Power Transmission Performance Verification of a Non-contact Power Supply System for Railway Vehicles

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The development of a Non-contact Power Supply system (NPS) in various devices is in progress. When applying the NPS to railway vehicles, an increase in loss is anticipated because A.C. magnetic flux causes eddy currents in the rails with magnetism and conductivity. A figure-of-eight coil configuration was proposed whereby the eddy current loss can be reduced. Using this coil configuration, an NPS for railway vehicles was designed. A prototype NPS was made for trials on the test line at the Railway Technical Research Institute on the basis of this design. Results of power-transmission tests conducted on the vehicles both when stopped and when running, confirmed that the NPS was a suitable power source for railway vehicles.

Keywords: non-contact power supply, figure-of-eight coil, power supply with running

1. Introduction

A Non-contact Power Supply system (NPS) in various devices has been in development. Particularly, a non-contact battery charging device for electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) has been developed to eliminate the need for plug connections in the automotive field. This paper therefore describes work to develop a non-contact power supply system for railway vehicles [1] [2]. The system can eliminate mechanical contact parts, such as pantographs. Therefore, the system decreases the danger of electric shocks or leaks, and provides maintenance-free features.

Recently, battery-run or hybrid trains equipped with battery cells have been in commercial use on the Japanese railway system [3]. However, battery cells for running trains increases the overall weight of car bodies whereas it is desirable to reduce weight as much as possible. Applying the non-contact power supply system to these vehicles, would make it possible to charge battery cells safely and easily. The weight of the battery cells of these vehicles can be reduced by charging the battery cells at intermediate stations.

In this work, an application concept for local lines was examined, and an NPS for the concept was designed (300-kW-class). After that, a proto-type NPS (50-kW-class) was developed and the power supply characteristics on the test track were evaluated.

2. NPS for railway vehicles

2.1 NPS methods

Various NPS methods exist, such as inductive coupling, magnetic resonance, micro wave, etc. Inductive coupling allows for a large capacity electric power supply with a short gap length. Magnetic resonance can supply electric power at long distance. However, according to current research, magnetic resonance only provides intermediate power of tens of kW. Micro wave can supply large capacity electric power at long distances, however, using high frequencies of over MHz, makes the conversion efficiency low compared with other methods. Since the electric energy required for railway vehicle traction is large, the required power capacity of the NPS is also large, and must be the order of hundreds of kW, even if the peak power is distributed between the battery and the NPS. Consequently, in this study, inductive coupling which is capable of large capacity power supply was adopted as the method for NPS in railway vehicles.

2.2 Circuit topology

Reactive power caused by the leakage flux of the transmission coil is generally compensated for using a resonance capacitor in the non-contact power supply system by means of the electromagnetic induction. There are 4 topologies according to whether the resonance capacitor is connected in series or in parallel to the primary coil and the secondary coil (Table 1). The SS and the PP topologies that are capable of using the same control method both on the primary side and the secondary side are suitable for bi-directional power supply. In SP topology, if using the constant voltage source on the primary side, the secondary voltage becomes constant and the power of the source follows the value of the load passively [4]. With SP topology, the primary power source can supply the needed power without communication with the vehicle as the secondary side. In this work, SP topology was selected as the circuit topology for NPS in railway vehicles.
2.3 Coil configuration

In cases where the non-contact power supply system is applied to railway vehicles, transmission coils are generally installed between the bottom of the vehicle and the rail. The leakage flux of the transmission coil that poses the problem of the increasing eddy current loss in the rail and that of the environmental magnetic field should be reduced by decreasing the magnetomotive force or designing a low leakage flux coil configuration. In this work, the length of the primary coil is long. The efficiency of the NPS is greatly affected by the eddy current loss from leakage flux in the primary coil. A rectangular coil and a three phase wave winding coil were proposed as the coil configuration (Fig. 1) [5]. The rectangular coil reduces the leakage flux by adopting the ferrite core to the primary coil. The magnetic flux is mostly confined within the ferrite core. The three-phase wave winding coil reduces the leakage flux with dipole flux distribution in the transport direction. A figure-of-eight coil was proposed which is capable of decreasing the leakage flux with dipole flux distribution between the rails. Figure 2 shows the schematics of the NPS with the coil configuration of the figure-of-eight coil. In this coil configuration, eddy current loss in the rail is quite low even without the ferrite core. The primary coil can be configured with only 4 cables. Therefore, we call the primary coil as a feeder cable.

3. Application concept

To determine the required specifications of the NPS, estimations were made for applying the concept to a local line. The length of the line was 25 km, with 11 stations. The vehicle of the concept was a two car train with battery cells. The battery was charged at every station with the NPS. The estimated volume of the required battery cells of the concept was 66 kWh. This concept can reduce the number of required battery cells compared with a 222 kWh model in which the battery cells are charged only at terminal stations. Figure 3 shows the schematic of the NPS used in the concept model. A feeder cable of 85 m was installed at a station and in short sections surrounding the

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**Table 1** Compensating NPS topologies

| Secondary   | Primary               | Series compensated | Parallel compensated |
|-------------|-----------------------|--------------------|----------------------|
| Series compensated |                       | SS topology        | PS topology          |
| Parallel compensated |                   | SP topology        | PP topology          |

(Circuits on the left and right are the primary side and the secondary side respectively)
station. Running power supply near the station made it possible to increase the volume of charging energy per station. The required power of this NPS model was 300 kW.

