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Evaluation of the operational life of direct current motors

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Abstract. This article is devoted to the issue of technical diagnostics in urban electric transport. To resolve the issue, it is necessary to translate the qualitative determination of the TS on some quantitative basis. The formalization of qualitative definitions is a necessary condition for the construction of formal (computable) diagnostic algorithms.

1. Introduction

The relevance: The operational reliability of the traction electric-motor decreases suddenly after the depletion of the operational life. Life cycle extension methods should maintain the operational reliability of a direct current traction motor (DCTM) equal or close to the nameplate data for a number of years. On the one hand, the life cycle extension of an electric machine should have an economic effect, and on the other hand, technical measures of operational reliability maintaining cause an increase in material expenditures. Therefore, a position is required where the difference between the result obtained and the cost is positive. In this case, the life cycle extension is an appropriate and cost-efficient task.

2. Tasks evaluation of the engines operating resource

It can be said that maintaining the operational reliability of an electric machine that has reached the end of its service life at an appropriate level entails an increase in technical and economic effect. Therefore, scientific research is aimed at determining the economically justified level of reliability of electric machines for a given year in certain areas of their use.

The work poses the following tasks:

- research how the deviations of the design and technological parameters of the electromagnetic and mechanical nature influence the quality of functioning of the collector-and-brush assembly unit (DCTM);
- determine the effective set of parameters for diagnosing the technical state of the collector-and-brush assembly unit and monitor its performance with the most informative value and distinctiveness;
- explain the selection of diagnostic signals and their parameters for assessing the sparking rate and the surface condition of the collector of the traction motor, research the statistical characteristics of these parameters;
- develop a method and device for monitoring the state of the collector' surface taking into account the influence of the collector' profile on the sliding contact stability.

A direct current traction motor is the most important element for rolling stock that determines its reliability in general.



At the present time, there is a trend towards the development of automated diagnostic systems for electric actuators without putting them into repair. It can significantly reduce the standby time of rolling stock (RS) and improve the accuracy of troubleshooting.

Traction motor (TM) is a complex multi-element technical system. Its individual elements are combined into numerous assemblies related to mechanical and electromagnetic systems. Issues with them are related to the non-identity of operating sequences.

Comprehensive solution of these issues: Mechanical and electromagnetic non-identity of operating sequences meets the modern requirements of scientific and technological progress, since one of the priority areas is to reduce losses associated with the components and parts wear, as well as the introduction of modern tools, methods, diagnostics, and repair of the TM collector-and-brush assembly unit. There are also external conditions affecting the TM along with internal issues. These factors include the environment, such as humidity, temperature, dust. With a decrease in pressure, heat removal from the elements deteriorates, which leads to overheating.

Thus, the topic of scientific research related to the development of means of DC motors state operational diagnostics is an important task.

Currently, rolling stock-operating organizations widely use the system of scheduled-preventive repair (SPR) in the operation of unrecoverable or disposable parts (electrical brushes, capacitors, resistors, devices, etc.). But it is unacceptable for modern rolling stock in general. It entails an increase in standby time of RS with DCTM during repair and the overall rise in the cost of operation, which negates the profitability of this type of actuator and further complicates the situation with asynchronous and synchronous motors. It does not take into account various developments, unequal load factors and, consequently, different wear of RS equipment. Obviously, the same equipment overhaul period at different wear leads to unnecessary consumption of material resources.

The systematic collection and analysis of statistical information about faults and failures of the RS, its weak assemblies, the researches of parts and assemblies wear common factors in the function of operating time are necessary conditions for improving the efficiency of production processes, reliability, and quality of maintenance and repair. The work on pre-repair defects and damage to electrical machines is called troubleshooting.

A significant number of rejections occur during the inter-repair period or are detected during preventive maintenance. Well-trained personnel, provided with a sufficient amount of automatic control features for the electric actuator, ensures the operation of the equipment with less expenditure of effort and means. A production base has been created in the rolling stock-operating organizations to ensure the traction rolling stock repair and its maintenance during operation. Most of the TM malfunctions over the research period are associated with damages at anchor and collector (Fig. 1).

