



Diagnostics of Electrical Connections of Electric Traction Network

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Abstract. Full-scale structural measurements of new and existing electric traction networks are becoming increasingly important because of the ever-increasing train speeds and associated effects. Higher speeds lead to increased loads and greater structural dynamic responses, increasing mechanical and electrical loads. Electrical contact connections are an integral part of the electric traction network: under operating conditions, the electrical installation circuit in many cases should allow to separate the elements from each other. At the same time, electrical contacts are a weak component in energy distribution systems, since the occurrence of large transient resistances in the contact area is one of the most common cases leading to heating of the connection and breakage of the catenary. The purpose of the work is to improve the performance reliability and prevent damage to the electric traction network by reducing the complexity of servicing bolted electrical connections through the development and mass implementation of visual diagnostics. The main parameter characterizing the bolted electrical connection is its resistance, the value of which depends on two interrelated factors: parameters of the contacting surfaces and the contact force. Research of thermal processes in the contact connection and determination of its performance characteristics allow to create a method of diagnosis of the state of the electrical connection on the basis of new methods using modern equipment.

Keywords: Electrical connection · Mathematical model · Transition resistance · Diagnostics

1 Introduction

Any electrical system consists of connections through which electricity is transmitted from the source to the end consumer. In the electric traction network, energy is transmitted from electrical substations to the electric rolling stock. And in case of failure of one of the electrical connections (EC), there may be significant economic damage due to the occurrence of interruptions in the movement of trains [1].

The problem with EC in the electric traction network arises due to degradation processes associated with the deterioration of the transient resistance [2]. When its value increases, the entire EC overheats and, as a consequence, the temperature rises to critical values.

Therefore, the determination and prediction of the state of EC is an important problem to improve the operational reliability of the main electric railways [3].

2 Problem Definition

There are distinguished two states of electrical connection: satisfactory and unsatisfactory. The state depends on the value of transient resistance (RT), resulting from contiguity of contact surfaces of a wire and clamp dies. Under service conditions the value RT 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. The main indicator of the state of the electrical connection is the defect rate and the contact transition resistance [4].

The heating defect rate is not a constant value and is a function of the time of flow of current through the electrical connection. Moreover, it can be assumed that the value of the defect rate itself does not depend on the current value, but on the ratio of the physical (mass, electrical resistance) and thermophysical parameters (specific heat capacity and heat removal) of the clamp and the wire that form the EC.

3 Solution

In work [4] it is proved that in the electric current supply mode indirect estimate of value RT by means of defectiveness coefficient ($K\theta$), 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. 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 [5], without current being taken into account, and receive an expression:

$$(C_j m_j + C_w m_w) \cdot \frac{d\theta}{dt} = -[0.01312 \cdot \theta^{1.49} + \varepsilon S \cdot 5.67 \cdot 10^{-8} [(T_j + 273)^4 - (T_a + 273)^4]] \quad (1)$$

where C_w is the specific heat capacity of a wire material ($\text{W} \cdot \text{s} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$); C_j is the specific heat capacity of a clamp material ($\text{W} \cdot \text{s} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$); 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 ($^{\circ}\text{C}$); T_j is the temperature of a clamp

(°C); $5,67 \cdot 10^{-8}$ ($\text{W m}^{-2} \text{K}^{-4}$) is the Stefan-Boltzmann constant; ε is the relative emittance for bronze ($\varepsilon = 0.6$); θ is the excess of temperature of electrical connection over ambient temperature (°C).

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

$$\Delta\theta_C = \left(0.0108Pt (C_j m_j + C_w m_w)^{-1} + \theta_0^{-0.49}\right)^{-2.03} \quad (2)$$

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_θ , which represents the ratio of temperature variations of electrical connection to temperature variations of a wire [6]. As mathematical models of heating and cooling for a wire and an electrical connection are known (Fig. 1,a), it is possible to investigate K_θ temporal variation in the course of the “heating - cooling” cycle and consider the additional factors influencing the estimate of an electrical connection [7].

In Fig. 1,b, showing K_θ variation in “heating-cooling” cycle, it is possible to conditionally single out four areas of a curve which describes the thermalphysic 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 [8].

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 [9]. 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_θ 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_θ 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 $25 \mu\Omega$ adopted in modeling is considered to be rated. Thus, it is proved that process of cooling cannot be neglected on estimating an electrical connection state, otherwise research results may turn to be erroneous and misleading.

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 [7] and [8].

