Recent Research and Development Activities in Maintenance Technologies for Electric Railway Power Supply Systems

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In order to ensure reliability and stability of the electric railway systems, adequate maintenance operation for the electric power supply system is an essential matter. On the other hands, its maintenance operation involves high cost, because this system has a huge spatial scale. Furthermore, working population in Japan has been decreasing today, resulting in high demands on improving efficiency of the maintenance operation. RTRI has therefore been tackling the issue of improving in quality, efficiency and cost of the maintenance operation for the electric power supply system. This paper describes recent RTRI’s research and development activities on the maintenance technologies for the power supply system in order to overcome these issues.

Keywords: power supply system, maintenance, predictive maintenance, proactive maintenance, CBM, RBM, digital twin

1. Introduction

Electric railways offer many advantages, including high energy-efficiency, environmental-friendliness, and high-speed mass transportation capabilities. Therefore, many railway lines are electrified, such as high-speed lines, major conventional lines, and urban lines. However, the infrastructure for the feeding circuits including contact lines, return circuits and traction substations, that forms the backbone of power supply for electric railways, requires maintenance works with high-cost and enormous labor to keep it functioning. At the same time, it is predicted that the Japanese labor force will decrease rapidly after 2025, though it has almost leveled off over the past decade. Consequently, there is an urgent need for railways to develop labor saving and efficient maintenance methods for electric power supply systems for railways.

The power supply technology research group at RTRI is working to design energy-saving, maintenance-saving and very reliable electric power supply systems. This paper introduces recent research and development activities from this field, with particular attention to research works for innovation in maintenance of electric power supply systems. Some of the projects were not originally aimed at resolving maintenance issues, but have produced results which could contribute to labor saving measures and more efficient maintenance.

2. Strategies to foster innovation in power supply system maintenance

As with maintenance of general systems such as social infrastructures and manufacturing facilities, the maintenance of power supply systems has also evolved over time. Figure 1 is a historical overview of maintenance procedures. Initially, large-scale equipment was maintained on a breakdown maintenance basis, where equipment was repaired only after it had completely broken down. This was followed by the spread of preventive maintenance, based on periodic inspection/maintenance. Today, the trend is for predictive maintenance and proactive maintenance.

Preventive maintenance is based on Time Based Maintenance (TBM), where inspections/maintenance are carried out at fixed intervals, with or without any malfunction. In contrast, predictive maintenance monitors the health and performance of equipment allowing maintenance to be carried out as soon as any degradation is detected. Preventive maintenance relies on Condition Based Maintenance (CBM), supported by innovative technologies such as condition monitoring sensors and decision-making techniques to ensure timely maintenance according to the monitored data. For example, in the case of overhead contact lines, contact wire wear progresses relatively early; wear that exceeds the admissible threshold may lead to rupture, which can cause large-scale transport disruption. Therefore, an inspection car was introduced to periodically perform inspections of contact wires in order to ascertain progress of wear, and a system for planning timely contact wire replacement was implemented. ICT (information and communication technology) has been advancing in recent years, and is expected to be allow higher frequency or real-time condition monitoring by using IoT and AI. However, there are still many issues affecting the effective, low-cost monitoring of electric power supply systems, which are...
constantly subject to high voltage. Proactive maintenance is based on the concept that the essential causes/factors underlying serious problems should be eliminated where possible, and those which cannot be removed should be monitored with condition based maintenance. Proactive maintenance can be interpreted therefore, as a higher-level concept than predictive maintenance.

In addition to condition based maintenance where maintenance is carried out according to the condition of equipment, risk based maintenance is also increasingly used. Risk based maintenance evaluates the magnitudes of the risk involved in equipment failure based on data about inspections and malfunctions. Maintenance of different components is then prioritized accordingly, and can be applied to vast power supply system infrastructure.

The power supply technology research group at RTRI is conducting research and development in order to find ways to shift power supply system maintenance for electric railways from preventive to predictive maintenance, and then onto proactive maintenance. The following chapters introduce recent efforts to achieve this aim.

