

Vehicle Detection Method Using Search Pulses from the Receiver Side via a DC Voltage Sensor on the Transmitter Side for Dynamic Wireless Power Transfer

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Abstract—In Dynamic Wireless Power Transfer (DWPT), where vehicle speeds are high and charging times are extremely short, a sensorless vehicle detection system is required, as it demands high detection accuracy and fast response speed without additional sensor devices. Therefore, we propose a vehicle detection method using a search pulse from the receiver side, which can further reduce standby losses, employing the DC voltage on the transmitter side as a threshold. The proposed method demonstrates utility through clarifying its principles and static characteristics, enabling earlier vehicle detection, while simulation results confirm its feasibility. Furthermore, simulation results confirm that vehicle detection is possible 5ms faster than conventional methods for DWPT at 60 km/h.

Keywords— *Dynamic Wireless Power Transfer, DWPT, Vehicle Detection, Standby Loss*

I. INTRODUCTION

As environmental issues such as global warming become increasingly severe, various studies are being conducted to promote the spread of electric vehicles (EVs), which impose less environmental burden. However, challenges for EVs include limited driving range, charging time, and battery weight [1][2]. As a solution, research on dynamic wireless power transfer (DWPT) is gaining attention [3]. This system wirelessly transmits power through magnetic coupling between a transmitter coil embedded in the road and a receiver coil installed in the moving vehicle. The practical application of DWPT holds promise for improving EV challenges, but issues remain to be addressed for full implementation, including standby losses, leakage magnetic fields [4], and power transfer to high-speed vehicles. To resolve these challenges, proper control of vehicle detection

is required. Vehicle detection refers to a system that detects moving vehicles and transmits power only when a receiver coil is present above the transmitter coil. Previous studies have examined methods using detection coils [5] and wireless communication [6], but these suffer from disadvantages such as detection delays and false detections [7]. In DWPT, the vehicle running speed is high and the power transfer time is extremely short. Therefore, vehicle detection requires not only high detection accuracy but also fast response speed. Consequently, sensorless detection methods that do not use additional sensor devices have been researched [8][9]. This method detects the presence of a vehicle by applying a low-power search pulse from either transmitter side or receiver side, then measuring the resulting changes in current and voltage at the receiver side or transmitter side using current or voltage sensors. Vehicle detection using search pulses from the transmitter side leads to inverter losses due to the inverter being constantly driven, and results in standby losses and leakage magnetic fields because a constant current flows through the transmitter coil. Furthermore, it is difficult to distinguish vehicles that do not require power supply. On the other hand, vehicle detection using search pulses from the receiver side [10][11] eliminates inverter losses and reduces standby losses because no current flows through the transmitter coil in the standby state. Furthermore, since the number of receiver coils in any given section is fewer than the number of transmitter coils, losses due to applying search pulses are also low. In addition, vehicles that do not require power can be supplied only to those that do by not applying the search pulse to them.

This paper proposes a new vehicle detection method using search pulses from receiver side. Previous methods have performed vehicle detection at the receiver side using current sensors with threshold detection. In contrast, the proposed method performs vehicle detection at receiver side using DC voltage sensors. This enables faster vehicle detection. Furthermore, since vehicle detection is performed using a voltage sensor, higher accuracy and improved noise immunity are anticipated. Therefore, the usefulness of the proposed method is verified through simulations of static and dynamic characteristics.

II. THEORY

A. Double-LCC Topology

Various circuits have been studied for DWPT, with the Double-LCC circuit shown in Fig. 1 being a prime example [12]. In the Double-LCC circuit, vehicle detection is not required due to the low received power during low coupling, but standby losses and leakage magnetic fields occur. The equivalent circuit of Fig. 1 using AC voltage sources is shown in Fig. 2. At this time, the resonance frequency ω_0 can be expressed as in equation (1). Furthermore, using the pulse width α_{Tx} of the transmitter side converter and the pulse width α_{Rx} of the receiver side converter, the conversion equations between the DC voltage sources V_{DC} and V_{Bat} and the AC voltage sources V_{Tx} and V_{Rx} can be expressed using the Fourier transform as shown in equation (2). α_{Tx} and α_{Rx} are set to 30° in the standby state and 150° in the WPT state. The current i_1 flowing into the transmitter side inverter from the LCC circuit is given by equation (3). The constant A_{LCC} determined by the circuit parameters of the Double-LCC circuit is used.