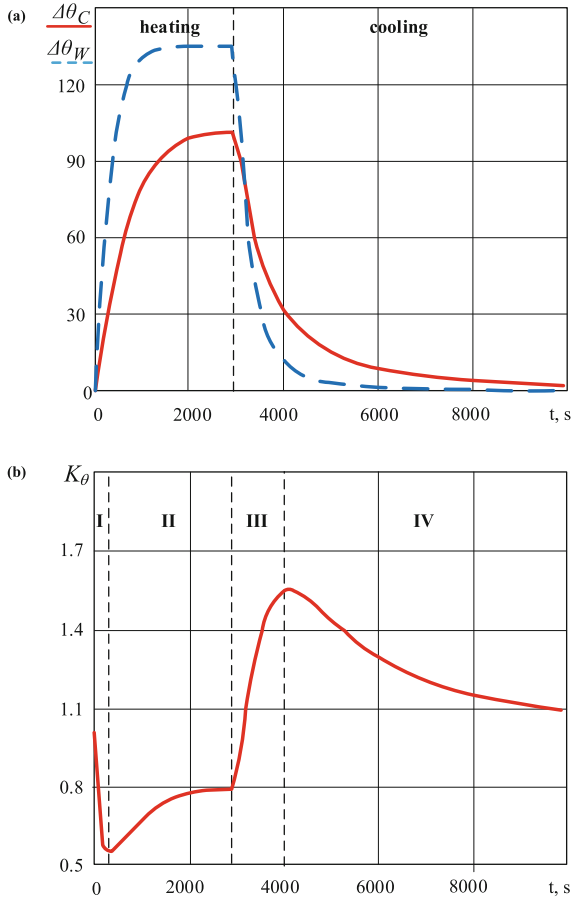


Fig. 1. “Heating-cooling” cycle of a clamp: a – temperature variation of a wire $\Delta\theta_W$ and an electrical connection $\Delta\theta_C$ related to the time period of conventional nominal current flow through them $I = 600$ A, at $T_a = 24$ °C; b – change of defectiveness coefficient K_θ with heating considered at $R_T = 25$ $\mu\Omega$

The Program performs calculations of differential equations concerning wire heating and electrical connections [3]. Applying the Program operation algorithm, the value of K_θ 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_n, t_k, t_d, t_c – covering the maximum and minimum values of changes of the graph [11]. The value of transient resistance ($r, \mu\Omega$) is set as well.

Plotting the graphs of dependence of coefficient K_θ 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_θ , 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_θ , 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 [4].

To confirm the above hypothesis, models of heating and cooling of the wire and EC are constructed. The ratio of these models makes it possible to investigate the defect rate over time. And in this case, it is possible to estimate the change in the defect rate at different values of the transient resistance, talking about the state of EC.

The study [9] showed that each transient resistance corresponds to a characteristic change in the defect rate. Thus, there is a theoretical assumption that during operation, it is possible to indirectly determine the transient resistance of EC by changing the defect rate, that is, to determine its current state.

To confirm the theoretical developments and approve new criteria for assessing the state of EC, on a specially developed bench, tests were carried out with real currents of 200, 400, 600, 800 A and with EC transition resistances of 20, 40, 60 $\mu\Omega$. Operational tests confirmed mathematical models of new evaluation criteria.

Based on these data, an algorithm for diagnosing EC was created, which allows to make an accurate assessment of the state of EC [5].

The measurement algorithm procedure (Fig. 2):

1. Constant monitoring of the defect rate value. To do this, the temperature is measured at two points with a time interval Δt .
2. The diagnostic algorithm is selected by the value of the defect rate.
 - 2.1 In the “cooling” mode, the state is evaluated by two criteria after the time has elapsed.
 - 2.2 In the “heating” mode, the minimum point is measured after the time has elapsed.
 - 2.2.1 Constant temperature measurement at two points with a time interval of 5 min + Δt .
 - 2.2.2 At the end of the measurement time, the slope of curve of the change in the defect rate value is determined.
3. The result of measurements of the electrical connection state parameters.

