Sensorless Metal Object Detection Using Transmission-Side Voltage Pulses in Standby Phase for Dynamic Wireless Power Transfer

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***Abstract*— In the Wireless Power Transfer (WPT) by magnetic field resonant coupling, the presence of a metal foreign object between two coils is dangerous due to overheating caused by induction heating. Most previous studies have focused on detection methods for the static WPT (S-WPT), which targets stationary electric vehicles (EVs). In the S-WPT, the power supply time is long, and foreign metal objects tend to heat up. However, the dynamic WPT (D-WPT) is expected to generate less heat than the S-WPT because of its short power supply time and long standby time. We studied the types and sizes of metals which must be detected in D-WPT and the appropriate detection methods for them. We propose a detection method by applying voltage pulses to the transmitter circuit and measuring the steady-state value of the transmitter current. By performing detection only during the standby time specific to D-WPT, the reference impedance can be made small and free from effects of misalignment with the power receiver coil. From the heating experiment, we determined that the metals which must be detected in the 20 kW D-WPT system were ferromagnetic and the minimum size was 50 mm × 50 mm. The detection experiment showed that the invasion of the metal objects which must be detected reduced the steady-state value of transmitter current by at least 20%. In conclusion, the proposed method can be implemented at a low cost and satisfy the required detection accuracy in the D-WPT.**

Keywords*— *wireless power transmission, induction heating, foreign object detection, dynamic wireless power transfer

I. Introduction

With the growing concern over environmental issues such as global warming and air pollution in recent years, electric vehicles (EVs) have been attracting attention around the world. They use electricity as their energy sources and do not emit CO_2 while driving. Contrary to this trend, the actual penetration rate of EV is still low because consumers are dissatisfied with the short cruising range and the long charging time. To solve this problem, the Wireless Power Transfer (WPT) technology based on the magnetic resonance coupling method is being actively researched [1]. This technology has been applied to the Static Wireless Power Transfer (S-WPT), which supplies power to stationary EVs, and the Dynamic Wireless Power Transfer (D-WPT), which supplies power to EVs in motion [2]. The D-WPT enables EVs to be powered constantly while driving, thus providing an unlimited cruising range and eliminating the need to consider charging time.

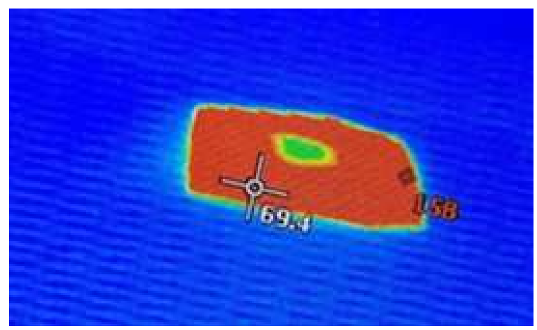

Fig. 1. Temperature deviation of a steel sheet in 1.5kW S-WPT after 3 sec.

However, there are still some issues in establishing WPT technologies, including D-WPT. The magnetic field between two coils can induce eddy currents in metal objects intruded to the power transfer area and causes them to generate heat. Fig. 1 shows that the temperature deviation of a steel sheet intruding 1.5 kW S-WPT. After only three seconds, the temperature of a portion of the steel sheet reaches over 150 ℃. In addition, when living objects are exposed to magnetic fields, there are concerns about health hazards. Therefore, WPT devices must detect foreign objects, and various foreign object detection (FOD) methods have been proposed. We focused on Metal Object Detection (MOD).

According to previous studies, there are two types of MOD: mechanical and thermal detection, and electromagnetic

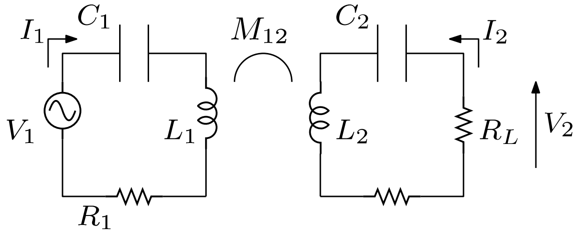

Fig. 2. WPT circuit model without a metal object. The left circuit is the transmitter circuit, and the right circuit is the receiver circuit.

