Maintenance Cycle for Overhead Catenary Systems for Battery-powered Electric Trains

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Battery-powered electric trains charge their batteries through collection of a large current from contact wires through their pantographs whilst at a standstill in stations. This current tends to be larger than that collected by normal trains when immobile in a station. Usually, current flowing through a contact wire causes an increase in the temperature of the contact wire. In the case of battery-powered electric trains, pantograph contact strips do not slide along the contact wire in non-electrified sections, allowing an oxide-like film to form on the contact wire depending on the number of days of exposure. The influence of this film on current collection is thought to be high, though this has not yet been evidenced. Consequently, the authors of this paper conducted exposure tests, measuring the thickness of the film on contact wires, contact-resistance, and numerically simulating thermal conduction, to unravel the unknowns surrounding influence of this film. This paper reveals the influence of the film and proposes a method and cycle for maintenance in the light of these experiment results.

Keywords: battery-powered electric train, temperature rise, film, maintenance method, maintenance cycle

1. Introduction

Battery-powered electric trains only run with their pantographs sliding along contact wires in electrified sections, and consume the power stored in their batteries in the non-electrified sections. They recharge their batteries when immobile in stations, by collecting power from the power supply system via their pantograph and the overhead contact line. However, the recharging process generates heat in the current collecting materials due to the flowing current. Since battery-powered electric trains must recharge in a limited time, the current collected when at a standstill tends to be higher than on normal electric trains.

The contact wires in the catenary system are tensioned to maintain power supply system’s required geometry and to ensure proper contact with pantographs. When the temperature of the contact wire reaches 90 degrees centigrade, it begins to soften [1]. If the temperature exceeds this level, the wire may even break.

The temperature of the contact wire increases due to mainly to current flow, but also depending the external influences of the atmosphere and sunlight. Two types of heat are generated by the flowing current: joule heat generated due to current flowing through the materials, and heat due to the current flow in the film on the materials.

On normal railway trains, not battery-powered electric trains, the pantograph contact strip slides along the contact wire periodically; therefore, there is no cause for concern about a film forming on the contact wire. In the case of the battery-powered electric trains however, the pantograph contact strip does not slide along the contact wire when the batteries are used as the driving power source. This is the reason why in the case of battery-powered electric trains, the thickness of the film on the contact wire has a significant influence on the rise in temperature. However, the relationship between film formation rate, film thickness and contact resistance has not yet been quantified sufficiently.

Exposure tests, temperature tests, and numerical simulations were therefore conducted in order to understand the influence of this film on the increase in temperature of the contact wire.

This paper presents the results of those experiments, and based on these results proposes a method and cycle for maintenance which should be applied to battery-powered electric trains running in electrified sections.

2. Charging of battery-powered train

A battery-powered electric train is able to run through electrified and non-electrified sections without passengers having to change trains. JR East operates battery-powered electric trains on the Karasuyama line [2]. JR Kyushu also
began operating similar trains from the autumn of 2016 [3]. Other countries, for example France, Spain, China, Taiwan, etc. also operate battery-powered trains [4]. Given the advantages of these trains for improving customer services, they are likely to become increasingly common in the future.

Figure 1 shows a model line consisting of an electrified section and a non-electrified section where battery-powered electric trains are operated. The section between Station A and Station B is electrified and the battery-powered electric train can run using power collected from the catenary and pantograph systems. The section between Station B and Station C is not electrified so the train runs on battery power. Therefore, the battery-powered electric train needs to be recharged at Station B and Station C while it is at a standstill.

The time needed for recharging depends on the size of the current, and may influence services. Therefore, railway companies prefer using large currents to reduce recharging time. This however increases the temperature of the contact wire due to electric resistance, and also the risk of contact wire rupture. If railway companies used rigid conductor wires in their power supply systems, the problem would be solved. However, for practical reasons of maintenance, cost and connection to conventional lines, they use catenary/pantograph systems, and large currents mean that the film on the contact wire significantly influences the rise in temperature of the contact wire, leading to possible breakages of contact wire as explained above.