As can be seen from the diagram, the main issues are insulation breakdowns and shifting. The overlap on the collector often goes with a circular fire with the transfer to the body and the burning out of machine parts that fall into the burning area. The cause of shifting is usually pollution and oiling of the collector, accumulation of coal dust in bar-to-bar grooves. To eliminate the consequences of breakdown and reruns, the failed coil or section is replaced, the insulation is restored. Vibration is of traction motor. Increased vibration is the cause of burning without a common factor, causing brushes to break away from the collector, the brush sparking, and increased collector heating. These features cause rapid abrasion of brushes in height and the formation of abundant graphite dust. Vibrations and noise with high-frequency components appear when rubbing brushes against a collector or contact wheels in an electric machine.

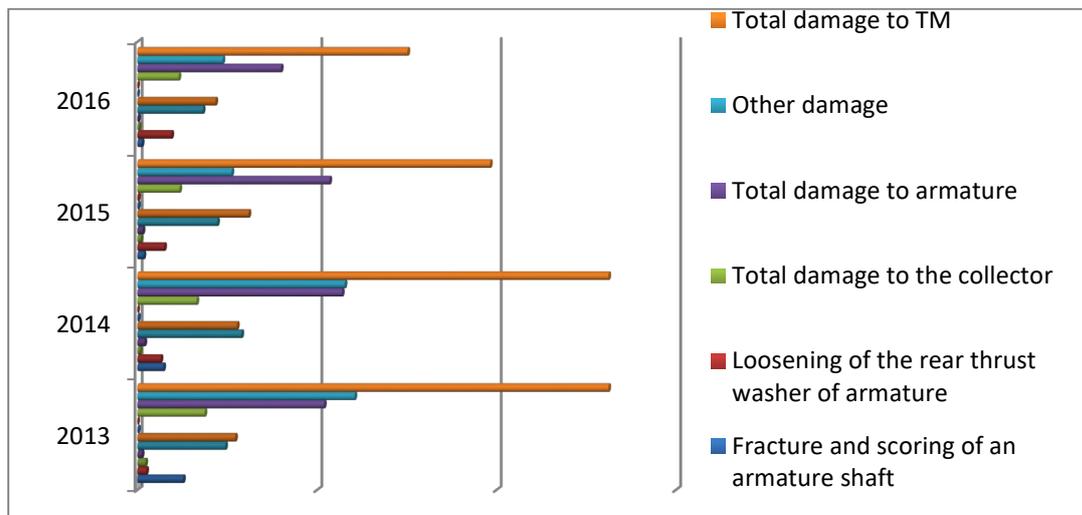


Figure 1. Cases of all damages

Damage to the TM collectors may occur in the collector non-cylindrical surface formation due to its unequal brushing wear during long-term work, breaking the polishing of the collector surface with scratches on it due to unequal pressing of individual brushes on the collector and their hardness, burning plates by commutation failure, their flashing in the case of a circular fire on the collector during machine overload, etc.

The causes of rejections of anchor bearings are the allowable bearings heating temperature rise, their contamination during assembly or the presence of a contaminated lubricant, its excess, wear or destruction of bearing parts if the latter being imbalanced, small radial clearance, friction in bearing seals [1]. The most likely causes of low-frequency oscillations (from 0 to 300 Hz) are an eccentricity, imbalance of rotating masses, imperfection of rolling bearings, violation of the geometry of slider bearers [2]. Brushes EG-2AF have the friction coefficient equal to 0.35 when idling, and operating under load, it decreases to 0.014. In these conditions, great importance appears to be in the vibration resistance of brushes, their ability to resist intense wear and destruction (chipping) with increased vibration. At present, a set of vibro-acoustic devices, which are used to diagnose inter-shaft, inter-rotor and other rolling bearings, is used quite effectively to control the vibration state of the motor. On the other hand, the vibration itself is a source of serious damage and accidents.