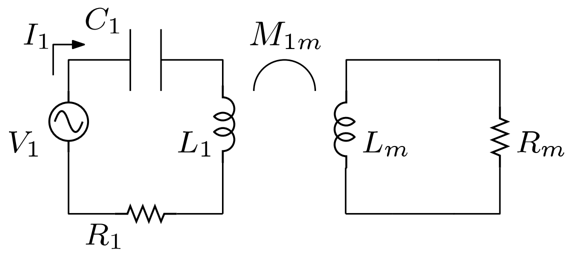

Fig. 3. Transmitter circuit with a metal object. The left circuit is transmitter circuit, and the right circuit is the equivalent circuit of a metal object.

detection [3]. The former examples are light sensors [4], magnetic sensors [5], and image processing [6]. The latter examples are based on a resonance frequency deviation [7], a quality factor deterioration [8], and a detection coil to detect induced electromotive force changes [9], [10]. Many of the aforementioned methods assume S-WPT, and these detection methods perform during power transmission to the stopped receiver coil. On the other hand, applying these existing methods to D-WPT is expected to be difficult because the power transfer time is short, and the receiver coil is always moving. Also, it needs high accuracy because even a tiny metal object quickly generates heat due to the power supply time in S-WPT. Alternatively, since the supply time of D-WPT is short and intermittent, it may not require as much detection accuracy as S-WPT.

We propose a MOD method based on the input impedance deviation using the transmission-side voltage pulses for D-WPT. In the proposed method, voltage pulses are applied to the power transmitter circuit during the standby time when no vehicle is present and detects foreign metal objects from the amplitude change of the current waveform. Since the transmitter circuit impedance is minimal during standby time, a metal object significantly changes the impedance so that this method can detect small metal objects without additional sensors and circuits. A MOD method by comparing impedances was proposed in the previous research [12]. The method performs when power supplying and the transmitter coil is magnetically coupled to the receiver coil since it assumes S-WPT. In this case, it is difficult to detect a tiny metal because the input impedance is large even when there is no metal. However, in the case of D-WPT, the reference impedance can be reduced in our method because of no magnetic coupling during the standby time.

This paper focuses on the foreign metal object in D-WPT. We determined the characteristics of objects which must be detected and proposed a detection method using transmission-side voltage pulses in standby time in D-WPT. In section II, the theory of the proposed method is described using a circuit model. In section III, the heat generation experiments conducted to determine the metals to be detected by D-WPT and the results are presented. In section IV, the detection experiments conducted using the proposed method on the metals determined in the previous chapter and the results are presented. Section V draw conclusions of our works.

II. Theoretical Analysis for the Proposed MOD Method

A. *WPT circuit with a foreign metal object*

As a circuit model of the WPT, the series-series (S-S) topology is shown in Fig. 2. The subscript "1" indicates the transmitter side, and "2" indicates the receiver side. I and V represent current and voltage, respectively. R is the internal resistance of the transmitter coil, and L is the self-inductance. C is the resonant capacitance. R_L in the receiver circuit is a load resistance. M_{12} is the mutual inductance between two coils.

When a metal object exists on the transmitter coil, the equivalent circuit model is shown in Fig. 3 [11]. If the receiver coil does not exist or the gap between the two coils is far apart, only the transmitter coil is affected by the object. L_m and R_m are the self-inductance and resistance of the equivalent circuit of the metal foreign object. M_{1m} means the mutual inductance between the transmitter coil and the object. The coil's self-inductance L_1 and the internal resistance R_1 change by the metal object's presence as follows:

$$L_1 \to L_1 - \frac{(\omega M_{1m})^2}{R_m^2 + (\omega L_m)^2} L_m, \tag{1}$$

$$R_1 \to R_1 + \frac{(\omega M_{1m})^2}{R_m^2 + (\omega L_m)^2} R_m, \tag{2}$$

where ω means the operating angular frequency. According to (1) and (2), L_1 becomes smaller, and R_1 becomes larger. Hence, due to the foreign metal object, the transmitter circuit is no longer in resonance and the impedance of the circuit increases.

