Determination wear intensity of electrical brushes in DC machines considering impact of collector's surface

V V Kharlamov, D I Popov, M F Baysadykov

Omsk State Transport University, 35 Marksa pr., Omsk, Russia
emoe@omgups.ru, popovomsk@yandex.ru, marsel_b@mail.ru

Abstract. One of the most loaded units affecting the reliability of DC machines is the collector-brush unit. There is a continuous process of mechanical, electrical and chemical interaction of the electric brushes with the collector during operation of the DC motor, which increases the wear of the electric brushes. In a result of the analysis of the works, devoted to the study of the operation of the collector-brush unit’s elements, the authors proposed a mathematical model for determining the intensity of wear of electric brushes, which allows taking into account the effect of the collector profile on the electric brushes wear intensity. The basic data and dependencies for modelling the movement of the electric brush on the collector surface, which based on the design scheme, are presented. A distinctive feature of the developed scheme is that the elastic force at the contact of the brush with the surface of the collector is determined from the side of each collector plate. For the above scheme, a system of differential equations is compiled, allowing simulating the movement of the brush in the radial and tangential direction during its interaction with the surface of the collector. The resulting mathematical model allows us to determine the trajectory of the brush and the oscillations of the elastic force that occurs at the point of contact of the brush with the collector, with different parameters of the collector-brush unit’s elements and modes of operation of the machine, causing a certain frequency of rotation of the armature. Taking into account the above mathematical model, a software product has been developed for calculating the wear rate of DC motor electric brushes during its operation. The practical value of the work is that the use of the developed software allows you to find more optimal operating parameters for the collector-brush unit of DC motor with a minimum of time.

1. Introduction
There is a complex process of mechanical, electrical and chemical interaction of electric brushes with collector during operation of DC motor. In view of the lesser hardness of the electric brushes material, they are more prone to wear, which necessitates a relatively frequent change of the brush. The intensity of electric brushes wear depends lot of factors, which affecting on the current collection process, and the parameters of the system: pressing force of friction surfaces and their mutual displacement, coefficients of friction, design of the brush holder, current density in contact, presence of spark formation and etc. In this case, in commutator DC machines sparking under brushes can considerably increase wear of the electric brushes. Non-timely replacement of worn brushes generally leads to damage of the commutator and loss of serviceability of the electric machine. In this connection, there remains a problem of monitoring and timely warning of the failure of the elements of the collector-brush assembly.

2. Task
The analysis of the works [1-7] devoted to the study on the wear process of the collector-brush assembly elements, shows that the wear of the brushes can be divided into three components: friction wear $\Delta I_f$, electrocorrosion wear $\Delta I_{ec}$, electro-erosion wear $\Delta I_{er}$. The total wear of the brush is due to the combined action of these components. Generalization of expressions for determining $\Delta I_f$, $\Delta I_{ec}$, $\Delta I_{er}$ allowed for the authors to present a mathematical model of brush wear in the following form:

$$\frac{\Delta I}{\Delta t} = (n \cdot P_{av.br}) \cdot K_f + \left( n^2 \cdot f^2 \cdot P_{av.br} \right) \cdot K_{ec} + (n \cdot W_s) \cdot K_{er},$$

where $t$ – time of work;
$n$ – motor speed;
$P_{av.br}$ – average value of the brush spring;
$I$ – current flowing through the brush;
$W_s$ – spark energy;
$K_f$ – coefficient of friction wear;
$K_{ec}$ – coefficient of electrocorrosion wear;
$K_{er}$ – coefficient of electro-erosion wear.

This presented mathematical model (1) is not fundamentally new, but the authors have developed the principle of experimentally determining the values of coefficients $K_f, K_{ec}, K_{er}$. For this, three experiments are necessary to measure each component of the wear rate individually [8].

The expression (1) makes it possible to find the intensity of brushes wear taking into account the basic parameters of the operation of the motor, but it is worth noting, in operation of the motor, the brush is exposed to additional factors, among which it can be noted: environmental conditions, influence of the surface of the collector profile.

Environmental parameters (dust, humidity, gas composition), affecting the operating conditions of the current collection system, should be attributed to the factors, the account of which in mathematical models is possible, but impractical, due to the fact that this will increase the complexity of the calculation, and reduce their accuracy. The reason for that is because these factors are not independent and cannot be regulate during operation process of an electric motor.