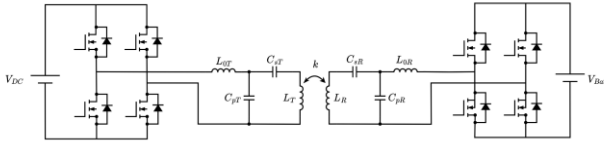


Fig. 1 Double-LCC Circuit

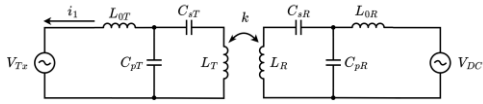


Fig. 2 Double-LCC Circuit with AC voltage sources

$$\omega_0 = \frac{1}{\sqrt{L_{0T}C_{pT}}} = \frac{1}{\sqrt{L_T \frac{C_{pT}C_{sT}}{C_{pT} + C_{sT}}}} = \frac{1}{\sqrt{L_{0R}C_{pR}}} = \frac{1}{\sqrt{L_R \frac{C_{pR}C_{sR}}{C_{pR} + C_{sR}}}} \quad (1)$$

$$V_{Tx} = \frac{2\sqrt{2}}{\pi} V_{DC} \sin\left(\frac{\alpha_{Tx}}{2}\right), \quad V_{Rx} = \frac{2\sqrt{2}}{\pi} V_{Bat} \sin\left(\frac{\alpha_{Rx}}{2}\right) \quad (2)$$

$$i_1 = \frac{k\sqrt{L_T L_R}}{\omega L_{0T} L_{0R}} V_{Rx} = A_{LCC} V_{Rx} k \quad (\because A_{LCC} = \frac{\sqrt{L_T L_R}}{\omega L_{0T} L_{0R}}) \quad (3)$$

B. Proposal Method

The proposed vehicle detection method employs a full-bridge inverter with four switching elements (MOSFETs) connected across the terminals of an LCC resonant circuit, as shown in Fig. 3. In this configuration, the transmitter side and receiver side converters can each operate as an inverter and a rectifier, respectively. When the MOSFETs are driven to operate as an inverter, this is termed Inverter Mode; when they operate as a rectifier, this is Rectifier Mode. Furthermore, when the MOSFETs are not driven and rectification occurs via the body diodes, this is termed Idle Mode. In the standby state, a search pulse is transmitted from the receiver side in Inverter Mode to the transmitter side in Idle Mode. This direction of power transfer is called reverse transmission. In the WPT state, when power is being supplied to the vehicle, power is transmitted from the transmitter side in Inverter Mode to the receiver side in Rectifier Mode. This direction of power transfer is called forward transmission.

Previous studies have used the amplitude of the AC current i_1 shown in Fig. 4(a) as the vehicle detection threshold. In contrast, the proposed method obtains the DC average value V_1 of the AC voltage v_1 shown in Fig. 4(b) using a low-pass filter and employs this as the vehicle detection threshold. The flowchart for vehicle detection in this case is shown in Fig. 5.

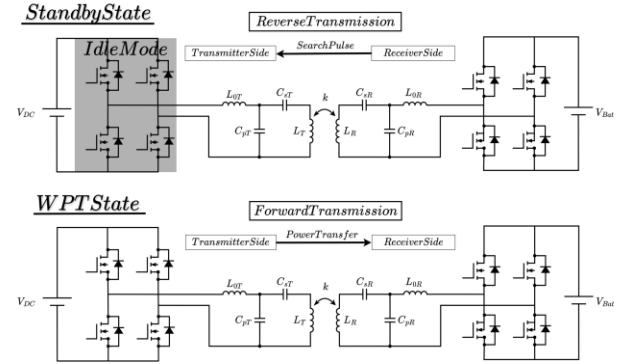
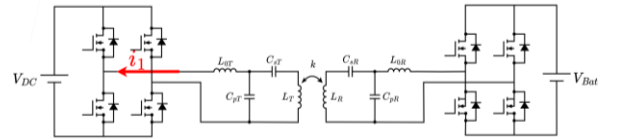
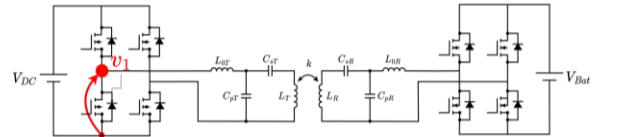


