Experimental Study of Mathematical Models of the Heating Defect Coefficient for the Heating-Cooling Cycles of an Electrical Connection

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Abstract. Reliable electrical connections are responsible for the trouble-free operation of entire systems where the load (electric stock) is roughly alternating. This circumstance makes it more complicated to identify the current state of the electrical connection during operation. During operation, the value of the transient resistance increases, as the tightening torque of the clamp dies is reduced (loosening) and the oxide films appear in sites of the wire and clamp joint. For the satisfactory condition, the value of the transient resistance should not exceed the value equal to the ohmic (linear) conductor resistance. Therefore, the aim of this work is the research study and comparison of the mathematical model to assess the state of the electrical connection under operational conditions that indirectly determines the actual value of the transient resistance.

1. Introduction

According to Russian State Standard GOST 12393-2013, the heating defect coefficient under the stationary condition can help to identify the condition of the electrical connection, which is defined in strict accordance with the measurement method and is inconsistent with the actual mode of the electrical connection operation in the traction energy system [1]. The mode of such a connection constantly experiences cyclic changes in heating and cooling, which is associated with the amount of current flowing in the overhead network [2].

2. Experimental studies

The adequacy of the research conducted and the mathematical model [3] obtained is proposed to be verified through experimental heating on the test bench specially designed and built (figure 1).

The testing bench is the electromechanical complex consisting of the mechanical mounting, connection point and the induction circuit connected to the current source (RIT-3000). The tension block and conductor joints are removed to increase the measured surface of the wire.

The RIT-3000 device allows the current to be supplied to the test electrical loop ranged from 0 to 3000 A, which makes it possible to heat the electrical connection within the wide range of temperatures [4]. The supplied current is monitored by an ammeter.

The contact resistance was measured in the open circuit using the Sonel MMR-630 microohmmeter. The resistance was measured three times to obtain the average value. The heating
temperature and distribution of the heating field of the electrical connection were recorded using a Fluke Tix500 thermal imager.

![Figure 1](image1)

**Figure 1.** The test bench for the current-conducting elements of catenary suspension: 1 - metal frame; 2 - temperature measurement points; 3 - connecting wires; 4 - test terminal of the overhead line; 5 - variable transformer; 6 - bus line of parallel wire; 7 - KS-053 conductor joints; 8 - power transformer; 9 - thermal imager installation location; 10 - PS-70 suspended insulators; 11 - tension clamps; 12 - guard cable joist; 13 - safety cable.

When the current of the given value is supplied, the wire and the test terminal are heated. The entire process is recorded by the thermal imager, namely: data record for 30 minutes from the start of heating since the transformer is turned on and for 40 minutes after the transformer is turned off while cooling. This allows recording the slightest temperature deviation from the standard and determining the extent of efficiency of the connecting reinforcement, unlike the wire, to reject the heat from its surface than the wire [5].

The structural features of the testing bench provide the conditions that are basically identical to the operational ones [6]. The connection diagram of the measuring sensors and their locations (figure 2) meets the test requirements.

![Figure 2](image2)

**Figure 2.** Connection diagram of sensors when testing connections: ▽ - connection points of heating temperature sensors; ◀ - connection points of potential ends of the measuring tool; ✗ - connection points of current ends the experiment was of three stages.
At stage I, the heating-cooling cycle was analyzed. The test clamp was heated with subsequent cooling under the given current at different transient resistance of the contact. The current value was equal to 200, 400, 600, and 800 A. The transient resistance was regulated by the tightening torque of the bolted connection and set to 20, 40 and 60 $\mu\Omega$. The heating took 30 minutes, cooling, 50 minutes. The total measurement took 80 minutes.

At stage II, operational modes of heating and cooling were simulated. This is due to the fact that under the real conditions the current constantly changes in the traction energy system [7-8]. For this purpose, heating was performed at the variable current value within the 5-minute interval in the following sequence: 600, 200, 400, 800, 200, 600 A. The total measurement took 30 minutes. Moreover, all the values of transition resistance: 20, 40 and 60 $\mu\Omega$ were tested.

All tests were carried out at the ambient temperature of +22 °C, the current was maintained unchanged during the test with the error of 3-5 %. It is important to note that during the heating process, the ambient air temperature inside the room increased to 33 °C.

The measurements were performed in compliance with the requirements. The clamps were assembled using a torsion-type torque wrench with an arrow mark and a varying tightening torque from 10 to 40 N·m. Depending on the bolt type, the tightening torque is 30 or 40 N·m. The measurements were taken using a KS-053-8 clamp (M-95 and MF-100 wire connections), for which the defect coefficient was determined as $K_0$.

