Health assessment of the electrical contact-line connections in view of the operational traction load pattern of the electric rolling stock

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Abstract. Estimation of the traction energy system reliability and efficiency due to timely and immediate identification of heating sites of contact joints is the future-oriented technology for the condition oriented service and repair of the electrical equipment of energy providers. It is peculiar with the roughly alternating load of the electric current action during the day. This makes it difficult to identify the current state of the electrical connection. Thus, it becomes necessary to specify the dependence of changes in the assessment criteria of the electrical connection condition in operation.

1. Introduction

A traction power supply system is an extended object intended to transmit electric power to electric rolling stock. The peculiar feature of the railway power supply system is that traction load is not uniform within a day, which leads to abrupt change in electric current parameters. It is peculiar with the roughly alternating load of the electric current action during the day. Thus, it becomes necessary to specify the dependence of changes in the assessment criteria of the electrical connection condition in operation [1].

2. Experimental studies

To plot a real curve of the defect coefficient-time, it is required to measure the current consumption during several days. For this purpose, a trip was arranged to the substation of the Ussuri power supply substation, where power quality control devices were installed. These devices were connected to the power supply branches of the substation.

The measurements resulted in the effective current value and the measurement time. These measurements were made with a second-by-second averaging.

We combine the operational current data from a single power branch into a period of 300 s (5 minutes), (table 1) with specification of the effective current for this period.

$$I_{ef} = \frac{1}{3 \cdot Q_0} \sum_{i=1}^{m} \left(I^2_i + I^2_e + I_i \cdot I_e\right) \cdot \Delta t_i,$$

where $I_i$ – the value of the effective current in the i-th specific point (s – start, e – end), A; $\Delta t_i$ – the period in the effective current section between two specific points, s; m – the number of specific points on the effective current curve; $Q_0$ – estimated time period, s.
Table 1. Traction load data measurement of the contact-line power branch of the Ussuri traction substation.

| $t$ (s) | $I_{left}$ (A) | $t$ (s) | $I_{left}$ (A) |
|---------|----------------|---------|----------------|
| 300     | 629.8          | 5700    | 390.4          |
| 600     | 732.9          | 6000    | 485.4          |
| 900     | 832.6          | 6300    | 688.0          |
| 1200    | 639.1          | 6600    | 728.8          |
| 1500    | 644.5          | 6900    | 691.0          |
| 1800    | 450.3          | 7200    | 619.8          |
| 2100    | 497.3          | 7500    | 691.3          |
| 2400    | 625.3          | 7800    | 636.8          |
| 2700    | 689.9          | 8100    | 779.5          |
| 3000    | 517.6          | 8400    | 705.8          |
| 3300    | 423.5          | 8700    | 500.9          |
| 3600    | 566.3          | 9000    | 746.9          |
| 3900    | 508.1          | 9300    | 747.4          |
| 4200    | 539.5          | 9600    | 780.4          |
| 4500    | 489.5          | 9900    | 649.1          |
| 4800    | 632.8          | 10200   | 672.5          |
| 5100    | 472.7          | 10500   | 565.3          |
| 5400    | 471.3          | 10800   | 549.1          |

We plot a histogram of the current-time dependence for the current calculated. Histograms of the branch current-time dependence are combined with the math modeling of changes [2] in the heating defect coefficient (figure 1).

Based on the elaborated mathematical model, the computation software was created in the Mathcad environment to change the value of the active current in terms of its value and duration when considering the cooling process. The software helps to calculate differential equations for the wire and electrical connection heating resulting in the defect coefficient ($K_\theta$).

The software calculates differential equations for the wire and electrical connections heating. It results in the specification of the heating defect coefficient $K_\theta$ which is found by the ratio of the electrical connection heating to the wire heating that are a part of the relevant electrical connection [3]. We take the value 1.0 for the normal-maximum value of the defect coefficient. Connections with the transient resistance $R_T$ = 10, 17, 25 $\mu$Ω meet the requirements, where, at $R_T$ = 30 $\mu$Ω and 40 $\mu$Ω, the defect coefficient lies on the border [4], i.e., it changes within the normal range; at $R_T$ = 60 $\mu$Ω the connections are of improper quality and, accordingly, the bolt torque should be increased [5].

