Charging Infrastructure Design for In-motion WPT Based on Sensorless Vehicle Detection System

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***Abstract*—In-motion wireless power transfer (WPT) system is expected to achieve unlimited driving range of electric vehicles (EVs) independent of their battery capacity. Previous research has developed an in-motion WPT system with individual vehicle detection units for power transmission control. However, in this paper, a charging infrastructure of in-motion WPT is designed and implemented based on a sensorless vehicle detection system only using power converters and power transmitting coils. In addition, this paper presents a resonant capacitor integrated road coil considering construction complexity and safety issues due to resonant high voltage. Furthermore, influences of road structural materials are investigated to adopt a cheap and compatible structure. The feasibility of the constructed in-motion WPT system is demonstrated by a driving test.**

***Index Terms*—Electric vehicle, In-motion wireless charging, Charging infrastructure, resonant power transfer**

I. Introduction

Although electrification of transportation is an urgent issue, the diffusion of electric vehicles (EVs) is hampered by the short cruising distance and long charging time due to the limited battery capacity. In-motion wireless power transfer (WPT) is expected to expand the driving range of EVs and greatly improve convenience [1], [2]. A resonant power transfer with magnetic coupling has been adopted in many studies on in-motion WPT because it has the capability to deal with the coil displacement by the moving vehicle.

Previous research has developed an in-motion WPT system with individual vehicle detection units for power transmission control [3], [4]. However, adding a sensor may increase the cost of the power supply infrastructure and reduce its reliability. Furthermore, the construction method should be thoroughly studied to construct a practical system.

In this paper, an example of design and implementation of charging infrastructure for in-motion WPT is presented. A road coil is designed considering construction complexity and safety issues, and an influence of road structural materials are investigated to adopt a cheap and compatible structure. The road-side facility employs a sensorless vehicle detection system [5] and consists of only power converters and the road coils. The feasibility of the constructed in-motion WPT system is demonstrated by the driving test.

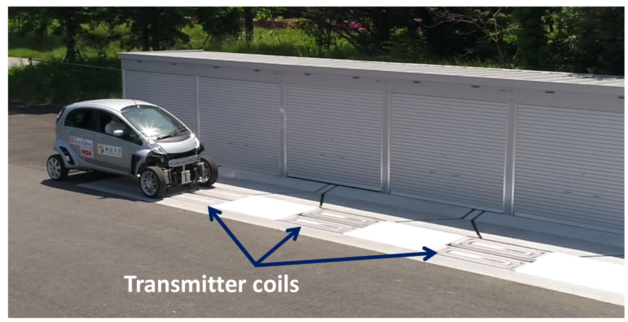


Fig. 1. In-motion wireless charging system for electric vehicles.

TABLE I
Specifications of in-motion wireless charging system.

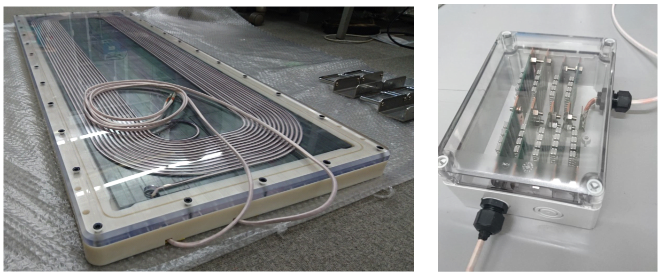
Total length	20 m
Total installed capacity	50 kVA
Maximum available DC bus voltage	600 V
Rated power of in-motion WPT from road to IWM	12 kW
Number of motors	2 (4)
Total WPT power from road to vehicle	24 kW (48 kW)

II. Charging Infrastructure

A. Specifications

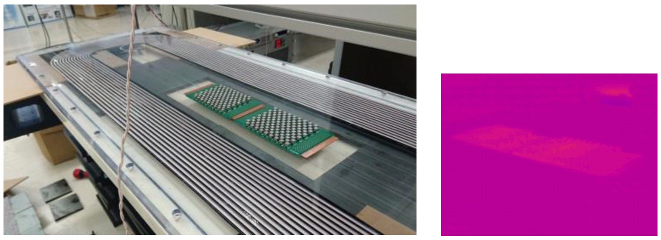
The authors have developed the in-motion WPT system for EVs, as shown in Fig. 1. The charging infrastructure consists of the power supply facility and the road coils for delivering power to the receiving coil mounted on the moving vehicle. The test vehicle employs the second generation of Wireless In-Wheel Motor (W-IWM2) [6] on the front wheels, and can receive power from the road coils during running.

