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Dynamic Wireless Power Transfer System for Electric Vehicles to Simplify Ground Facilities - Sensorless Vehicle Detection and Power Control Strategy -

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Abstract

In order to simplify ground facilities of a dynamic wireless power transfer system for electric vehicles, this paper proposes a control strategy for detecting the approximation of vehicles to the road-side transmitter without using additional sensors and for switching the operation modes of the road-side and vehicle-side systems without using communication between both sides. Compared to the conventional strategy, the proposed method can permit the vehicle-side control not only to maximize the transmitting efficiency but also to achieve power control.

Keywords: Wireless charging, Dynamic wireless power transfer, Vehicle detection, Power control.

1 Introduction

A dynamic wireless power transfer system can extend the limited driving distance of electric vehicles (EVs) and reduce the size of an energy storage system of EVs [1]–[3]. Since wireless power transfer via magnetic resonance coupling [4, 5] has the capability of the highly efficient mid-range transmission and robustness to misalignment between a transmitter and receiver, this technologies has suitable characteristics for the dynamic charging system. In order to apply the dynamic wireless power transfer system to roadways over long distances, it is important to simplify the ground facilities as much as possible in terms of cost and maintainability.

This paper proposes a control strategy for detecting the approximation of vehicles to the transmitter without using additional sensors and for switching the operation modes of the road-side and vehicle-side system without using communication between both sides. Although the conventional strategy is difficult to distinguish the vehicle-side power control from the disappearance of the receiver, the proposed strategy can eliminate the detection error and permit the vehicle-side charging control not only to maximize the transmitting efficiency but also to achieve power control.

2 Dynamic Wireless Power Transfer System

2.1 A unique set of challenges

Dynamic wireless power transfer for EVs should be recognized not as extended technologies of static wireless charging but as a novel technology based on requirements of transportation systems. The most important thing is that the ground facilities should be simplified as much as possible. Because they have to be installed into all of the electrified sections, a high-cost structure is impermissible. Additionally, a highly-efficient operation and a stable energy supply are required. However, the system configuration should be designed with particular attention to the following assumptions.

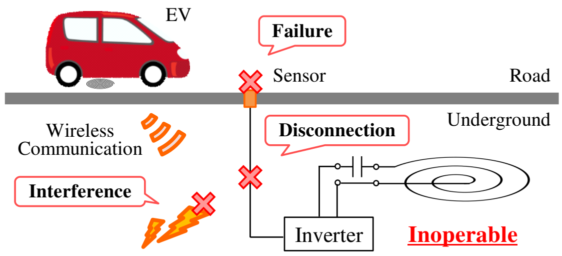


Figure 1: Vehicle detection problems with communication and additional sensors.

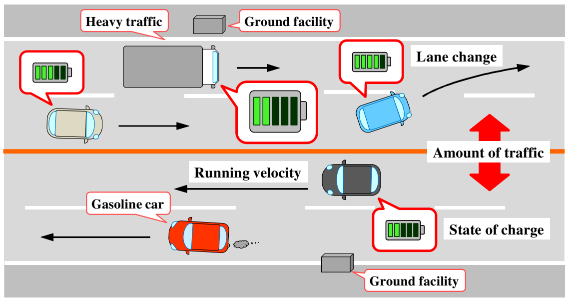


Figure 2: Many and unspecified vehicles on the road.

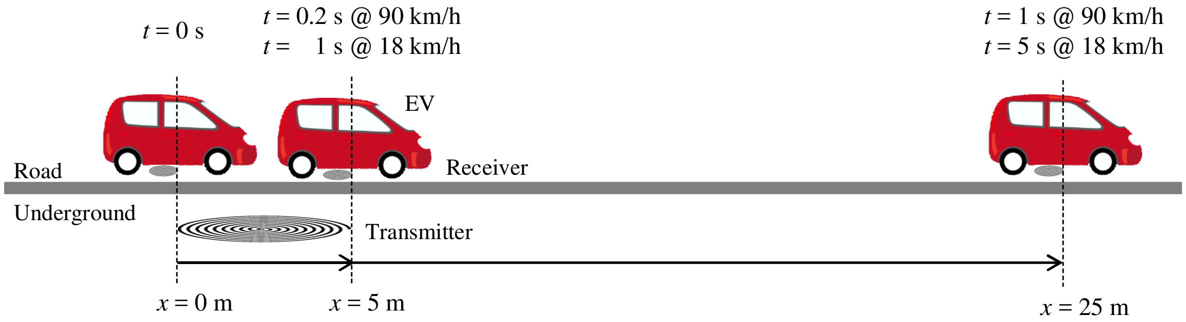


Figure 3: Charging time for dynamic wireless power transfer considering vehicle velocity.