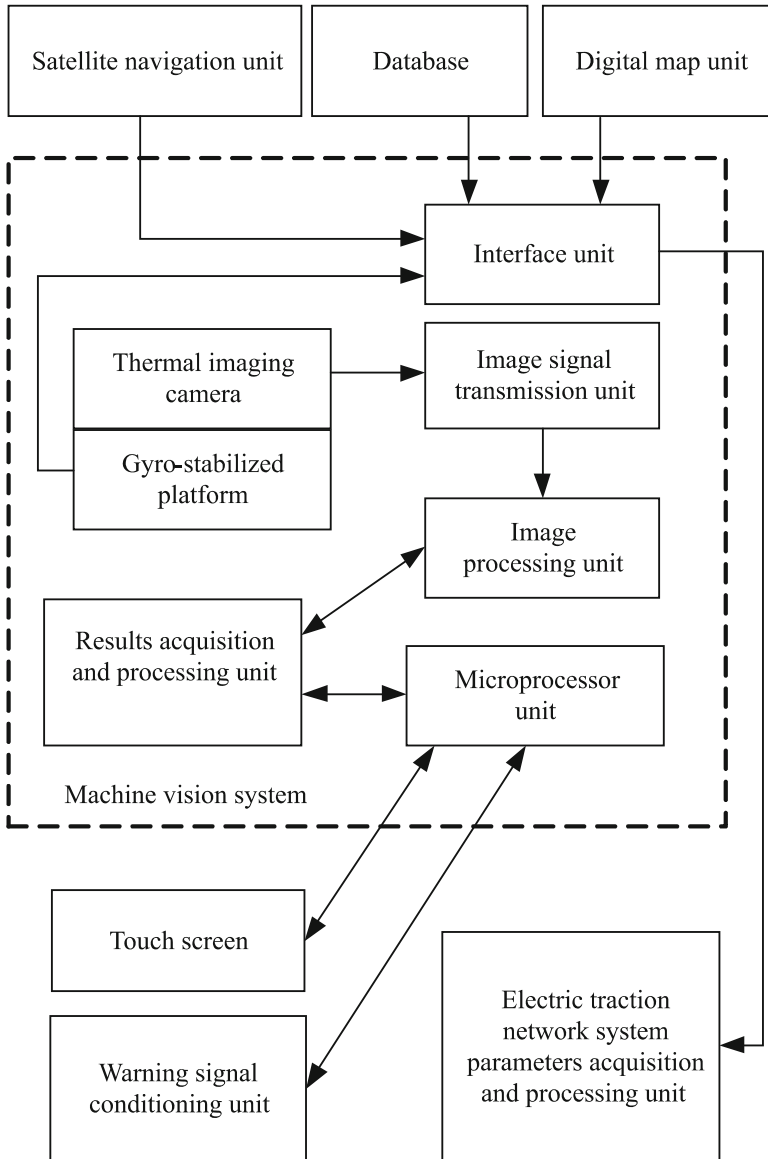


Fig. 2. The algorithm of the method for remote determination of the state of EC

Based on the obtained values of the slope and the value of the defect rate, a conclusion is drawn about the current state of the electrical connection. Next, activities are proposed depending on the current and forecasted state.

It is also necessary to pay attention to the different times required to obtain an opinion on the state of EC. In the “heating” mode, the measurement time is longer than

in the “cooling” mode. However, in the “cooling” mode there is no possibility to make a forecast.

From the described algorithm it can be seen that the account of both heating and cooling in the technique makes it possible to more accurately assess the state of the electrical connection. A failure to take into account one of the modes can lead to a false assessment. The assessment of the use of special methods and means of diagnosing EC is carried out [6].

To automate this algorithm, a measurement method is proposed, which is based on the acquisition and processing of images from a thermal imaging camera. It can be used to determine the temperature at the connection point and on the wire of the electric traction network. These two points are processed according to the presented models and the result of the current state of EC is given.

On the basis of the received technique it is possible to make operation algorithm of a remote method of monitoring of the EC state.

The method is based on the acquisition and processing of images from a thermal imaging camera, which can be used to determine the state of EC, as well as to determine other parameters of the traction power supply system (TPS) using measuring equipment [7].

The place of installation of the measuring equipment can be a car roof, or an embankment if the equipment needs to be moved by crew.

The process of obtaining and converting information (Fig. 3) starts with image acquisition by thermal imager. Then the image gets into the image signal transmission unit, and then into the interface unit, where the streaming video (or a series of frames) is generated. In turn, the interface unit receives geographical coordinates (when the position of the measured equipment changes, or the rolling stock moves), date, time, etc. from the satellite navigation system (GPS) unit [8]. The interface unit also receives terrain information from the digital terrain map unit. In turn, the streaming video of the interface unit is sent to the database and to the unit for acquisition and processing of TPS parameters, which is available at the Department of Power Supply Systems. This unit allows to process such parameters as I , U , φ , etc., obtained both in research of catenary system, and in research of traction substations [9].

Next, the image from the image signal transmission unit enters the interface unit, in addition, it enters the image processing unit (Fig. 3), which interacts with the unit for acquisition and processing of the obtained results (Fig. 4). With the help of a micro-processor, the information from this unit is transmitted to the warning signal conditioning unit and directly to the touch screen.

The key information provided by modern mobile laser scanning systems is information about the laser pulse reflection points. Each reflection point has its own coordinates in the global coordinate system and a certain set of characteristics (intensity, color, accurate time stamp, and others). The set of laser reflection points forms a point cloud.