4. Design of a 300kW NPS

A transmission coil that can be installed under the car body was designed. The coil inductance was assumed by magnetic field analysis. A high frequency AC current is generally used for non-contact power supply by inductive coupling. When a high frequency current is used, the AC resistance increases due to the skin effect and the proximity effect. These AC resistances have a close relationship with the frequency. Thus, the operational frequency should be carefully selected. To prevent the increase of AC resistance, a litz wire is generally applied to the conductor of the cable and coils. Furthermore, the proximity effects at some frequencies were estimated using the magnetic field analysis [6]. From the simulation results, an operational frequency of 10 kHz was used. Table 2 shows the specifications of the designed NPS. The designed coil can be installed in the area between the bogies of one car. The system is able to increase the collection power capacity by increasing the voltage of the power source and adding extra pickup coils of which outputs are connected in parallel.

5. Development and verification of the proto-type

5.1 Development

To evaluate the performance of the system on the actual railway track, a 50 kW-class proto-type system was developed, and its power collection performance was evaluated on a test track using a test vehicle. The right-hand column of Table 2 shows the specifications of the proto-type. In consideration of the decrease in the power capacity to one sixth (300 kW to 50 kW), the source voltage and the number of pickup coils were changed from the designed value to one sixth of it. Figure 4 shows the feeder cable and the pickup coils. The system starts power supply au-

| Table 2 Specifications of NPS |
|-------------------------------|
| Designed | Proto-type |
| Source output | 300 kW | 50 kW |
| Source voltage $V_a$ | 750 V | 125 V |
| Frequency | 10 kHz |
| Configuration | Feeder cable, 18 pickup coils | Feeder cable, 3 pickup coils |
| Mechanical gap length | 75 mm |
| Feeder cable | Turn number $N_1$ | 1 turn |
| | Length in the transport direction | 85 m | 13.2 m |
| | Rated current $I_1$(RMS) | 400 A |
| Pickup coil | The number of turns $N_2$ | 4 turns |
| | Rated voltage $V_2$(RMS) | 440 V |
| | Rated current $I_2$(RMS) | 160 A |

(a) Feeder cable

(b) Pickup coils

Fig. 4 Proto-type of the NPS
tomatically when the test vehicle enters the section where the feeder cable is installed using a position sensor. Figure 5 shows the schematic of the experimental circuit. The experimental setup is applied in such a way that a high frequency inverter energizes the feeder cable, the outputs of the three pickup coils are converted into DC by a full-wave rectifier, and the output is connected to the load.

A coaxial cable was used to connect the high frequency inverter to the feeder cable.

5.2 Power supply test under stationary conditions

The basic power supply characteristics of the prototype under stationary conditions were verified. The load resistor was connected to the NPS output. The high frequency inverter supplied the power to the onboard resistor when the vehicle was stopped in the area where the feeder cable was installed. Figure 6 and Fig. 7 show the voltage and current wave forms of the power source and the load respectively. As shown in Fig. 6, the voltage of high frequency inverter switched when the current was around zero. Thus, the high frequency inverter achieved the low switching loss operation. The system supplied the load resistor with the power of 38.7 kW at a frequency of 10.8 kHz. The efficiency of the power transmission between the output of the high frequency inverter power source and the input of the load resistor was 72.6 %. Figure 8 shows the loss distribution. The large part of the loss was the feeder
5.3 Running power supply tests

Basic running power supply characteristics were examined. The circuit configuration was the same as for stationary tests. Figure 9 shows the time chart of the power of the load at each speed. The high frequency inverter started power supply when the vehicle enters the section where the feeder cable was installed. The result indicates that the power increasing characteristics at each speed were mostly the same. The power reached a steady-state after 1.5 s. The time required for power to reach a steady-state can be shortened by changing the control parameters of the high frequency inverter. The control parameters of high frequency inverter were not optimized in this examination. Table 3 shows the power supply characteristics at each speed in the steady-state. The steady-state data at over 20 km/h could not be recorded because the vehicle passed the section where the feeder cable was installed before the power supply achieved a steady-state. The result indicates that the inductive coupling can supply the electric power whatever the vehicle speed is. These results indicate that the proto-type can achieve stable power supply regardless of the running conditions.

5.4 The coordinate power supply of the NPS with a battery unit (stationary condition)

In an actual vehicle, the load value fluctuates with traction, braking, air conditioning, etc. Therefore, the NPS must provide stable power supply even under the influence of these fluctuations in load, in coordinated fashion with other power supply devices such as the battery unit. The coordinated operation of the NPS with the battery unit when stationary was thus demonstrated. Figure 10 shows the schematics of the circuit configuration. The output of the NPS was connected to the chopper, the voltage was raised from 600 V to 1500 V and the power was supplied through the 1500 V line to the onboard apparatus of the main circuit. Figure 11 shows the time chart of coordinate power supply. The positive battery power indicates discharge and the negative battery power indicates charge. NPS output was set constant between the points A and D. Between the points B and C, the load value increased, the battery unit supplied power to the load and NPS output was stable. After the point D, the charging of the battery was started by increasing the output power of the NPS. As shown in the time chart, the battery was charged by the NPS. These results demonstrated that the NPS can supply the power to the load with the battery and charge the battery. Thus, verification showed that the developed NPS is effective as a power source for railway vehicles.

6. Conclusion

A prototype NPS for railway vehicles was produced and tested at the Railway Technical Research Institute. The prototype supplied electric power of about 40 kW to the onboard resistor. As a result of the power-transmission tests conducted on both stationary and running vehicles, it
was verified that the NPS is effective as a railway vehicle power source.

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