1) Additional sensors and communication increases the risk of vehicle detection failure and decreases the chargeable intervals in the electrified sections (Fig. 1).

2) Control system should be designed without signal communication between the ground facilities and the vehicles because many and unspecified vehicles exist on the road (Fig. 2).

3) Mode change from vehicle detection to power transfer should be done in a moment because charging time is limited due to the vehicle velocity and the transmitter coil structure (Fig. 3).

In this paper, a sensorless vehicle detection method and power control strategies are introduced.

2.2 Experimental setup

The circuit configuration of the dynamic wireless power transfer system is shown in Fig. 4. The road side provides power to the transmitter using the full-bridge inverter. Since this paper uses Series-Series (SS) compensated wireless power transfer via magnetic resonance coupling, the transmitter and receiver are designed as follows:

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \tag{1}$$

where ω_0 is the operating angular frequency of the inverter.
The vehicle side rectifies the receiving power using Half Active Rectifier (HAR), which is used for the vehicle detection method and the power control strategies. The DC-DC converter controls the load current for the battery charging. The envelops of the road-side current and the vehicle-side current are measured for the vehicle detection strategy.
The experimental equipment is shown in Fig. 5. The receiver is driven by the motor to simulate the vehicle running and the transmitting gap is set to 100 mm. The specifications of the experimental system are indicated in Table 1. The vehicle detection system and power control strategies are implemented with a DSP (PE-PRO/F28335A, Myway)

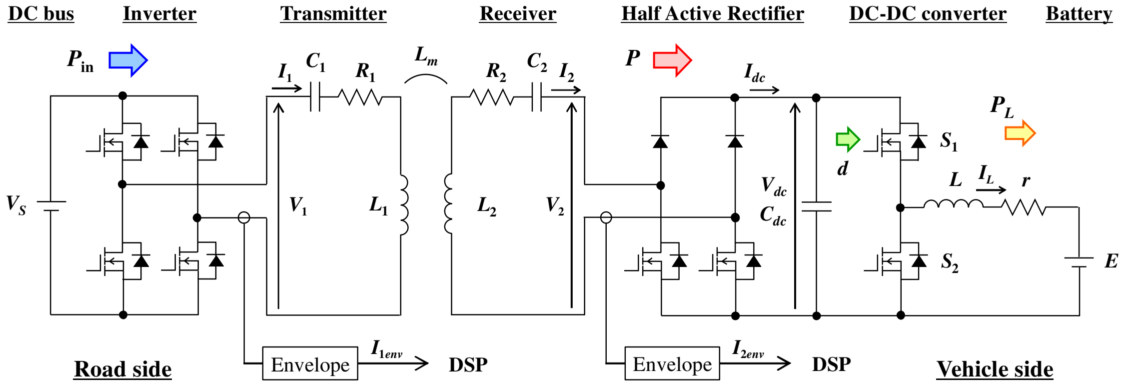
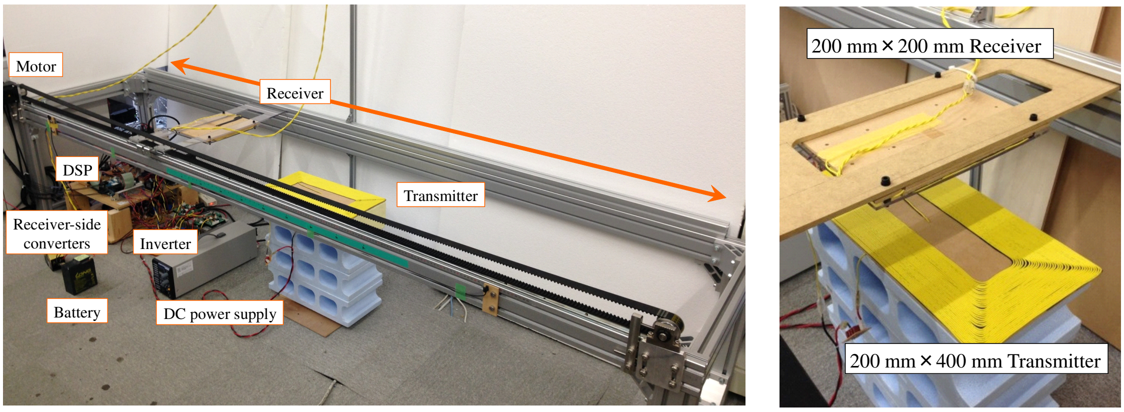