3. Digitalization of maintenance

3.1 Digital twin

As stated previously, effective condition based maintenance requires both condition monitoring sensors and decision-making techniques to ensure timely maintenance work is carried out in the light of monitored data. However, in the case of contact lines systems spanning large areas, subject to large currents and high voltage, special techniques are required to ensure data transmission and power supply to condition monitoring sensors: this makes dense installation of sensors difficult. Contact lines systems can be more effectively monitored, therefore, from a running vehicle. However, contact line dynamic quantities (displacements, stresses, etc.) which are essential indices for determining the health of the equipment, depend on vehicle conditions, such as running speed and meteorological conditions (temperature and wind), then it is not easy to evaluate these dynamic quantities under worst conditions only from data captured by a specific vehicle.

RTRI believes that these problems can be overcome by digitalizing maintenance, namely using a key technology called “Digital twin”, shown in Fig. 2. Contactless contact lines will be taken as an example to explain what Digital twin technology is: first, precise measurements are made of the static three-dimensional geometry of overhead contact lines using a running vehicle, and a refined digital model of the overhead contact lines is built from the measured data. Then, the dynamic behavior of the overhead contact lines and pantographs is evaluated through numerical simulation under various conditions. Finally, future deterioration of the overhead contact lines is predicted through numerical simulation. Periodic updates of the static digital model make it easier to understand temporal variations in the static geometry of the overhead contact lines. Finally, the specific type and timing of maintenance is proposed in accordance with this information. Digital twin is also effective for proactive maintenance, because the effect of equipment improvements such as changes in fitting positions and types, and tension, can be quantitatively predicted by using the digital model.

3.2 R&D to realize the digital twin method

To realize the digital twin method, the following technologies are critical:

1) Advanced equipment condition monitoring technology;
2) Simulation technology enabling accurate reproduction of the behavior of actual equipment;
3) Technology to predict and evaluate the degradation progress based on current equipment behavior.

The R&D conducted to develop these technologies are briefly introduced below.

3.2.1 Advanced equipment condition monitoring technology

In order to build a refined digital model of the equipment, accurate and effective monitoring technology of the equipment condition is essential. This paper introduces a contactless measuring device for overhead contact lines which facilitates the efficient construction of a digital model of overhead contact lines.

As shown in Fig. 3, the contactless measuring device for overhead contact lines [1, 2] is installed on the roof of a vehicle to measure the static three-dimensional geometry of the overhead contact lines. Laser scanners and line cameras are used for sensing. The stereo images of the overhead contact lines are acquired at the operating speed, and their three-dimensional digital model is built by image processing. The distinct feature of this device is its capacity to measurement the installation position not only of the contact wire but also the messenger wire and auxiliary messenger wire that support the contact wire. In addition, the device can identify the position of fittings on the overhead contact lines, such as droppers and connectors. Several methods for extracting fittings have been developed. Currently RTRI in association with Meidensha Corporation, is developing an extracting system [3] that detects fittings, identifies their type, and also provides a diagnosis.
of their state of health automatically by machine learning (Fig. 3). It is already possible to automatically extract fittings on overhead contact lines from image data acquired at a velocity of 130 km/h with an accuracy of no less than 90%. Current work is focused on increasing the accuracy of detection.

### 3.2.2 Simulation technology to accurately reproduce behaviors of real equipment

RTRI has been developing a number of simulators that can reproduce the behavior of sub-systems constituting the railway system and the railway simulator which is an integrated analysis tool combining them. With regard to power supply system simulation, a pantograph/catenary simulator [4] is under development to accurately reproduce the dynamic behavior of overhead contact lines and pantographs. The combination of this simulator with the contactless measuring device for overhead contact lines introduced in the preceding section is a powerful tool to realize the digital twin technology for overhead contact lines.

In association with Prof. Iwao of Tokyo City University a three-dimensional electromagnetic thermal fluid simulation method (Fig. 4) is also being developed to reproduce the dynamic behavior of arc phenomena which significantly affects contact wire and pantograph contact strip wear. Currently, the dynamic behavior of an arc column can be reproduced in limited conditions [5]. In future, the simulator will be upgraded to predict arc induced wear.

