uniform wear, otherwise the probability estimate of the failure-free work of the SG will be set too high.

In conclusion, we can point out that the mathematical model of dependence $P_2(t)$ allows us to predict the sought for reliability of the synchronous generator of the rail service car when the initial resource is worked off for any real operating conditions and to assign the optimum maintenance frequency.

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