The specifications of the in-motion WPT system is indicated in Table I. The total length and installed capacity are designed to 20 m and 50 kVA, respectively. The available maximum DC bus voltage is 600 V and its amplitude is controlled by a power converter. While the rated power of in-motion WPT from the road to IWM is 12 kW, the test vehicle equipped with the two W-IWM2 units on the front wheels can receive power up to 24 kW. Furthermore, it is possible to charge 48 kW with the four-wheel drive with the W-IWM2 units.



(a) 1st prototype coil. (b) Resonant capacitor.

Fig. 2. Power transmitter comprising coil and resonance capacitor.



(a) Experimental setup. (b) Temperature.

Fig. 3. Fundamental experiment on feasibility of integrated coil.

B. Coil design

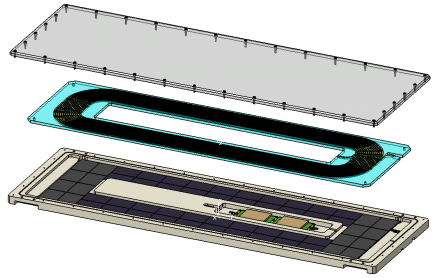
The first prototype of the road coil is shown in Fig. 2(a). It consists of the coil winding and ferrite back plates. The coil is molded in the plastic case to increase the mechanical strength and the resonant capacitor, which is shown in Fig. 2(b), is connected to the road coil for resonant coupling. However, the divided coils and capacitors increase construction complexity and also create safety issues due to resonant high voltage. Therefore, the capacitor integrated road coil is designed and implemented in this study.

First of all, the feasibility of the integrated road coil is demonstrated by the fundamental experiment, as shown Fig. 3. The resonant capacitor was placed on the center of the road coil and the ferrite back plates around the capacitor ware removed. Then, the power transfer experiment was conducted for verifying that no significant temperature rise occurred. In addition, because the drastic efficiency reduction was not confirmed, the feasibility of the resonant capacitor integrated road coil was validated. Consequently, the second prototype of the road coil integrated with the resonant capacitor was designed and implemented, as shown in Fig. 4.

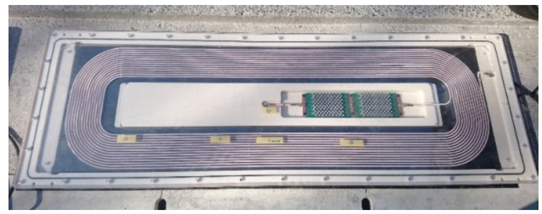
Since this section presented only the fundamental study, the additional experiments will be done to obtain detailed data as a future work.

C. Influence of road incidental equipment

In order to build the charging infrastructure, it is necessary to consider the influence of the road structure materials. In particular, construction materials with reinforced concrete (e.g. pavement, curbstone, and groove including rebar) may adversely affect power transfer with magnetic coupling. Although a dedicated road, which does not use these materials, can easily guarantee a highly efficient power transmission, it should be avoided in terms of cost and compatibility.

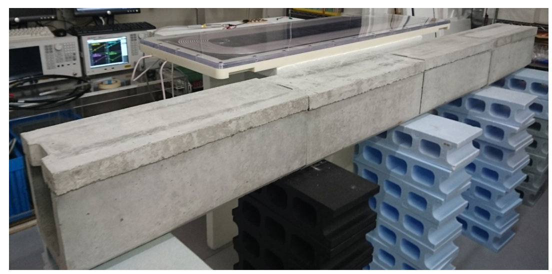


(a) 3D CAD.

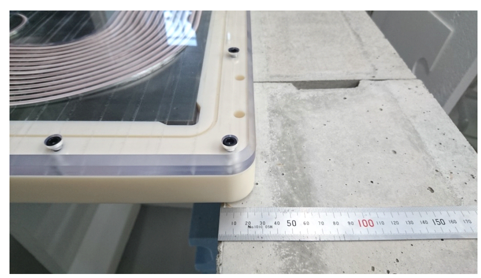


(b) 2nd prototype coil.

Fig. 4. Resonant capacitor integrated road coil.



(a) U-shaped groove with rebar.



(b) Overlap length adjustment.

Fig. 5. Parameter analysis when arranging U-shaped groove with rebar.