Based on the plotted curves, the current dependence of $K_\theta$ is built (figure 2). During the initial period of the wire and electrical connection heating at 600 A for the transient resistance $R_T$ = 25 $\mu$Ω, the coefficient $K_\theta$ does not exceed 1.0. The curve of the defect coefficient for the transient resistance $R_T$ = 30 $\mu$Ω when the current 600 A is applied also does not exceed 1.0 and shows a slight further rate of increment.

When changing the load current value from 600 to 200 A within the time range between 5 and 10 min, the wire and electrical connection get cooled to the new steady value of heating at 200 A. In this case, the defect rate for the transient resistance 25 $\mu$Ω and 30 $\mu$Ω tends to increase.
Figure 1. A fragment of the math modeling of the defect coefficient dependence on the time of exposure to cyclic traction load.

Figure 2. Dependence of the defect rate on current, when six current values are applied such as: 1 – $R_T = 30 \mu\Omega$, 2 – $R_T = 25 \mu\Omega$.

With the further change in the current value from 200 to 400 A, the wire and electrical connection are slightly heated [6]; within this range, the defect rate for the transient resistance $R_T = 25 \mu\Omega$ remains within 1.0, since for the transient resistance $R_T = 30 \mu\Omega$, the defect coefficient exceeds the permissible value and remains within 1.1-1.2.
Further, the wire and electrical connection are significantly heated at 800 A, the defect rate for the transient resistance $R_T = 25 \, \mu\Omega$ tends to decrease and does not exceed 1, for $R_T = 30 \, \mu\Omega$, the defect rate also goes down and remains within 1.

When changing the load current value from 800 to 200 A within the range of 20 to 25 minutes, the cooling process occurs [7], where the defect rate for both curves increases sharply, exceeding the permissible value, namely, $R_T = 25 \, \mu\Omega \, K_{\theta} = 1.2$; for $R_T = 30 \, \mu\Omega \, K_{\theta} = 1.4$. If the current value of 600 A is reached, the defect rate for the two curves decreases, but it exceeds 1.0.

Based on the presented curves, it can be concluded that in the case of cooling, the $K_{\theta}$ coefficient may exceed the permissible value, while it is possible to control the obtained values for satisfactory and unsatisfactory electrical connections and further consider them in the process of electrical connection health assessment [8].

Next, let’s study the exposure of the change in the ambient temperature on the value of the defect rate (figure 3).

![Figure 3. Dependency curves of the defect rate on the ambient temperature of various values ($R_T = 25 \, \mu\Omega$).](image)

During the initial period of the wire and electrical connection heating at 600 A, the defect rate changes exposed to the ambient temperature ($T_a$) of various values ($T_a = -20; -10; 0; +10; +20 \, ^\circ\mathrm{C}$), no significant influence of the ambient temperature on the value of the defect rate in the heating phase was reported. The heating temperature of the wire and clamp is also subject to minor changes.

During the cooling period (current reduction to 400 A) there is a clear difference between the defect rate values: at $T_a = -20^\circ\mathrm{C}$ the defect rate $K_{\theta}$ increases but does not exceed 1.0; at $T_a = +20^\circ\mathrm{C}$ the defect rate increases $K_{\theta}$ and reaches the value of 1.0; at $T_a = -10; 0; +10 \, ^\circ\mathrm{C}$ the defect rate is intermediate.

During the period of further heating at 400 A, the rate $K_{\theta} = 1.0$ at $T_a = +20^\circ\mathrm{C}$ and $+10^\circ\mathrm{C}$; the rate $K_{\theta}$ remains within the range of 0.9 – 0.95 at $T_a = -20^\circ\mathrm{C}$.

