A Study of Structure of Inductive Power Transfer Coil for Railway Vehicles

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This paper describes an optimized design of secondary coils in the inductive power transfer (IPT) system for railway vehicles. The gap between the primary and secondary coils is large, and the weight of the onboard secondary coil needs to be reduced. Thus, we propose a design method of dimensions of the secondary coils and unique cross-section of the secondary coils to improve the induced voltage and to reduce the self-inductance of the secondary coil. Further, practical issues that arise when applying the design to the railways, for example, human exposure to time-varying electric and magnetic fields, are examined.

Keywords: inductive power transmission, electromagnetic induction, magnetic cores

1. Introduction

Recently, high frequency Inductive Power Transfer (IPT) systems are studied in order to realize contactless electric power supply to automobiles, railways, household electrical goods and artificial hearts (1)–(14). Applications that use IPT systems offer several advantages over contact power transfer system since there is no physical connection between the primary and the secondary coils. In railway application, IPT systems reduce maintenance cost of pantograph and overhead wire. Moreover, IPT systems are suitable for the route where overhead wire is undesired due to scenery preservation perspective, and also suitable for magnetic levitated vehicle which cannot utilize contact power transfer method. In this paper, we describe a contactless power transfer method especially for railway vehicle. Previously, discussions regarding contactless power transfer methods are mainly focused on feeding power to stationary object, such as parked electric vehicle. In this kind of fixed point power transfer method, the vehicle needs a lot of auxiliary power such as batteries to reserve the power for travel. The weight and necessary space for the auxiliary power will become huge as the vehicle needs a long distance travel. Therefore, it is important to examine and develop IPT system for moving vehicles (movable IPT system).

A primary coil with ferrite cores have been examined (11) to improve the coupling between the primary and the secondary coil, however it is not economical and maintainable to install huge amount of expensive cores along a long distant railway. Thus, this paper examines on almost infinitely long cable-type primary coil without cores, which are laid parallel to the moving direction of a vehicle. They are the most simple and economical primary coil construction to provide power for the railway vehicles.

While the IPT systems robust over the lateral misalignment between the primary and the secondary coils are examined to apply to the electric vehicles (15)–(21), the lateral misalignment of a railway vehicle which is traveling along the moving direction straightly is not so large compared with the electric vehicles (22). However, two suspensions between body and bogie, and between bogie and wheels in the railway vehicles cause larger vertical vibrations of the on-board-coils compared with the electric vehicles which have only one suspension. Therefore, the gap between two coils should be kept large to avoid a hazardous contact during high speed travel. In the stationary IPT system, a secondary coil which is attached to the bottom of the vehicle can operate mechanical up-and-down motion to reduce the magnetic gap between the primary and the secondary coils. On the other hand, the movable IPT system cannot reduce the magnetic gap mechanically. As a result, the movable IPT system requires a special designed secondary coil to obtain high performance because the gap should be kept large. Thus, installed ferrite core in the secondary coil is indispensable to increase the magnetic coupling between the primary and the secondary coils.

Since the secondary coils are installed on the railway vehicles, especially on the magnetic levitated vehicles, their weight reduction is strongly required. Hence, the shape of the secondary coil for large air gap should be optimized to reduce the weight. In this paper, in order to design the most suitable coil dimensions for large gap, the theoretical relationship between the magnetic fluxes and the coil dimensions are examined. Furthermore, since reactance voltage and eddy current loss generated into the vehicle also should be reduced, we examined an optimized cross-section and ferrite core shape in the secondary coil, which is different from those of the stationary IPT system.
This paper described the method of designing the dimensions of the coils and the unique structure of secondary coil suitable for the movable IPT system that is designed by using magnetic analysis and experiments. In addition, practical issues such as human exposure to time-varying electric and magnetic fields (EMF) are examined to apply the movable IPT system to high speed railway.

