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Determination of the characteristic points of approximation for traction electric machines of electric rolling stock

Olga Filina[1,*], *Anna* Yashagina[1], *and Olga* Salnikova[2]

[1]Kazan State Power Engineering University, Krasnoselskaiastr., Kazan, 420066, Russia
[2]Kazan State University of Architecture and Engineering,.Green str., Kazan, 420043, Russia

Abstract. The paper presents a new approach to the selection of characteristic points on the current-voltage curve (CVC) of the brush contact of traction electric machines, for their approximation in the form of three different functions, with characteristic points of transition to the field weakening mode. The problem of raising resources by using new design electro brushes. This constructive solution is consistent with the specific types of traction motors used in urban and rail transport and satisfies the technical conditions for their operation. A construction brush holders, which will save the cost of electro, in connection with their wear and tear due to friction on the walls of the brush holders. Improving the quality of machines saves material means and human resources, increase the profitability of their use, resulting in a significant increase in productivity. The method of calculating the current-voltage characteristics of a new type electro brushes, the distinguishing feature of which is the introduction of a cross section of the body brush. In the course of the experiment revealed steadily increasing rate of proposed electro brushes, compared with the standard of the same type EG61A. Data collected during the experiment showed that electro brushes with a transverse incision is more stable contact with the collector.

1 Introduction

The main direction in increasing the resource of brushes is to change the design of the brush assembly and the brush itself, taking into account the fact that their development and implementation will not require significant financial costs. Increased current densities in brushes, high linear and angular speeds of rotation of collectors and slip rings, and an extremely widened range of other influencing factors: operating temperatures, shock and vibration loads. In addition to the static pressure created by the brush holder pressure device, the collector brush of the Direct Current Motor is affected by dynamic forces due to vibration of the Brush Contacts of Control, bearing assemblies, and the unbalance of the anchor.

2 Tasks evaluation of the engines operating resource

To determine the characteristic sections of the change in the current density in the brushes, let us turn to the technological modes of operation of traction motors of a diesel locomotive of the 2TE10V (M) series in real operating conditions. Due to the fact that the traction motor speed control system is automatic, to determine the current density under the brush in real operating conditions, we need to know the dependence of the motor current I_m on the locomotive speed. It is determined by the current of the traction generator I_a at each speed value, taking into account the switching one of the relay circuit of the transitions RP - 1 and RP - 2. Fig. 1 shows a diagram of switching on the relay of transitions RP - 1 and RP - 2 of a diesel locomotive 2TE10V (M)

For example, let’s consider the current-voltage curve of an EG-61A electro graphitized brush (40x25x60mm) used on an ED - 118B traction electric motor used on 2TE10V and 2TE10M diesel locomotives. The current characteristics of the traction generator [1] of the GP - 311B diesel locomotive at various positions of the driver's controller handle are given in Fig. 2 and in table. 1.

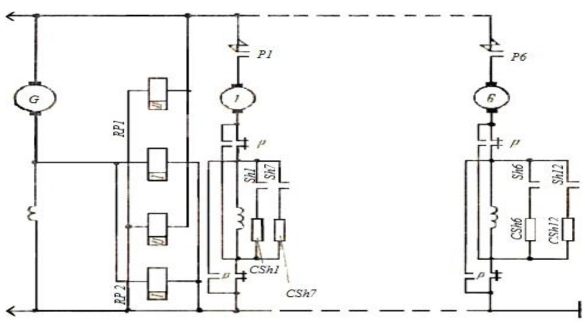

Fig. 1. Circuit of switching on the relay of transitions RP1 and RP2 of the diesel locomotive 2TE10V (M): *G* - traction generator; *NG* - independent excitation winding of the traction generator; I - the starting winding; *RP1, RP2* - transition relay (I - current coils: U - voltage coils); *P1 — P6* - power contactors; *1-6, 1'-6'*- traction electric motors and their

* Corresponding author: olga_yuminova83@mail.ru

excitation windings; *Sh1-Sh6* and *Sh7-Sh12* - excitation attenuation contactors of the first and second stages; *ShH1 – ShH12* - excitation attenuation resistors; *P* - reverser contacts.

