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ESTIMATING THE PROBABILITY OF THE EMERGENCY OPERATION OF THE QUARRY ELECTRIC LOCOMOTIVE TRACTION ELECTRIC DRIVE

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ABSTRACT

The paper deals with the problem of the assessment of the functionality of the multi-motor direct current traction electric drive of the quarry electric locomotive. The problem of the failure of electric drive motors because of extremely unsatisfactory state of the rail tracks and the wear of wheel pairs is analyzed. Taking into account the number of the existing repaired electric motors the probability of fitting up the traction electric drive with the electric motors with the widest electrical parameters variety is determined.

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Introduction. The problem of improving the efficiency of quarry electric locomotives operation is being solved during several decades [1, 2, 3], but it has not been solved yet. Modern achievements and the latest developments of scientists in the field of the control of electromechanical systems (EMS), in particular, the electric drives of industrial electric locomotives [4, 5, 6], do not enable getting the required results as the condition of the rail tracks, mechanical equipment and traction electric motors is extremely unsatisfactory. It should be taken into account that the mentioned factors are directly interconnected and it is impossible to solve the problem of the high-quality repair of electric motors without the improvement of the condition of the tracks and wheel pairs. Fig. 1 contains fragments of rail tracks of quarry electric locomotives providing the transportation of the mining muck.

Such defects reflect on the state of the surface of the wheel pairs (Fig. 2). In some cases the wheel diameter decreases by 10-12 mm (Fig. 2, a), and new dents cause the appearance of the analogous damage of the rail surface (Fig. 2, b), and even variation of the geometry of the rail head.

Appearance of hollows, caverns, dents results in slippage, which additionally damages the rail track and the wheels at the point of their contact. When the diameter of a wheel decreases, the wheels in the wheel pair rotate at different speed, which results in continuous slippage of the wheel surface against the rail surface [7]. During the slippage the load is distributed irregularly between the traction motors. Motors with a higher load overheat and quickly fail also due to the presence of low-quality electricity in the contact network [8-14]. Motors are repaired at specialized repair enterprises allowing the following deviation of the output parameters according to the GOST state standard: the armature winding – 10% and the excitation winding – 2% [11-18]. The irregularity of the parameters results in irregular rigidity of mechanical characteristics and in irregular distribution of the load among the motors. That is why the research of the operation modes of quarry electric locomotives is a topical problem.

Fig. 1. Fragments of the rail track condition: a) – break, b) – hollow, c) – dent

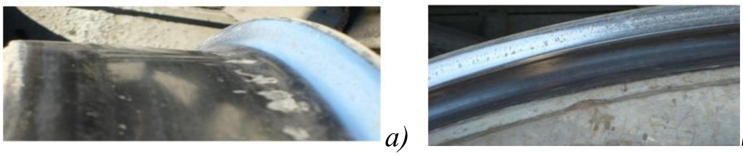

Fig. 2. Fragments of the wheel pairs condition: a) – change of the wheel diameter, b) – dent

Problem Statement. Electric locomotive OPE-1A (OPE-1AM) is the main type of the quarry electric locomotive at Poltava Ore-Dressing and Processing Enterprise. It is designed for the operation on the strip mining railways electrified by alternating current with the voltage of 10000 V, the frequency of 50 Hz, ruling gradient of 60‰. The servicing part of the traction unit consists of six two-axle bogies, two in each section. The bogies are equipped with two wheel-motor blocks consisting of a wheel pair and a traction motor. Direct current series excitation motors DT9N (NB-511 for OPE-1AM) are used as traction motors; in continuous duty their rated power is 418 kW at the rated voltage and current respectively 1500 V and 300 A, maximal rotation frequency 160 s-1.