B. *Transmitter circuit in MOD mode*

In our proposed method, the MOD is conducted by comparing the input impedance when there is no power receiver coil. In this situation, the circuit diagram is expressed as shown in Fig. 3 when a metal object intrudes. Assuming that the transmitter circuit is perfectly resonant, the transmitter circuit's impedance is equal to R_1. However, by the intrusion of a metal object, the impedance of the transmitter circuit is increased by ΔZ as described in (3).

$$\Delta Z = \frac{(\omega M_{1m})^2}{R_m^2 + (\omega L_m)^2} R_m - j\omega \frac{(\omega M_{1m})^2}{R_m^2 + (\omega L_m)^2} L_m \tag{3}$$

The transmitter coil is powered by an inverter which can be operated as a constant voltage source. Therefore, the impedance change can be observed by measuring the current

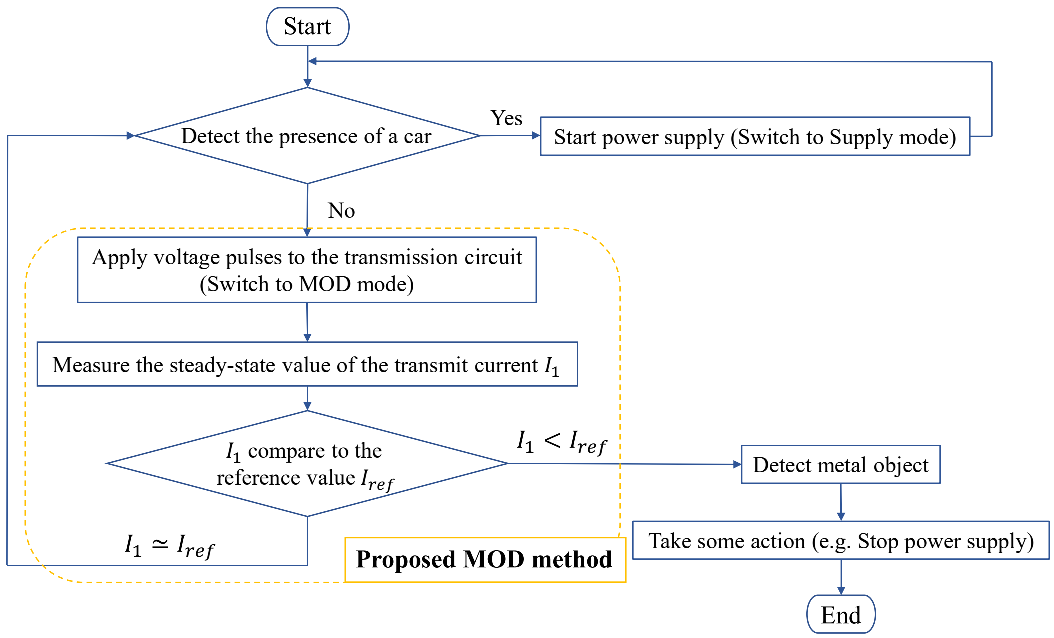

Fig. 4. Procedure of the proposed method.