There are a lot of parameters which define the process of interaction between electric brush and collector. Parameters such as beat, eccentricity, taper, the concavity, barrel crown is the result of improper state of the metal processing equipment and does not significantly affect the wear of the brushes. To a much greater extent, the wear of the brushes is influenced by the profile of the collector, determined by differential heights of collector plates relative to base distance from axis of armature rotation.

The problem of mathematical models for determining the intensity of wear of electric brushes given in [1-7] is that they either neglect the influence of the collector’s surface, or the collector’s surface is given as a function. This approach reduces the accuracy of calculation and doesn’t allow obtaining reliable data about operating time of the electric brushes.

The purpose of this work is to develop mathematical model of mechanical interaction of the brush with collector’s surface and software for determining the rate of electric brushes wear in DC machines.

3. Mathematical modelling

In electric machines, movement of the brush should be considered in the form of oscillations in three degrees of freedom: radial, tangential and rotary [9]. The design of modern brush holders does not allow for brush to have any significant angles of rotation and tangential movements. In this connection, in many mathematical models usually considered only radial displacements and calculation is carried out by the equation of motion along the vertical axis $Oz$ (fig. 1). This simplification of the task leads to not being counted tangential pressing forces of the brush on the brushholder walls ($F_{c1}, F_{c2}$) and proportional to them radial forces of dry friction of brush about wall of brush holder ($F_{bh1}, F_{bh2}$) which participate in motion along vertical axis.
For determine the impact of the collector profile on the operation of the brush accepted that the movement of the brush occurs in the radial and tangential direction.

In compiling the design scheme and the differential equations of motion of the brush, the following assumptions are adopted:

1. Angular velocity of the collector is considered constant \((\omega_c = \text{const})\).
2. The forces of interaction of the brush with the walls of the brush holder and with the surface of the collector are considered to be elastic.
3. Viscous forces in points of brush contact with side walls of brush holder and collector surface are ignored due to small values of brush movement speed.
4. Action of spring on the brush is effected through lever of brush holder; pressure from spring is constant due to slight change of value of pressure at deformation of spring.
5. The friction forces between the brush and the other elements are proportional to the normal pressure (linear).
6. The brush is completely solid - there is no deformation of the brush.

On the design scheme (fig. 1) the following elements are presented: collector surface in the form of plates, brush, brush holder’s body and pressure spring. There is dry friction force between brush and side walls of brush holder. At the top the brush is pressed to the collector by a pressure spring in the point \(A\). Between the brush and the walls of the window of the brush holder there is a gap.

![Design Scheme of Brush Holder and Forces Acting on Brush](image)

**Figure 1.** The design scheme of the brush holder and the forces acting on the brush:
(a) – in the absence of brush contact with the walls of the brush holder; (b) – upon contact of the brush with the right wall of the brush holder; (c) – upon contact of the brush with the left wall of the brush holder.

In the design scheme, the following notations are adopted:
- \(z\) – generalized coordinate of the brush along the vertical axis;
- \(y\) – generalized coordinate of the brush along the horizontal axis;
- \(M\) – mass of brush with taking into account mass of brush holder lever;
- \(P_{ci}\) – elastic force in the contact of the brush and collector from the collector plates;
- \(i\) – number of the collector plate under the brush;
- \(P_l\) – vertical force of the lever pressing on the brush at the point \(A\);
- \(\omega_o\) – angular velocity of the armature of the electric motor, rad/s;
- \(Mg\) – gravity force acting on the brush;
- \(F_{fl}\) – friction force between brush and brush holder lever;
Friction force between the brush and the collector:

\[ F_{fc} = f_c \cdot P_c. \]  

(3)

Friction force between the brush and brush holder walls:

\[ F_{bh1} = f_{bh1} \cdot F_{c1} \cdot \text{sign}(z); \]

(4)

\[ F_{bh2} = f_{bh2} \cdot F_{c2} \cdot \text{sign}(z), \]  

(5)

where \( f_{bh} \) - the dry friction coefficient of sliding between the brush contact surface and the side walls of the brush holder;

\( f_c \) - the dry friction coefficient of sliding between the brush contact surface and the collector.

