Recent Topics on Power Supply Technology

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The COVID-19 pandemic continues to have a significant impact on railway business. Although it is still difficult to have a clear vision about a Post-Covid Society will be like for the moment railway services must be more reliable in order to avoid concentrations of passengers due to delays or cancellation of trains. In the longer term, railways must focus on lowering carbon emissions and improving maintenance. To this end, RTRI has been engaged in research to improve the reliability of power supply equipment, to save energy during train operation and to improve maintainability of power supply systems. This paper describes some of the outcomes achieved at RTRI through this recent research.

Keywords: power supply, power supply facilities, enhanced reliability, energy saving, low maintenance

1. Introduction

The COVID-19 pandemic that started in December 2019 still rages on with no end in sight in Japan. The pandemic has also affected railway business tremendously and it is too early to even attempt to envision a post-COVID-19 business environment. However, one thing appears certain: that is, people are demanding ever greater reliability in railway services, at least for now, to avoid congestion stemming from disruptions due to problems with facilities and equipment faults. With regards to the longer term, there are growing calls for the railways to reduce their carbon footprint to prevent global warming. In May 2020, JR East announced that it would redouble its CO$_2$ emissions reduction efforts in its railway business, aiming to achieve net zero CO$_2$ emissions by FY2050. At the same time, Japan faces an ageing population and declining birthrates: the productive population for FY2019 shrank 0.5% (about 400,000 people) year-on-year, confirming the declining trend.

Against this backdrop, study groups for power supply technology at RTRI have set targets and been striving to achieve higher reliability of power supply facilities and equipment, to realize greater energy savings and reduce maintenance. This paper presents some of the recent achievements from this work.

2. Enhancing the reliability of power supply facilities and equipment

High-resistance ground faults in DC feeding circuits are difficult to detect as the ground fault current is smaller than the load current in normal operation. Once they occur, ground fault failures can lead to major damage to the facilities and equipment, fire and other problems, which can easily lead to major transport disruptions.

For these reasons, it has been a challenge for many years to establish detection methods for and protection methods from high-resistance ground faults in DC electric railways [1]. Detection methods for high-resistance ground faults thus far proposed include those that use discharge gap devices and those that use protective wires. This, however, requires additional parts such as protective wires to be installed on contact line systems and is not conducive to reducing maintenance. This has led to a search for methods to detect high-resistance ground faults within substations.

While various condition monitoring devices have been installed at substations as well in recent years, detailed waveforms of substation output current during a high-resistance ground fault incident on a commercial line were also recorded (1000 Hz sampling, resolution 10 A, recorded for about 30 seconds) for the first time [2]. Detailed analysis of the waveforms recorded in the incident identified irregular, fluctuating components in large amounts not usually observed in normal operation. In the incident, intense arcs were observed on the equipment near the ground fault, and those arcs appeared to have caused the irregular, fluctuating components of the substation output current. Based on this assumption, a detection method for high-resistance ground faults through the monitoring of substation output current (Fig. 1) was proposed [3].

Figure 1 shows the algorithm for detecting currents associated with high-resistance ground faults. Feeding current waveforms are put through a band pass filter to remove low frequency components and high frequency components above several hundred hertz and selectively and
strongly dampen ripples after rectification (that are integral multiples of power frequencies). In the process, irregular, fluctuating components in a relatively low frequency range are extracted. A ground fault is diagnosed when fluctuations above the threshold continue in that range for over a set period of time. When applied to the waveforms of the substation output current from the high-resistance ground fault incident, the method successfully detected a ground fault in a faulty circuit. When applied to a normal circuit, the method did not erroneously detect any ground fault.

This method is effective in detecting ground faults above 1000-ampere with intense arcs. This development has contributed greatly to preventing high-resistance ground faults that can cause serious damage. Since the method is not sensitive enough to detect ground faults with smaller currents, this avoids unnecessary false detections in these cases, as the associated irregular, fluctuating components in the substation output current are not large enough to be picked up by the method. Now work is underway to develop a method for detecting ground faults through the sharing of data on energy transmission between substations and vehicles.