At stage III, the curves were plotted for the temperature of the contact joint and the wire depending on the heating-cooling cycle period, and the defect coefficient was calculated. These were followed by the dependence curves and the data obtained were analyzed by comparing them with the theoretical data of the developed model.

Using a software package for the SmartView thermogram processing, the temperature values were obtained during the tests (figure 3) with a 1-minute interval.

![Figure 3. Screenshot processed in SmartView environment.](image)

The obtained temperature values were reported in the Microsoft Excel software package, which calculated the heating defect coefficient $K_0$ and plotted the temperature-time curve [10].

The results of the experiment, as well as the curves of the mathematical model plotted to model operational modes demonstrate that the experimental values stay within the limits of the bars.

The Fisher criterion is calculated using the formula,

$$F_{emp} = \frac{\sigma^2_x}{\sigma^2_y}$$  \hspace{1cm} (1)

where $\sigma^2_x$ and $\sigma^2_y$ are the variances of the first (larger) and second (smaller) samples, respectively.
If the empirical value \( F_{\text{emp}} \) is less than or equal to the critical value \( F_{\text{crit}} \) corresponding to the selected significance level, the variance of random variables is recognized as identical.

A function offered by the Microsoft Excel software package was used to determine the critical values of the F-distribution. The values of calculated criteria for resistances of 17, 40 and 60 \( \mu\Omega \) are shown in table 1.

**Table 1.** The values of calculated criteria.

| transient resistance (\( \mu\Omega \)) | \( F_{\text{emp}} \) | \( F_{\text{crit}} \) |
|--------------------------------------|-----------------|-----------------|
| 17                                   | 1.044           | 1.841           |
| 40                                   | 1.101           |                 |
| 60                                   | 1.112           |                 |

Table 1 shows that the empirical values of the criterion do not exceed the critical ones. So, for the significance level, \( \alpha = 0.05 \) the mathematical model is authentic.

Approximating curves were plotted for all the experimental data obtained since these smooth out the data fluctuations and more clearly display the type of the dependence [11]. The approximation was performed using three points.

Imagine the dependence of the coefficient at the \( K_\theta \) current of 800 A (figure 4). It is seen in figure 4 that, with the transient resistance of the clamp equal to 20 \( \mu\Omega \) (the normalized value is 25 \( \mu\Omega \)) and the current value of 800 A, the maximum value of the defect coefficient in the heating cycle is 0.84 \(( t = 31 \text{ minutes})\). As per the requirements of [3], the heating defect coefficient for connections made using the bolted ram clamps should not exceed 1.0.

![Figure 4](image-url)

**Figure 4.** Dependence of the defect coefficient from time for the transient resistance of 20 \( \mu\Omega \) at the current of 800 A.

It is obvious that the situations may arise during the performance where the transient resistance of the feed clamp will be more than 30 \( \mu\Omega \), which results in overheating of the feed clamp and its subsequent failure.

When the clamp and wire cease to be exposed to the traction current \(( t = 34 \text{ min})\), their cooling phase occurs. In this case, there is a sharp jump in the defect coefficient, since the wire temperature decreases much faster than the temperature of the clamp. When the time \( t \) reaches 39 minutes, the wire temperature decreases to such a value that at any time the defect coefficient takes values greater than one, which indicates the unsatisfactory state of the clamp. However, and this is significant to consider, the value of the transient resistance in the experiment, equal to 0.20 \( \mu\Omega \), indicates the satisfactory state of the clamp.
Therefore, when determining the state of electric connection, the heating and cooling phases should be considered. By the time \( t = 80 \) minutes, the wire and the clamp temperature is adjusted, so the defect coefficient is reduced to the normalized value.

Let's consider the defect coefficient pattern when the current of 800 A flows through the bolted connection, but only for several values of the transient resistance \([12]\). During the analysis of the data presented in figure 5, the direct correlation was established between the value of the heating defect coefficient and the value of the transient resistance \( R_T \); the value of the transient resistance and the rate of change \( R_T \) of the defect coefficient itself in the heating phase (angle \( \Psi \)).

Consequently, the higher is the value of the defect coefficient and the speed of its change (in the heating phase), the transient resistance of the electrical connection is correspondingly greater [13].