Figure 4: Circuit configuration and experimental circuit of dynamic wireless power transfer system



(a) Whole picture of the experimental system

(b) Transmitter and receiver

Figure 5: Experimental setup

3 Sensorless vehicle detection

3.1 Input impedance of the system

This paper focuses on the input impedance of the system. The equivalent circuit of the wireless power transfer system is illustrated in Fig. 6 [8]. When the operating angular frequency of the inverter and the resonance frequencies of the transmitter and receiver are given by eq. (1), the input impedance Z_{in} is expressed as follows:

$$Z_{\mathrm{in}} = R_1 + \frac{(\omega_0 L_m)^2}{R_2 + R_L} \tag{2}$$

where R_L is the equivalent resistance including the power converters and the load on the vehicle side. Although Z_{in} changes according to the mutual inductance L_m between the transmitter and receiver, R_L is determined by the load condition on each vehicle. As a result, it is difficult to achieve the sensorless vehicle detection with only (2).

3.2 Standby mode with HAR

In this paper, the HAR is used for distinguishing between the standby mode and charging mode. The operation modes of the HAR are shown in Fig. 7 During the charging mode, the HAR is operated as the diode rectifier by turning off the lower arm MOSFETs. Then, the receiving power flows into the vehicle-side system. On the other hand, during the standby mode, the lower arm MOSETs of the HAR are turned on and the receiver is shorted. Then, the equivalent resistance R_L becomes 0. Therefore, the road side can detect each vehicle based on eq. (1) using $R_L = 0$.

Table 1: Parameters of the experimental setup

Parameter	**Value**
DC voltage source amplitude V_S	18 V
Operating frequency f_0	100 kHz
Transmitter inductance L_1	417.1 μH
Transmitter capacitance C_1	6.03 nF
Transmitter resistance R_1	1.83 Ω
Receiver inductance L_2	208.5 μH
Receiver capacitance C_2	12.15 nF
Receiver resistance R_2	1.28 Ω
DC-DC converter inductance L	1000 μH
DC-DC converter capacitance C	1000 μF
DC-DC converter resistance r	0.2 Ω
Battery voltage E	6 V
Searching period T_{search}	10 ms
Search pulse width T_{pulse}	0.5 μs

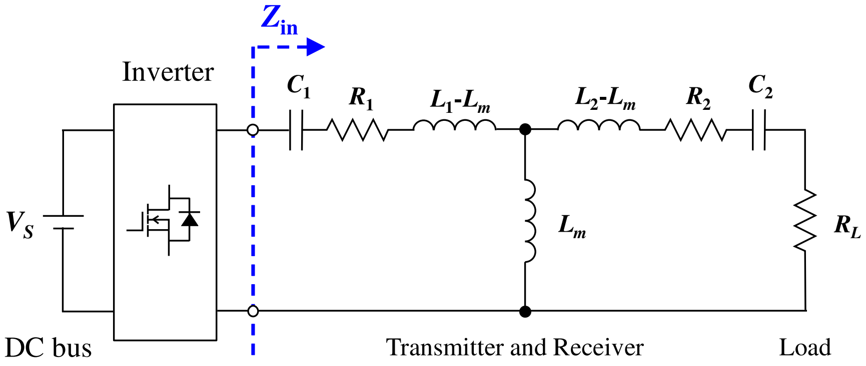


Figure 6: Input impedance of the dynamic wireless power transfer system.