3. Experiments to understand the influence of the film forming on the contact wire, on the rise in temperature of the contact wire

Two experiments and numerical simulations were conducted to gain insight into the influence of the film that forms on the contact wire on increase in temperature of the contact wire. Figure 2 shows the flow chart to illustrate this study.

First, exposure tests were carried out in a bay area and a mountainous area along a railway line for about one week to one year and the film thickness on each sample was measured.

Second, the contact resistance between the contact strip of the pantograph and the contact wire was measured using the contact wire and pantograph samples. This experiment shed light on the relationship between the number of days of exposure and film resistance.

Finally, a numerical simulation was performed. A model was developed using the electric and thermal field analysis obtained through finite element method analysis, and the coefficient determined by rise in temperature tests conducted by passing current through a pantograph and a contact wire. The developed simulation method was used to estimate the temperature change in the contact wires covered in the film and the pantograph.

On the basis of these results, a maintenance method and maintenance cycle were then proposed for overhead catenary systems used by battery-powered electric trains for charging.

| Table 1 | Exposure test conditions |
|---------|--------------------------|
| Sample  | Copper based contact wires |
| Period of exposure | Bay area |
| 6 days | 10 days |
| 21 days | 14 days |
| 121 days | 27 days |
| 205 days | 98 days |
| 289 days | 198 days |
| 361 days | 284 days |
| 365 days | |
3.2 Contact resistance measurement

The contact resistance was measured between the contact wire samples retrieved from the exposure tests and the pantograph contact strips. Figure 5 shows the method used for measuring the contact resistances. A pantograph with four contact strips was used with a 54 N push-up force so a four-terminal method was used where voltage and current are measured. The contact resistances and their averages were calculated from the measurements.

Table 2 shows the materials used in the exposure tests. Copper based contact wires and contact strips were used, which are often used on Japanese meter-gauge railways.

Figure 6 shows the relationship between contact resistance and period of exposure. The contact resistance increased with the length of exposure up to about 200 days. For periods of exposure over 200 days, contact resistance on the samples exposed in the mountainous area tended to decrease. The reason for this was not identified. The contact resistance increased with the length of exposure on samples exposed in the bay area. The approximate relationship curve between exposure and contact resistance for the bay area is shown in Fig. 6. The relationship between period of exposure (D) and contact resistance (R) is shown by (3).

\[ R = 5.3 \times 10^{-3}D \]

3.3 Numerical simulation results

The finite element method was used for the electric and thermal field analysis in the simulation program to analyze the rise in temperature due to electric current. The
software used, Femtet, was developed by Murata software Co., Ltd.

The contact area needed to be on the surface in the simulation, and the contact wire had 1mm of wear on its surface as shown in Fig. 7.

Heat dissipation, $W_s$, was assumed to occur through natural convection in the simulation and was calculated by (4). $C$, $\theta$ and $\theta_0$ were the coefficients set in Femtet for natural convection, temperature of the object, and room temperature, respectively. Table 3 shows the parameters (the contact resistivity and the thermal coefficient) used in the simulation.

The radius of the contact area between the contact wire and the contact strip also needed to be calculated. The radius was derived from the contact resistance which is the contact resistance in the absence of any film on the contact wire. Equation (5) is the calculation equation for the radius. The electric resistivity of the contact wire, contact strip and the contact resistance are indicated by $\rho_1$, $\rho_2$ and $R_c$ respectively. The contact resistance was determined through the experiment in Fig. 5.

Figure 8 shows the relationship between the contact resistance and the contact force. It shows that the contact resistance did not depend on the size of the current. Figure 9 shows the calculation results for (5) and Fig. 8. These results were applied for the following discussion on the simulation.

Figure 10 shows the relationship between the change in temperature and the size of the current for each contact resistance. The change in temperature grew as the current was raised and also as contact resistance increased.