2. Basic Structure of Movable IPT System for Railway Vehicles

The IPT system utilizes the principle of electromagnetic induction. Without contacting, the primary coil feeds power to the moving secondary coils by utilizing high frequency current. Figures 1(a) and (b) show the basic structures of the stationary and the movable IPT systems respectively. The x-direction is moving direction, the y-direction is lateral direction, and the z-direction vertical direction. Coil dimensions for the x-direction and the y-direction are defined as coil length and coil width respectively.

Since stationary IPT system has same rectangular-shaped primary and secondary coils that are facing each other, their magnetic fluxes are crossed all over the coil. On the other hand, movable IPT system has infinitely long primary coil and the secondary rectangular coil. As a result, the magnetic fluxes cross only one side parallel to the x-direction. In addition, the movable IPT system has larger air gap than the stationary IPT system in order to avoid hazardous contact during traveling.

Figure 2 shows one example of the movable IPT system for railway. A plurality of the secondary coils are attached to the railway body in order to supply necessary power to railway and a plurality of the cable-type primary coils without cores are laid parallel to several hundred kilometers railway track. Table 1 shows numeral example of IPT system for railway.

As the high frequency primary current generates large reactance voltage along the route, capacitors are connected in series at regular interval in order to compensate for the inductivity of the primary coil like the IPTS utilized by the magnetic levitation vehicle. Figure 3 shows the equivalent primary circuit of the movable IPT system for railway. The capacitors are chosen so that the series resonant circuit is tuned to the system operating frequency.

This paper examines the movable IPT system for railway vehicles with condition of 200 mm air gap, and 20 kHz/250 A magneto motive force (MMF) in the primary coils. Furthermore, in order to install the secondary coils under the bottom of the railway vehicle, the movable IPT system requires following features;

- Weight of the secondary coil should be light. (Target: 5 kg/kW)
- Reactance voltage of the secondary coil should be reduced.
- Eddy currents losses generated at the bottom of the vehicle should also be decreased.

3. Examining Cross-sectional Design of Coils

3.1 Optimizing Coil Winding Dimensions

Magnetic fluxes are crossed only between the sides parallel to x-axis. Induced voltage of the secondary coils is proportional to their length, but not to their width. Thus, the induced voltage per the coil width depends on the magnetic gaps. Therefore best width of the coil against the magnetic gap should be studied.

First, we examine a theoretical relationship between the magnetic flux and the coil dimensions by using a two-dimensional model as shown in Fig. 4.

The magnetic flux density for z-direction $B_z$ by the primary current $I_1$ at the point $(y, G)$ could be expressed by coil width $W$, coil length $L$, magnetic gap $G$ and magnetic permeability $\mu_0$ as the Eq. (1). Equation (2) expresses the magnetic flux for the z-direction $\Phi_z$ in the secondary coil and indicates that $R$, which is the ratio of $W$ to $G(R = W/G)$, is related to $\Phi_z$.

$$B_z = \frac{\mu_0 I_1}{2\pi} \left( \frac{W}{2} + y \right) \left( \frac{W}{2} - y \right) + \frac{W}{2}$$

$$\Phi_z = \frac{\mu_0 I_1}{2\pi} \left( \frac{W}{2} + y \right) \left( \frac{W}{2} - y \right) + \frac{W}{2} \right) \left( \frac{W}{2} - y \right) + \frac{W}{2}$$

$$R = \frac{W}{2}$$

$$\Phi_z = \frac{\mu_0 I_1}{2\pi} \left( \frac{W}{2} + y \right) \left( \frac{W}{2} - y \right) + \frac{W}{2}$$

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magnetic gap to obtain the largest induced voltage per coil
zero when 
and its differential in Eq. (5).

\[ H(R) = \frac{\Phi_z}{L \cdot I_1 \cdot W} = \frac{\mu_0 I_1 L}{2\pi} \left( \log |R^2 + 1| \right) \]

To examine the R at the maximum value of H(R) under the any magnetic gap G, function F(R) is defined in the Eq. (4) and its differential in Eq. (5). Figure 5 shows the relationships of F(R), dF(R)/dR, and R. Since dF(R)/dR becomes zero when \( R = 2 \), the F(R) has the maximum value when \( R = 2 \). As a result, the H(R) has the maximum value when \( R = 2 \) under each magnetic gap G.

