

Contact interaction “brush – collector” and working efficiency of locomotive traction electric motor

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Abstract. The working efficiency of locomotive traction electric motors of direct current is largely determined by the reliability of the collector-brush assembly. The paper presents the results of simulation of the contact interaction “brush-collector” in the traction electric motor of an electric locomotive. The influence of the structural features of the brush holder, the conditions and operating modes on the contact area “brush-collector”, and the quality of switching is considered. Technical solutions for improving the current collection quality in the contact “brush-collector” and ensuring the working efficiency of traction electric motors of locomotives are proposed.

1 Introduction

The working efficiency of locomotive traction electric motors (TEM) of direct current is largely determined by the reliable operation of the collector-brush assembly (CBA) [1]. The technical state of the collector-brush assembly is affected by two groups of factors: of electrical and mechanical nature [2]. Electrical factors are determined by the switching adjustment, the sort of brush, the asymmetry in the magnetic system and the arrangement of the brush holders along the circumference of the collector, the position of the brushes relative to the geometric neutral, the contact area of the brushes with the collector, etc.

The influence of mechanical factors such as balancing of the armature and the collector, the solidity of the collector and the quality of its processing, the technical condition of the brush holders and the pressure of the brushes on the collector, the effect of external and internal vibrations, dynamic impacts associated with the variable nature of the load, etc. are equally important.

2 Object and methods of research

The collection of current in the power supply circuit of the traction electric motor occurs under conditions of intermittent contact interaction of collector plates with brushes. And this interaction for one winding has a periodic character with a time-varying area of the contact area. The dependence of the contact area on the time $S(t)$ is a very important characteristic.

The contact time of the plate with one brush (Fig.1)

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$$t_{\text{cont}} = \frac{b_{\text{sw}} + b_{\text{pl}}}{\omega_a r_{\text{coll}}}, \quad (1)$$

where b_{sw} , b_{pl} – width of brush (sweeper) and plate, respectively;

ω_a – armature rotation speed;

r_{coll} – outer radius of collector.

The frequency of contact depends on the number of brush brackets in the motor

$$t_f = \frac{\varphi_{\text{sw}}}{\omega_a}. \quad (2)$$

Here $\varphi_{\text{sw}} = 2\pi / m$ – central angle between adjacent brushes (sweepers);

m – number of brush brackets.

During the time t_{cont} , the contact interaction of the brush and the plate occurs under conditions of their relative slip. The contact time t_{cont} has three characteristic sections denoted by dots,

$$t_1 = \frac{b_{\text{pl}}}{\omega_a r_{\text{cont}}}; \quad t_2 = \frac{b_{\text{sw}}}{\omega_a r_{\text{cont}}}. \quad (3)$$

During the rotation of the armature, the collector plate is in interaction with the brush and with the air. The areas of contact with the brush $S_1(t)$ and the air $S_2(t)$ are functions of time (fig.1).

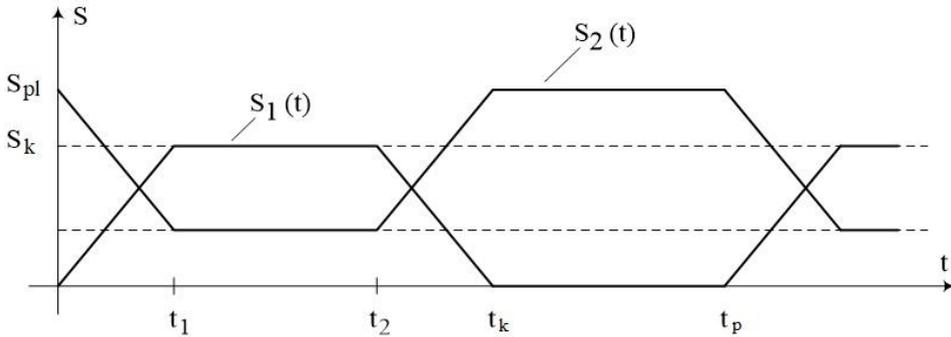


Fig. 1. Function of contact area.

$$S_{\text{pl}} = l_{\text{pl}} b_{\text{pl}}; \quad S_k = b_{\text{pl}} a_{\text{sw}}, \quad (4)$$

where a_{sw} and l_{pl} – longitudinal dimensions (length) of the brush and the plate (fig. 2).