This section presents a parameter analysis when arranging the U-shaped groove with rebar in the vicinity of the road coil, as shown in Fig. 5. The overlap length of the coil and groove was adjusted to -20, -10, 0, 10, 25, and 50 mm. Then, the internal resistance of the road coil, which represents loss component, did not change drastically and it implies that construction materials with the rebar can be installed below the bottom surface of the road coil. This is because the

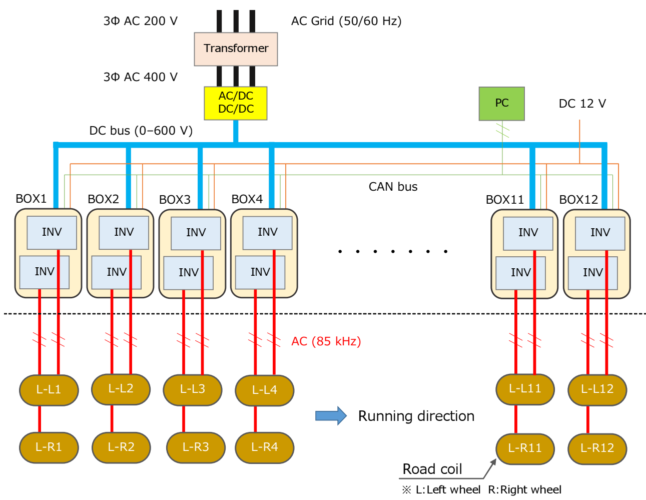
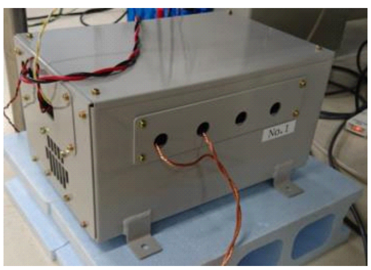
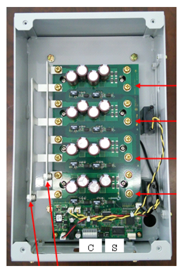


Fig. 6. Power supply configuration.



(a) Appearance.



(b) Circuit board.

Fig. 7. Inverter box for vehicle detection and power transmission control.

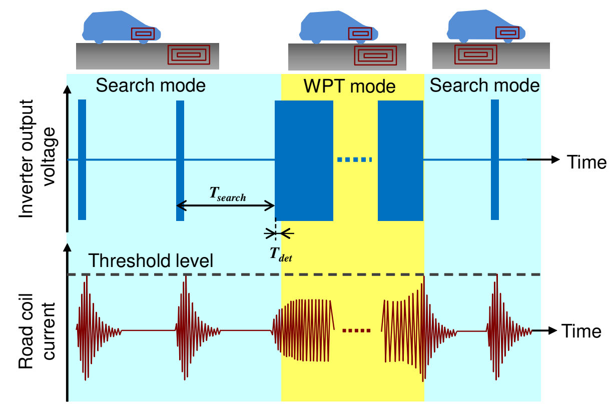
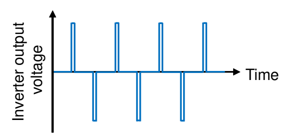
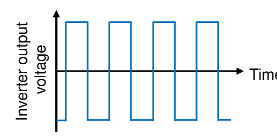


Fig. 8. Concept of sensorless vehicle detection system.



(a) Search mode.



(b) WPT mode.

Fig. 9. Waveforms of inverter output voltage.

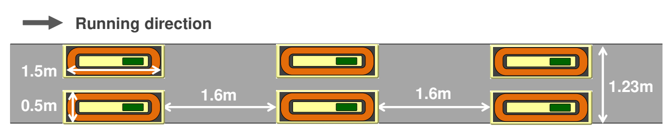


Fig. 10. Arrangement of road coils for driving test.

magnetic field is trapped by the ferrite back plate of the road coil and does not significantly affect the rebar. Consequently, the U-shaped groove with rebar was adopted as a drainage mechanism in the constructed charging infrastructure.

D. Power supply configuration

The configuration of the charging infrastructure for in-motion WPT is illustrated in Fig. 6. The transformer is used to isolate the charging infrastructure from the AC grid and the amplitude of the AC voltage is boosted from 200 V to 400 V. The AC/DC converter (VF64R, Toyo Denki Seizo K.K) supplies the DC input voltage of the DC/DC converter (VF66CH, Toyo Denki Seizo K.K), and the DC bus voltage is controlled by the DC/DC converter.