In the future, it is proposed to create a database of the desired objects. Each database item contains information about the object. In the future, the database element will be called the object model. Since the railway infrastructure facilities are sufficiently standardized, their geometrical parameters can be defined in advance and contained in the model itself. Thus, the problem of automatically determining the geometric

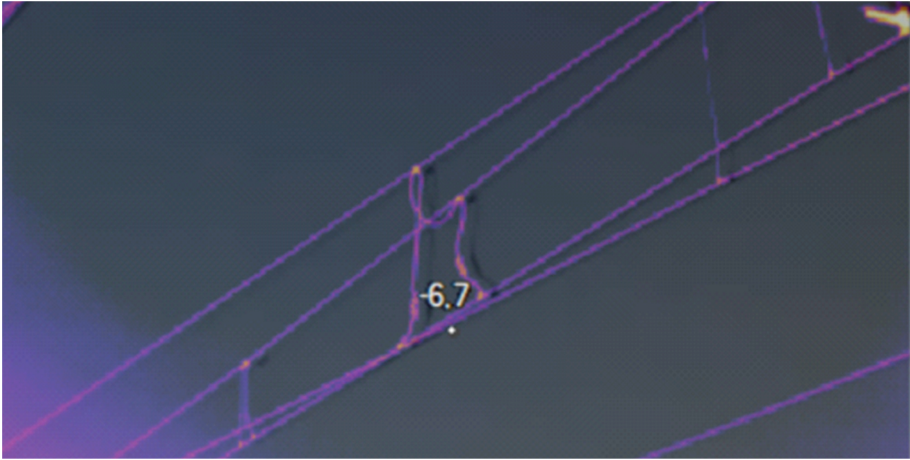


Fig. 3. View from the thermal imager

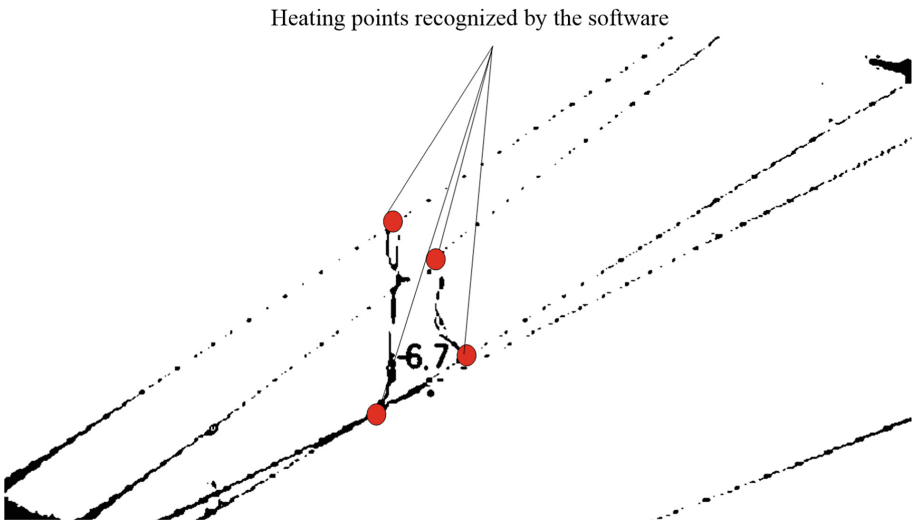


Fig. 4. View from the processing unit

parameters of objects is reduced to the problem of detecting objects corresponding to the database models in the point cloud, and then determining the orientation and position of the found objects in a certain global coordinate system.

The image processing algorithm is based on machine vision technology. To construct a plane, two parallel or intersecting lines are required. Characteristic lines by which we determine the location of the electric traction network wires and determine the location of the EC: always present in the analyzed image; it is possible to construct

two characteristic lines that are parallel; have a known size of the segment of the distance between the characteristic lines, have their own linear parameters. Highlighting these parameters, as well as areas with high temperature will allow to compile data on the heating of the electric traction network wires and EC [10].

Currently, the units for processing received information can be compact [11], which allows them to be placed in a mobile control device or permanently on the rolling stock.

4 Conclusions

Thus, the characteristic features of determining the state of EC in the operating mode are revealed. This will make it possible in the future to create stationary and mobile measuring complexes for diagnosing the connecting elements of the electric traction network, which will significantly reduce the damage caused by interruptions in the movement of trains.

There is no doubt that this technology of diagnosing EC can be in demand in other sectors of the economy in terms of safety of processes and human life [12]. For example, according to the statistics of emerging fires, about 30% is due to EC overheating as a result of emergency operation of the electric network due to high transient resistances [13].

At facilities with their own electrical system (buildings, ships, aircrafts, production, etc.), devices for monitoring the EC quality according to the proposed diagnostic technique can be created, which can save people's lives and reduce economic damage due to process flow disruptions.

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