Therefore, the coil width should be twice the length of the magnetic gap to obtain the largest induced voltage per coil width at any magnetic gap.

Next, decrease in the magnetic flux in the secondary coils by the lateral misalignment is examined. When the secondary coil is shifting a lateral distance \( r \) as shown in Fig. 4, the magnetic flux could be expressed as follows.

\[
\Phi_{t,\Delta} = \int_{-\infty}^{\infty} B_z \, dy \times L = \frac{\mu_0 I_1 L}{4\pi} \log \left( \frac{R + \frac{t}{G}}{\frac{t}{G} + 1} \right) + \log \left( \frac{R - \frac{t}{G}}{\frac{t}{G} + 1} \right) \]

Here, the difference in F(R) by the lateral misalignment of \( r (\Delta F_i(R)) \) is defined as the Eq. (7).

\[
\Delta F_i(R) = \frac{\Delta \Phi_i}{L \cdot I_1 \cdot R} = \frac{\Phi_i - \Phi_{t,\Delta}}{L \cdot I_1 \cdot R} \]

When applying IPT system for the railway vehicles, the lateral misalignment is assumed to be only 20 mm (22). Figure 6 shows the relationships of \( \Delta F_i(R), \Delta F_i(R)/dR \) and R under this condition. This figure indicates that the \( \Delta F_i(R) \) have the maximum value at \( R = 0.7 \), which means that coil width should not be designed at \( R = 0.7 \) and the design \( R = 2 \) is also suitable from perspective of the lateral misalignment.

Furthermore, almost the same characteristics of the coils with cores could be confirmed by the Integral Equation Method of the ELF/magic 3.80 (24).
type A has the thinnest cross-section whose width is larger than depth, the type C has the thickest, and the type B is in middle. Figure 9 shows results of self-inductance of these coils and Fig. 10 shows results of induced voltage against the air gap. Figure 9 indicates that the type A has the smallest self-inductances, because its magnetic fluxes are not concentrated compared with thick coils as shown in Fig. 11. Moreover, the three types of coils have almost same induced voltage as each other as shown in Fig. 10, because the thinner coil has smaller magnetic gap with constant air gap, while the magnetic fluxes by the primary coil does not concentrate to the thin coil as shown in Fig. 11. Thus, these results mean that the cross-section of coil winding should be thinner.

3.3 Employment of Ferrite Cores When the secondary coils are located under bottom of vehicle, which is made of conductive materials, eddy currents are commonly generated in base structure of the vehicle. Since these eddy currents not only cause temperature rise of the base structure of the vehicle but also decrease induced voltage of the secondary coil, they decrease overall power transfer performance. In order to improve the performance, the movable IPT system has ferrite cores installed into the secondary coils. In this section, the performance on the secondary coils with the flat cores are verified by using analytical and experimental model as shown in Fig. 12. Analytical results in this section are calculated by ELF/magic 3.80 considering the magnetic saturation in the ferrite cores and the following section also use the same way. Experimental conditions are the same with the experiments in Sect. 3.2. Figure 13 shows both analytical and experimental results of induced voltage of the Type A coil without and with ferrite cores respectively. This figure also shows the results without and with aluminum plate (AL), which imitate the base plate of vehicles. The experimental
values are accurately matching with the analytical values as shown in this figure. These results indicate that the aluminum plate decreases the induced voltage, for example, the induced voltage without cores with AL decrease to 50% of that without cores without AL. On the other hand, ferrite cores are effective to improve the induced voltage because the ferrite cores not only increase fluxes by primary coil but also decrease fluxes to aluminum plate, for example, the induced voltage with core with AL decrease to only 85% of that with core without AL.