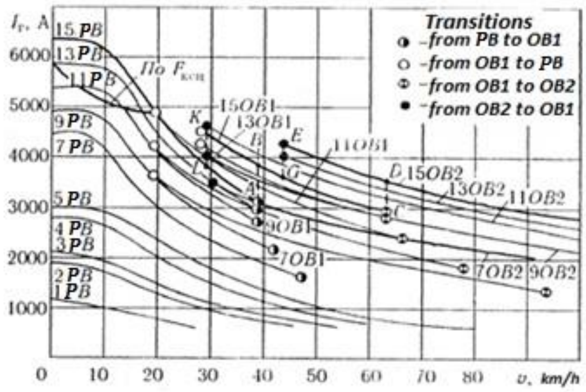

Fig. 2. Dependence of the current of the generator of diesel locomotives 2TE10V (M) on the speed.

Table 1. Variants of the composition of the beverage Maksym.

Service department	Name of products	standard value	Dimensions	Q-ty
T	Coal brush	EG61A	2(12.5 × 40 × 52/64)	6780
DOP	Coal brush	EG61A	2(10 × 40 × 64)	810
			Total	7590

Let us consider the movement of the locomotive at the 15th position of the controller, which corresponds to the maximum value of the generator current, and, consequently, to the maximum total value of the current density under the brushes of the traction electric motor and the main generator. With an increase in speed from 0 to 38 km / h, the locomotive runs in full field (PB on the figure), and the generator current varies within the range from 6500A to 3050 - 3100A. With a further increase in speed, the weakening of the field (OB1 on the figure) is switched on and the current changes abruptly to a value of 3800A and at a speed of 63 km / h reaches a value of 2850 - 2900A.

Further, there is a transition to the second stage of weakening the field OB2 and the current increases to 3500A. It can be seen from the figure that the characteristics of PB, OB1 and OB2 are nonlinear and differ significantly from each other and, therefore, the current density curves also differ, i.e. The current-voltage curve for the EG-61A electric brush, the range of current density variation under the brush should be divided into $j \in (0 - 8.3)$ A/cm^2, $j \in (11.6 - 8.3)$ A/cm^2, $j \in (16 - 11.6)$ A/cm^2 over the corresponding intervals of speeds $v \in (0 - 38)$, $v \in (38 - 63)$, $v \in (63 - v_{design})$. Thus, the type of the approximating current-voltage curve function is selected in accordance with the technological mode of operation of the traction machine of the locomotive, which significantly increases the accuracy.

Having carried out experiments on the experimental setup of the Omsk University of Ways of Communication and according to the methodology developed at the Department of General Electrical Engineering and Electrical Machines [2, 3], we obtained the CVC of the EG-61A electric brushes. The experiment was carried out for both composite and solid electric brushes with an increased resource [4, 5].

The obtained statistical data were processed using the Staistica 6.0 program. Figure 3, 4 shows the current-voltage curve of the EG61A electric brush (a) - composite with an increased resource, (b) - solid. The divergence of the ascending and descending branches is explained only by the change in the properties of the collector polish.

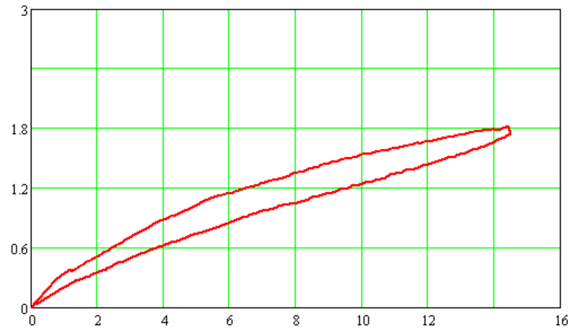

Fig. 3. Current-voltage curve of brushes EG-61A, obtained using an experimental setup - composite brushes (n = 1500 rpm).

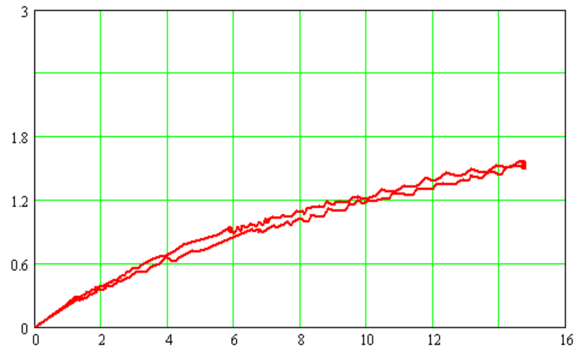

Fig. 4. Current-voltage curve of brushes EG-61A, obtained using an experimental setup - solid brushes (n = 1500 rpm).