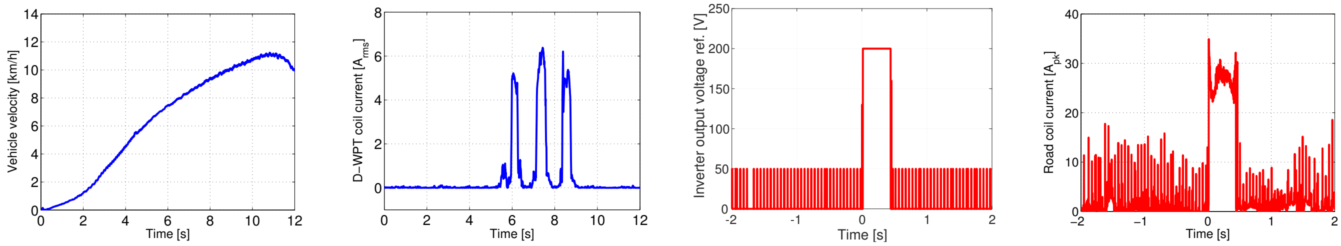
Each power supply box, which is shown in Fig. 7, is powered from the DC bus and composed of two inverters to excite the road coils. In this study, because the test vehicle equipped with the W-IWM2 units on the front wheels can receive energy from the right and left coils, the road coils are arranged as shown in Fig. 6.

In order to implement a practical in-motion WPT system, accurate vehicle detection and appropriate power transmission control are required. In this study, a sensorless vehicle detection system [5] using only the road coil and inverter is adopted. Although the control sequence is individually operated by the embedded CPU of each inverter, the experimental PC is connected to each inverter through the CAN bus to write the control program, execute the control sequence, and display the experimental data.

III. Sensorless Vehicle Detection System

In this chapter, only the concept of the sensorless vehicle detection system is described. When the receiver coil attached to the running vehicle approaches the road coil, the input impedance of the WPT system is gradually increased and the road-side facility can detect its impedance change using a search pulse injection. As a result, the vehicle detection and power transmission control can be achieved only with the inverters and coils without using additional sensors by observing the coil current.

Fig. 8 shows the control sequence for the vehicle detection and power transmission. When the receiving coil is far from the road coil, the road coil current is increased sharply after the search pulse injection. Then, the current exceeds the threshold level and it means that the coupling strength is not sufficient. On the other hand, when the current does not exceed the threshold level within the detection time, the road-side facility detects the approach of the vehicle and starts power transmission control. As the vehicle passes over the coil, the



(a) Vehicle velocity. (b) Receiving coil current. (c) Inverter output voltage reference. (d) Road coil current.

Fig. 11. Driving test result of in-motion wireless power transfer.

input impedance of the WPT system decreases again, so the road-side facility detects the increase in the road coil current and stops the power transmission control.

Additionally, in order to reduce standby power at the vehicle detection, the voltage waveforms are designed to be different between searching and power transmission, as shown in Fig. 9. Although the design parameters should be determined appropriately, these design methods are not discussed in this paper, so please refer to [5].

IV. Driving Test

This chapter presents the driving test of the in-motion WPT using the implemented charging infrastructure and the test vehicle equipped with the front-wheel W-IWM2 units. In this experiment, the road coils are arranged as shown in Fig. 10 and the in-motion WPT is conducted using the right lane of the road coils and the W-IWM2 unit on the right front wheel of the test vehicle. The test condition is indicated in Table II and the sensorles vehicle detection system is applied to the inverters of the road-side facility.

Fig. 11 shows the driving test results. Note that time series of the vehicle-side data (Fig. 11 (a), (b)) and the road-side data (Fig. 11 (c), (d)) do not accord because they were independently measured in the vehicle and the road-side facility. As shown in Fig. 11(a), while the test vehicle is driving, the in-motion WPT is executed three times as shown in Fig. 11(b). Fig. 11 (c), (d) correspond to the road-side inverter output reference and the road coil current of the second coil set. From these results, the search mode and the WPT mode are properly operated and the feasibility of the constructed charging infrastructure with the sensorless vehicle detection system is demonstrated.

V. Conclusion

This paper presented an example of design and implementation of charging infrastructure for in-motion wireless charging of EVs. The constructed in-motion WPT system can handle up to 12 kW per wheel and transfer 48 kW to the vehicle with the four-wheel W-IWM2 units. The charging infrastructure was designed based on the sensorless vehicle detection system and the driving test demonstrated the feasibility of the constructed in-motion WPT system. Then, the resonant capacitor integrated road coil was employed considering the safety issues due to resonant high voltage and the U-shaped groove with rebar was applied to the road incidental equipment to reduce the installation cost.

TABLE II
Driving test condition.

Operating frequency f_0	89 kHz
Road-side DC bus voltage V_S	200 V
Wheel-side DC link voltage V_{DC}	500 V
Search pulse voltage V_{search}	50 V
Searching period T_{search}	10 ms
Detection time T_{det}	400 μs

As future works, a high power experiment of in-motion WPT will be demonstrated and a simultaneous power transfer from the road coils to the front wheels will be conducted.

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