### 3.2.3 Technology to predict and evaluate progress of degradation from equipment behavior

Though the maintenance of power supply systems for electric railways is mainly aimed at preventing serious problems caused by degradation such as corrosion, wear, abrasion and fatigue, it is still difficult to quantitatively predict and evaluate their progress. As part of the drive for digital twin technology, elucidation of these degradation phenomena is extremely important. To illustrate the type of research being carried out to this end, this paper introduces research on the wear phenomenon caused by the sliding contact between contact wires and contact strips [6]. Contact wire and contact strip wear are seriously affected by the current flowing through them because high currents cause an increase in temperature on the contact surface resulting in melting of the contact wire and the contact strip even if the contact between the contact strip and the contact wire is good. In order to quantitatively evaluate this phenomenon, a theoretical formula to estimate the melted volume of contact wire due to the current was derived. When a contact strip made of iron-based sintered alloy was combined with a hard copper contact wire, the estimated melted volumes using this formula were compared with experimental results. Figure 5 shows the outcome of this comparison. Although a dispersion of the experimental results can be observed, this figure shows that both results show similar tendencies.

RTRI is also conducting a number of basic studies on degradation prediction, such as development of a method to evaluate the remaining serviceable life of transformers in substations [7], and a method for quantifying contamination of the surface of insulators with marine salt and corrosion of pins under the insulators [8].

### 4. Towards proactive maintenance and risk based maintenance for power supply systems

#### 4.1 Proactive maintenance

As previously stated, the core concept of proactive maintenance is removal of the essential causes/factors of serious problems. This section introduces some of the re-
search and development activities carried out in this field. Substations for electric railways are in principle operated remotely. Therefore, metal cables for controlling and monitoring various pieces of equipment are installed in and around substations. Since this represents a very high number of cables, in the region of 500-1000, inspection and replacement of cables is time consuming and labor intensive. Reducing the number of cables by digitalizing transmission of information can facilitate substation maintenance. This possibility was therefore investigated [9]. The study revealed that data transmission using wireless technology presented reliability issues. However, it also confirmed that data transmission over Ethernet or power line telecommunication systems was applicable for control and monitoring of equipment with a high degree of reliability, though data transmission was delayed by about 80-300 ms, which is longer than conventional transmission times using metal cables.

In the case of overhead contact lines, simplifying the equipment itself, in other words, reducing the number of members to be maintained is one way to reduce the labor required for maintenance.

Hence, many railway operators in Japan have been promoting simplification/integration of overhead contact lines on conventional lines (introduction of feeder-messenger wire, transformation of high-voltage power distribution lines into cables on the ground, etc.), such as the integrated overhead contact wire system used by JR East. Similarly, reducing the number of lines (from 3 lines to 2 lines) on high-speed lines, by replacing compound catenary systems with simple high-speed heavy catenary systems, has been introduced on the Tokaido Shinkansen operated by JR Central.

In association with JR East, RTRI has also developed two types of simple high-speed catenary system [10] for 320 km/h and for 360 km/h. Introducing these systems when replacing auxiliary messenger wires currently used on compound catenary systems, will make it possible to reduce the labor required for maintenance.

4.2 Risk based maintenance

The basic concept of risk based maintenance is to evaluate the risks inherent in the equipment in relation to cost. RTRI is currently working on the research on the quantification of risk caused by contact line system problems.

Figure 6 (a) is a risk matrix where likelihood (occurrence frequency) and impact (loss) of each problem are plotted based on maintenance data. This diagram enables a quantitative study of maintenance priorities. Figure 6 (b) is an example of a Life Cycle Cost (LCC) evaluation of overhead contact lines according to several maintenance strategy scenarios.

The research on risk evaluation for power supply systems has only just begun; therefore, there are still some issues to be resolved regarding the collection of problem and maintenance data. RTRI will continue its research and studies aimed at developing risk based maintenance.

5. Conclusion

This paper introduces the direction of recent RTRI research and development on maintenance of power supply systems for electric railways. RTRI is involved in various research and development activities in addition to those introduced in this paper, aimed at saving labor and developing more efficient maintenance. RTRI will conduct broad research aimed at developing innovative technologies for the sustainable development of railway systems, and always welcomes guidance and cooperation from other railway operators and other parties engaged in similar work.

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Fig. 6 Examples of risks and Life Cycle Cost (LCC) evaluation for overhead contact lines

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Research Areas: Dynamics of Pantograph-Catenary System, OCS Maintenance, Reduction of Pantograph Noise