From Figure 5. it can be seen that the current-voltage curve of the split electric brush is higher, which is explained by the additional resistance in the cross section, which, in accordance with the theory of optimal switching, should improve the switching properties of the electric brush. The same picture is observed for the current-voltage curve of the same brushes with a rotation frequency of n = 1000 rpm, n = 1500 rpm.

Subsequently, the current-voltage curve was averaged and the range of variation of the current density under the brush was divided into intervals $j \in (0 - 8.3)$ A/cm^2, $j \in (11.6 - 8.3)$ A/cm^2, $j \in (16 - 11.6)$ A/cm^2, which corresponds to the mode of switching on RP - 1 and RP - 2. As an example, Figures 5 - 7 show the estimates of the mathematical expectations of the current-voltage curve for solid and composite electric brushes with an increased resource EG-61A for a traction motor with rotation frequencies, respectively, equal to n = 500, 1000, and 1500 rpm, with highlighted current density intervals. The range of rotation frequency change is selected based on the speed characteristics of the ED118B type traction motor, which corresponds to the set speed of the locomotive [1].

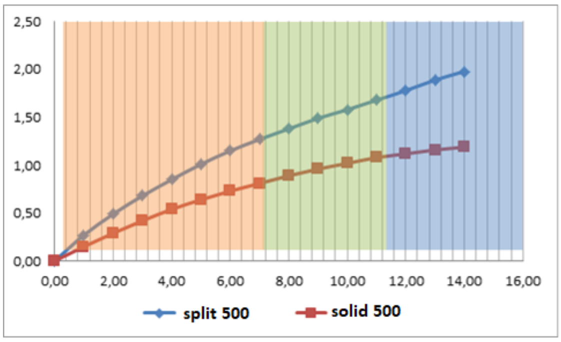

Fig. 5. Average dependence of the voltage drop ΔU, V on the current density j, A/cm^2 for composite brushes with an increased resource and continuous brushes for motors with a speed of n = 500 rpm.

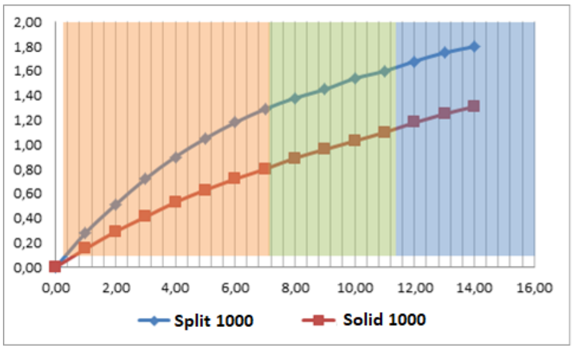

Fig. 6. Average dependence of voltage drop ΔU, V on current density j, A/cm^2 for brushes with rotation frequency n = 1000 rpm.

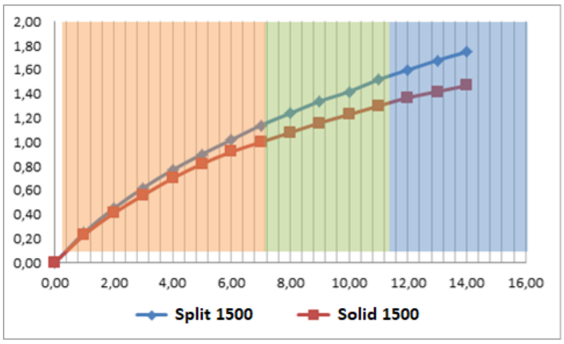

Fig. 7. Average dependence of voltage drop ΔU, V on current density j, A/cm^2 for brushes with rotation frequency n = 1500 rpm.

To approximate the current-voltage curve of the electric brushes, the following functions were used [2]:

$$\Delta U = \frac{A \cdot j}{j + B} \quad (1)$$

$$\Delta U = A \cdot \left(\frac{j}{B}\right)^{1/C} \quad (2)$$

$$\Delta U = A \cdot arctg(B \cdot j) \quad (3)$$

where j –current density; A, B and C - coefficients.

