Research and Development on Power Supply Systems for a Sustainable Society

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Carbon neutrality is a necessary goal as a countermeasure against climate change. Therefore, it has become more important to promote further energy saving and the use of energy storage systems in railway systems. Notwithstanding, falls in passenger traffic due to COVID-19 have had a significant impact on railway management, and reducing infrastructure maintenance costs has become an urgent issue. This paper presents recent research and development on power supply systems, especially for decarbonizing the railways and reducing resources required for maintenance of overhead contact line systems.

**Key words:** electric power supply system (EPSS), overhead contact line (OCL) equipment, sustainability, decarbonization, energy-saving, maintenance-saving

1. Introduction

At the United Nations Summit on Sustainable Development held in September 2015, Sustainable Development Goals (SDGs) were adopted as international goals for a sustainable and better world that should be achieved by 2030. This agenda included goals related to electricity and energy: “Affordable and Clean Energy” and “Climate Action”. To this end, in October 2020 Japan’s Prime Minister announced a decarbonization policy aimed at reducing greenhouse gas emissions, such as carbon dioxide (CO₂), to virtually zero by 2050. This accelerated the integration of active decarbonization plans into management policies, through ESG (Environment, Social, and Governance), including for railway operators.

To reduce the burden on the global environment, in “Research and Development Creating the Future of Railways — RESEARCH 2025” (current Master Plan from FY 2020 to FY 2024), RTRI has set the research task, “Low-carbon power feeding networks by coordinated power control” as part of the subject, “R&D toward the future of railways” (hereinafter, Future-Oriented Task) with a target of practically applying outcomes in about ten years from now. The research tasks in questions focus on electric power, which accounts for approx. 96% of energy consumption required for train operation in Japan, and in addition to “Reduction of energy consumed by railways”, which we have been working on for some time, it aims to reduce carbon by actively utilizing renewable energy from the power grid, external to the railway. For this reason, its major feature is to work on the construction of a method that enables coordinated control between railway energy storage systems (ESS) and the power grid (Fig. 1).

On the other hand, in terms of the domestic railway business environment, research also takes into account issues already predicted, including population decline due to declining birthrates and an aging population, a resulting decrease in passenger volumes, and the securing sufficient labor required for infrastructure maintenance. Nevertheless, since the COVID-19 pandemic outbreak in FY 2020, passenger volumes have declined faster than expected, and some predict that the effect of the pandemic will be prolonged. Thus, we are urgently required to provide R&D outcomes that raise the infrastructure sustainability by enabling resource reduction and selective allocation, such as life extension, maintenance-saving, and labor-saving by automating inspections in the maintenance of infrastructure including the EPSS.

RTRI has set the Future-Oriented Task, “Labor saving by digital maintenance” in the current Master Plan. We will work toward the construction of an integrated analysis platform for equipment status data and automatic diagnostic technology, in addition, will...
promote the practical application of outcomes from the FY 2019 and earlier Master Plans, thereby providing effective outcomes to address the above needs.

This paper introduces R&D on decarbonization and R&D on maintenance labor-saving for OCL equipment.

2. R&D on decarbonization

2.1 Efforts required for decarbonization

The following is a non-exhaustive list of efforts made to achieve a decarbonized society: Energy suppliers increase the ratio of non-fossil energy, such as renewable energy and reduce CO₂ emission intensity associated with energy consumption, in addition, establish separation, capture, storage and other technologies for CO₂ emissions which are unavoidable.

The main efforts of consumers include controlling energy consumption by introducing energy-saving technology and, for users of fossil fuels, promoting the conversion to non-fossil fuels, for example, by electrification or hydrogen utilization. For suppliers to increase the ratio of variable renewable energies such as solar and wind power, the resilience of the power system is required to be strengthened, and consumers are required to have flexible adjustment capabilities such as load leveling and energy storage.

Most railway operators are consumers, and the decarbonization of railway operations with high electrification rates largely relies on the efforts of suppliers, but consumers should also steadily increase measures that can be rationally introduced, centering on energy-saving.

2.2 R&D on energy-saving

Regarding R&D for energy-saving in train operation, our past efforts regarding the EPSS include developing a high-voltage DC feeding system that applies power conversion technology [1] and making power utilization more efficient by applying energy storage technology and superconducting technology; in addition, we developed the Train Operation Power Simulator, which can quantitatively evaluate the effects of introducing these technologies [2].

The research task that we are currently working on, “Low-carbon power feeding networks by coordinated power control”, aims to establish an algorithm that assumes the introduction of ICT enables high-speed ground-train and train-to-train communication. This algorithm will generate a train performance curve for each train, which should provide the most energy-saving performance in consideration of the utilization rate of regenerative energy, in real-time according to operating conditions. For example, if a train is delayed this may lead to other delays due to late departures or suspended operations and deceleration between stations because of signals, resulting in increased train operation time relative to the schedule. Figure 2 shows the energy-saving train performance curve that was obtained when the maximum speed between stations was reduced by minimizing as much as possible the increase in stop time due to late departure or suspended operation and allocating that time to the time traveled between stations.

The Train Operation Power Simulator was used to estimate the substation power consumption for one hour, including the period during which delays were introduced. The results showed that the proposed method can reduce power consumption by approx. 1% to 2% [3].

Besides, we aim to propose a method for creating a schedule that is expected to be the most energy-saving in consideration of the utilization rate of regenerative energy, assuming that the station-to-station section train operation time is allowed to be revised in creating the schedule. However, since revising train operating times may negatively impact passenger experience, we are aiming to achieve both energy-saving and ensure passenger convenience, while quantitatively evaluating the convenience.

We expect to reduce energy consumption by several percent compared to train operation energy based on the conventional timetable and train operating method by utilizing the above outcomes.

