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Development of a method of calculating the temperature of a survey assembly when preparing a train dispatch

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***Abstract*—The features of the thermal state of the current collection unit «contact wire – contact insert of the current collector» in the conditions of preparation of electric rolling stock for the journey are considered. As part of the study, a methodology has been developed for estimating the heating temperature of the power sliding contact zone in the conditions of train preparation for journey. Application of the method will help to reduce the number of «burnouts» of the contact wire due to the exact selection of the heating/cooling time of the train for a certain heating/conditioning current when preparing the electric rolling stock for the journey.**

It was established that the cause of the «burns» of the contact wire in the parking lots when preparing the train dispatch is the excess of the permissible temperature of the power sliding contact as a result of the prolonged action of the heating/conditioning current. The standard approach for determining the duration of heating is based on the average values of the loads on the system and therefore does not take into account some factors, for example, the state of the contact wire, the state of the contact insert of the current collector, the number of cars in the train, and so on. The proposed technique is based on the classical theory of electrical contact and the theory of heating a homogeneous body, which makes it possible to accurately assess the thermal state of the power sliding contact and convenient enough for use in operating conditions.

The results of the work are of practical value, since the technology of preparing a train for dispatch can be supplemented by calculating the contact temperature «contact wire element – contact insert element» in accordance with the proposed methodology. This will allow for a specific train in specific conditions to apply a set of measures to prevent «burnout» of the contact wire in the event of a possible temperature exceeding the permissible value.

Keywords—contact wire; current collector insert; heating current; permissible temperature; electrical contact; «burn-out» of the contact wire.

I. INTRODUCTION

In ground electric transport, a very common scheme for transferring energy to board is the use of power sliding contact. This type of contact consists of a contact wire and collector elements mounted on the slider of current collectors of electric rolling stock. The operating conditions of the sliding force contact are especially difficult and are characterized by a wide range of ambient temperatures, the presence of precipitation in the form of rain and snow, ice and frost deposits, gas contamination of the surrounding atmosphere, etc.

The wires used for the contact network during manufacture are drawn in the cold state, which leads to an increase in the temporary tensile strength and a decrease in ductility [1]. When heated, the wire loses these qualities and the more, the higher the temperature and time of its exposure. Therefore, in accordance with the standards [2], the temperature of the wires of the contact network in the most adverse conditions should not exceed the maximum permissible value.

A rather frequent problem when preparing a train for a flight is a «burn-out» of the contact wire when the electric heating system of the cars is working or when they are air-conditioned. The train is in the stationary state on the station tracks and the heating/conditioning current flows through the sliding power contact «contact wire – contact insert of the current collector». In such a situation, the deterioration of the cooling conditions of this unit, a rough calculation of the time the heating/cooling currents flow through the unit, can lead to significant temperatures in the contact. Under the influence of high temperatures, the copper contact wire loses its mechanical properties and, consequently, leads to its «burning out», that is, loss of integrity and breakage. Such situations lead to significant delays in the train schedule, are fraught with the danger of electric shock to personnel, and require additional resources to restore the contact network. In this regard, work aimed at analyzing the thermal state of the power sliding contact and the development of methods for calculating its temperature under the described conditions is an urgent task. The solution to this problem will help reduce the number of cases of destruction of the contact network elements and will improve the reliability of the railway transport as a whole.

II. LITERATURE ANALYSIS AND PROBLEM STATEMENT

Quite a lot of attention is paid to solving the problem of increasing the operational properties of contact wires and inserts of current collectors [3–14]. The properties of any electrical contact are determined by the size of the contact area, the quality of the contact surface and contact pressure. It is known that the actual contact area is a small fraction of the visible contact area, and the total separation area is divided into many individual spots (α-spots). Thus, the discrete nature of the contact of solids is the main reason for the increased electrical resistance between the contacting planes [3, 4]. When significant currents are transmitted through such systems, a significant amount of heat is also generated at the contact point, which, under certain conditions, can be a problem. The wires of the contact network for various types of suspensions can be heated by current up to 100...120ºC, while the mechanical load is from 10 to 21 kN. Short-term or long-term heating causes a decrease in the strength of the wires, which leads to a significant decrease in the coefficient stock strength [4]. In [5], the values of the operational thermomechanical load on the contact wires are substantiated. A contact wire subjected to mechanical and thermal stress and worn during current collection has a coefficient stock strength of 2,5. The research results [4, 5] are used by the authors to determine the boundary conditions for the load for a partially worn contact wire.