During the standby mode with HAR, the mutual inductance L_m versus the input impedance Z_{in} is shown in Fig. 8. Since L_m increases according to the approximation of the receiver to the transmitter, Z_{in} is also increased in the same manner. From (2), Z_{in} is expressed as a real number, The changes in Z_{in} can be detected by applying the input voltage V_1 and by measuring the input current I_1.

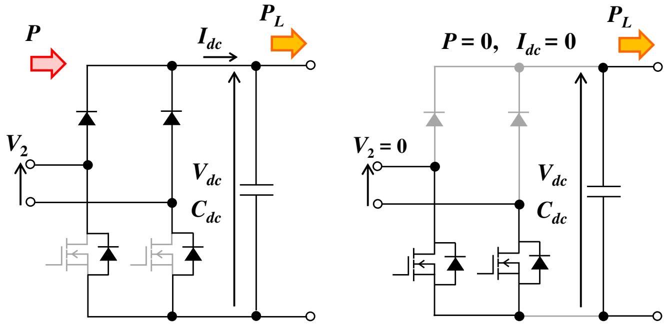
3.3 Searching voltage pulses [6]

In order to reduce the detection power losses, the searching voltage pulses are introduced. When the searching voltage pulses with the resonance frequency of the transmitter and receiver is applied to the transmitter as shown in Fig. 9, the decrease in the road-side current is caused by the proximity of an EV equipped with the receiver as shown in Fig. 10. Therefore, the vehicle detection is achieved by measuring the road-side current envelope I_{1env}.

After the road side detects the vehicle approximation, the road-side inverter starts to operate for transmitting power. Then, the vehicle side can detect the receiving power using the vehicle-side current envelope I_{2env}. After that, the vehicle side can start the charging control for achieving efficiency maximization and power control.

3.4 Vehicle-side power and efficiency control [7]

The DC link voltage V_{dc} is optimized for maximizing the transmitting efficiency using the HAR and the load current I_L is controlled by the DC-DC converter for power control. Because the optimized voltage



(a) Rectification mode. (b) Short mode.

Figure 7: Operation modes of Half Active Rectifier.

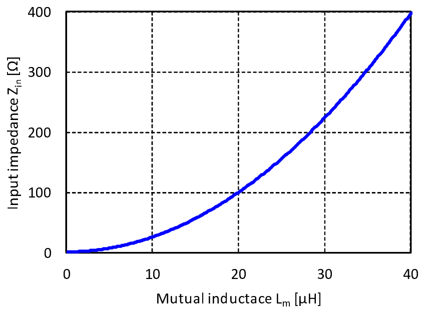


Figure 8: Mutual inductance L_m vs. input impedance Z_{in} during short mode of HAR.

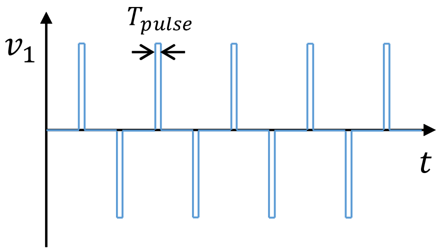


Figure 9: Search pulses at resonance frequency.

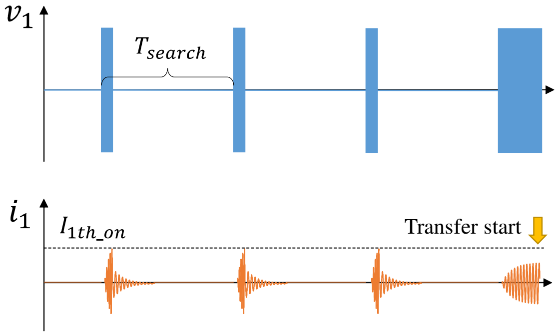


Figure 10: Search pulses and road-side current.

is determined by the mutual inductance L_m between the transmitter and receiver, L_m is estimated using the measured DC link voltage V_{dc} and current I_{dc}.
If the conventional vehicle detection method is applied to the road-side facilities and the vehicle-side system, the vehicle-side power and efficiency control cannot be implemented. When the DC link voltage V_{dc} is controlled by the HAR, the rectification mode and short mode of the HAR have to be repeated even during the charging mode on the vehicle side. Then, the road side mistakes the vehicle-side control for the disappearance of the receiver because the conventional strategy detects the receiver passing above the transmitter using the mode change from the rectification mode to the short mode of the HAR. It causes a detection error and should be improved.