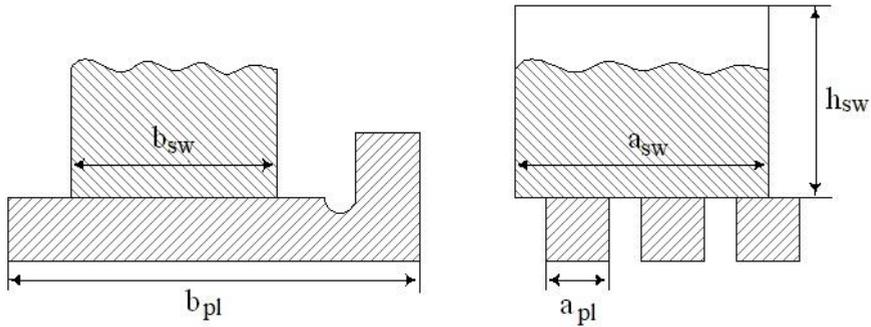


Fig. 2. Contact of brush with collector plates.

Dependencies of $S_1(t)$ and $S_2(t)$ for one period of time t_n are determined by functions [3]:

$$S_1(t) = \begin{cases} \frac{S_{\text{cont}}}{t_1} t & \text{when } 0 \leq t < t_1 \\ S_{\text{cont}} & \text{when } t_1 \leq t < t_2 \\ S_{\text{cont}} \left(1 - \frac{t - t_2}{t_1}\right) & \text{when } t_2 \leq t < t_{\text{cont}} \\ 0 & \text{when } t_{\text{cont}} \leq t < t_n \end{cases} \quad (5)$$

$$S_2(t) = \begin{cases} S_{\text{pl}} - \frac{S_{\text{cont}}}{t_1} t & \text{when } 0 \leq t < t_1 \\ S_{\text{pl}} - S_{\text{cont}} & \text{when } t_1 \leq t < t_2 \\ S_{\text{pl}} - \frac{S_{\text{cont}}}{t_1} (t_{\text{cont}} - t) & \text{when } t_2 \leq t < t_{\text{cont}} \\ S_{\text{pl}} & \text{when } t_{\text{cont}} \leq t < t_n \end{cases} \quad (6)$$

During the time t_n , physical processes of a mechanical and electrical nature occur on the area $S_1(t)$, accompanied by deformation, destruction and heating of materials of the contacting bodies. In the area $S_2(t)$, the heat exchange between the material of the plate and the air is performed.

The thermal field in the materials of plates and brushes is formed by the forces of elastic-viscous friction and the forces of destruction of the material [4], as well as from the action of thermal energy sources created by the electric field, the latter being dominant for high-power motors with standard design parameters. Thermal energy of a mechanical nature takes on significant values when symmetry breaking occurs in the contact area of brushes with the collector plates.

It should be noted that the mechanical moving contact leads to micro-destruction of the material of the contacting bodies with micro-chipping. When the chips get into the electric field, they warm up to very high temperatures and thereby contribute to the development of the sparking process at the TEM collector.

The work A_{FF} on overcoming the forces of resistance in the area of contact is produced by the forces of the motor's electromagnetic field. This is an unproductive expenditure of electric power. The whole work can be represented as a sum $A_{FF} = A_{ED} + A_{PD}$.

The component A_{ED} is spent on elastic deformation of the material. The work A_{PD} is spent on plastic deformation and on the destruction of the material [5-7]. The thermal energy Q_M released as a result of mechanical interaction is numerically equal to the work A_{PD} .