A further reduction in the number of rejections may be due to better repair, improvement of the existing technology. The system is divided into blocks based on the unity of the product functioning and the physical processes occurring in it.

Therefore, the introduction of maintenance and repair system is the right resolution to the issue of ensuring the facilities durability.

According to statistical indicators, it is possible to determine the availability factor of an RS for the considered period of operation by the SPR. It is expressed by the formula:

$$A_i = \frac{M_{UT}}{M_{UT} + M_D T_{CM}} \quad (1)$$

where M_{UT} is the average work time;

$M_D T_{CM}$ is the average non-work time due to the implementation of unscheduled types of maintenance and repair performed to eliminate all faults and failures for the same period of operation (except for cases of vandalism, third-party culpability, incorrect operation, etc.).

Considering the probability of no-failure (PNF) at all time intervals for each of the TM assemblies, the probability of failure-free operation during time t means the probability of an event $\{\tau > t\}$, when the product (TM) will not fail during time t . I.e. symbolically it is written like this:

$$p(t) = P\{\tau > t\}, \quad (2)$$

where t is the specified time;

τ is the time before product failure, a random value.

The function $p(t)$ is often called the reliability function. It is believed that $p(0)=1$ and with increasing time t , this function monotonically decreases, tending to zero.

The probability that after time t , the assembly will work smoothly for a time x ,

$$P^*(t)=1-\frac{n(t)}{N}, n(t)\leq N \quad (3)$$

The value of $\sigma = \sqrt{D\tau}$, where the mean-square deviation shows the deviation of the service life τ from its average $M\tau$.

It is seen to be considered that τ_i ($i=1, 2, \dots$) are independent and equally distributed random values with the distribution function $F(t)$.

The coefficients “ C_k ” form a random amplitude probability distribution. The reliability functions will change depending on the flows of elements failures over time. In particular, according to the law of Weibull, it can be represented as an equation:

$$P(t)=\exp[-\lambda t^\alpha] \quad (4)$$

where λ, α – parameters.

If vectors of durability of r_i reflect properties in a reference state, and the index of $R(t/r)$ is equal to the conditional probability of failure-free operation at a stage of operation of t , then probability of failure free operation for any system taking into account change of a condition of the $U(t/r)$ system and an index of its quality of $V(t/r)$ can be expressed by means of the corresponding functions.

The following types of electric stock clusters failures stock are most widespread and demonstrate that 20-25% of the total number of failures fall to the share of traction engines. Charts of malfunctions of TED are provided on Fig. 2 and 3.

Experimental studies carried out by the authors to assess the influence of external vibrations on the work of the current-collecting assembly were performed on an experimental setup where experiments have been carried out. The developed test method contains a list of reliability indicators to be monitored, as well as the following data for each specific reliability indicator: acceptance $P\alpha$ and failure $P\beta$ levels of the failure-free operation probability, risks of consumer β and manufacturer α , the test method, the test plan, the list of parameters characterizing the state of products, test conditions (values of influencing factors, their sequence, duration), and the decision rule. A feature of the applied method of sequential analysis is that the number of test items is not fixed in advance for given α and β but depends on the observations outcome.

A mechanical wear of the collector depends on the area of contact with the electrical brushes and their state. Repair of a restored technical system (a brush with a detachable lower section) developed by the authors (patent No. 182855 of the Russian Federation for the brush assembly of an electric machine) is less expensive than a new one. Knowing the nature, the rate of change of the output process parameter, and its limiting value, one can determine the operational life of the collector-brush assembly before the next maintenance or repair. The pressure of the brush on the collector is also measured.