3.5 Proposed control strategy

The flowchart of the proposed control strategy is illustrated in Fig. 11. In order to change the operation modes without using communication between the road side and the vehicle side, the road-side system chooses the search mode or the transfer mode based on the envelop of the road-side current I_{1env} . Besides, the vehicle-side system switches the standby mode and the charging mode according to the envelop of the vehicle-side current I_{2env}.
Compared to the flowchart in [6], the proposed control strategy simplifies the conditional equations. From the transfer mode to the search mode, the road side only check if I_{1env} is larger than the threshold. Because I_{1env} during the short mode of the HAR becomes small compared to the rectification mode of the HAR, the proposed strategy can eliminate the detection error and permit the vehicle-side charging control not only to maximize the transmitting efficiency but also to achieve power control.

4 Experiment

Experiments of the proposed control strategy are verified with the experimental setup, which is shown in Fig. 5. The road-side and vehicle-side current envelops are sent to a DSP and compared to their thresholds. The operation modes of both sides are changed based on the measured current envelops.

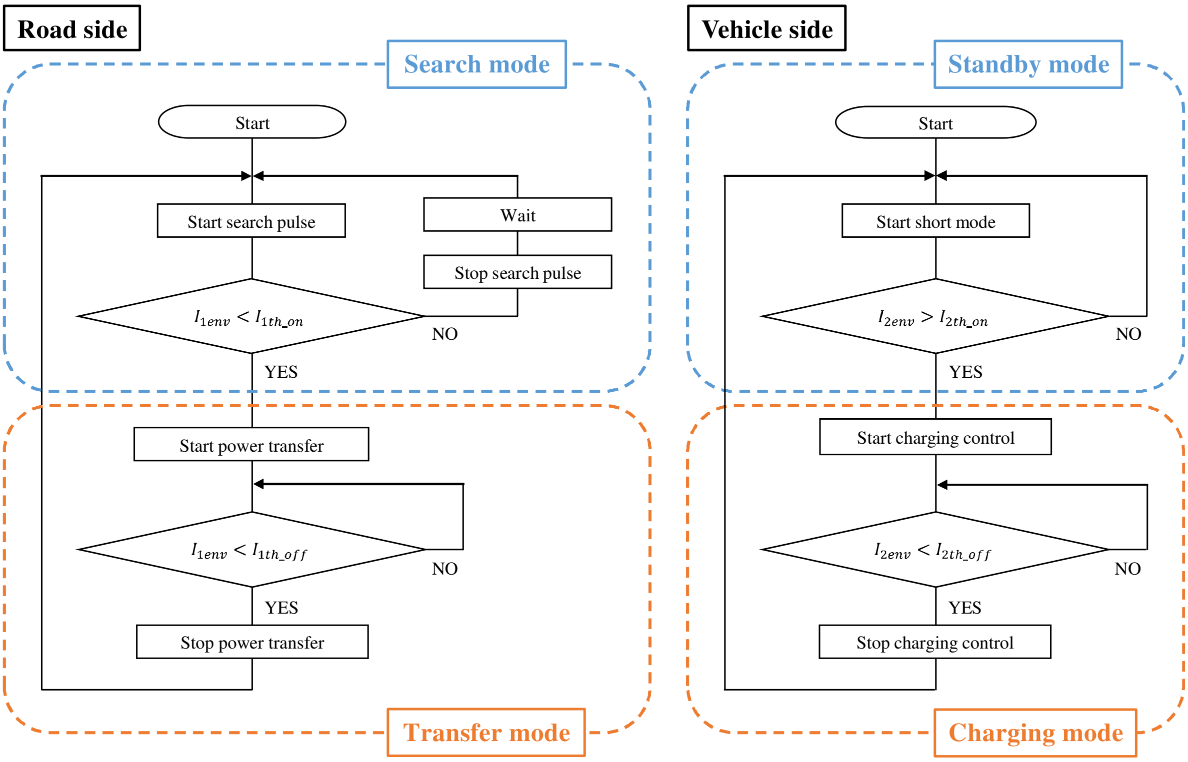
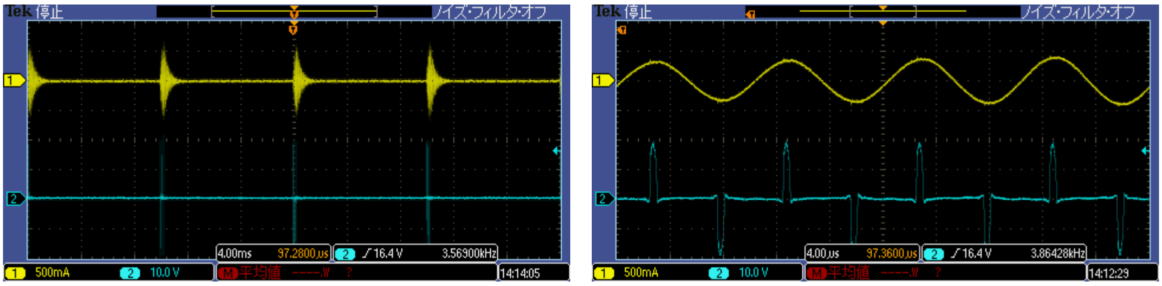
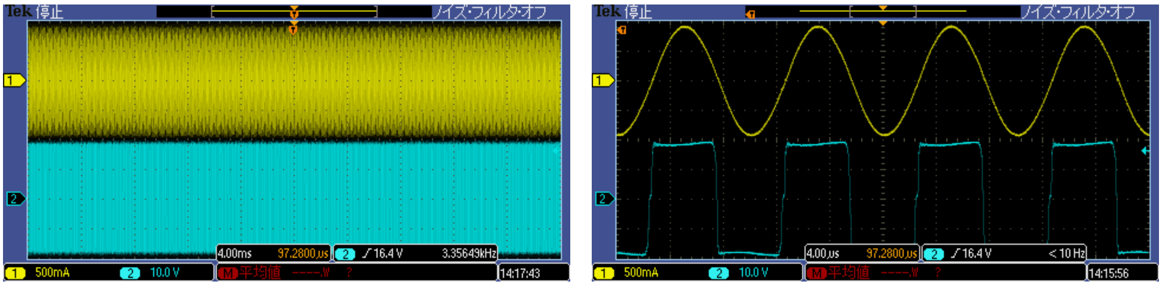