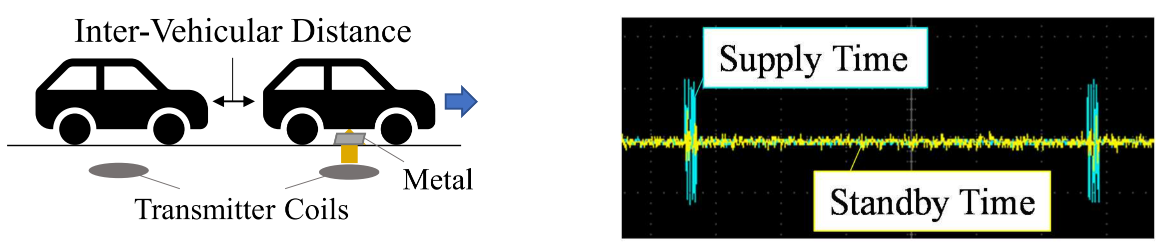

Fig. 5. The left figure shows the diagram of D-WPT. The right figure shows the voltage waveform applied in the experiment.

value. The proposed MOD method can be achieved by measuring the transmitter current and comparing the current value with the reference value.

C. *Flowchart of the proposed method*

Fig. 4 shows the flowchart of the proposed method. The first step is to detect the presence of a vehicle. The vehicle detection method is assumed to be a method using voltage pulses from the receiver coil [13]. When a car is detected, it moves to Supply mode and supplies power to the car. If not, the transmitter coil switches to MOD mode and applies voltage pulses to the transmitter circuit. Then, it measures the steady-state value of the current I_1 and compares I_1 to the reference value I_{ref}. If I_1 is almost the same to I_{ref}, it returns to the car detection, or if I_1 is lower than I_{ref}, it detects the presence of the foreign metal object. For practical purposes, I_1 and I_{ref} are effective values. The reference value I_{ref} is measured with no foreign object (e.g., during embedding or maintenance).

There is a possibility that the system may supply power to the vehicle before detecting the foreign metal object, but this is not a problem because the metal hardly heats up with a single supply and the system always switches to the MOD mode between vehicles by detecting the presence of a vehicle in an appropriate cycle.

TABLE I. TRANSMITTER COIL SPECIFICATIONS

Parameters	Values
Coil Length	0.697 m
Coil Width	0.267 m
Self-inductance	200.7 μH
Resistance (with Capacitor)	159.8 mΩ
Operating Frequency	85 kHz

III. MEASUREMENT EXPERIMENT OF FOREIGN METAL OBJECTS' TEMPERTURE IN D-WPT

A. *Experimental condition*

As previously stated, the foreign metal object in the D-WPT may not generate as much heat as in S-WPT. Therefore, the size of the metals to must be detected may be different from the S-WPT standard. To get information on the actual temperature of metal objects in D-WPT, we measured the test objects' surface temperature placed on the power transmitter coil. An overview diagram is shown in Fig. 5. By conducting an intermittent and short power transmission, we simulated the D-WPT situation on the S-WPT bench system setup with the specifications given in Table 1. The experimental bench is

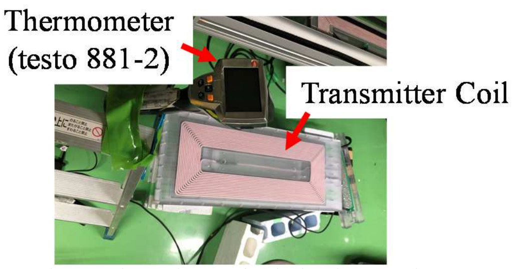

Fig. 6. The equipment for the heating experiments.

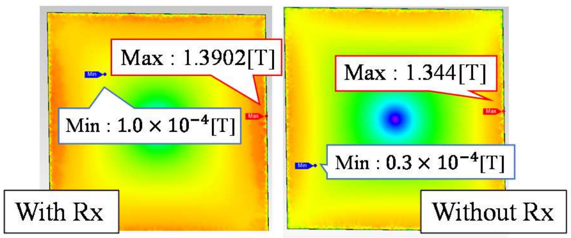

Fig. 7. The contour plot of the magnetic field of a steel sheet. The left figure is with a receiver coil, and the right figure is without a receiver coil. The simulation was conducted in JMAG.

shown in Fig. 6. We measured the following three cases. "Distance" means the inter-vehicular distance.