The TM collector-brush assembly as a subject of diagnosis can be in one of the states that form the set of states W , which can be divided into the following subsets: A – good technical states when the values of all structural and output parameters are within acceptable limits and, therefore, the collector-and-brush assembly unit is functioning normally; B^1 – faulty technical state when at least one structural or output parameter is beyond the permissible limits. On the other hand, the set of the collector-and-brush assembly unit states can be divided into subsets: E – operational states when most of the main structural and output parameters are within acceptable limits and the collector-and-brush assembly unit performs specified functions; D – rejections of the collector-and-brush assembly unit, the loss of its performance.

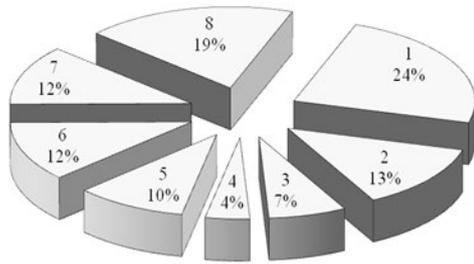


Figure 2. Fault diagram of tram traction motors: 1 – oiling; 2 – damage to the anchor bearers; 3 – shifting, flashing, burnings, tightening of the collector bars; 4 – collector scoring; 5 – the collector surface runout; 6 – melting of brazes from collector lugs; 7 – breakdown and inter-turn closing of the armature winding; 8 – other faults.

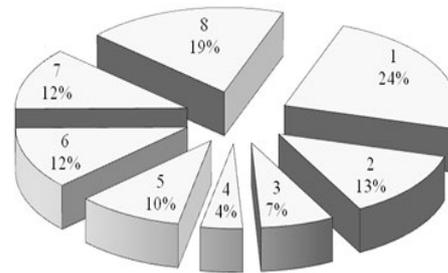


Figure 3. Fault diagram of the trolley bus traction motors: 1 – insulation breakdown and inter-turn armature closing; 2 – melting of brazes from collector lugs; 3 – oiling in the core; 4 – collector surface runout; 5 – damage to the anchor bearers; 6 – low winding insulation; 7 – insulation breakdown and inter-turn closing of the main and additional poles; 8 – other faults.

The connection of the considered states of the collector-and-brush assembly unit can be illustrated by the equations:

$$A + B' = W / (E \setminus D) = W \setminus AB_t = 0; E/D = 0; \tag{5}$$

$$B_t/E = C; A JG \setminus D = W, \tag{6}$$

where G is a subset of faulty but operational states.

In case a state belongs to the subsets G or D , it is necessary to resolve the issue of diagnosing, i.e. defect recognition.

Accept the smallest values:

$$S = \sum_{i=1}^n \left(aN_i^{\frac{1}{4}} - \frac{6}{N_i} - R_{nep i} \right)^2 \tag{7}$$

System natural frequency

$$\omega_0 = \sqrt{k / M_D} \tag{8}$$

Oscillatory acceleration is determined by a formula

$$a = \omega^2 X = (2\pi F)^2 X = \frac{4\pi^2}{T^2} X \text{ (cm/sec.}^2, \text{ m/s}^2\text{)}. \tag{9}$$

The current has a harmonic proportional to the speed of rotation of the armature. Then, for example, when modulating the rotation harmonics of the rotor (the inner wheel of the bearer) at the first type combination frequency [i.e. if we take $\omega_1 = 2\pi(qf_{H.K} \pm mf_B)$, $\omega_2 = 2\pi f_B$], the vibration spectrum may have got lateral components at frequencies

$$kf_B \pm n(qf_{H.K} \pm mf_B), \tag{10}$$

and if the signal is modulated at a frequency $kf_{H.K}$ by a second combinational frequency [i.e. $\omega_1 = 2\pi(q_1 f_B \pm m_1 f_C)$, $\omega_2 = 2\pi f_{H.K}$] at frequencies

$$kf_{H.K} \pm n(q_1 f_B \pm m_1 f_C), \tag{11}$$

where $q=1, 2, 3, \dots, m=1, 2, 3, \dots$ - are harmonic numbers.