Consider the process of interaction of the brush with the collector’s surface during electric motor operation. The following initial data are used for the analysis:

- \( N_c \) - number of collector plates;
- \( \beta \) - the value of brushing the ceiling;
- \( \Delta \) - the total gap between the bar and the wall of the brush holder;
- \( M \) - the mass of the brush;
- \( P_l \) - the value of pressing the brush;
- \( D \) - the diameter of the collector;
- \( b_c = D \cdot \pi / N_c \) - width of the collector plate;
- \( b = b_c \cdot \beta \) - width of the brush;
- \( c_{br} \) - modulus of elasticity of collector’s material;
- \( c_{bh} \) - modulus of elasticity of brush holder’s material.

To evaluate the effect of collector’s surface on the operation of the brush, it is necessary to have the real profile of the collector as source data, which can be obtained with the use of special measuring devices, for example, a device for checking the profile of the collector of the PKP-5M, which developed in Omsk State Transport University. The input data for constructing the collector profile will be represented in the form of the height of the collector plates relative to the base (zero) level.

When the brush passes over the surface of the collector, occur a radial vibrations of the brush, associated with the parameters of the collector profile. At the surface of the collector profile close to cylindrical, these vibrations are absent and the brush operates practically without tearing. In the actual operation, the surface of the collector is far from the cylindrical, because the heights of the collector plates differ from each other. In the case where the height of the collector plate is greater than the height on which the brush is located, the brush is run on the collector plate, which leads to deformation of the material of the collector under the brush and the appearance of the elastic force at the point of contact. The resulting force can be calculated from the equation:

\[ P_t = \sum_{i=n}^{n+\beta} S_i \cdot c_c, \]  

(6)

where \( S_i = \sum_{i=n}^{n+\beta} b_{cil} \cdot \delta_{i} \) - projection of volume of deformable material on vertical plane;

\( b_{cil} \) - width of the brush of the \( i \)-th plate of the collector;
δ_{ci} = (\eta_i(t) - z(t)) - linear deformation value of the i-th plate of the collector under the brush;
\eta_i(t) - height of the i-th plate of the collector;
n - number of plate contacting trailing edge of brush.

In the presented model the elastic force \( P_k \) is determined from the side of all collector plates under the brush. The calculation is carried out in three stages:

1) For determining the action on the side of the collector at each moment of time it is necessary to know the number of plates located under the brush, as well as their relative heights. In this connection, the first collector plate is assumed to be under the running edge of the brush, a maximum from heights of collector plates located under the brush is taken as the initial height of the brush:

\[ \eta_{imax} = \max \{ \eta_i \} \]  
where \( \eta_i \) – height of the i-th plate of the collector;
\( N_{ci} \) – number of the collector plate located under the oncoming edge of the brush;
\( N_{ci+\beta} \) – number of the collector plate located under the trailing edge of the brush.

By setting the initial conditions, it is possible to calculate the elastic force at the point of contact of the incident edge of the brush with the collector:

\[ P_{cte} = \begin{cases} 
  c_e \cdot (\eta_{N_{ci}} - z), & \text{if } \eta_{N_{ci}} > z; \\
  0, & \text{if } \eta_{N_{ci}} < z. 
\end{cases} \]  

2) At the second stage elastic force is calculated at points of brush contact with plates, fully located under it. Number of collector plates fully located under brush can be calculated by:

\[ N_{abp} = \left[ \frac{b_w - b_c \cdot (1 - l(t) - q \cdot b_c)}{b_c} \right] \]  
where \( q \) – incomplete quotient from division \( l(t) \) on \( b_c \).

\[ P_{ceu} = \begin{cases} 
  c_e \cdot (\eta_i - z), & \text{if } \eta_i > z; \\
  0, & \text{if } \eta_i < z. 
\end{cases} \]  

3) The third step involves calculating the elastic force at the point of contact of the trailing edge of the brush with the collector plates:

\[ P_{cte} = \begin{cases} 
  c_e \cdot (\eta_{N_{ci+2[N_{abp}]}}, z), & \text{if } \eta_{N_{ci+2[N_{abp}]} > z}; \\
  0, & \text{if } \eta_{N_{ci+2[N_{abp}]} < z}. 
\end{cases} \]  

The elastic force arising under the entire contact area of the brush with the surface of the collector can be calculated by the expression:

\[ P_c(t) = P_{cte} + P_{ceu} + P_{cte}. \]  

The differential equations of brush motion in brush holder can be written as follows:

\[ \begin{align*}
  M \ddot{Z} + F_{bh1} + F_{bh2} - P_l - Mg + P_c &= 0; \\
  M \ddot{Y} + F_{b} + F_{fc} - F_{c1} + F_{c2} &= 0. 
\end{align*} \]  

Solution of the system of differential equations (13) makes it possible to calculate the change of the elastic force at the points of contact of the brush with the surface of the collector, and also to obtain data on the horizontal and vertical movement of the brush as it moves along the collector.