When calculating both the frictional forces and the conditions for the passage of electric current in the contact area, the actual contact area of the contacting bodies S_a is very important. By the actual area we mean the areas on which the approach of the material is of the order of $d \leq 3A_0$ (A_0 is the parameter of the crystal lattice).

Under these conditions, the forces of molecular interaction (van der Waals forces) arise, and the transition of conduction electrons is not accompanied by ionization of air (electric arc).

One of the main causes of TEM failures is the unsatisfactory operation of CBA, which leads to a disruption of the current collection process [8]. The conditions of current collection are significantly influenced by the geometrical parameters of the contacting surfaces of the brushes and plates of the collector (contact area). Since the brush is an active element of the switching process, a decrease in the area of its actual contact with the collector leads to an increase in the current density and, as a consequence, to increased sparking during switching of the armature section.

The conditions for switching of TED as a whole are determined by the set of contact conditions of the brushes with each collector plate [9]. One of the important parameters of the contact mechanics in CBA is the obtaining of the "mirror" on the working surface of the brushes. The nature of the current distribution in the brush contact depends more on the fitting of the brush to the collector, the quality of its processing, and the state of the polish. In addition to these factors, the current distribution in the brush contact largely depends on the force of pressing the brush and the location of application of this force.

Thus, the switching capacity of the brushes (current-voltage characteristic) and the state of the working surface of the collector affect the quality of the operation of CBA [10].

The quality of the finishing of the collector is important. With a decrease in the roughness of the collector plates, the number of points of direct contact between the brush and the collector increases, which leads to a decrease in the actual current density in the contact. Along with this, the conditions for the mechanical interaction of the collector and brushes are improved [11].

Let's consider the process of mechanical interaction between the brush and the collector using the example of the operation of CBA of the electric traction motors EDP-810 of the electric locomotive 2ES6.

The brush holder of TEM mentioned above (fig.3) consists of a casing 2 with two split brushes 4 inserted in its windows. Pressing the brushes is provided by the flat shanks 3 of the spiral springs. Spiral springs are located on the axis fixed in the casing of the brush holder with a cotter pin.

A special feature of the design of the brush holder for traction electric motors of the electric locomotives 2ES6 is the change in the location of the application of the pressure force of the spring: from the edge of the brush near the spring to the far edge as the brush wears out. This results in an uneven distribution of the pressure of the hold down spring shank over the surface of the brush, which causes uneven wear of the brushes and a decrease in the actual area of the "brush-collector" contact.

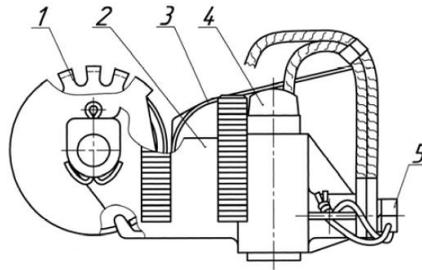


Fig. 3. Design of the brush holder for TEM of the electric locomotive 2ES6.

Traction electric motors of electric locomotives work in a reversible mode. In the technical documentation for maintenance and repair of TEM, dimensional tolerances are established for the brush holder windows in the collector-brush apparatus both in width and length [12, 13]. In this regard, there is a gap between the brush holder and the brush, so that the brush can be installed on the collector with a skew during operation. For traction electric motors of the electric locomotives 2ES6, an additional unfavorable effect on the location of the brush in the brush holder window is caused by the uneven distribution of the pressure of the hold down spring over the brush surface due to the structural feature of the brush holder.

All this can lead to the fact that the entering edge of the brush wears out faster than the leaving edge, which, as a result, takes a sharp shape. After reversing the traction motor, the edge of the brush which was the leaving one becomes entering edge, and the previously formed sharp edge begins to chip. There is a clogging of bar-to-bar grooves with coal particles (closure of adjacent collector plates among themselves), sparking arises at the collector, which can lead to failure of TEM in operation.