Within the time range of 15 to 20 minutes, 800 A is used for heating, and the defect rate becomes much less than 1.0.

It is known based on presented curves that the ambient temperature is minor on the value of the defect rate [9], but during the cooling process, the ambient temperature more intensively affects the value of the defect rate that should be considered when looking for additional criteria for the health assessment of electrical connections in operation [10].
3. Study of additional criteria for the health assessment of electrical connection for the heating-cooling cycles

To study the dependence of the angle $\Psi$ on the transient resistance $R_T$, a curve is plotted (figure 4) in the MathCAD software environment.

Knowing the value of the angle $\Psi$, which shows the rate of the defect rate gain under the heating, it is possible to predict the state of the conductive clamp for the entire time interval of the electric load [11].

To study the dependence of the angle $\Psi$ on the transient resistance $R_T$, we estimate its value exposed to currents of various amperage (figure 4).

When heated at 600 A within the time interval 0 to 5 minutes, the angle $\Psi = 10^\circ$ at $R_T = 25 \mu\Omega$, the angle $\Psi = 15^\circ$. When heated at 800 A within the time interval of 15 to 20 minutes, the angle $\Psi = 8^\circ$ at $R_T = 25 \mu\Omega$, at $R_T = 40$ microohms, the angle $\Psi = 14^\circ$.

We can conclude based on the obtained data, that, first, the angle $\Psi$ does not depend on the value of the flowing current, and, second, the greater the transient resistance, the greater the angle $\Psi$. Therefore, this dependence of the angle $\Psi$ directly correlates with the $R_T$ value for different heating-cooling cycles.

![Figure 4](image.png)

**Figure 4.** Curves of the defect rate $K_\theta$ exposed to current of various amperage (1- $R_T = 40 \mu\Omega$, 2- $R_T = 25 \mu\Omega$).

Also, the Figure 4 helps to identify that the value of the defect rate itself also specifies the health of electrical connection, since the curve 1 with the non-satisfactory transient resistance is higher than curve 2 with the satisfactory transient resistance [12]. Thus, two evaluation criteria can be processed at once for a cyclic traction load when defining the health of the electrical connection: the value of the defect rate itself and its change velocity (angle $\Psi$).

To assess the current state, the algorithm is elaborated to study the defect rate for non-steady modes of electric load operation [13] (figure 5).
The principle of the algorithm is as follows: the source data are entered on the status of bolted electrical connection, then it is surveyed as per the algorithm checking the temperature difference between the connection and the wire [14], then, on the base of the above, the phase of heating or cooling is specified. During the heating phase, the defect rate, additional criteria and the transient resistance are specified, and, as a result, the current state can be identified [15]. Next, the algorithm re-runs the cycle (depending on their number). At the specified number of cycles is completed, the current settings of bolted electrical connections are defined and the curve of the defect rate is plotted, and the state of the electrical connection is reported.
4. Conclusions
An application is elaborated in the Mathcad mathematical environment to calculate the change in the defect rate for a series of heating-cooling cycles simulating a rapid load alternating pattern.

We can conclude based on the obtained data, that, first, the angle $\Psi$ does not practically depend on the value of the flowing current, and, second, the greater the transient resistance, the greater the angle $\Psi$. Consequently, this dependence of the angle $\Psi$ allows the indirect calculation of the $R_T$ value when currents of various amperage are applied.

In addition, the elaborated software helped to calculate the change in the defect rate for actual operating currents at the Ussuri Power Supply Division of the Far Eastern Railway. The modeling results of real current changes showed that the defect rate value ranges from 0.5 to 1.35 with the satisfactory resistance of the electrical contact of 25-30 $\mu\Omega$, where the connections with nonsatisfactory resistance range 1.4 to 2.3. Based on the above, the connections of satisfactory and nonsatisfactory state can be ranked even if the load is transient as per the value of the defect rate.

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