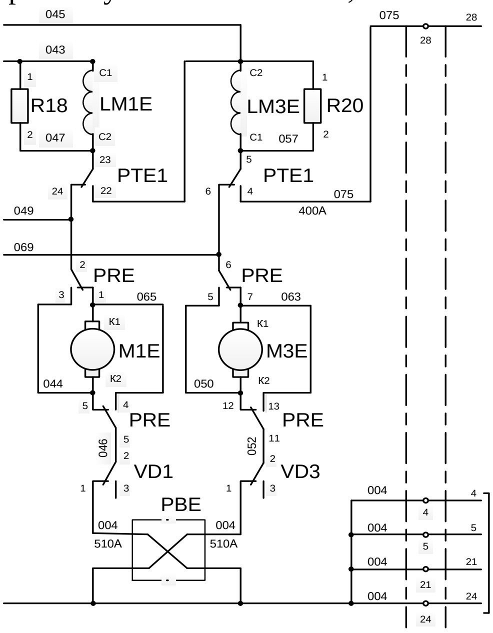

Fig. 3. A fragment of the basic power circuits of the electric locomotive TED: M1E, M3E – traction motors; PRE – reverser; PTE1 – brake switch; PBE – Locomotive wheelslip relay; C1-C2 – motors field winding; R18, R20 – shunt resistors of the motor field winding; VD1, VD3 – disconnectors of the motor; K1-K2 – motor armature; LM1E, LM3E – inductance of the motor field winding.

An electric locomotive is manufactured in a three-section variant and consists of a driving electric locomotive, a diesel section, a motor dump car. Sometimes a second motor dump car is installed instead of a diesel section. An electric locomotive is equipped with 12 traction motors. In the traction, autonomous and brake modes traction motors are connected in parallel in each traction unit (Fig. 3).

Admissible 10% deviation of the armature winding parameters in repaired traction motors is determined according to heat condition [7, 8, 9, 10, 13-15] and, if forced ventilation of the motors is available, allows long-term operation. However, it should be taken into consideration that an electric locomotive is equipped with 12 traction motors that are not especially selected for the operation in a multi-motor electric drive system as they are motors of the same type. In this case there is a possibility of such a situation when one electric locomotive unit will contain motors with parameter deviation within the tolerance but of opposite values. Let us consider a probability of such a situation.

Let there be N motors in the repair fund; they are characterized by a vector of a certain parameter deviation from the norm $\Delta=[\Delta_1\ \Delta_2 \ldots \Delta_i \ldots \Delta_N]^T$. Value Δ_i, that characterizes i-th motor may be both positive and negative and may repeat m times($1 \le m \le N$).

Results of the Research. We introduce an upper-triangle matrix of the modules of the first final pairwise differences ∇ characterizing the difference between the motors in the pair according to the preset parameter:

$$\nabla = \begin{pmatrix} 0 & \nabla_{12} & \nabla_{13} & \cdots & \nabla_{1j} & \cdots & \nabla_{1N} \\ 0 & 0 & \nabla_{23} & \cdots & \nabla_{2j} & \cdots & \nabla_{2N} \\ 0 & 0 & 0 & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \nabla_{ij} & \cdots & \nabla_{iN} \\ 0 & 0 & 0 & 0 & 0 & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & \nabla_{(N-1)N} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad (1)$$

With the dimension of $N \times N$ (the number of the elements $(N^2-N)/2$), its elements are calculated by the following rule:

$$\nabla_{ij} = \begin{cases} |\Delta_{ij}| = |\Delta_i - \Delta_j|, & \forall i < j \\ 0, & \forall i \ge j \end{cases}. \quad (2)$$

If $\nabla_{ij} \approx 0$ or $\nabla_{ij} = 0$, it means that the difference between the i-th and the j-th motor by preset parameter Δ, is respectively minimal or absent.

We are interested in the maximal value $\max(\nabla_{ij}) = \nabla_{\max}$. Naturally, $\nabla_{\max}$ may repeat k_{max} times (in theory $1 \le k_{max} \le N-1$).