In order to examine the induction heating of the bottom of vehicles caused by secondary currents, AC resistances of the secondary coils are examined. Figure 14 shows experimental results of AC resistance of the Type A coil. AC resistance without cores with AL is increased compared with that without cores without AL because of the eddy currents in the AL. On the other hand, that with cores with AL increases a little because the eddy currents are sufficiently decreased by the cores, which shield fluxes generated from the secondary coils. Therefore, the cores on the secondary coils are necessary not only for improvement of the induced voltage but also for decrease in the induction heating of the bottom vehicles.

4. Optimized Design of Ferrite Cores

As we have described before, the ferrite cores are effective in improving the performance on the movable IPT system, even though they are located in only the secondary coils. Since these experimental results are accurately matching with the analytical results by the ELF/magic, this section examine optimization of structure of the ferrite cores in the secondary coils analytically.

4.1 Basic Structure of Ferrite Cores

The conventional IPT systems utilize the flat-type cores as shown in Fig. 15. On the other hand, the general electric machines utilize the E-type core to reduce the magnetic resistances in the flux lines generated by the primary coils as shown in Fig. 16. In the movable IPT system, it is important to reduce not only these magnetic resistances but also the weight of ferrite cores of the on-board secondary coils. Therefore, we propose the uneven-type cores as shown in Fig. 17, which can reduce the magnetic resistances as much as that of E-type cores and have as light weight as the flat-type cores.

4.2 Optimizing the Structure of Ferrite Cores

We examine the optimized cores that are structured with uneven-type cores on secondary coil. In order to examine contribution to improvement of the induced voltage by the cores, flux distributions in the uneven-type cores of the secondary coil are studied. Figure 18 shows flux distribution at primary current of 250 A. This figure indicates that central part of the uneven-type cores is not effective to collect fluxes by primary coil, since this part of the cores is not the flux path by the primary coil. On the other hand, over-hanged cores are effective to improve the induced voltage. Hence, it is worth to examine the characteristics of the secondary coils with...
over-hanged edge and central part cores removed from the uneven-type cores to keep same weight as shown in Fig. 19. Figure 20 shows the induced voltage against the over-hang width of cores under the same weight condition. This result indicates that the coils with optimized cores have maximum value at the over-hang width of 60 mm, which means that cores with half of central part removed are the most optimized structure.

Figure 21 shows the induced voltages and the weights of the secondary coils with several types of ferrite cores when they have magnetic gap of 200 mm and thickness of ferrite cores of 4 mm. Weight of the coils with the optimized core’s coil is 21 kg, which is the same as that of uneven-core’s coil. We can find that the coil with uneven-type cores increases the induced voltage to 118% from the coil with flat cores, and the coil with the optimized cores to 131%.

Figure 22 shows that flux density of the secondary coils with the flat cores and the optimized cores respectively. These figures indicate that the optimized core can collect the magnetic fluxes effectively.

Furthermore, in order to obtain output power of 6.0 kW, we have estimated that the magneto motive force (MMF) of the secondary coils should be 980 A. At the secondary MMF of 980 A, maximum magnetic fluxes in the ferrite cores are 0.4 T, which is less than the saturation flux density 0.45 T, as shown in Fig. 23. Therefore, coils with the optimized cores could attain the target of 5 kg/kW.

5. Applying to Railway System

In order to apply the movable IPT system to railway, some critical issues should be examined. Human exposure level to time-varying EMF should comply with ICNIRP regulation and the induction heating of foreign metal object caused by the high frequency magnetic field should be avoided. Furthermore, total efficiency of the IPT system should be estimated. This chapter examines these practical issues for industrial application.

5.1 Meeting the ICNIRP Regulations

IPT systems should comply with ICNIRP regulation to limit human exposure to time-varying EMF. The ICNIRP stipulates that general public should not be exposed to body average RMS flux densities greater than 27 μT in frequency range of 0.3 kHz to 10 MHz. This section examine magnetic field generated by the primary and the secondary coils by utilizing ELF/magic.