Fig. 3 System Configuration



(a) Threshold values used in previous research i_1



(b) Threshold used by the proposed method v_1

Fig. 4 Threshold for vehicle detection

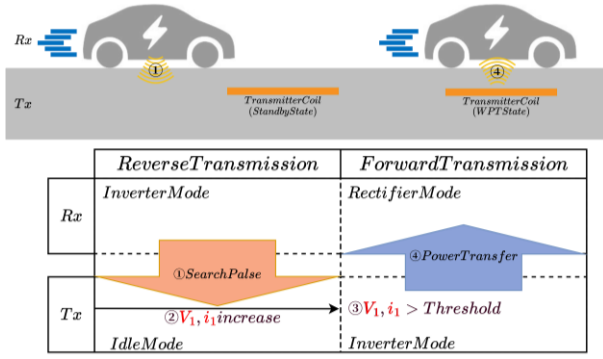


Fig. 5 Flowchart for vehicle detection

C. Detection Process

The parameters of the circuit elements used are shown in Table 1 below. Fig. 6 shows the transmitter side half-bridge inverter, considering the stray capacitance C_{OSS} and pull-down resistance $R_{pull-down}$. From Fig. 6, the possible range of AC voltage v_1 is clamped by the MOSFET body diode. Therefore, considering the diode voltage drop as V_f , it becomes as shown in equation (4).

$$0 - V_f \leq v_1 \leq V_{DC} + V_f \quad (4)$$

For simplicity, ignore the diode voltage drop and consider it as in equation (5).

$$0 \leq v_1 \leq V_{DC} \quad (5)$$

the input impedance Z_C ignoring $R_{pull-down}$ is given by equation (6), while the input impedance Z_{RC} considering $R_{pull-down}$ is given by equation (7).

$$Z_C = \left| \frac{1}{j2\omega_0 C_{OSS}} \right| = 9.36 \times 10^2 \quad (6)$$

$$Z_{RC} = \left| \frac{\frac{1}{j2\omega_0 C_{OSS}} \times R_{pull-down}}{\frac{1}{j2\omega_0 C_{OSS}} + R_{pull-down}} \right| = 9.36 \times 10^2 \quad (7)$$

From equations (6) and (7), the pull-down resistance impedance is sufficiently large to be considered negligible. Therefore, in an equivalent circuit showing only the stray capacitance C_{OSS} and pull-down resistance $R_{pull-down}$, the AC voltage v_1 is affected only by the stray capacitance C_{OSS} and can be expressed as in equation (8).

$$v_1 = \frac{1}{2C_{OSS}} \int i_1 dt \quad (8)$$

Next, Fig. 7 shows a graph explaining the cause of the increase in the DC voltage V_1 . From equation (3), the alternating current i_1 can be considered a function of the coupling coefficient k . As the vehicle approaches the transmitter coil and the coupling coefficient k increases, the amplitude of the alternating current i_1 increases. Similarly, from equation (8), as the coupling coefficient k increases, the amplitude of the AC voltage v_1 also increases due to the influence of the stray capacitance C_{OSS} . Therefore, as seen in

the region $t_1 \leq t \leq t_2$ in Fig. 7, the amplitude of the AC voltage v_1 increases. At this time, the AC voltage v_1 is clamped at $0 \leq v_1$ due to the MOSFET's body diode, as shown in equation (5). Consequently, the DC voltage V_1 obtained by passing the alternating voltage v_1 through a low-pass filter takes a positive value and increases as the coupling coefficient k increases. As v_1 continues to increase, due to the range defined by equation (5), the AC voltage v_1 becomes clamped at $v_1 \leq V_{DC}$ under the influence of the MOSFET's body diode, as shown in the region where $t_3 \leq t$ in Fig. 7. Consequently, the DC voltage V_1 obtained by applying the AC voltage v_1 to a low-pass filter converges to the value given by equation (9). A threshold value smaller than this is set to perform vehicle detection.