Let us estimate the probability of the situation when during the selection of 12 motors for a locomotive there will be a pair corresponding to $\nabla_{\max}$: a) once; b) at least once.

On the basis of the hypergeometric distribution of probabilities it is possible to write down a probability that during the selection of 12 motors out of N the number of the chosen ones will include exactly k ($1 \le k \le k_{max}$), corresponding to $\nabla_{\max}$:

$$p(\nabla_{\max}, k) = \frac{C_{k_{\max}}^{k} \cdot C_{N-k_{\max}}^{12-k}}{C_N^{12}}. \quad (3)$$

Then for the probability of the extraction of one such pair it is possible to write down (one pair – k=2):

$$p(\nabla_{\max}, 2) = \frac{C_{k_{\max}}^{2} \cdot C_{N-k_{\max}}^{10}}{C_N^{12}}.$$

In practice N=100...400. Let us consider the “worst” case when the repair park is minimal, i.e., N=100 and, e.g. there is a chance to select k_{max}=12 (6 pairs) of motors with the maximal difference by the parameter. Then

$$p(\nabla_{\max}, 2) = \frac{C_{12}^{2} \cdot C_{88}^{10}}{C_{100}^{12}}.$$

Taking into account that $C_n^k = n!/(k!(n-k)!)$ and n is big, Stirling’s formula will be used for the calculation of factorials:

$$n! \approx \sqrt{2\pi n}\left(\frac{n}{e}\right)^n.$$

Then $$p(\nabla_{max}, 2) = \frac{C_{12}^{2} \cdot C_{88}^{10}}{C_{100}^{12}} = 0.284, \text{ i.e. } 28.4\%. \quad \ldots\ldots\ldots..(4)$$

The probability of the situation when during the selection of 12 motors at least one pair will be with the maximal difference of the conditions is:

$$p(\nabla_{max}, (k=2) \vee (k=4) \vee (k=6) \vee (k=8) \vee (k=10) \vee (k=12)) = \sum_{m=2,4...12} \frac{C_{12}^{m} \cdot C_{88}^{12-m}}{C_{100}^{12}} = 0.314, \quad (5)$$

i.e. 31.4%.

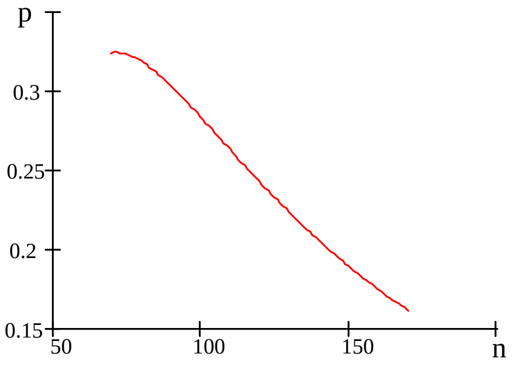

Fig. 4. The probability of the situation when during the selection of 12 motors out of n motors of the repair park one pair will be with the maximal difference of the parameters

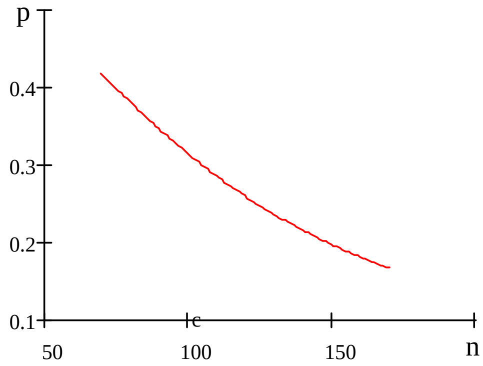

Fig. 5. The probability of the situation when during the selection of 12 motors out of n motors of the repair park at least one pair will be with the maximal difference of the parameters

The obtained results reveal that in every third case there may be a situation that will be unfavorable from the point of view of the reliability characteristics of the wheel pair of the electric locomotive after repair.