When analyzing the contact pair «contact wire – contact insert of the current collector» is the monitoring of the state of the contact surfaces, as well as the measurement of their actual geometric dimensions. In [6], a measurement method was proposed, when the working surface of the contact wire is captured by several linear scanning cameras, local wear is analyzed in real time. Further, because of the information received, the final calculation of the wear of the contact wire is made. This method is very complicated from the point of view of technical implementation, and most fully reveals its potential in the dynamic measurement of contact wire wear. In the conditions of the station in places of equipment and preparation of trains, it is more rational to periodically measure the geometry of the contact wire at the control points. For this, classical measuring instruments, for example, a micrometer, are quite applicable. This method of controlling the wear of the contact wire is the basis of the proposed method.

One of the features of the sliding electrical contact «contact wire – insertion of the current collector» is the relatively large currents with a small contact pressure. All together leads to the release of a large amount of heat in the areas of contact [7, 8]. Which in turn causes various kinds of degradation.

In [7], the interaction between the pantograph and the contact wire was analyzed, as a result, it was established that during current collection, the temperature of the contact point rises very quickly and can exceed the maximum permissible value regulated for the contact wire. The results [7] are comparable with the conclusions and conclusions obtained in [8] during the experimental study of the operation of the electrical contact «contact wire – current collector plate» in a static position.

Contact pressure largely depends on the speed of the electric rolling stock, and the actual contact area between the surfaces of the contact wire and the pantograph contact insert depends on the force with which the current collector presses the contact insert to the wire. Since smooth surfaces do not exist, the contact between the contact insert and the contact wire is realized through the so-called contact bridges [9], resulting in contact resistance, the magnitude of which depends on the temperature in the contact. Because of significant currents flowing through the contact, the electrical component of wear appears, the contact bridges melt, and the material of the contact wire loses its strength. However, insufficient attention was paid to contact resistance, as one of the key parameters reflecting the current collection efficiency. Changes in the contact resistance of the pantograph and the contact system at different electric currents and normal forces were analyzed in a static contact state [10, 11]. The work [12] is devoted to modeling the contact interaction between the contact wire and the pantograph, where the relationship between the magnitude of the pressing force of the contact insert of the current collector onto the contact wire and the value of the electrical resistance of this assembly is demonstrated.

In a number of robots [13, 14], low heat resistance of copper contact wires and their loss of mechanical properties at temperatures of 100ºC and a tensile load of 11 kN/mm^2 are shown. After 250 hours of operation under such conditions, partial recrystallization of the wire material occurs. After 500 hours, the material is completely recrystallized with a decrease in wire strength by 30% and a decrease in its cross section.

When considering the mechanisms leading to loss of strength by the contact wire, the presence of the second contact, the contact insert, is practically not taken into account, and the properties of the insert itself certainly affect the strength properties of the wire [15]. But the damaged surface of the contact insert leads to an increase in contact resistance, which means to local overheating of the contact wire, and the degree of softening depends on the duration of the overheating. Therefore, the proposed method takes into account not only the geometry and quality of the working surface of the contact wire, but these same parameters of the contact insert are taken into account, which certainly has a positive effect on the calculation results.

In [16], the results of modeling the mutual thermal effect of the elements of electric contacts are presented, and such a model can be applied to electric traction. The model confirms the thermal behavior of the «contact wire – contact insert of the current collector» system.