An important factor affecting the uneven wear of brushes is the extension of the traction runs of electric locomotives 2ES6 (up to 900-1000 km). In this case, even with the minimum gaps between the brush and the casing of the brush holder, uneven wear of the entering and leaving edges of the brushes occurs due to a long-term rotation of the electric motor in one direction. As a result, after a change in the direction of the locomotive, phenomena similar to those described above occur.

3 Results

At the testing station of the service locomotive depot, a number of experiments were conducted to study the effect of long-term rotation of the TEM armature in one direction and changing the direction of rotation on the work of the collector-brush assembly (the “mirror” of the brush contact) [14]. The essence of the experiments was that a long bedding of the brushes to the collector was carried out with one direction of rotation. After complete bedding of brushes, the reverse of TEM was performed, and one of the modes simulating the working circuit for connecting the electric motors of the DC electric locomotive (sequential (S) - I mode, sequential-parallel (SP) - II mode, parallel connection (P) - III mode) at the rated armature current without weakening the field of the excitation winding was set. The experiment was carried out until the brushes were completely bedded after the reverse with the formation of a new “mirror”. In each TEM operation mode, the degree of bedding (the width of the “mirror”) and also the quality of commutation (sparking dynamics) was measured at certain intervals by means of the switching control device PKK-2M, whose operation is based on measuring the sparking pulses under the leaving edge of the brush.

The experiments showed that immediately after the reverse, the “overthrow of mirror” of the brushes happens. Namely, a new “mirror” begins to form over the old one (fig. 4). At the initial moment of formation of the new “mirror”, a “peak” sparking arises, the value of which

depends on the mode of operation of TEM. The most unfavorable condition immediately after the reverse of TEM is its transfer to the III-rd mode of operation (“P” - connection). With this connection of traction electric motors, the sparking rate can reach 3600 conventional units on the scale of the device (about 2 points according to GOST 183-74).

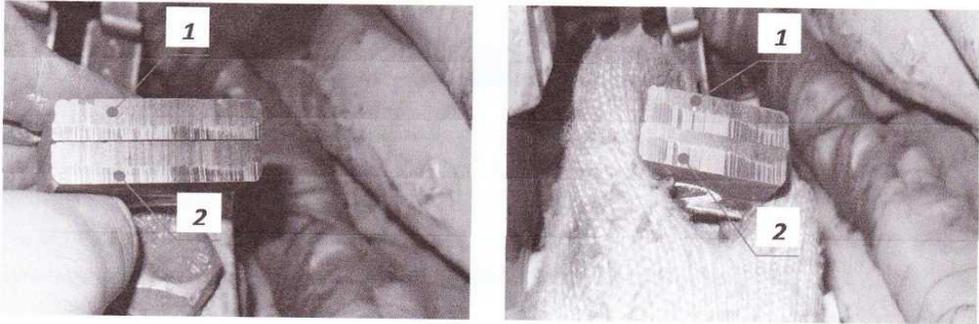


Fig. 4. Formation of the “mirror” after the reverse? Where: 1 – “mirror” before the reverse; 2 – “mirror” after the reverse.

Thus, in order to eliminate the adverse phenomena associated with the skewing of brushes in the windows of brush holders of traction electric motors of 2ES6 electric locomotives, it is necessary to improve the quality of repair of the collector-brush assembly, including by minimizing tolerances and wear according to the geometry of the brush holders, and also to improve the design of TEM’s brush holder to ensure uniform distribution of brush pressure on the collector and to eliminate their skews in the brush holder windows. These changes will lead to an increase in the working capacity of traction electric motors, which will positively affect the operational reliability of electric locomotives 2ES6.

The size of the uneven wear of the brush is determined by the size of the contact area between the brush and the collector, which mainly depends on two factors: the nature of the roughness (the number and height of roughness) in the “brush-collector” contact area, and the value and direction of the pressing force of the spiral springs shanks of the brush holder.

The influence of the parameters of the structural elements of the collector-brush assembly on the actual contact area “brush-collector” will be considered according to the design model (fig. 5).