As mentioned above, to get real assessment of the said probabilities it is necessary to know the law of distribution of value Δ_i of the preset parameters as it would allow the assessment of the share of the motor pairs with maximal deviations from the preset parameter.

Let Δ^k be a casual deviation of the *k*-th parameter of the electric motor after repair. For the convenience of further reasoning let us pass to relative deviations

$$\delta^k = \frac{\Delta^k}{r_{nom}^k} \cdot 100\%, \quad (6)$$

where r_{nom}^k – rated (published) value of the required parameter. As transform (6) is of linear character, the form of the law of distribution of probabilities of Δ^k and δ^k coincide. Let the law of distribution δ^k be preset by the density of probability $f_{\delta^k}(x, \Theta^k)$, i.e. $\delta^k \sim f_{\delta^k}(x, \Theta^k)$, where $\Theta^k = \left(\Theta_1^k, \Theta_2^k, ..., \Theta_1^S\right)^T$ – vector of the distribution parameters. It is necessary to:

1) assess $f_{\delta^k}(x, \Theta^k)$;

2) assess the probability of the situation when two motors of size *N*, randomly chosen out of the repair fund, will have critical deviations by the *k* - th parameter;

3) assess the probability of the situation when two motors of size *N*, randomly chosen out of the repair fund, will have critical deviations by at least one of *k* ($k=\overline{1,K}$)parameters.

The assessment of the law of distribution $f_{\delta^k}(x, \Theta^k)$ requires structural and parametrical identification of the model. Taking into account the complexity of obtaining the sufficient amount of empiric data, which would provide the opportunity to suggest and verify a definite statistical hypothesis as to the model, we will consider the assessment of the law of distribution based on a number of a priori assertions and suppositions.

By virtue of the central limit theorem we can suppose, that the law of distribution δ^k should have a normal or at least an asymptotically normal law of distribution with zero mathematical expectation (μ=0):

$$f_{\delta^k}(x,\mu,\sigma)=\frac{1}{\sqrt{2\pi}}e^{\frac{-(x-\mu)^2}{2\sigma^2}}. \quad (7)$$

However, according to the standard requirements, the absolute value of the post-repair deviation of the preset parameter k cannot exceed a certain admissible value. Otherwise the electric motor is considered unfit for operation and does not replenish the repair fund. In other words, in practice, it is necessary to have not a normal but a truncate normal law of distribution with symmetrical boundaries and it should be preset by the following expression with four parameters:

$$f_{\delta^k}(x,\mu,\sigma,x_1,x_2)=\begin{cases}0 & x\le x_1\\ \dfrac{\phi\left(\frac{x-a}{\sigma}\right)}{\sigma\left(\Phi\left(\frac{x_2-a}{\sigma}\right)-\Phi\left(\frac{x_1-a}{\sigma}\right)\right)} & x_1<x\le x_2,\\ 0 & x>x_2\end{cases} \quad (8)$$

Where $\phi(x)\frac{1}{\sqrt{2\pi}}e^{-\frac{t^2}{2}}$ – Laplace's function, $\Phi(x)=\frac{1}{\sqrt{2\pi}}\int_0^x e^{-\frac{t^2}{2}}dx$ – Laplace's integral function. In this case three out of four components of the distribution parameter vectors can be considered exactly preset:

$$\Theta^k=\begin{bmatrix}\mu\\ \sigma\\ x_1\\ x_2\end{bmatrix}=\begin{bmatrix}0\\ \sigma_k\\ x_{1k}\\ x_{2k}\end{bmatrix},$$

where x_{1k}, x_{2k} – particular tolerances for the k-th parameter, $\sigma_k=\frac{1}{(n-1)}\sum_{i=1}^{n}(\delta_i^k-mean(\delta_i^k))^2$ – sample point unbiased and consistent assessment of parameter σ, $mean(\delta_i^k)=\frac{1}{n}\sum_{i=1}^{n}\delta_i^k, n$, n – sample size.