3. Making Power Supply Facilities More Energy Efficient

It is widely known that railways are more energy efficient than other transport modes and that its CO₂ emissions per unit distance per passenger is only about 14% of that for passenger cars (FY2017). The high energy efficiency of railways is largely attributed to electrification. With many of the main lines already electrified, however, even higher energy efficiency cannot be achieved through extended application of existing methods: this calls for more novel approaches. Accordingly, RTRI has been pursuing relevant projects including the development of new power supply facilities, such as an intelligent rectifier capable of actively controlling the output voltage of rectifier substations to limit the restriction of regenerative braking and a superconducting feeding system suitable for extended substation intervals and voltage drop limitation of overhead contact lines (OCLs), and the proposal of a new charging/discharging method for ground-based energy storage systems [4]. Of these projects, this paper presents an outline of a high-voltage DC feeding system that reduces feeding loss and increases efficient use of regenerative electric power.

DC electric railways are low-voltage, high-current systems characterized by a large Joule loss caused by the resistance of OCLs and significant voltage drops. These issues can be resolved effectively by increasing the nominal voltage. This, however, requires changes including modification of the substation equipment and traction circuit and the improvement in insulation performance of OCLs, making a voltage increase impractical. For these reasons, a high-voltage DC feeding system has been proposed that keeps the current voltage on the OCL while adding a high-voltage feeder to which voltage higher than that on the OCL is applied [5]. The system, shown in Fig. 3, makes use of DC-DC converters installed at and between substations to transmit electric power between the OCL and high-voltage feeder. There exists only a small body of research however, on specific methods to control the DC-DC converter which plays an important role in ensuring the efficient use of regenerative electric power.

Accordingly, by applying the operation of an auto transformer (AT) for the autotransformer-fed AC feeding system to the DC feeding circuit, a DC-AT control [6] was newly proposed that works to maintain a constant ratio between the voltage of the high-voltage feeder and that of the OCL (Fig. 4). The control method has the following characteristics: one is that, as there is a linear relationship between the load status of the OCL and the distribution of the electric potential of the high-voltage feeder, the electric potential gradient of the OCL matches that of the high-voltage feeder between the adjoining DC-DC converters, generating no circulating current; and another characteristic is that the operation of the AT, a linear element, is simulated by the DC-DC converter, offering a consistent circuit control.

A DC-DC converter to which the DC-AT control is applied can be considered an impedance transformer, something like a transformer. When the ratio of the voltage of the OCL to that of the high-voltage feeder is set to 4, the resistance of the high-voltage feeder as converted into the resistance of the OCL is only one sixteenth of when the voltage ratio is 1. This is equivalent to the resistance of the OCL between the DC-DC converters apparently becoming smaller, offering the benefits of reduced transmission loss and increased amounts of regenerative electric power available for efficient use. However, as self-arc-extinguishing semiconductor elements used as a component of DC-DC converters cannot withstand overload, the rated capacity must be set to a level close to the instantaneous maximum load.

To overcome this issue, a method was developed for limiting the power transmission volume for the DC-DC converter, or the instantaneous maximum load for the DC-DC converter, by introducing a resistance equivalent to the AT’s leakage impedance into the DC-AT control. This has
made it possible to reduce the rated capacity, and in turn the cost and size, of the DC-DC converter.

Figure 5 shows an example of simulated energy saving achieved by the introduction of a high-voltage DC feeding system. It shows the power consumptions of the relevant substations for a full-weekday operation with a typical train schedule before and after the introduction of the high-voltage DC feeding system. In this particular simulation, an energy saving of about 2.6% was achieved.

While energy saving technologies including those mentioned above directly contribute to a reduction in CO₂ emissions from train operation, renewable energies are expected to occupy an increasingly large share of the energy mix in total power generation in Japan. This trend also emphasizes the importance for the railway sector to actively embrace renewable energies in its effort to reduce its carbon footprint. Consequently, in FY2020, besides its projects on energy saving technology, RTRI launched R&D to actively tap renewable energies for railways.

Fig. 5  Simulated energy saving effect after the introduction of high-voltage DC feeding system

4. Low maintenance of power supply facilities

The maintenance of railway facilities and equipment has transformed from breakdown maintenance, largely post-failure repair operations, to preventive maintenance focusing on regular inspection and maintenance activities. It is anticipated, however, that securing enough numbers of highly skilled inspection and maintenance specialists will become difficult in years to come.

Accordingly, railway operators have been trying to transition further to predictive maintenance, timely maintenance of appropriate items based on condition monitoring. In order to be at the forefront of this shift, RTRI has been researching and developing low maintenance technologies focusing on the utilization of digital technology.