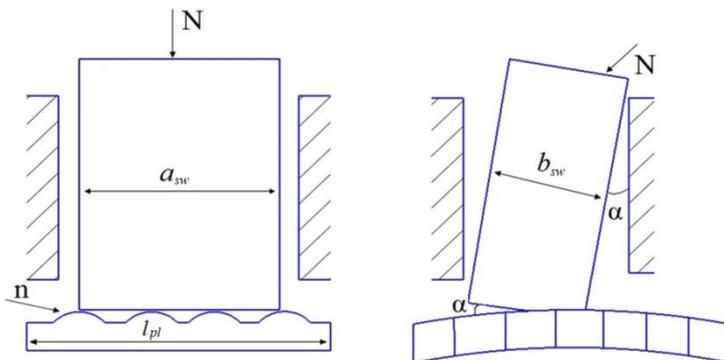


Fig. 5. Design model.

When processing the working surface of the collector, microroughness appears on it, the size and quantity of which are determined by the quality of turning.

There is a load for one roughness on the collector plate [3]

$$P = \frac{Nl_{pl}}{na_{sw}}, \quad (7)$$

where N – pressing force of the spiral spring shank of the brush holder;

n – number of roughness along the length of the collector plate (depends on the quality of the turning of the collector during repair of TEM);

l_{pl} – collector plate length;

a_{sw} – brush (sweeper) length.

The load P is distributed over the contact area of the brush (plane) and the roughness of the collector plate (cylinder), which is rectangular with a width

$$b = 4\sqrt{\frac{P}{\pi l}(k_1 + k_2)R}, \quad (8)$$

where R – roughness height;

l – length of contact area;

k_1, k_2 – coefficients depending on the elasticity of the material (brushes and collector plate, respectively), calculated by formula [15]:

$$k_i = \frac{1 - \mu_i^2}{E_i}, \quad (9)$$

where μ_i – Poisson's ratio;

E_i – modulus of elasticity of material.

To estimate the value of wear of the contacting surfaces, it is necessary to find the length l of the contact area between the brush and the collector plate.

Intensive wear of the material of the contacting surfaces will end under the condition [16]

$$\tau_c \leq \tau_{ul}, \quad (10)$$

where τ_c – circumferential stress at the contact area;

τ_{ul} – ultimate circumferential stress of fracture of softer contacting material.

Circumferential stress at the contact area [17]

$$\tau_c = \frac{Pf_{sf}}{S_c}, \quad (11)$$

where f_{sf} – coefficient of sliding friction of the brush along the collector plate;

$S_{cont} = b \cdot l$ – contact area of the brush and one roughness of the collector plate.

Under condition that $\tau_{sh} = \tau_{ul}$

$$Pf_{sf} = 4l\sqrt{\frac{P}{\pi l}(k_1 + k_2)R} \cdot \tau_{ul}. \quad (12)$$

From the equation (12) we get the value of the length of the contact area at which the intense wear of the brush material ends,

$$l = \frac{Pf_{sf}^2\pi}{16R(k_1 + k_2)\tau_{ul}^2}, \quad \text{or} \quad l = \frac{Nl_{pl}f_{sf}^2\pi}{16na_{sw}R(k_1 + k_2)\tau_{ul}^2}. \quad (13)$$

Then the actual “brush-collector” contact area through which the current collector will be performed,

$$S_{act} = \frac{4na_{sw}}{l_{pl}} \sqrt{\frac{PIR(k_1 + k_2)}{\pi}} \quad (14)$$

When the condition $l = \frac{b_{sw}}{\cos \alpha}$ is reached, the length of the contact area will reach the maximum value (where b_{sw} - the width of the brush (sweeper), and α - the angle of the gap between the brush and the casing of the brush holder).

In general, the change in “brush-collector” contact area can be represented as $S = A\sqrt{l}$ (fig. 6).