Figure 24 shows a diagram illustrating cross section of railway system, assuming that the cross section of the railway vehicle would be composed of squared-shaped aluminum. As shown in this figure, passengers could be kept away enough from the coils in railway system. Figures 25(a) and (b) show calculation results on the magnetic fields generated from primary MMF of 250 A and secondary MMF of 980 A respectively at frequency of 20 kHz. Therefore, the movable IPT system when applying to railway vehicles could comply with ICNIRP regulations.

5.2 Influence on Foreign Objects

When applying to the movable IPT system to railway vehicles, induction heating of metal foreign objects, and interference to other equipment should be examined. As for the facility of the railway
system, induction heating of the body of the vehicles and the steel rail should be examined. However, the eddy current losses in the aluminum railway body is decreased enough since the cores of the secondary coils shield the magnetic field as discussed in Sect. 3.3. And steel rail whose gauge is 1,435 mm is kept away enough from the primary coil whose width is 400 mm. As a result, the temperature rise of steel rail would become only less than 1 degree.

On the other hand, equipments for railway are installed inside the aluminum body of the vehicles, which could shield the fluxes as discussed in Sect. 5.1. As a result, there would be no influence on other equipments. Furthermore, in high-speed railway application, metal foreign object such as aluminum can could not be put into the railway track because general public are prohibited to enter the track and maintenance vehicles inspect entire railway track prior to railway operation.

5.3 Total Efficiency In order to examine the total efficiency of IPT system for railway vehicles, a power transfer test was conducted by utilizing a one-400th miniature model which imitates the fields of the IPT system for railway vehicles shown in Table 1. Table 2 shows the specifications of inverter for primary circuit. The movable IPT system has 1 turn cable-type primary coil in the field, however, due to the rated currents of the inverter in the primary circuit, this model has a 3 turn cable-type primary coil to flow the MMF of 250 A, and 15 turns secondary coil with cores whose specifications are shown in Table 3. Figure 26 shows a power transfer circuit. Both primary and secondary circuits have resonant capacitors connected in series and the secondary circuit has a rectifier and a load which is composed of resistor. Figure 27 shows waveform examples of primary and secondary MMF, and it also shows output voltage and current. These figures show that the primary coil could supply power of over 6.0 kW to the secondary coil stably at output voltage of 125 V and the output current of 50 A.

As railway system could always detect the position of the vehicles, standby power does not largely decrease the total efficiency. Thus, this paper define the total efficiency of movable IPT system as shown in Eq. (8) assuming the increase in the primary loss ($P_l$) when utilizing the 1 turn primary coil instead of 3 turns coil, where $P_{in}$ is the input power of the primary coil, $P_{out}$ the output power of the secondary coil. In this power transfer test, the total efficiency could achieve 85%.

$$\eta = \frac{P_{out}}{P_{in} + P_l} = \frac{I_{out}V_{out}}{V_1I_1 \cos \theta + 2fI^2R_1}, \quad (8)$$

6. Conclusion

In this paper, a basic structure of movable IPT system for railway vehicles was examined. In railway application, the on-board secondary coil is required to reduce the weight as possible and should have optimized structure for the infinitely long primary cable-type coil. This paper proposed the methods to design dimensions of the primary and the secondary coils and indicates the simply result that the coils width should be twice the length of the magnetic gap to obtain the largest induced voltage per coil width. Moreover, optimized cross section of secondary coils for movable IPT system was...
discussed assuming that the secondary coils are attached under the railway body. We proposed a unique structure of secondary coils, which has thinner flat cross-sections of conductors with over-hanged edges and removed central part to improve the induced voltage without increasing the weight. Finally, some issues regarding the magnetic field when applying to railway were discussed and we concluded that the movable IPT system could apply to railway vehicles.

References


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