Wear is a complex physical and chemical process. The generally accepted criterion for brush failure is considered to be its wear Δh to half the initial height H_0, but not exceeding the maximum permissible value Δh_{mp}, that is, the brush fails if

$$\Delta h > \Delta h_{mp} = 0{,}5 H_0. \quad (4)$$

and, therefore, the condition for its trouble-free operation will be the opposite ratio

$$\Delta h < \Delta h_{mp} \quad (5)$$

The next stage of the experiment consisted in processing the obtained statistical data and selecting functions; for this purpose, the Staistica 6.0 program was also used.

In the course of work, it was found that in the range $j \in$ (0 - 8.3) the current-voltage curve is most accurately approximated by the equation $\Delta U = A \cdot arctg(B \cdot j)$, while the trigonometric function arctg used in it is odd and, therefore, when it is used, the change in the polarity of the current in the brush contact will be taken into account.

In the range $j \in$(11.6 – 8.3) A/cm^2, the current-voltage curve is most accurately approximated by the equation $\Delta U = \frac{A \cdot j}{j + B}$, at the same time in the range $j \in$(16 – 11.6) A/cm^2 – by equation $\Delta U = A \cdot \left(\frac{j}{B}\right)^{1/C}$

Figure 8 shows the real current-voltage curve of the brush contact and its approximation by three equations (1), (2), (3).

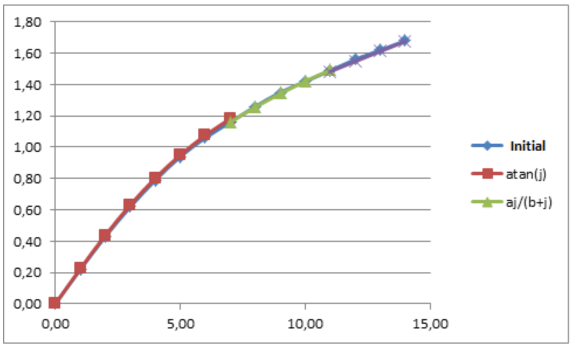

Fig. 8. Approximations of the current-voltage curve of an electric brush with an increased resource by various functions.

As can be seen from the figure, with a real current-voltage curve of approximation by three functions, the final and initial curves practically coincide, which will ensure maximum accuracy in calculations.

Distribution of the residual resource Δh of brushes (Fig. 9) of diesel locomotives of the 2TE10 series during the run before current repair (TP3) at the Yudino locomotive depo, which averaged 220 thousand km across the depot [3].

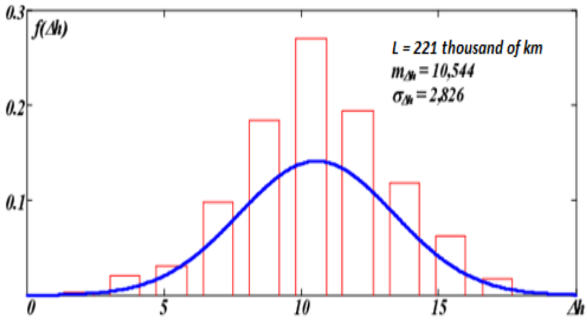

Fig. 9. Distribution of parameters over the height of the residual life of the brushes.

For brushes EG 74 (solid):
- mathematical expectation $m_{V\Delta h}$ = 10.544,
- root-mean-square deviation $\sigma_{V\Delta h}$ = 2.826.

Figure 10 shows the dependence of the operating time of standard and split brushes for rolling stock.

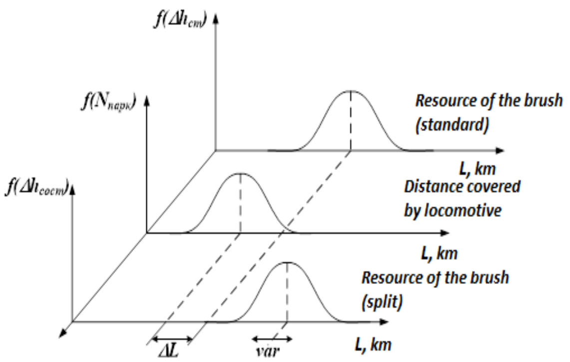

Fig. 10. Distribution of the assigned resource of a standard brush and a split brush with a locking part, depending on the distance covered by the rolling-stock.