The frequency of the harmonics resulting from the engine operation and previously called “speed” ones-, are defined as follows:

$$f_z = \frac{N_L n}{60}, \quad (12)$$

where N_L is the number of collector bars on the DC motor, n is the rotor speed, U/min, 60 is a number that allows counting minutes in seconds.

The frequency spectrum is limited to a certain frequency f_g . The center frequency of the f_0 range is selected since there is no more than one maximum of the function spectral density $S_w(f)$ in each subrange.

If the function $f^*n(n)$ within the boundaries of possible values does not have jumps that correspond to the available information about Rn , namely:

$$f_0^*(r) = \begin{cases} \frac{R}{R_B - R_a} & \text{при } R_a < r < R_B \\ 0 & \text{при } R_a > r; \quad r < R_B \end{cases} \quad (13)$$

where the value of R is distributed in the interval $[R_a, R_B]$ evenly, so the distribution in the number (4...10) of indicators does not give an accurate implementation of R within the interval $[R_a, R_B]$.

These functions can be determined using the experiment planning theory by implementing the planning matrix of a full factorial experiment for four factors (matrix type 2^4). Thus, we have in this example: fault A_1 occurs in the case of simultaneous going beyond the standard parameters S_1 and S_3 , fault A_2 with parameters S_2 and S_4 , and fault A_3 with parameters S_3 and S_4 (table 1).

Table 1. Diagnostic matrix

Diagnostic parameters	Possible damages		
	A_1	A_2	A_3
S_1	1	0	0
S_2	0	1	0
S_3	1	0	1
S_4	0	1	1

This issue of defects detection and distinguishing comes down to a spectral analysis of their vibration. The quantitative and high-quality changes can lead to sudden failure both in contact couple-, and beyond it (corrosion, erosion, excessive increase in current or temperature, blows, pushes, vibration). The correct interpretation of such range allows not only to recognize defects-, but also to establish their interrelation and nature (depth) of their interactions. Calculations should be carried out by means of the COMPUTER.[2]

Wear rate of the collector α is affected by a large number of random factors-, diverse by nature, therefore distribution α is considered normal. These malfunctions occur usually after $16 \cdot 10^3$ km of a run, the wear on height is only 20 mm and it is unsuitable to operation. Influence of misalignment degree on the level of vibration can be reduced by application of couplings. The increased vibration caused by the insecure shaft interface, defects of bearings or fans, turn-to-turn short-circuits on an anchor, a double rigidity of an anchor, resonances of separate clusters etc cannot be eliminated with balancing of an anchor. Therefore they constitute the greatest danger from all mechanical influences to which isolation on stream is exposed (owing to the accumulation of an extremely large number of small deteriorations in isolation). In places where rod stock pull out of grooves the bigger number of breakdowns occurs (in process and at preventive tests), than in other parts of rod stock. It is promoted by gradual weakening of winding fastenings, both in grooves, and in front parts. Vertical vibrations cause in hydraulic generator rotor elements alternating stresses which are imposed on tension from centrifugal forces and the rotating moment. The measuring technique of a wear in the course of the electric motor tests is described in GOST P 51667-2000 and involves the measurement of the electric brush length an before and after a test cycle (each 20 or 50 h).

The distinction of statistical characteristics estimates of of vibration loading of each brush holder gives the chance to receive the functional dependence between the change of transfer resistance of brush and collector assembly and size of the maximum acceleration regardless of brush type. The main issue of monitoring and rationing of machines vibration consists of the parameters selection for the intensity of vibration process characteristic.