$$V_1 = \frac{V_{DC}}{2} \quad (9)$$

The conduction behavior of the MOSFET diodes in the half-bridge at this time is shown in Fig. 8. When V_1 increases in Fig. 8(a), (a-1) when i_1 flows in, charge accumulates in v_1 , increasing v_1 and V_1 . (a-2) When i_1 flows out, according to equation (5), the diode D_2 conducts to ensure $0 \leq v_1$. On the other hand, when V_1 converges in Fig. 8(b), (b-1) when i_1 flows in, the diode D_1 conducts to ensure $v_1 \leq V_{DC}$ according to equation (5). (b-2) When i_1 flows out, the diode D_2 conducts to ensure $0 \leq v_1$ according to equation (5).

In the case of Fig. 8(a-1), a small current i_R flows through the pull-down resistance $R_{pull-down}$, as shown in Fig. 6. Similarly, in the case of Fig. 8(a-2), a current i_D flows through the diode D_2 . The sum of the time integrals of currents i_R and i_D equals zero, and current i_R can be expressed as in equation (10).

$$i_R = \frac{v_1}{R_{pull-down}} \quad (10)$$

From equation (10), since the pull-down resistor $R_{pull-down}$ has an impedance large enough to be neglected, the current i_R can be approximated as shown in equation (11).

$$i_R \approx 0 \quad (11)$$

From equation (11), since the currents i_R and i_D take values such that the sum of their time integrals equals zero, the current i_D can be approximated as shown in equation (12).

$$i_D \approx 0 \quad (12)$$

Therefore, in the case of Fig. 8(a-2), it follows that the time integral of the clamped AC voltage v_1 over the region $t_1 \leq t \leq t_2$ in Fig. 7 is very small.

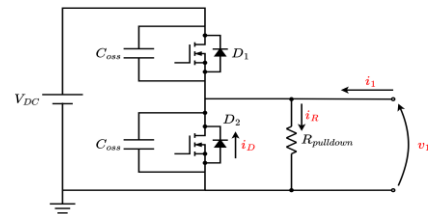


Fig. 6 Equivalent circuit of the transmitter side inverter

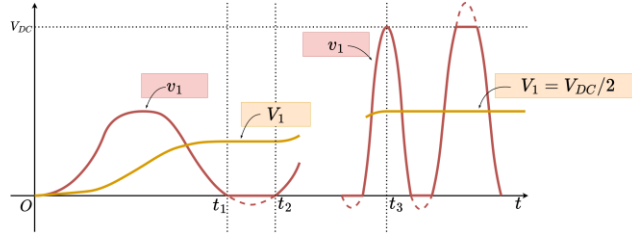
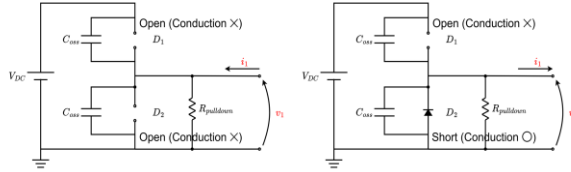
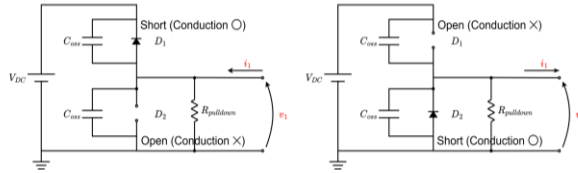


Fig. 7 Principle of increasing V_1



(a-1) When i_1 flows in (a-2) When i_1 flows out
(a) When V_1 increases



(b-1) When i_1 flows in (b-2) When i_1 flows out
(b) When V_1 converges

Fig. 8 Conduction behavior of MOSFET diode

Table 1 Parameters of circuit

Parameter	Value
V_{DC}	300 V
V_{Bat}	200 V
L_{OT}	49.3 μ H
C_{pT}	71.1 nF
C_{sT}	22.4 nF
L_T	0.206 mH
L_R	51.5 μ H
C_{sR}	0.140 mF
C_{pR}	0.133 mF
L_{OR}	26.4 μ H
C_{OSS}	0.33 nF
$R_{pull-down}$	100 k Ω