The reliability indicator is a quantitative characteristic of one or several properties corresponding to the reliability of the brush.

Improving reliability is associated with certain material costs. Brushes belong to that part of the Direct Current Motor, which, during operation, is fundamentally characterized by wear failures due to the gradual abrasion (wear) of the brushes. Economics is the main criterion for solving most of the practical issues of reliability. The accuracy of determining the reliability indicator increases as the repetition of information increases, approaching its limit - the mathematical deviation.

The final stage of the method consists in determining the resource of the brush T_{br}.

$$T_{br} = \frac{l_b - l_{bd}}{\Delta W/\Delta t} \quad (6)$$

Where ΔW – brush wear value; L_b – length of the brush; L_{bd} – length of the brush with defects.

The failure rate is the probability of a brush failure per unit time after time t, provided that no failure occurred before time t. The occurrence of a failure is always associated with the occurrence of a fault condition. The failure rate of brushes in the Brush contact unit when using λ_u and storing λ_{st} are calculated by the formulas:

$$\lambda_u = \lambda_b K_f K_a K_m \quad (7)$$

$$\lambda_{st} = \lambda_{x.c.g.} K_a, \quad (8)$$

where λ_b is the basic brush failure rate when tested under rated electrical load and normal temperature;

$\lambda_{x.c.g.}$ - the failure rate of the brush according to the results of tests for storage in the packages of the manufacturers;

K_a - coefficient of acceptance, reflecting the level of quality of manufacture of the brush;

K_f - coefficient of factual rigidity, taking into account the degree of rigidity of the conditions of use of the brush;

K_m is coefficient of mode that takes into account the change in the basic failure rate depending on the electrical load and the ambient temperature.

A random number of failures can have a certain range of values, and each value is accepted with a certain probability.

According to the required probabilities of no-failure operation, the resource is determined for each Brush Contact Device (BCD)

$$T_{Ubcd} = -\frac{ln(\dot{P}_{Ubcd})}{\sum_{i=1}^{N} n \cdot \lambda_{Ubcd}} \quad (9)$$

Maintenance-free service life assembling units can be expressed by the following equation:

$$\tau = \frac{S_{max} - S_{inp}}{tg_{\alpha}} \quad (10)$$

where τ – maintenance-free service life of assembling unit;

S_{max} – maximum permissible weakening of the spring pressure during wear;

S_{inp} – a value characterizing the initial pressing force of the running-in brush;

tgα – the value characterizing the intensity of the increase in brush wear.

Using the algorithm, it is possible to calculate on a computer the number and size of brushes for a DC electric machine of a given power and to determine the probability of sparkles operation (FBG) of the brushes used on them.

The algorithm is shown in Fig 9. The initial data for the calculation are divided into two groups. The first group is the indicators of the electric machine for which the brushes are calculated: P - power, kW; U - voltage, V; I_m - current, A; T_m - operating mode (generator, motor); Dk - collector diameter, m; n_a - rotation frequency, rpm.

The second group - indicators of brushes and the material from which they are made: tsh, ash, rsh - tangential, axial and radial dimensions of the brushes, mm; Δrsh is the resource of the brushes, mm; η - coefficient of efficiency of using the material of brushes,%; IP is the number of pairs of brushes; TIP - type of brushes; MAR - grade of material (grade of brushes); J - permissible current density, A/cm^2; A, B, C, K - indicators characterizing the wear properties of brushes.

The total contact area of all brushes to be installed on the machine:

$$\sum F_{br}=I_m/J. \quad (11)$$

The number of pairs of brushes of different polarity required for this purpose

$$p=\sum F_{br}/F_{br} \quad (12)$$

and the current passing through one pair of brushes of different polarity

$$I_{br}=I_m/p. \quad (13)$$

These formulas can be used if the contact surface area of one brush is selected:

$$F_{br}=t_{br}a_{br}. \quad (14)$$

The dimensions tsh and ach are outlined in advance, and at this stage of the calculation it is necessary to determine how many brushes with the intended cross-sectional dimensions will need to be installed on a machine of a given power.