![Fig. 7 Cross section of contact wire](image)

**Table 3 Parameters used in simulation**

| Parts           | Contact resistivity (\(\Omega\) m) | Thermal coefficient (W/mK) |
|-----------------|-----------------------------------|-----------------------------|
| Pantograph head | 4.91 \times 10^8                  | 140                         |
| Contact wire    | 1.17 \times 10^8                  | 375                         |
| Contact strip   | 2.86 \times 10^7                  | 55.5                        |

![Fig. 8 Relationship between contact resistance and contact force](image)

**Fig. 9 Relationship between contact radius and contact force**

![Fig. 10 Relationship between size of current and change in temperature](image)

4. Application to railways

Tension is kept in contact wires to maintain the geometry of the catenary system and to ensure good contact with the pantograph. When the temperature of the contact wire reaches 90 degrees centigrade, it begins to soften. Given the tension in the contact wire, in the worst case scenario, it could break. To prevent this, the maximum temperature the contact wire can reach is set to 90 degrees centigrade in Japan. However, atmospheric conditions, temperature and direct sunlight also need to be taken into account, which can contribute up to 40 to 43 degrees centigrade \([5]\) of the contact wire temperature. Taking this into account, the maximum temperature the contact wire can reach due to joule heat is 47 degrees centigrade.

Applying this limitation to Fig. 10, the combinations of contact resistance and recharging current to raise the temperature of the contact wire up to the maximum limit are 250 A/2.23 mΩ, 275/1.86 mΩ, 325 A/1.16 mΩ, and 490 A/0.74 mΩ respectively.

In the case of 250 A/2.23 mΩ, 13.8 months would be required to arrive at the contact resistance of 2.23 mΩ based Fig. 6 or (3). To keep the contact wire temperature at 47 deg-
degrees centigrade or less, railway companies would have to carry out maintenance to keep the contact resistance down by removing the film on the contact wire. One approach to remove the film on the contact wire is polishing. Polishing can be carried out in depots and on sidings etc.

Railway companies usually apply leeway to maintenance cycles, rather than waiting until the maintenance cycle expires. That leeway is generally around half-way through the full maintenance cycle (one cycle being the time required for the limit value to be reached).

Table 4 shows the time limits and maintenance cycles for each recharging current. In order to keep the temperature of the contact wire to 47 degrees centigrade or less, railway companies would have to carry out maintenance on their contact wires according to the cycle shown in Table 4.

### 5. Conclusions

A battery-powered electric trains recharge their batteries when immobile in stations, by collecting power from the power supply system via their pantographs and the overhead contact lines. However, the recharging process generates heat in the current collecting materials due to the flowing current. Since battery-powered electric trains must recharge in a limited time, the current collected when at a standstill tends to be higher than on conventional electric trains.

The temperature of the contact wire rises when a current is passing through it; in the case of large currents, the change in temperature however tends to depend on the influence of a film that can form on the contact wire.

The relationship between the rate at which this film thickens, the film thickness, and the contact resistance have not been sufficiently quantified.

Therefore, exposure tests and temperature tests were carried out, and a simulation program was developed to gain insight into the influence of this film on the rise in temperature of contact wires. This study produced the following findings:

1. The film thickens with exposure. The layer of the films that formed on contact wire samples in the bay area was thicker than the layer found on samples retrieved from mountainous area.
2. The layer of the film on samples in the bay area thickened at twice the rate of those in the mountainous area.
3. Simulation results showed that the combinations of contact resistances and recharging currents for which the temperature of the contact wire reached the maximum limit of 47 degrees centigrade in Japan, were 250 A/2.23 mΩ, 275/1.86 mΩ, 325 A/1.16 mΩ, and 490 A/0.74 mΩ.
4. The periods of exposure that led to the contact wire temperature reaching the maximum limit were approximately 13.8 months, 11 months, half a year, and 4 months, for the currents 250 A, 275 A, 325 A and 490 A, respectively.
5. Anticipated maintenance cycles are therefore recommended at half the maximum periods of exposure that lead to the contact wire temperature reaching the maximum limit. Polishing was suggested as a method for removing the film from the contact wires.

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