It is known that an increase in temperature leads to a deterioration in the mechanical properties of conductive materials, the change of which strongly depends on the duration of heating [17]. Slow (within 2 hours) heating of hard-drawn copper leads to a sharp decrease in the tensile strength σ_{str} at a lower temperature than when they are heated for a short time (within 10 seconds). Slow heating of a solid-drawn copper rod with a diameter of 50 mm leads to recrystallization of the rod in the zone T = 200 ° C and then to a rapid decrease in its strength to the strength level of the same rod from soft copper zone T = 300 ºC. In view of the foregoing, it can be assumed that the group most at risk is when the train in the parking lot is preparing for the journey while the current collector is in the raised state for heating in the winter or air conditioning in the summer. The features of this mode include: the absence of airflow at the contact point; prolonged flow of heating current through a fixed contact.

All this allows us to argue that it is advisable to conduct a study on the analysis of thermal processes at the contact point of the contact wire and the contact insert of the current collector, as well as the development of methods for calculating its thermal load specifically for the conditions of preparation of the train for the journey.

III. THE PURPOSE AND OBJECTIVES OF THE STUDY

The aim of the work is to study the thermal state of the power sliding contact «contact wire element – current collector insert element» («EKP–ETV») in conditions of preparing the train for the flight, when the contact is stationary and the heating/conditioning current flows through it.

To achieve this goal, the following tasks were set: 1. Determine the cause of the breakdown of the contact wire at the point of contact with the pantograph of a train consuming current in the parking lot. 2. To determine a set of factors affecting the amount of current consumed by the rolling stock during its preparation for the journey, leading to «burnout» of the contact wire. 3. Develop a methodology for calculating the temperature of the power sliding contact «contact wire – contact insert of the current collector».

IV. METHOD FOR CALCULATING THE THERMAL LOAD OF THE POWER SLIDING CONTACT

The winter temperature standards in long-distance passenger trains range from 18 to 20ºC, in suburban trains from 11 to 13ºC. Heating should be turned on in the case when the air temperature drops below plus 10ºC [2, 18]. To achieve the indicated temperatures, it is necessary to keep the current collector in the raised state for a considerable time during the electric heating of the wagons during preparation of them for the journey, especially after the sludge of the wagons. On passenger electric locomotives and direct current electric trains when powered by the current collector of the electric heating circuits of the train during parking, the continuous current $I_{\text{т}}$ is 200...300 A or more [19]. Consider the heating of the contact wire element through which the heating current flows

$$I_{\text{h}} = \frac{I_{\text{т}}}{k}, \quad (1)$$

where k – the number of rows of inserts on the runner;

EKP – an element of the contact wire that is in contact with one current collector insert on the current collector runway when the electric rolling stock is stationary (Fig. 1);

ETV – is an element of the current collector insert that is in contact with the EKP (Fig. 1).

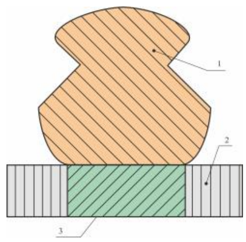

Fig. 1. Contact «EKP – ETV» (1 – cross section of the EKP taking into account its nose; 2 – longitudinal section of the collector insert; 3 – part of section 2, which is in contact with the EKP)

EKP has a length equal to the width of the contact insert. With such a short length of the stationary EKP, there is a danger that when the heating current flows through the «EKP–ETV» contact, this element may heat up to a temperature above the permissible value.

In this regard, the task is: to develop a methodology for determining by calculation the temperature of heating the EKP at different heating currents I_h, which flows through the contact «EKP-ETV». This calculation, first of all, must be carried out under critical conditions. Critical conditions are conditions that contribute to increased heating of the EKP. These conditions include: wear of the contact wire; reduction in pressing on the contact wire from the side of the current collector; ambient temperature.

It is proposed to consider the «EKP – ETV» contact from the point of view of the theory of electrical contact. According to the design, the «EKP – ETV» contact can be assigned to flat connecting mutually fixed, similar, for example, bolted contacts [20].

According to the classical theory of electrical contact resistance, the real resistance of solid surfaces occurs in areas consisting of separate spots (contacting contact protrusions), which are randomly located on the visible contact surface. For a theoretical assessment of the factors affecting the contact transition resistance R_t, contact models are widely used [21, 22]. For practical calculations R_t, the empirical formula is used [23, 24]:

$$R_t = \frac{k_0}{F^n}, \qquad (2)$$

where k_0 – coefficient depending on the properties of contact materials, $\Omega \cdot$kg; n – coefficient depending on the number of contact points of contact surfaces. For flat contact $n=1$; F – force that compresses contacts, kg.

