Improving the mathematical model of wear of contact elements of pantograph during very high-speed movement

V M Philippov\textsuperscript{1,2}, A N Smerdin\textsuperscript{1}

\textsuperscript{1}Omsk State Transport University, 644046, Omsk, Marx av. 35, Russia
E-mail: \textsuperscript{2}fvm-omgups@mail.ru

Abstract. The long-term development program of the Russian Railways holding provides for a comprehensive modernization of the railway infrastructure by 2025 in order to create high-speed and very high-speed railways to increase passenger and freight traffic. Taking into account the existing energy strategy of Russian Railways, the energy intensity of the company for 2020 should decrease by 25–27% compared to 2005, which means that a comprehensive implementation of energy and resource-saving technologies remains necessary.

For the transport of passengers and goods with speeds over 200 km / h, it is necessary to modernize the design of the contact network, current collection devices, and the track’s upper structure. In the article [1] it was already noted that a change in the design of the collector assembly of the electric rolling stock entails significant financial and time costs. Less expensive is the use of contact elements with an extended service life, providing reliable, economical and environmentally friendly transmission of electricity to rolling stock.

1. Introduction

The long-term development program of the Russian Railways holding provides for a comprehensive modernization of the railway infrastructure by 2025 in order to create high-speed and very high-speed railways to increase passenger and freight traffic. Taking into account the existing energy strategy of Russian Railways, the energy intensity of the company for 2020 should decrease by 25–27% compared to 2005, which means that a comprehensive implementation of energy and resource-saving technologies remains necessary.

For the transport of passengers and goods with speeds over 200 km / h, it is necessary to modernize the design of the contact network, current collection devices, and the track's upper structure. In the article [1] it was already noted that a change in the design of the collector assembly of the electric rolling stock entails significant financial and time costs. Less expensive is the use of contact elements with an extended service life, providing reliable, economical and environmentally friendly transmission of electricity to rolling stock.

2. Question Status
A small number of specialists are engaged in the study of wear of contact elements and contact wires in the world. So, G. Bucca, A. Collina in their work [2] describe a method for predicting the wear of slip rings and contact wires, and H. Yang, B. Hu, Ya. Liu, X. Cui, G. Jiang in [3] consider the process of interaction of a contact pair under conditions of very high-speed motion and significant current loads. However, in Russia these studies cannot be fully applied due to the specifics of climatic and weather conditions, as well as operating conditions.

The most important operational characteristic of the elements of contact pairs of current collection devices (CCD), which determines the reliability and efficiency of electric power transmission to electric rolling stock, is the wear rate. Wear of both the contact wire (current lead) and the contact inserts (contact elements) above the critical values is unacceptable. One of the ways to increase the service life of contact pairs is to choose the materials used for their manufacture, as well as the functioning parameters of the current collector devices that best meet the requirements of the quality of current collector and save resources.

The quality of current collection depends not only on the state of the sliding contact elements, but also on many other factors (Figure 1), due to the features of the process of interaction between current collectors and contact suspensions (current conductors). One of the characteristic factors that have a significant effect on the wear of the elements of the contact pairs of the CCD under very high-speed motion is the traction current, the value of which can reach 3000 – 3500 A at certain times, increasing (including due to thermal impact) the electromechanical wear in whole.

![Figure 1. Factors affecting the wear of contact pair elements.](image)

Employees of the laboratory ‘Designs of contact networks, power transmission lines and current collection’ of Omsk State Transport University developed and successfully tested a program and methodology for testing the elements of contact pairs of CCD electric vehicles for wear [4].

The implementation of the methodology requires specialized experimental complexes, as well as a significant investment of time and resources. To reduce the amount of experimental research, a combined method can be used a combination of the required minimum experimental research of real
objects (or their analogues) and calculation methods based on mathematical modelling of processes occurring in contact pairs of current collector devices.

Due to the fact that the collector element and the current-carrying wire are a unit that operates during very high-speed movement in conditions of increased electromechanical wear, the mathematical model of the interaction of the contact pair elements is improved in two directions [5]: the mechanical wear model is improved (depending on the magnitude of contact pressing, considered in [1]) and the improvement of the model of electrical wear (from the effects of an electric current flowing through the contact).

As part of the research work ‘Increasing the life cycle of contact inserts of the current collector of main electric rolling stock in very high-speed traffic’, which received support from the Grants Council of the President of the Russian Federation, this article will discuss the improvement of the electrical component of the wear model of contact pair elements in very high-speed traffic.

3. Improving the mathematical model

The process of electrical wear of the elements of contact pairs of CCD is represented using the functional dependence:

$$I_h = \psi_2(\gamma, Q, s, P_g, I_M, I_{E_0}, i),$$

where $\gamma$ is an indicator of the arc resistance of the material; $Q$ – the amount of electricity determined by the average value of the arc current $i$ and its burning time $t$; $s$ – friction path length; $P$ – contact press value; $g$ – complex characterizing the change in wear of the material due to increased surface roughness; $I_M$ – mechanical wear rate (without electric current flow); $I_{E_0}$ – wear rate when an electric current flows through a contact without sparking; $i$ – value of electric current flowing through the contact.

A feature of purely electrical wear is the difficulty (and in most cases the impossibility) of obtaining the results of experimental studies. That is why R. Holm proposed to consider the influence of the electric current flowing through the contact on the wear of the elements of the contact pairs as an additional factor [6] that changes the mechanical wear.

The functional dependence (1) was already presented in [7] in the form of a mathematical model that takes into account most of the factors shown in Figure 1, with the exception of those that occur in conditions of very high-speed motion. Thus, due to the lack of consideration of the aerodynamic effects of the air flow and the speed of the electric rolling stock on the processes occurring in an electric sliding contact, the results of calculations by the model will not be sufficiently accurate. So, under conditions of low speeds of electric rolling stock (up to 60 km / h), the calculation error in relation to the results of experimental studies of electromechanical wear does not exceed 5%, at speeds above 150 km / h the error becomes more than 10%.