If the development of methods for determining the size of the value of the indicators tsh and ash has a long history, then the issues of determining the radial size of brushes are borrowed from standard value 12232.1–77. The current stage in the development of electrical engineering sets the task of standardizing the average service life and total resource of electrical machines, the service life without changing the brushes installed on them within 2000 hours and rationing some other indicators that quantitatively assess the reliability of their operational properties. These circumstances cannot but influence the choice of the radial size of the brushes, and it must not only comply with the standard, but also ensure that the requirements for reliability are met. The method for assessing these indicators has been continuously improved and changed several times. At present, a system for checking their wear resistance has been created and is operating, the main provisions of which are formulated in the guideline document RD.16.188 - 84.This document provides for checking the wear resistance of brushes on the corresponding real electric machines in the process of carrying out:

- bench acceptance tests of brushes at the enterprises where they are manufactured;
- periodic bench tests of brushes at the same enterprises;
- periodic bench tests and tests for the reliability of electric machines with brushes, produced at electric machine-building enterprises;
- acceptance, comparative and certification tests of brushes on electric machines in operation at industrial enterprises in various sectors of the national economy.

The criteria for quantitatively evaluating the results of the described tests are the indicators of the minimum operating time of brushes T_{min}, their gamma - percentage operating time Tγ, the average operating time T_{av}. After the tests carried out, the values of the values N_t, T and Δr_i included in them are obtained. Based on the use of these initial values, the entire stipulated calculation is performed:

A. Data obtained during the test of brushes:

Δri - brush wear, mm; T - test duration, h; NT is the number of brushes observed for the period T, pcs.

B. Preliminary calculations of brush wear characteristics:

$$\nu_{br}=\frac{1}{N_T T}\sum_1^{N_T}\Delta r_i;\quad \sigma=\sqrt{\frac{1}{N_T-1}\Sigma\left(\frac{\Delta r_i}{T}-\bar{\nu}_{br}\right)^2};\quad K=\frac{\sigma}{\hat{\nu}_{br}};\quad \rho_0=\frac{N_T}{(N_T-1)(N_T-2)\sigma^3}\sum_1^{N_T}\left(\frac{\Delta r_i}{T}-\overline{\nu_{br}}\right)^3. \quad (15)$$

C. Calculation of indicators of the reliability of the brushes.

The operational tension of the sliding contact of electrical machines Pν is the product of the main factors that determine the wear of the brushes working on the machines: the peripheral speed on the working surface of their collector νk and the current density in the sliding contact J. To calculate the values of Pν, the formula

$$P_V=\nu_K J=1000\frac{\pi D_K n_a}{60}\frac{2P}{Ua_{br}t_{br}N_{br}}\approx 105\frac{P}{U}\frac{D_k n_a}{a_{br}t_{br}N_{br}}, \quad (16)$$

where P is the power of the machine, kW;

U - machine voltage, V;

N_{br} - the total number of brushes installed on it;

D_k - collector diameter, m;

n_a - rotation frequency, rpm.

Taking Pν as an argument and linking with it the values of the average wear rate of brushes ν_{br}, obtained in the process of observing their normal industrial operation, made it possible to apply the methods of regression analysis for their subsequent mathematical study and generalization and the analytical relationship between them is represented by the formula

$$\bar{\nu}_{br}=A+BP_V+CP_V^2. \quad (17)$$

Here are the constants A, B and C, determined by the brand of brushes and the operating mode of electrical machines.

The problem comes down to determining the probability of failure-free operation (FBR) of brushes using the formula

$$P(t)=F_0\left(\frac{\Delta r_{br}/t-\bar{\nu}_{br}}{\sigma}\right), \quad (18)$$

where P(t) is the probability of failure-free operation;

F_0 - function, the calculated values of which are normalized by standard value 19460 - 74;

Δr_{sh} - brush resource, mm;

t - is the duration for which the FBG is calculated;

ν_{sh} - brush wear rate, mm / h;

ó - characteristic of wear rate dissipation, mm/h.