The compressive force of the contacts consists of three components: static and dynamic pressing forces of the current collector, aerodynamic lifting force. In a stationary state, there is only a static pressing force of the current collector, which is created by its working springs. In the general case of heavy current collectors, the static pressing force should be within 90...130 N, for light-type current collectors – 70...110 N [23, 24].

We accept that the contacting planes of the EKP and ETV are parallel to each other. From the formula (2) it follows that the electrical resistance of the «EKP–ETV» contact is inversely proportional to pressing the contact wire and does not depend on the area of their contact. The number of points of contact increases with increasing pressure. This circumstance is, along with a decrease in the height of the contacting contact protrusions, one of the reasons for the decrease in resistance R_t.

The solution of this problem involves the thermal calculation of the considered contact in order to determine the heating temperature of the contact wire element under certain operating conditions and comparing it with an acceptable value. It is practically impossible to accurately calculate the thermal process due to the variety of channels through which heat is released to the environment. The calculation of heat transfer is also complicated by the nonlinear dependence of the amount of heat transferred on temperature. In such conditions, it is advisable to resort to a number of assumptions and the widespread use of experimental data.

Conducting experiments in order to study all types of heat transfer from the «EKP–ETV» contact into the environment, combining them into one equivalent form and establishing a common heat transfer coefficient is problematic. Therefore, it is proposed to use the dependence of the temperature of the EKP surface on the specific power value (Fig. 2), which is released into the environment due to convection and radiation, which are available for contact similar to that considered [20].

The following methodology (algorithm) for calculating the steady-state temperature of the «EKP–ETV» contact joint is proposed. Define:

1. Type of electric locomotive or electric train.
2. Type of current collector, number of rows of slip rings on its runner, insert material and its dimensions.
3. Type of contact wire, its wear as a percentage of the initial cross section.
4. Transient resistance R_t of one contact «EKP–ETV» with a minimum pressing force F on the contact wire from the side of the current collector. For this, the calculated dependence (2) is used.
5. The value of the current through the current collector during heating/cooling of the train. It is recommended to initially take $I_T = 300$ A. (according to the results of measurements in the wintertime under the conditions of the TCh-8 locomotive depot, the average current value was at the level of 300 A).

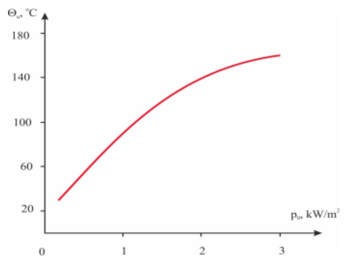

Fig. 2. The dependence of the contact temperature «EKP–ETV» on the specific power from the heat transfer surface.

6. Heating/cooling current I_h through one contact «EKP-ETV». For this, dependence (1) is used.
7. The heat-transfer surface S1 of the EKP element due to convection and radiation, taking into account the wear of the contact wire. The geometric dimensions of the contact wire of copper and its alloys are given in GOST2584-86 [27], so the values H and R are given in table 4 of this document.

   The size h (Fig. 3) that characterizes the actual value of the height of the contact wire. Its connection with the cross-sectional area of the contact wire is established by the tables given in Appendix 3 of the

Rules for the Design and Maintenance of the Contact Network of Electrified Railways [28].

With some wear of the contact wire, a platform with a width a (Fig. 4) is formed on its working part, half of this size $\frac{a}{2}$ is determined by the following expression [28–32]:

$$\frac{a}{2} = \sqrt{R^2 - H_1^2} = \sqrt{R^2 - \left(R - \left(H - h\right)\right)^2} . \quad (3)$$

Denoting by x the length of the arc of the worn-out section (this section is shaded in Fig. 3), we determine its value:

$$x = \frac{2\left(\arcsin\left(\frac{a/2}{R}\right)\right) \cdot 2\pi R}{360^\circ} . \quad (4)$$

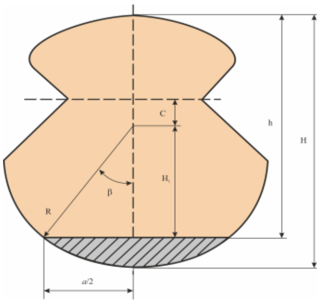

Fig. 3. The cross section of the contact wire when it is worn.