III. STATIC

A. Theoretical Formula

Therefore, the alternating voltage v_1 can be expressed using the complex voltage $\tilde{V}_1$ as shown in equation (13).

$$v_1 = \sqrt{2}|\tilde{V}_1| \sin \omega_0 t + \frac{\sqrt{2}}{2}|\tilde{V}_1| \quad (13)$$

At this time, the complex voltage $\tilde{V}_1$ can be expressed as in equation (14) for an equivalent circuit showing only the stray capacitance C_{OSS} and the pull-down resistance $R_{pull-down}$.

$$\tilde{V}_1 = \frac{i_1}{j2\omega_0 C_{OSS}} \quad (14)$$

Substituting equations (2) and (3) into equation (14) yields equation (15).

$$\tilde{V}_1 = \frac{A_{LCC} V_{Rx}}{j2\omega_0 C_{OSS}} k = \frac{A_{LCC} \frac{2\sqrt{2}}{\pi} V_{Bat} \sin\left(\frac{\alpha_{Rx}}{2}\right)}{j2\omega_0 C_{OSS}} k \quad (15)$$

The condition for the DC voltage V_1 to converge at $t = t_3$ in Fig. 7 can be expressed as in equation (16).

$$V_1 = \bar{v}_1 = \frac{1}{T} \int_0^T v_1 dt = \frac{\sqrt{2}}{2} |\tilde{V}_1| = \frac{V_{DC}}{2} \quad (16)$$

Substituting equation (15) into equation (16) yields equation (17). Therefore, the value of the coupling coefficient k when the DC voltage V_1 converges is obtained as shown in equation (18).

$$\frac{\sqrt{2}}{2} \times \frac{A_{LCC} \frac{2\sqrt{2}}{\pi} V_{Bat} \sin\left(\frac{\alpha_{Rx}}{2}\right)}{2\omega_0 C_{OSS}} k = \frac{V_{DC}}{2} \quad (17)$$

$$k = \frac{\pi \omega_0 C_{OSS} V_{DC}}{2 A_{LCC} V_{Bat} \sin\left(\frac{\alpha_{Rx}}{2}\right)} = 0.018 \quad (18)$$

From equation (18), it can be said that the DC voltage V_1 converges when the coupling coefficient $k = 0.018$. Therefore, by using the DC voltage V_1 as the threshold, vehicle detection can be achieved earlier than when the coupling coefficient $k = 0.018$.

Furthermore, the alternating current i_1 when the coupling coefficient $k = 0.018$ is given by equation (19) from equation (3). Taking the maximum possible value of coupling coefficient k in DWPT as $k_{max} = 0.2$, the alternating current i_{1max} at this point is given by equation (20).

$$i_1 = A_{LCC} \frac{2\sqrt{2}}{\pi} V_{Bat} \sin\left(\frac{\alpha_{Rx}}{2}\right) k = 0.11 \quad (19)$$

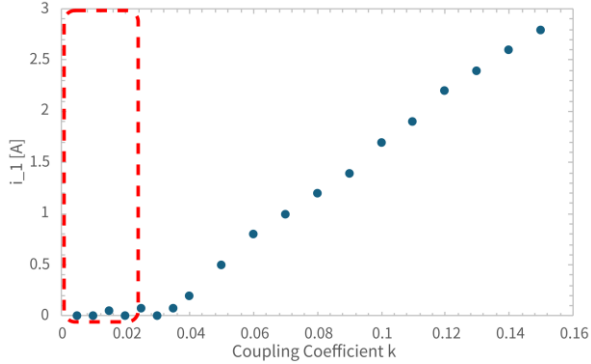
$$i_{1max} = A_{LCC} \frac{2\sqrt{2}}{\pi} V_{Bat} \sin\left(\frac{\alpha_{Rx}}{2}\right) k_{max} = 1.33 \quad (20)$$

From equations (19) and (20), when the DC voltage V_1 converges, the AC current i_1 increases by only 9% of its maximum value. Therefore, from the perspectives of noise margin and detection sensitivity, the risk of false detection is extremely high. Therefore, it is considered more appropriate to set the threshold when the AC current i_1 is larger than at the point when the coupling coefficient $k = 0.018$. Therefore, using the AC current i_1 as the threshold results in vehicle detection that is significantly slower than at the point when $k = 0.018$. Consequently, the proposed method using DC voltage V_1 exhibits excellent responsiveness and converges rapidly to a stable value. Using DC voltage V_1 as the threshold is expected to enable earlier vehicle detection.