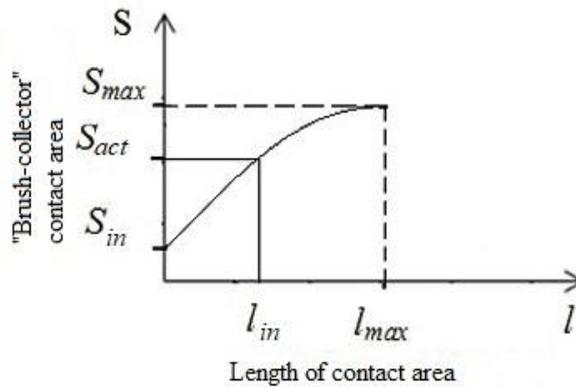


Fig. 6. Dependence of the “brush-collector” contact area on the length of the contact area.

The intensity of mechanical wear of the brush material depends on the value of the circumferential stress at the “brush-collector” contact area

$$\tau_{csw} = \frac{Nf_{sf}}{S_{act}}. \quad (15)$$

With an acceptable brush wear along the height, the force N remains constant; the coefficient f_{sf} is also a constant. Then the value of the circumferential stress, and hence the intensity of the brush wear, will be determined by the actual contact area of the brush with the collector. The smaller the S_{act} , the greater the τ_{csw} and the higher the wear rate of the brush material.

4 Conclusions

The obtained mathematical model shows that when the collector-brush assembly of TEM of the electric locomotive 2ES6 operates, the structural feature of the brush holder exerts an effect on the actual “brush-collector” contact area, resulting in an uneven distribution of the pressure of the hold down spring shank over the brush surface, the quality of finishing of the collector during repair (number and height of roughness on its surface), and also the physical and mechanical properties of brushes and collector plates [18].

To ensure a uniform distribution of the pressure of the spring shank on the brush surface, to improve the stability of the contact area and the quality of the current collector in the contact “brush-collector”, an improved design of the brush holder is proposed [19] (fig. 7), including a

casing 1 with windows into which two split brushes 2 are inserted, axis 5 fixed in the casing with a cotter pin, on which two clamps 3 and spiral springs 4 are mounted.

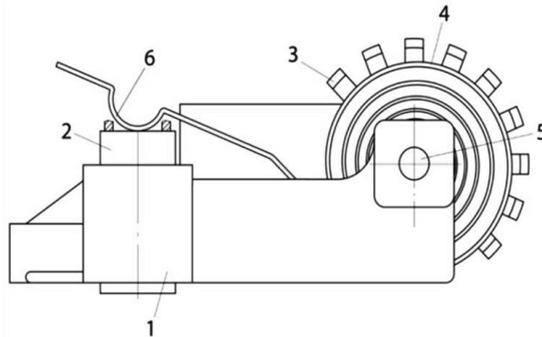


Fig. 7. Improved brush holder.

The shanks of the spiral springs are made in the form of a semicircle 6, so the pressure occurs within the central part of the brushes over the entire range of their allowable wear by height. This ensures uniform distribution of pressure of the hold down spring shank over the brush surface and the stability of the actual “brush-collector” contact area.

In the brush holder of the traction electric motor EAF-810 of the electric locomotive 2ES6 due to the uneven distribution of the spring pressure on the brush as the brush is bedded to the collector, the actual “brush collector” contact area will vary from S_{in} to S_{max} (fig.6), and hence the intensity wear of the brush will change: it will be maximum in the beginning, and then it will come to the normative value specified in the documentation for this brand of brushes. In the brush holder of the proposed design, the actual contact area of the brush with the collector remains nearly constant at all operating modes of TEM close to S_{max} . In this case, the wear rate of the brush material will also be nearly constant, corresponding to this brand of brush.

The proposed brush holder makes it possible to improve the quality of the current collection in the collector-brush assembly of the traction electric motor by providing a uniform distribution of the pressure of the hold down spring shank over the surface of the brush, increasing the contact area stability and reducing the intensity of mechanical wear of the brushes, which will lead to improved operation and increased working efficiency of TEM of the electric locomotives 2ES6.

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