If L_n indicates the perimeter of the new contact wire, then the perimeter of the wire with some wear will be equal to $\left(L_\text{n} - x\right)$, which means that the heat transfer surface of the EKP element is equal to:

$$S_1 = \left(L_\text{n} - x\right) l , \quad (5)$$

where l – current collector insert width.

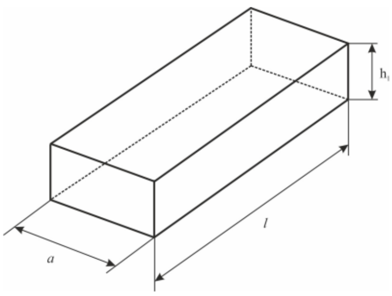

Fig. 4. The element of the current collector insert (ETV).

8. The surface S_1 of the collector element of the collector of the collector that heats up due to convection and radiation (Fig. 4):

$$S_2 = 2h_1 \cdot a + a \cdot l , \quad (6)$$

where h_1 – current collector insert height; $2h_1 \cdot a$ – end surfaces of ETV; $a \cdot l$ – lower surface of the ETV.

9. Power loss ΣP :

$$\Sigma P = P_k + P_p + P_v = I_\text{h}^2 \cdot R_\text{t} + I_\text{h}^2 \cdot \rho_p \frac{l}{S_\text{EKP}} + I_\text{h}^2 \cdot \rho_v \frac{h_1}{S_\text{ETV}} , \quad (7)$$

where ρ_p – resistivity of the material of the contact wire; S_EKP – cross-sectional area of the EKP taking into account wear and tear; ρ_v – specific resistance of the material of the collector insert; S_ETV – ETV cross-sectional area taking into account wear.

10. Specific heat transfer power p_0 :

$$p_0 = \frac{\Sigma P}{S_1 + S_2} . \quad (8)$$

11. Considering EKP and ETV as a single structure with heat transfer surface $S_1 + S_2$ according to the schedule in Fig. 2 determine the surface temperature Θ_u of the specified design.
12. The maximum permissible temperature Θ_p for the selected type of contact wire is taken from table 4 of the Rules for the design and maintenance of the contact network of electrified railways [28].
13. The ratio between Θ_u and Θ_p. Draw conclusions and make recommendations as appropriate.

V. CONCLUSIONS

The results of this work, namely the methodology, allows us to quickly determine the thermal state of the sliding contact «contact wire – contact insert of the current collector» in operating conditions when preparing a train dispatch. The standard approach for determining the duration of heating/conditioning is based on the average values of the loads on the system and therefore does not take into account some factors, for example, the state of the contact wire, the state of the contact insert of the current collector, the number of cars in the train, and so on. The proposed technique is based on the classical theory of electrical contact and the theory of heating a homogeneous body, which makes it possible to accurately assess the thermal state of the power sliding contact and is convenient enough for use in operating conditions.

The methodology does not require significant calculations and the initial data are information available for measurement and control by the station or depot. It should be noted that in the calculations, formula (2) does not take into account the degree of contamination of the working surface of the contact wire, and, therefore, in actual use, the value of R_t can slightly exceed the calculated value.

A feature of the technique can be considered the need to have a dependence of the «EKP – ETV» contact temperature on the specific power from the heat transfer surface. Obtaining such a dependence is a separate problem that can be solved in the future.

The disadvantages include the limited application of it only to the conditions for preparing the train in the parking lot.

The work has an applied aspect because it makes it possible to improve the standard technological process – the technology of preparing a train dispatch. At the same time, the material presented is part of a broader work aimed at improving the efficiency and reliability of the electrified railway transport, namely, solving problems associated with the transmission of electricity to the vehicle's side by means of a power sliding contact.

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