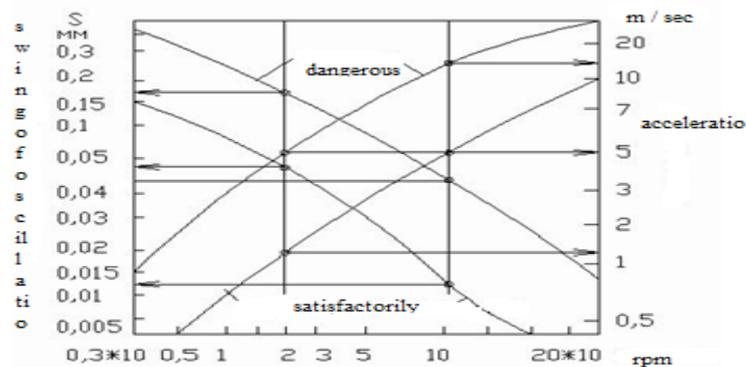


Figure 4. Vibration rates of machines, depending on the frequency of vibrations and accelerations

Eventually in the course of machine operation the rigidity of vibrating parts fastening can weaken, not only further increase of this vibration, but also some decrease in resonant frequencies is result of it that is especially dangerous when the working frequency is on the site of characteristic where vibration increases with the increase in frequency, therefore, of rather small shift of characteristic that vibration sharply increased.

According to the schedule of figure 4.- of machine base vibrations with a frequency of 2000 fluctuations a minute, a range of $S=0.05$ of mm and acceleration up to $1.2 \text{ m}\cdot\text{s}^{-1}$ a satisfactory assessment is given to the machine operation.

Increase in the vibration of the electrical machines shown in Fig. 4 demonstrates the emergence of damages though vibration is a source of serious damages and accidents. As a result of a wear of electric insulating materials at operation, the shorting voltage decreases and the probability of system survival decreases respectively. The physical nature of elements and communications can be any. [3]

The decrease in a shorting voltage of isolation does not depend on the frequency of vibrations (within 500-1000 vibrations a minute), but depends on the amplitude of vibrations. The device the single acceleration sensors is shown in Fig. 2. Sometimes the user should install vibration sensor to inaccessible places permanently, and in such cases the user can either remove cables to available places and to measure vibration in them by the device, or to unite these sensors in the stationary system of diagnostics.

Therefore it is expedient to consider a question of inertness of a system and to reveal influence on its quantitative characteristics of operational factors of work of brush and collector assembly on EPS. In the modern control and diagnostics devices, at least, of the rotating inventory, vibration becomes a main type of the analyzed processes, actively forcing out many other processes including thermal.

Purpose of vibration monitoring (Fig. 5) is the detection of brush and collector assembly vibration condition changes in operational process for which defects of an electric brush are the reason in many cases.

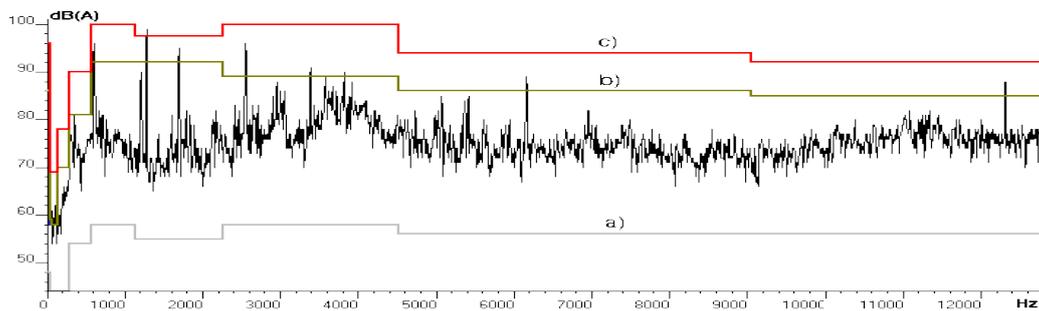


Figure 5. Monitoring the vibration state of the machine. a) – the threshold of a weak vibration signal; b) – the threshold of the average vibration signal; c) – the threshold of a strong vibration signal.

3. Conclusion

Thus, the development of automated monitoring systems for the rolling stock electric motor with the development of the DC motors state operational diagnostics means is an important task. The research of the brush-collector assembly reliability represents a typical example of the non-disassembly diagnostics of vibration tests method application for the study of the individual elements reliability. The above static equation makes it possible to predict the normal operation of the electric brush on the rolling stock in the future.

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