The developed mathematical model of mechanical interaction of the brush with the collector’s surface makes it possible to take into account vibrations of the brush in the process of its movement along the collector and can be used for calculation of the intensity of wear of the brush.

4. Software development
The authors developed an algorithm [10] for determination the wear intensity of electrical brushes. With considering mechanical interaction of brush with collector surface in mathematical model (1) was written the program “Prediction of the service life of brushes of DC machines”. Main window of the program is shown in fig. 2.

The developed software product allows making the following types of calculations:
- calculation of the constant coefficients of the wear components $K_f$, $K_{ec}$, $K_{er}$;
- calculation of the components of the wear intensity of the brushes $\Delta I_f$, $\Delta I_{ec}$, $\Delta I_{er}$ and the total intensity of brush wear $\Delta I$;
- calculation of the change in time of the elastic force during the brush moves along the collector;
- service life of electric brushes depending on engine operating parameters.

The program provides for the calculation of changes in the elastic force in contacts of the brush and collector’s surface and taking into account this effect on the intensity on the brushes wear. The calculation result includes the following indicators:
- graph of the vibrations of the brush made in the radial direction;
- graph of the change of the elastic force at the contact points of the brush with the collector.

Calculations show that the elastic force acting on the brush from the collector side is not constant, and during engine operation it is subject to oscillations, the range of which varies widely, and having a direct impact on the electro-corrosive component of the brush wear intensity $\Delta I_{ec}$. This action can be estimated from the calculated value of the elastic force in the contact $P_c$ by using the presented mathematical model.

The determination of $\Delta I_{ec}$ carried out by dividing the obtained values of $P_c$ by $j$ intervals and finding the average pressure value in contact $P_{av}$ into each of them, and probability of getting into each from of $j$ intervals values of the elastic force $f(P_{av})$. Expression (1) will assume the following type:

$$
\frac{\Delta I}{\Delta t} = (n \cdot P_{av, vr}) \cdot K_f + \left( n^2 \cdot I^2 \right) \sum_{j=1}^{n} (P_{av} \cdot f(P_{av}))^{1/2} \cdot K_{ec} + (n \cdot W_s) \cdot K_{er}.
\tag{14}
$$

For further calculation and visual display of the results, the developed software product provides output to a separate window of results, which can be displayed as a graph of the change in elastic force or a histogram of its distribution (Fig. 3).
Figure 3. The display of the histogram of the change of the elastic force at the point of contact of the brush with the collector’s surface

Figure 4. Window for displaying data on elastic force change at the point of brush contact with the collector

In fig. 4 shows the main results of the calculation, including: average pressure in the contact, the vibration acceleration reported to the brush from the collector side, the wear rate by components, as well as the stability of the contact operation, which is the percentage of time that the brush detaches from the collector surface. After click on the button “Calculation of wear with the collector profile”, the brush life is recalculated, and the results displayed in a separate window (Fig. 5).

Figure 5. The results of calculation of changes to the resource brush
Thus a software product is created which based on the developed mathematical models of brush wear and mechanical interaction of the brush with the collector profile, and makes it possible to calculate service life of electric brushes and to determine main parameters of operation of brushes with consideration of main parameters of operation of engine and material of brushes.

5. Conclusions
On the basis of the design circuit of the collector-brush unit of the DC machine, a mathematical model is created, which makes it possible to evaluate the effect of the collector’s surface on the stability of operation of the brush assembly and to determine the path of movement of the brush and the vibrations of the elastic force, which occurs in contact point of brush with collector, at various parameters of collector-brush assembly and engine operating modes. The developed model differs in that it takes into account both radial and tangential oscillations of the brush, which occur during engine operation.

Based on the proposed mathematical model, software has been developed for determining the wear rate of electric brushes of a DC machine and assessing the impact of the main operational and technological parameters on this process. The developed software is intended for use in the process of adjustment and maintenance of the electric motor and makes it possible to determine the more optimal conditions of operation for the elements of commutator-brush assembly in DC machines with minimum time.

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