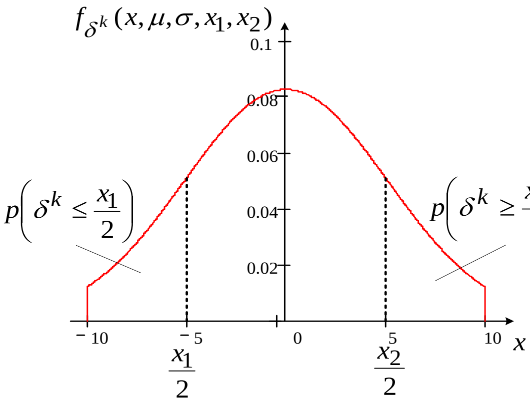

Fig. 6. A view of the density of the distribution of the truncate normal distribution with a parameter vector

$$\Theta^1=\begin{bmatrix}\mu\\ \hat{\sigma}_1\\ x_{11}\\ x_{21}\end{bmatrix}=\begin{bmatrix}0\\ 5.077\\ -10\\ 10\end{bmatrix}.$$

Then the probability of getting into the left-hand and the right-hand critical zone are equal and are determined as

$$p\left(\delta^k\ge\frac{\max}{2}\right)=p\left(\delta^k\le\frac{\min}{2}\right)=p\left(\delta^k\ge\frac{x_2}{2}\right)=\int_{\frac{x_2}{2}}^{x_2}f_{\delta^k}(x,\mu,\sigma,x_1,x_2)dx. \quad (9)$$

Consequently, the probability of the situation when during the selection of two motors for one wheel pair one will choose two specimens with deviations by the preset parameter k that will be diametrically opposite and of the type that $|\delta_1-\delta_2|\geq x_1$, will be equal to the following, according to the theorem of multiplication of dependent events

$$p\left(\left|\delta_1^k-\delta_2^k\right|\geq x_1\right)=p\left(\left(\delta^k\leq\frac{x_1}{2}\right)\cap\left(\delta^k\geq\frac{x_2}{2}\right)\right)=2\cdot p\left(\delta^k\leq\frac{x_1}{2}\right)p\left(\frac{\delta^k\geq\frac{x_2}{2}}{\delta^k\leq\frac{x_1}{2}}\right). \qquad (10)$$

Finally, the probability of the situation when two motors of size *N*, randomly selected out of the repair fund, will have critical deviation by at least one of *k* parameters can be calculated by formula:

$$p\left(\left(\left|\delta_1^1-\delta_2^1\right|\geq x_{11}\right)\cup\left(\left|\delta_1^2-\delta_2^2\right|\geq x_{12}\right)\cup\ldots\cup\left(\left|\delta_1^K-\delta_2^K\right|\geq x_{1K}\right)\right)=1-\prod_{k=1}^{K}p\left(\left|\delta_1^k-\delta_2^k\right|<x_{1k}\right). \qquad (11)$$

As an example, let us consider a case with two parameters: armature winding resistance ($R_я$) and excitation winding resistance ($R_в$). The distribution parameter vector for the armature

$$\Theta^1=\begin{bmatrix}\mu\\ \hat{\sigma}_1\\ x_{11}\\ x_{21}\end{bmatrix}=\begin{bmatrix}0\\ 5.077\\ -10\\ 10\end{bmatrix}.$$

For the excitation winding – $\Theta^2=\begin{bmatrix}\mu\\ \hat{\sigma}_2\\ x_{12}\\ x_{22}\end{bmatrix}=\begin{bmatrix}0\\ 1{,}106\\ -2\\ 2\end{bmatrix}$.

The assessment of parameter σ is obtained on the basis of the selective data

Then, according to formula (6), the following is true for the armature:

$$p\left(\delta^1\geq\frac{\max}{2}\right)=p\left(\delta^k\leq\frac{\min}{2}\right)=p\left(\delta^k\geq5\right)=\int_5^{10}f_{\delta^1}(x,0,5.077,-10,10)dx=0.145.$$

It means that ≈15 motors at N=100 have the value of resistance exceeding half of the admissible one on the right, i.e. 5%, and the same number of motors with deviation on the left.

