Search for additional criteria to estimate the electrical connection state under the impact of currents of different value

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Abstract. The paper reports on search for additional criteria to estimate the electrical connection state in the operating mode characterized by abrupt change in electric current parameters. The results obtained in the course of theoretical studies are based on the use of methods of mathematical and experimental modeling of thermal processes in electrical connections of a traction power supply system. New criteria for estimating the state of the electrical connection for cyclic traction load have been found out. Investigation of the defectiveness ratio in the “heating-cooling” cycle makes it possible to estimate the current state of the electrical connection under service conditions.

1. Introduction
A traction power supply system is an extended object intended to transmit electric power to electric rolling stock. It consists of a set of electrical connections of bolted-type accomplished by clamping the fastened wires with bronze dies. No-failure system-wide operation depends on reliable work of such electrical connections [1]. The peculiar feature of the railway power supply system is that traction load (electric rolling stock) is not uniform within a day, which leads to abrupt change in electric current parameters [2]. The given circumstance complicates a current state estimate of an electrical connection.

2. Problem definition
There are distinguished two states of electrical connection: satisfactory and unsatisfactory. The state depends on the value of transient resistance ($R_T$), resulting from contiguity of contact surfaces of a wire and clamp dies. Under service conditions the value $R_T$ increases as tightening torque of clamp dies decreases (loosening) and oxide films are formed in places of a wire and clamp contact. For satisfactory state the value of transient resistance should not exceed the value equal to the ohmic resistance of a conductor. It follows, the purpose of work is search for additional criteria to estimate an electrical connection state under service conditions, as these criteria are able to indirectly determine an actual value of $R_T$.

3. Solution
In work [3] it is proved that in the electric current supply mode indirect estimate of value $R_T$ by means of defectiveness coefficient ($K_0$), with heating considered, is possible and, as a result, the same holds good for estimate of electrical connection state. However, the diagnostic data on current-carrying clamps obtained with the help of a thermal imaging camera have shown that the lack of the similar data analysis of cooling mode leads to doubtful estimate of current state of bolted-type electrical connection [4].
Therefore, there arises a need to investigate not only heating, but also cooling of an electrical connection, since only joint consideration of both modes can offer profound qualitative evaluation of the existing indicators influencing the electrical connection state estimate.

At present there is no mathematical model of electrical connection estimate within cooling mode. The authors of the given paper offer to transform the universal equation of heat balance of electrical connection [6], without current being taken into account, and receive an expression:

\[
(C_j m_j + C_w m_w) \cdot \frac{d\theta}{dt} = -\left[ 0.01312 \cdot \theta^{1.49} + \epsilon S \cdot 5.67 \cdot 10^{-8} \left[ (T_j + 273)^4 - (T_a + 273)^4 \right] \right],
\]

where \( C_w \) is the specific heat capacity of a wire material (W·s·K\(^{-1}\)); \( C_j \) is the specific heat capacity of a clamp material (W·s·K\(^{-1}\)); \( m_w \) is the mass of a wire clamped between dies (kg); \( m_j \) is the mass of a clamp (kg); \( S \) is the area of an exterior surface of a clamp (m\(^2\)); \( T_a \) is the air temperature (°C); \( T_j \) is the temperature of a clamp (°C); 5.67·10\(^{-8}\) (W·m\(^{-2}\)·K\(^{-4}\)) is the Stefan-Boltzmann constant; \( \epsilon \) is the relative emittance for bronze (\( \epsilon = 0.6 \)); \( \theta \) is the excess of temperature of electrical connection over ambient temperature (°C).

To determine temperature of electrical connection we will transform the above equation (1) and receive the dependence defining temperature change on time in the course of cooling [6]:

\[
\Delta \theta_C = (0.0108Pt(C_j m_j + C_w m_w)^{-1} + \theta_0^{-0.49})^{-2.03},
\]

where \( P \) is the perimeter of a wire cross section (m); \( t \) is the time period of current flow (s).

The received expression (2) describes temperature variation of clamp dies in the course of time when traction current is not flowing through the electrical connection. It gives a possibility to investigate process of cooling and to estimate its influence on \( K_\theta \), which represents the ratio of temperature variations of electrical connection to temperature variations of a wire [7]. As mathematical models of heating and cooling for a wire and an electrical connection are known (figure 1.a), it is possible to investigate \( K_\theta \) temporal variation in the course of the "heating - cooling" cycle and consider the additional factors influencing the estimate of an electrical connection [8].