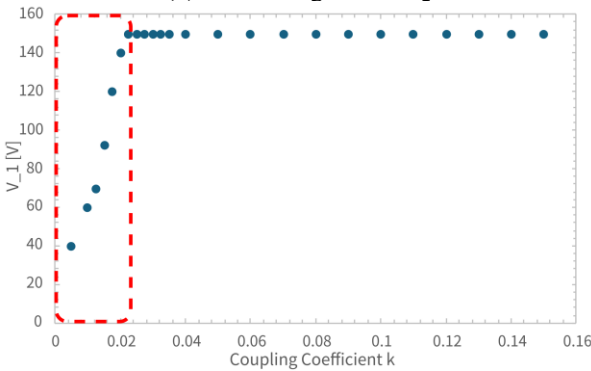
B. Static Analysis

Fig. 9 shows the output waveforms of the alternating current i_1 and DC voltage V_1 for the coupling coefficient k during reverse transmission in the Static Wireless Power Transfer (SWPT). The DC voltage V_1 in Fig. 9(b) has reached a stationary value near the coupling coefficient $k = 0.02$. This value is equivalent to the coupling coefficient k at the convergence point of the DC voltage V_1 calculated using equation (16). Therefore, the theoretical formula and static characteristics are found to match. Furthermore, near the coupling coefficient $k = 0.02$, where the AC current i_1 in

Fig. 9(a) approaches zero, the DC voltage V_1 in Fig. 9(b) converges to a stable value. Therefore, in the vehicle detection method using the DC voltage V_1 as the threshold, detection is possible within the enclosed area in Fig. 9. This indicates that earlier detection is possible compared to the vehicle detection method using the AC current i_1 as the threshold, from the perspectives of noise margin and detection sensitivity.



(a) Alternating current i_1



(b) DC voltage V_1

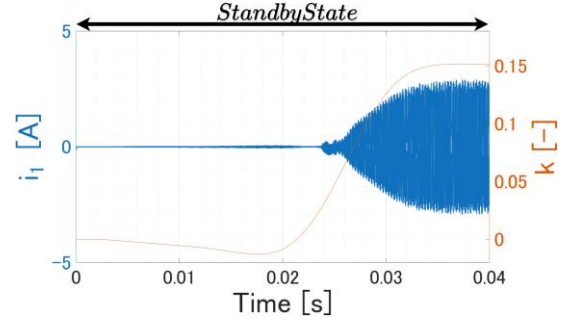
Fig. 9 Output waveforms of i_1 and V_1 for coupling coefficient k during reverse transmission in SWPT

IV. SIMULATION

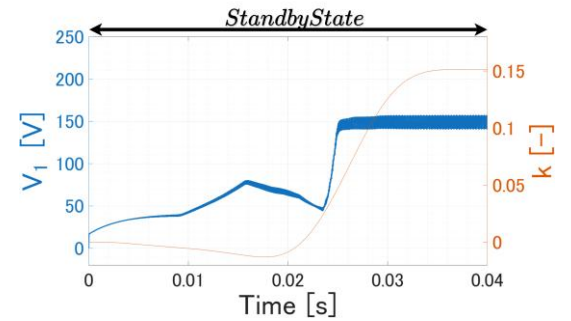
The proposed vehicle detection method is verified through simulation in MATLAB. The simulation employs the parameters shown in Table 1. At 60 km/h on a DWPT, the threshold is determined via reverse transmission, followed by vehicle detection from the reverse transmission to confirm power transfer in the forward transmission.

A. Reverse Transmission

Fig. 10 shows the output waveforms of the alternating current i_1 and DC voltage V_1 for the coupling coefficient k during reverse transmission. Based on Fig. 10, the threshold value of the direct current voltage V_1 for vehicle detection was empirically determined to be 100 V, which is two-thirds of the maximum possible value.