Based on the above, we can conclude that the indirect method can be used to define the value of the transient resistance and judge the quality of the electrical contact. Based on this, it is possible to identify the state of bolted electrical connections under the real operating conditions [14-15].

![Figure 5. Approximating curves of the defect coefficient for various transient resistances at the current of 800 A.](image)

3. Results and discussion
In addition to the experiments performed on the testing bench, the temperatures of the feed clamps were measured on the real section of the catenary suspension under operating conditions. In this case, it was impossible to define the current value, which depended on the intensity and nature of the train traffic, so the temperature values were recorded without actually determining the transient resistance of the electrical connection.

On the real section of the overhead network, a thermal imager was used to record the temperature changes in the electrical connection and on the wire at the 1-meter distance which is included in this connection. Parameters were recorded for two cases. In the first case, the temperature data were recorded for the bolted electrical connection that had been in operation for more than 10 years. In the second case, it was replaced by installing a new feed clamp and cleaning the contact surfaces.

The heating defect coefficient is calculated as per the obtained values (figure 6).
It is seen in figure 6 that the feed clamp is constantly exposed to the heating-cooling cycles. Field tests have shown that the value of the defect coefficient of the clamp with long-term operation varies within the range of 1.4 to 2.2; and as a new clamp is installed in this unit - 0.75 to 1.3.

The conducted researches confirm the practical possibility to apply these theoretical assumptions.

4. Conclusions
To test all theoretical assumptions, a testing bench with the up-to-date equipment has been designed that allows to study the thermal processes in the electrical connection for various values of current and transient resistance.

An experiment was conducted under the laboratory and field conditions to confirm that the theoretical assumption on the change in the defect coefficient $K_\theta$ depending on time is natural and that it depends on the value of the transient resistance. The discrepancy between the data obtained by practical researches and calculations based on the Fischer criterion does not exceed 5%.

5. References
[1] Ignatenko I V and Vlasenko S A Determination of criteria to find the quality of an electrical connection 2016 Russian Electrical Eng. 87(2) 65-67
[2] Liu Xi-Yang et al Failure analysis and optimization of integral droppers used in high speed railway catenary system 2018 Engineering Failure Analysis 91 pp 496–506
[3] Ignatenko I V and Vlasenko S A 2020 IOP Conf. Ser.: Mater. Sci. Eng. 760 012024
[4] Lee V N, Khimukhin S N, Teslina M A and Ignatenko I V Reliability enhancement of electro feeding cramps on railways contact web 007 Modern materials and technologies: Materials of international VIII Russia – China Symposium 2 pp 49–52
[5] Xin Zhou, Schoepf T Detection and formation process of overheated electrical joints due to faulty connections 2012 26th International Conference on Electrical Contacts (ICEC 2012) 12909251
[6] Braunovic M Fretting in Electrical/Electronic Connections: A Review 2009 IEICE Transactions on Electronics E92.C Issue 8 pp 982-991
[7] Ignatenko I, Vlasenko S Diagnostics of Electrical Connections of Electric Traction Network. 2020 Advances in Intelligent Systems and Computing 1115 pp 69–78
[8] Bigun A Y, Sidorov O A, Osipov D S, Girshin S S, Goryunov V N and Petrova E V 2018 J. Phys.: Conf. Ser. 944 012016
[9] Tumanov A et al 2017 IOP Conf. Ser.: Earth Environ. Sci. 90 012027
[10] Samokhvalov V N and Samokhvalova Zh V 2019 IOP Conf. Ser.: Mater. Sci. Eng. 666 012068
[11] Davison P J, Lyons P F and Taylor P C Temperature sensitive load modelling for dynamic thermal ratings in distribution network overhead lines 2019 International Journal of Electrical Power & Energy Systems 112 1–11
[12] Zheng Z, Song R, Zhou Y, Ren C, Wang J and Ru Y Study on thermal overheating faults of electrical equipment connector based on thermal balance theory 2018 China International Conference on Electricity Distribution (CICED) Tianjin pp 555-560

[13] Wilson C, McIntosh G and Timsit R S Contact spot temperature and the temperature of external surfaces in an electrical connection 2012 26th International Conference on Electrical Contacts (ICEC 2012) 12909202

[14] Bindi M, Grasso F, Luchetta A, Manetti S and Piccirilli M 2019 J. Phys.: Conf. Ser. 1304 012006

[15] Liu Xi-Yang Failure analysis and optimization of integral droppers used in high speed railway catenary system 2018 Engineering Failure Analysis 91 pp 496–506