Figure 11: Flowchart of the proposed control strategy



(a) Overall view (b) Enlarged view

Figure 12: Road-side voltage and current in search mode



(a) Overall view (b) Enlarged view

Figure 13: Road-side voltage and current in transfer mode

Fig. 12 shows the road-side voltage and current in the search mode. The yellow line is the road-side current and the blue line is the road-side voltage. During the search mode, the searching voltage pulses are applied properly as shown Fig. 12(b). When the receiver is not existed, the road-side current is

(a) Test tracks

(b) Experimental vehicle

Figure 14: Real-scale dynamic wireless power transfer system.

drastically increased. Then, the road-side system estimates no existence of the receiver and stops to apply the searching voltage pulses.

Fig. 13 illustrates the waveforms in the transfer mode. The road-side inverter generates a square voltage wave and it can transfer power to the vehicle. The mode transient experiments are currently being tested and developed. Additionally, the real-scale dynamic wireless power system is being constructed and the demonstration system is also being implemented (Fig. 14).

5 Conclusion

This paper aims to simplify a system structure of ground facilities of a dynamic wireless power transfer system and proposes a control strategy for detecting the proximity of vehicles without using additional sensors and for switching the operation modes of the road-side and vehicle-side systems without using communication between both sides.

As a future work, the transient characteristics of the operation modes will be demonstrated by experiments. In addition, the proposed control strategies will be implemented to the real-scale dynamic wireless power transfer system and demonstrated the feasibility of the proposed method.

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