2.3 R&D on the utilization of ESSs

The Sixth Strategic Energy Plan, compiled by the Ministry of Economy, Trade and Industry, includes an ambitious outlook for the power generation mix in 2030 to raise the proportion of renewable energy to around 36% to 38%. It states that among renewable energies, solar power and wind power will account for around 15% and 6%, respectively; ensuring system coordination capabilities for these variable renewable energies will be increasingly important.

For railways in Japan, the introduction of ground-mounted or on-board ESSs is being promoted mainly for energy-saving applications by effectively using regenerative energy or for emergency running applications in the event of a power outage. In addition, the introduction of storage battery vehicles is in progress toward the electrification of railcars. There is also an example of introducing a large-capacity ESS for the purpose of peak shift, etc. of railway load.

In “Low-carbon power feeding networks by coordinated power control”, we are aiming to construct a system configuration and control method for ESSs of railways so that equipment for emergency running can be used for energy-saving or equipment for energy saving can be used for adjustment. This project also aims to establish a method for quantitatively evaluating the implementation impact of such measures and the effect on the life of equipment being used in this original way. Figure 3 shows an example of results of trial that were obtained from the example shown in Fig. 4, which includes a case where a large-capacity ESS installed in a substation is used for charging regenerative power and a case where it is also used for charging renewable energy connected to an AC system of the railway [4]. The conventional control, which charges only the regenerative power, reduces the amount of purchased power from the power company at the substation equipped with the ESS by 3.6 MWh compared to the case without an ESS. However, it reverses all renewable energy not consumable by the railway to the power company system. By contrast, the proposed control further reduces the amount of purchased power by 1.4 MWh by charging and utilizing renewable energy that was conventionally included in the reverse power flow.

By applying these results, we expect to improve the CO₂ reduction effect approx. 2 to 5 times relative to existing ESS.

Fig. 2  Example of the energy-saving train performance curve when a delay occurs [3]
3. R&D on maintenance labor-saving of OCL equipment

3.1 R&D on Life Extension and Maintenance Cycle Extension

OCL equipment is a single system, which requires high reliability. Therefore, it is important to prevent defects such as disconnection. In addition to regular patrols and inspection measurements, if equipment exhibits an anomaly, deterioration, or wear progress, it must be appropriately repaired, replaced, or handled otherwise. One of the issues with extending the life of equipment and the maintenance cycle is to reduce the wear of current collection materials such as contact wires and pantograph contact strips: we are working on basic research to elucidate the mechanisms underlying each type of wear, to propose measures for wear reduction.

To elucidate the wear phenomenon caused by the heat generated by energized contacts, we conducted a wear test using a direct-acting wear tester that can perform a sliding test with a constant contact force during energization, and also conducted a temperature analysis of the energized contacts; then, we created a current collection material energization wear type map (Fig. 5) [5]. In the figure, the vertical axis represents the contact voltage between the contact wire and contact strip, and the contact boundary coefficient on the horizontal axis represents the ratio of the electrical resistance including the surface coating resistance of the contact wire and contact strip. It shows that the type of wear due to heat generation of the energized contact clearly differs depending on the contact conditions. The differences among these types of wear are caused by the differences in melting point and electrical resistivity between the contact wire and contact strip.

Furthermore, to elucidate the wear phenomenon caused by frictional heat during sliding, we manufactured a rotary wear tester that can increase the sliding speed and measure the contact temperature. From the results of the wear test with this tester, the mechanical wear type was subdivided into four types according to the contact temperature (Fig. 6), clarifying the transition conditions of the respective wear types [6]. We will continue to work on the elucidation of the wear mechanism in consideration of the actual field conditions such as the internal temperature of the contact strip member, the zigzag deviation of the contact wire, and the effect of the train draft.

With regards to R&D that contributes to the reduction of salt damage countermeasures such as insulation strengthening and insulator cleaning, which are mainly performed in OCL equipment in coastal line sections, we constructed an insulator pollution degree estimation algorithm using public data on weather and topography [7]. Although the pollution classification was previously defined uniformly based on the distance from the coast, this method has enabled it to be subdivided, which is expected to lead to a review of maintenance in line with the actual conditions of each region.

3.2 R&D on automation of inspection

Regarding R&D on automation of OCL inspection measurement for the purpose of maintenance labor-saving, RTRI is working on anomaly detection of OCL metal fittings using image data acquired by the OCL non-contact measuring device [8] developed so far. As part of this, we have proposed an image normalization method using line position information [9]. When deforming an image of arbitrary size of a dropper or another extracted from image data to a constant size suitable for machine learning, this method deforms the image in a way which preserves information in the image near the
connection with the line where abnormalities are likely to occur
(Fig. 7).

We have obtained insight which suggests that anomaly detection accuracy can be improved by learning image data normalized by this method in unsupervised machine learning using a generative adversarial network.

Railway operators are conducting R&D on using unmanned aerial vehicles (drones) for OCL equipment inspection and image data collection. However, magnetic fields generated from OCLs or others may affect the flight control of drones. Especially on DC contact lines, a residual magnetic field is generated by magnetizing metal structures such as beams and steel pipe columns; this is thought to also affect flight during nighttime power outages. Therefore, RTRI has investigated the effect of the DC magnetic field on the flight control of drones and proposed the concept of flyable areas, based on the simulation of residual magnetic fields by the magnetization of metal structures [10].

4. Conclusions

This paper introduced R&D on decarbonization from the viewpoint of a Sustainable Global Environment and R&D on maintenance labor-saving of OCL equipment from the viewpoint of Sustainable Railway EPSS. In fact, these examples are only part of the various undertakings by RTRI for the realization of these targets. We will continue to work on original and innovative R&D for the sustainable development of railways and ask for the continued guidance and cooperation of railway operators and other related parties.

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