Generally, maintenance operations follow a cycle of “identification,” “prediction” and “maintenance.” Of these phases, “identification” is the most labor intensive in the case of power supply facilities. The introduction of automated and intelligent “identification” systems can greatly enhance low maintenance. Consequently, as part of its effort to automate the inspection/measurement of OCLs for the “identification” maintenance phase, RTRI developed a contactless measuring device for OCLs and method for measuring contact wire wear using the light section method. The former is mounted on the roof of an electric inspection car or commercial vehicle to inspect and diagnose various overhead lines (contact wires, messenger wires, etc.) and hardware (hangers, connectors, etc.) without physical contact while the latter is a small-sized highly accurate system for measuring contact wire wear.

The contactless measuring device for OCLs [7-10] employs a combination of image processing stereo measurement and laser measurement (with laser range scanner sensors) to measure the three-dimensional position of each overhead line and grasp the installation conditions of the automatic tensioner and other OCL components using image processing (Fig. 6 (a)). Currently, a related method is being developed that automatically identifies hangers, connectors and other hardware based on machine learning: image collection and analysis; identified data linked to measured three-dimensional positions of the OCLs; diagnoses; and classification of abnormalities. Accurate three-dimensional structures of OCLs complete with the positions of related hardware, if available, would make it possible to simulate the behavior of the OCLs depending on different pantograph conditions, offering an intelligent maintenance cycle for the OCL system.

The device was mounted on the roof of a commercial vehicle on a conventional line and trial measurements were conducted at speeds of up to 130 km/h. Amongst many findings, the trials found for example, that the device was capable of continuously measuring the three-dimensional positions of OCLs continuously measuring the three-dimensional positions of OCLs and was also able to measure the rotation angle of the balance weight tensioner pulley, as shown in Fig. 6 (b). In addition, repeated measurements of the contact wire’s static height and lateral deviation demonstrated an accuracy of +/-10 mm while over 90% of the hangers were automatically identified.

As for OCL hardware diagnosis, it is difficult to evaluate the accuracy in active-duty car testing. Therefore, a total of about 1,700 images of hangers in normal and various faulty states were prepared and machine learning-based analysis of those images was conducted to evaluate the accuracy of the diagnosis. The results, shown in Table 1, indicate

Fig. 6  Contactless OCL measuring device
Table 1  Examples of hanger abnormality classification results based on machine learning

| Hanger fault classification | Normal | Deformation | Lower open | Upper open | Missing cover |
|----------------------------|--------|-------------|------------|------------|---------------|
| True values                |        |             |            |            |                |
| Precision                  | 0.83   | 1.00        | 0.71       | 0.95       | 0.86          |
| Recall                     | 0.80   | 0.99        | 0.67       | 0.63       | 0.98          |
| F value                    | 0.81   | 0.99        | 0.67       | 0.63       | 0.92          |

an accuracy of about 80% for the current level of diagnosis. In many instances, a faulty hanger was evaluated as “normal,” i.e. the fault was overlooked, indicating that accuracy still needs to be improved. The identification and diagnosis of OCL hardware based on machine learning was made possible through cooperation with MEIDENSHA CORPORATION.

The method for measuring contact wire wear using the light section method [11] works as follows: first, a slit laser beam is radiated onto a contact wire from below and the emission line formed on the contact wire is shot using a two-dimensional camera to capture the bottom-half profile of the contact wire. The profile is then overlaid on the profile (circular) of a new contact wire to calculate the worn cross-sectional area (Fig. 7). In theory, the method is capable of measuring wear accurately even if the sliding surface is not even. The position of contact wire retaining hardware (hanger ears, double ears, etc.) and that position relative to the contact wire can also be measured. Verification of the system’s operating principle was conducted using a prototype installed on a Shinkansen vehicle.

It was found that the system was capable of measuring contact wire wear to an accuracy of within +/- 0.1 mm in remaining diameter.

The conventional contact wire inspection device may additionally require manual measurement or other actions when measurement accuracy is low, such as in unevenly worn areas. On the other hand, the light section method-based system is capable of measuring even those areas accurately, offering the possibility of eliminating manual measurement and thus helping to reduce maintenance.

Fig. 7  Contact wire profiles at a double ear and worn cross-sectional areas, obtained using the light section method

5. Conclusions

This paper outlined several recent RTRI research and development projects aimed at improving the reliability, energy efficiency and maintenance needs of railway power supply facilities. These examples only form part of the broader range of activities undertaken by RTRI for the realization of these targets. RTRI will pursue its efforts to propose unique and targeted technologies aimed at laying the foundations for a new era of electric railways. To this end RTRI always welcomes and encourages guidance from and cooperation with railway operators and other parties engaged in similar work.

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