In figure 1.b, showing \( K_\theta \) variation in "heating-cooling" cycle, it is possible to conditionally single out four areas of a curve which describes the thermalphysical processes occurring in the feeding clamp and branching wires. In the Inertial Component area when temperature of connection is much lower than that of wire, the function of the defectiveness coefficient, with heating considered, is of the minimum value, as for the defectiveness coefficient value, it depends on connection mass and the material it is made of. A point of an extremum, as regards to thermal characteristics, is explained by inertial properties of a clamp [9].

Then there is a process of determining a coefficient value due to balancing of a gradient of thermal fields of a clamp and the connected wires [10]. The third area represents a steady-set coefficient value in the heating mode. The coefficient value will depend on two components which influence heat balance of the system under discussion. The first component is a ratio of connection resistances and a wire (defectiveness coefficient with resistance considered). The second is a ratio of heat emission coefficients of a connection and a wire.

The fourth area shows sharp increase in \( K_\theta \) value with a distinctive point of a maximum. Such a behavior of the coefficient is explained by smaller cooling of an electrical connection, than that of a wire. It should be noted that at this moment \( K_\theta \) value considerably exceeds the rated value and is equal to 1.5 that has testified to unsatisfactory state of an electrical connection. At the same time the value of transient resistance of 25 µΩ adopted in modeling is considered to be rated. Thus, it is proved that the process of cooling cannot be neglected on estimating an electrical connection state; otherwise research results may turn to be erroneous and misleading.
Figure 1. "Heating-cooling" cycle of a clamp: a – temperature variation of a wire $\Delta \theta_{\text{W}}$ and an electrical connection $\Delta \theta_{\text{C}}$ related to the time period of conventional nominal current flow through them $I = 600$ A, at $T_a = 24$ °C; b – change of defectiveness coefficient $K_\theta$ with heating considered at $R_T = 25$ $\mu\Omega$.

The maximum value of coefficient being reached, its value decreases up to its steady-state value. On the basis of the offered mathematical model the Program for calculations in Mathcad computer environment was developed. The Program allows a user not only to consider cooling process but also
to change electric current parameters by substituting its value and time period of current flow [11] and [12].

The Program performs calculations of differential equations concerning wire heating and electrical connections [13]. Applying the Program operation algorithm, the value of $K_\theta$ is determined.

The Program includes the following data: 6 values of current which correspond to variables $I_1(t)$, $I_2(t)$, $I_3(t)$, $I_4(t)$, $I_5(t)$, $I_6(t)$. The current values are chosen one after another, proceeding from time intervals. The chosen time intervals are designated by a variable – $t_m$, $t_0$, $t_k$, $t_d$, $t_c$ – covering the maximum and minimum values of changes of the graph [14]. The value of transient resistance ($r$, $\mu\Omega$) is set as well.

Plotting the graphs of dependence of coefficient $K_\theta$ on time, the Program retains the previous data on an electrical connection and a wire and considers the when plots new graphs.

To obtain actual data of the algorithm performance, calculations of transient resistance of different value were carried out. In addition, values of current flowing through an electrical connection during heating and cooling modes were changed too.

Reasoning from the calculations made one can conclude that, in case of an electrical connection cooling, value $K_\theta$ can exceed the rated parameter used to estimate satisfactory and unsatisfactory states of an electric connection.

Being aware of the value of the inclination angle of a change curve $K_\theta$ and knowing that the angle shows the speed at which defectiveness coefficient increases during heating mode, one can predict current-carrying clamp state under the impact of electric load within the whole time interval of [3].

For assessment of adequacy of mathematical model pilot studies of heating of electrical connections were conducted. The experiment was made at a specially designed test bench, which is described in work [6].

The results of an experiment have proved comparability of their values to mathematical model illustrating $K_\theta$ value variations in reference to time. The margin of error is no more than 5% (figure 2). Thus, the received mathematical model is adequate.

![Figure 2](image-url)
4. Conclusions
There has been received dependence of temperature change of an electrical connection in cooling mode which defines model of $K_\theta$ change in reference to time under the impact of currents of different value. The adequacy of model at the experimental test bench has been proved.

Analysis of change of defectiveness coefficient dependence in the “heating-cooling” mode has allowed revealing additional criteria to estimate electrical connection state: steady-state value and speed of its change.

The received results will become a basis for development of the technique allowing estimating current state of an electrical connection under the impact of electric load in actual operating conditions.

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