(a) Alternating current i_1



(b) DC voltage V_1

Fig. 10 Output waveforms of i_1 and V_1 for coupling coefficient k during reverse transmission

B. Forward Transmission

The system is controlled to initiate transmission of the gate signal at the transmitter side when the DC voltage V_1 exceeds the threshold. Fig. 11 shows the output waveforms for transmitted power P_{in} , and received power P_{out} as functions of the coupling coefficient k .

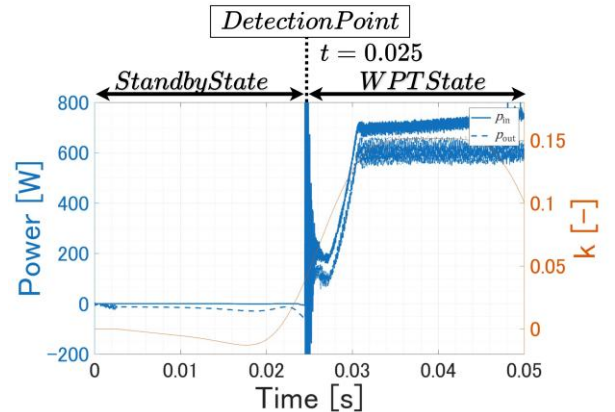


Fig. 11 Output waveforms for P_{in} and P_{out} for coupling coefficient k

From Fig. 11, we confirmed the switching of power transmission direction from reverse to forward transmission with a threshold set, as shown by the power transmission confirmation. Therefore, the vehicle detection of the proposed method can be considered sufficiently realizable.

Next, to compare conventional vehicle detection methods using amplitude of the AC current i_1 as the threshold, a simulation was performed under the same simulated conditions. Similar to the threshold used for DC voltage V_1 , the threshold was set to two-thirds of the maximum value obtainable from Fig. 10(a). Control was implemented such that transmission of the gate signal at the transmitter side commenced when i_1 exceeded this threshold. Fig. 12 shows the output waveforms for the transmitted power P_{in} and received power P_{out} as a function of the coupling coefficient k under these conditions.

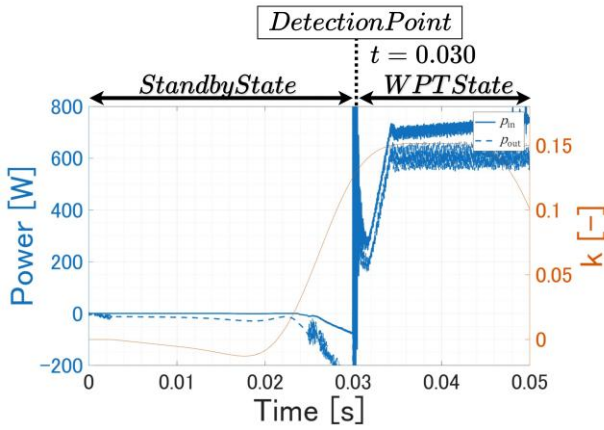


Fig. 12 Output waveforms for P_{in} and P_{out} for coupling coefficient k

From Fig. 12, in the vehicle detection method of the previous method using the amplitude of the alternating current i_1 as the threshold, the threshold is detected at time $t = 0.03$. On the other hand, from Fig. 11, in the vehicle detection method of the proposed approach using the DC voltage V_1 as the threshold, the threshold is detected at time $t = 0.025$. Therefore, it can be said that the vehicle detection of the proposed method enables detection 5 ms faster than the vehicle detection of the previous method. The time when the vehicle is directly above the transmitter coil resulting in maximum power reception is approximately 30 ms at 60 km/h. This represents a significant reduction in detection time. Furthermore, the greater the increase in vehicle speed and the shorter the power charging time, the more beneficial this becomes.

V. CONCLUSION

This paper proposes a vehicle detection method using search pulses from the receiver side, employing the DC voltage V_1 on the transmitter side as a threshold in the DWPT. Acquiring the threshold via a voltage sensor is expected to improve accuracy and noise immunity. Additionally, based on its principles and static characteristics, DC voltage V_1 exhibits excellent responsiveness and converges rapidly to a steady-state value. This confirms the usefulness of the proposed method for enabling faster vehicle detection. Furthermore, verification through simulations confirmed that the proposed method enables vehicle detection 5 ms faster than conventional methods at DWPT of 60 km/h.

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