Taking into account the provisions of the theory of similarity [8] and the need to take into account the aerodynamic effects of the air flow and the speed of the electric rolling stock in equation (1), it is possible to combine difficult to reproduce parameters into complexes, and secondary factors into simplexes [9]. Then, in accordance with the re-theorem and taking into account the works of I. Kragielski [10], E. Brown [11] and H. Biesenack [5], we obtain the following equation describing the process of electrical wear:

$$I_E = \left(\zeta_1 \cdot Bi \cdot \zeta_2(\gamma, Q, T_{h_i}) + \zeta_2 \cdot (X_1 \cdot Me)^{k_1} \cdot I_{E_0}(P, k_1, k_2)^{k_3} + \zeta_3 \cdot g(P X_3, X_4, T_{h_i}, k_4) \left(\frac{Q}{s}\right)^{1/2}\right) \cdot \theta(F_0, \phi, k)$$

where $\xi$ is the intensity of electrical discharge erosion; $\gamma$ – electrical discharge coefficient of the material of the element of the contact pair; $Q$ – the amount of electricity passed through an electric arc; $T_{h_i}$ – temperature gradient of the contact pair element; $Bi$ – Bio criterion; $\zeta_1, \zeta_2, \zeta_3$ – scale factors; $P$ – contact press; $k_1, k_2$ – functionals that determine the relationship between contact pressing and the type of current flowing through an electrical sliding contact; $k_3$ – current factor; $k_4$ – simplex that takes into account the content of graphite in the material of the element of the contact pair; $g$ – coefficient
characterizing material wear due to increased surface roughness; \( s \) – the length of the trace of burning an electric arc; \( X_1 = \left( \frac{P_{\text{eq}}}{I_{\text{eq}}^2} \right)^{\alpha_m} \) – complex, \( X_3 = (\text{Cu})^{\gamma_m} \), \( X_4 = \left( \frac{H_1(T_{\text{eq}})}{H_2(T_{\text{eq}})} \right)^{\epsilon_m} \) – simplexes [1];

\[ g(F_{0i}; \phi, K) = \left[ F_{0i} \left( \frac{\phi_{0i} \kappa_0}{\phi_{i1} \kappa_1} (0.1 + u_0) \right) \right]^{\gamma_m} \] – complex taking into account the influence of environmental factors (\( \phi_{0i}/\phi_i \) – the ratio of the average value of relative humidity for five years to the value of relative humidity at the time of research, \( \kappa_0/\kappa_1 \) – the ratio of the average dust content of the environment over five years to the value of its dust content at the time of research, \( u_0 \) – oncoming air flow aerodynamic impact on the contact insert); \( F_{0i} \) – Fourier criterion; \( \sigma_m \) – the coefficient of change in the influence of environmental parameters in the contact zone.

Thermal processes occurring in the elements of a contact pair of current collection devices are mathematically described by a system of Poisson partial differential equations and are given in [1].

4. Using data from other measurement systems

Figure 2 shows the histograms of the electrical wear of the contact elements obtained as a result of calculation using the existing (histogram 1) and advanced (histogram 2) mathematical models. When performing the calculations, the air flow rate was assumed to be \( 50 \text{ m/s} \).

![Figure 2. Graphite contact element wear rate calculated from existing and improved models.](image)

In Figure 2, the following notation is used: 1 – calculation results for the existing model; 2 – calculation results according to an improved model, 3 – trend line.

5. Conclusions

The analysis of the histograms in Figure 2 allows us to conclude that the calculation accuracy (relative to the trend line) is increased by the mathematical model (2) by taking into account the influence of the aerodynamic effects of the air flow and the speed of the rolling stock.

References

[1] Philippov V and Smerdin A 2020 *Modeling the mechanical wear of the contact elements of pantograph during high-speed movement* E3S Web of Conferences vol 157 (Novosibirsk), 01022

[2] Bucca G and Collina A 2009 *Wear* 266. https://doi.org/10.1016/j.wear.2008.05.006
[3] Yang H, Hu B, Liu Ya, Cui X and Jiang G 2019 *Engineering Failure Analysis* 104  
https://doi.org/10.1016/j.engfailanal.2019.06.060  

[4] Sidorov O and Philippov V 2017 *Simulation of Wear Processes of the Monorail Electrical Transport Current Collector Contact Elements* Advances in Intelligent Systems and Computing (Cham: Springer International Publishing AG) vol 692 p 59 – 68. https://doi.org/10.1007/978-3-319-70987-1_6  

[5] Biesenack H and Pintscher F 2005 Kontakt zwischen Fahrdraht und Schleifleiste–Ausgangspunkte zur Bestimmung des elektrischen Verschleißes Elektrische Bahnen 3  

[6] Holm R 1967 *Electric Contacts: Theory and Application* (New York: Springer) p 484  

[7] Sidorov O, Philippov V and Stupakov S 2015 *J. Frict. Wear* 36.  
https://doi.org/10.3103/S1068366615050128  

[8] Voznesenski V 1974 *Statistical methods of experimental design in feasibility studies* (Moscow: Statistica) p 192  

[9] Schenck H 1967 *Theories of Engineering Experimentation* (New York: McGraw-Hill Companies)  
https://doi.org/10.1115/1.3641806  

[10] Kragelski I, Dobychin M and Kombalov V 1982 *Friction and Wear Calculations Methods* (Oxford: Pergamon Press)  

[11] Brown E, Evdokimov Yu and Chichinadze A 1982 *Simulation of Friction and Wear in Machines* (Moscow: Mashinostroyenie) p 191