Analogously, for the excitation winding:

$$p\left(\delta^2\geq\frac{\max}{2}\right)=p\left(\delta^2\leq\frac{\min}{2}\right)=p\left(\delta^2\geq1\right)=\int_1^{2}f_{\delta^2}(x,0,1.106,-2,2)dx=0.15889.$$

Then the probability of the situation when during the selection of two motors for one wheel pair one will choose two specimens in which the deviations of the armature winding will be diametrically opposite and of such type that $|\delta_1-\delta_2|\geq10$ by formula (10) will equal:

$$p\left(\left|\delta_1^1-\delta_2^1\right|\geq10\right)=p\left(\left(\delta^k\leq-5\right)\cap\left(\delta^k\geq5\right)\right)=2\cdot p\left(\delta^k\leq-5\right)p\left(\frac{\delta^k\geq5}{\delta^k\leq-5}\right)=\frac{15}{100}\cdot\frac{15}{99}\cdot2=0.04545.$$

Analogously, for the excitation winding:

$$p\left(\left|\delta_1^2-\delta_2^2\right|\geq1\right)=p\left(\left(\delta^1\leq-1\right)\cap\left((\delta^1\geq1\right)\right)=2\cdot p\left(\delta^2\leq-1\right)p\left(\frac{\delta^2\geq1}{\delta^1\leq-1}\right)=\frac{16}{100}\cdot\frac{16}{99}\cdot2=0.05172.$$

Finally, the probability of the situation when two motors of size *N*, randomly selected out of the repair fund, will have critical deviation by at least one of the parameters analyzed by formula (11) will be:

$$p\left(\left(\left|\delta_1^1-\delta_2^1\right|\geq x_{11}\right)\cup\left(\left|\delta_1^2-\delta_2^2\right|\geq x_{12}\right)\right)=1-\prod_{k=1}^{2}p\left(\left|\delta_1^k-\delta_2^k\right|<x_{1k}\right)=1-p\left(\left|\delta_1^1-\delta_2^1\right|<x_{11}\right)p\left(\left|\delta_1^1-\delta_2^1\right|<x_{11}\right)=$$

$$=1-(1-0.04545)(1-0.05172)=0.095\approx0.10,$$

i.e. in every tenth case during the repair the selected pair may be of such a type that, at least by one parameter, there will be a deviation exceeding the admissible norms.

Conclusions. The performed analysis of the condition of the mechanical, electromechanical equipment of the quarry electric locomotives and rail tracks reveals that, due to the deviation of the parameters of traction motors after repair in the electric locomotive multi-motor electric drive there occurs irregular distribution of load among the motors, the overheat of more loaded motors and their failure. Irregular distribution of load causes slippage resulting in the damage of the rail tracks and the wheels of the electric locomotive. The calculated probability of fitting up the electric drive with motors with the widest variation of parameters reaches 30% in the existing repair park of traction motors. An analysis of mechanical characteristics of the two-motor electric drive has been carried out. It takes into account the slippage caused by the condition of the rail track. The growth of losses of the overloaded motor results in the decrease of its insulation durability by 25%. Taking into consideration the fact that there is no possibility of control of a separate track motor on the electric locomotive, high accident rate will remain in the future. The equalization of the irregular load among the motors caused by the irregular parameters and the deterioration of the coefficient of traction is only possible by means of additional control of the motor magnetic flux. Besides, the synthesis of a SMART-system of control of traction electric drive with the functions of self-control and analysis will provide the improvement of the efficiency of the operation of traction electric drives of quarry electric locomotives. It is also possible to solve the above problem by using additional power sources for electric motors, as alternative sources.

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