The necessary information is placed on an external medium in the form of directories I and II with a constant record length. The values of the MAR, J indicators are borrowed from the standards, and the A, B, C, K indicators are taken from the table and constitute the content of the reference book I. The values of Δr and η constitute the content of the reference book II. The algorithm of the computer program for calculating the tangential, axial, radial dimensions and the total number of brushes to be installed on an electric DC machine for general industrial purposes, with the probability of no-failure operation (FBR) set for the brushes, is shown in Fig.9

After entering the necessary initial data and drawing up the title (Fig. 2 - 4). The required record is searched in reference book I by the brand name (Fig. 5). Then the calculated area of the contact surface of the brush is determined (Fig. 6):

$$F_{\mathrm{br}}=I_{\mathrm{m}}/(JIP), \quad (19)$$

where IP is the number of pairs of brushes, introduced based on the general ideas existing in the electrical engineering industry about matching the power of a machine with the number of pairs of its poles (the IP indicator varies).

Next, we consider the records of reference book II with the type of brush corresponding to the selected one. In each case, reflecting the standard size of the brush, fixed by standard value, the area of its contact surface is determined. Brushes whose resource does not meet the condition are excluded from consideration

$$\Delta r_{\mathrm{br}} \geq v_{\mathrm{br}}\,(0.0244K+1)T\cdot 10^{-3}, \quad (20)$$

where T is the time during which the FBG of the brushes is 0.993, usually taken equal to 2000 hours.

Since the resulting values of the area S differ from the calculated Fsh, the closest values to it are found "from above" and "from below" - F´sh and F"u. The corresponding numbers of the brushes in the reference book are stored in the variables I1 and I2. In equations 19, 20, the utilization factors of the material of the brushes η1, η2 are calculated and the current densities J1ph and J2ph created in them. The results are printed (equation 21). If the values of J1f and J2f are significantly removed from the value recommended by resulting values, then the calculation continues, and control is transferred to the input of a new portion of data (equation 22). Thus, by varying the number of pairs of brushes, and in some cases their types, a set of required sizes is obtained. Preference is given to the one that, having the minimum difference in current density

$$\Delta J=J_{\mathrm{k}}-J<\epsilon, \quad (21)$$

the maximum value of the utilization factor of the brush material is realized.

As a result of the described calculation, for a DC machine for general industrial purposes, brushes will be determined, the dimensions and resource of which, with the required number of operating hours, will provide a probability of failure-free operation equal to 0.993. The fulfillment of this condition will be possible with the correct choice of the brand of brushes, which ensures the flow of the switching process envisaged by resulting values 183 - 74, and the technical condition of the electrical machine that meets the requirements of the current regulatory and technical documentation for it.

The mathematical expectation of the average wear rate of the brushes vsh is determined using the formula, where, together with the found value of Pv, the constants A, B and C from Table 1 should be substituted [15]. The choice of the latter should be coordinated with the choice of the brand of brushes planned for use. Substituting the corresponding values into the formula, it turns out that when using brushes of the EG2A brand

$$v_{\mathrm{br2A}}=1.89+(0.23\cdot 10^{-2})\cdot n_{\mathrm{a}}+0.46\cdot 10^{-4}\cdot n^2_{\mathrm{a}} \quad (22)$$

EG14:

$$v_{\mathrm{br14}}=1.81-0.61\cdot 10^{-2}\cdot n_{\mathrm{a}}+0.84\cdot 10^{-4}\cdot n^2_{\mathrm{a}} \quad (23)$$

The revealed advantage in the wear rate of brushes of the EG brand manifests itself in the calculation of reliability indicators. The number of hours of work is simply determined using the formula after solving it for t:

$$t=\Delta r_{\mathrm{br}}/(2.44\sigma+v_{\mathrm{br}}), \quad (24)$$

where v_{sh} is the wear rate of the EG14 and EG2A brushes, equal to mm / h;

σ - scattering parameter of the characteristic vsh, equal to the product of 0.01 Kvsh. (K2A = 70, K14 = 90).

3 Conclusion

1. This technique of averaging the current-voltage curve allows obtaining real characteristics for any type of electric brushes.

2. Current-voltage curve of a composite electric brush with an increased resource due to an additional voltage drop in the cross section of the brush above the current-voltage curve of a solid brush, which improves its switching properties.

3. Technological modes of loading the traction cars of a diesel locomotive determine the ranges of variation of the current density of the electric brushes, within which a more accurate approximation of the current-voltage curve is possible.

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