Case1. Vehicle Speed:5 km/h, Distance: 5 m

Case2. Vehicle Speed:10 km/h, Distance: 7.5 m

Case3. Vehicle Speed:30 km/h, Distance: 15 m

In our research group, the D-WPT system was implemented at a scale of 20 kW (500 V and 40 A) [14]. However, it is not easy to reproduce this scale from a safety standpoint because it needs high voltage and generates a large current. Therefore, noting that it is mainly the magnetic field due to the transmitter current relevant to induction heating, the input impedance was lowered by removing the power receiver coil, and a large current was applied at a small voltage. Fig. 7 shows the contour diagram of the magnetic field simulation of the surface of the metal object using JMAG. The presence of a receiver coil has little effect on the scale of the magnetic field, which is the cause of the induction heating.

Besides, the graph was extrapolated to 40A, assuming that the metal temperature is proportional to the square of the current value since the eddy current loss is proportional to the square of the magnetic field and the magnetic field is proportional to the current [15].

We used a steel sheet as a foreign object because it is ferromagnetic that quickly generates heat by eddy current. The thickness is 0.2 mm. We set 80°C as the temperature threshold referring to the standard for the stationary chargers [16].

B. *Experimental result*

Fig. 8 shows the experimental results on the three cases, which explained in the last subsection, respectively. The circles are the actual temperatures, and the lines are extrapolated by the least-squares method based on the measurements.

As shown in the figures, the slower the vehicle's speed and the larger the object becomes, the higher the saturation temperature of the object increases. Fig. 8 also shows that the temperature of a 50 mm × 50 mm object is expected to reach 80 °C at 40 A when the vehicle speed is 5 km/h. Therefore, we determined that the target of the FOD in our D-WPT system is a ferromagnetic object of 50 mm × 50 mm and larger.

IV. Experiment of Metal Object Detection

A. *Experimental condition*

As illustrated in Section III, in our D-WPT system, a steel sheet of 50 mm × 50 mm and larger must be detected. Therefore, we conducted the detection experiment on the same experimental bench to see whether the proposed method can detect them. Aluminum plates and steel sheets were used as foreign objects. Although aluminum is not a metal to be detected, we used it to check whether the proposed method is affected by the magnetism of the metal. To measure the difference in the current waveform depending on the position on the coil, we measured different positions of the metal as shown in Fig.9. In all experiments, the pulse width of the applied voltage was 5 ms, and the voltage's amplitude was 3 V.

B. *Experimental result*

The experimental results are shown in Fig. 9. In the absence of an object, the steady-state value of transmitter current is approximately 9 A. However, when the smallest piece of metal object intruded, it decreased to 7 A. Besides, it decreased as the size of the metal piece increased. Therefore, regardless of whether the metal is paramagnetic or ferromagnetic, the value changed by more than 20% for metals larger than 50 mm × 50 mm. Therefore, steel sheets and aluminum plates larger than 50 mm × 50 mm can be detected by this method. It achieves the aforementioned objective.

Fig.9 also shows the results when the steel sheet is placed at various locations in the coil shown in Fig.10. Even in the slightest change in amplitude, the change is 20% compared to the reference value. Therefore, we conclude that detection is possible no matter where the object is in the power transmission area.

V. Conclusion

In this study, we conducted the heat generation and detection experiments of foreign metal object in D-WPT. From the heat experiment results, we confirmed that a steel sheet with a size of 50 mm×50 mm or larger heats up in the range of vehicle speed of 5 km/h or more in the D-WPT system [12]. From the experimental results, we defined the size of the metal object that must be detected as 50 mm×50 mm and larger. Then, we proposed a MOD method based on the impedance deviation of transmitter circuit using the transmission-side voltage pulses. The detection experiment showed that a 50 mm square steel sheet reduced the pulse current amplitude by at least 20%. Thus, the proposed MOD mechanism satisfies the required accuracy in D-WPT without external circuits or additional sensors.

Acknowledgment

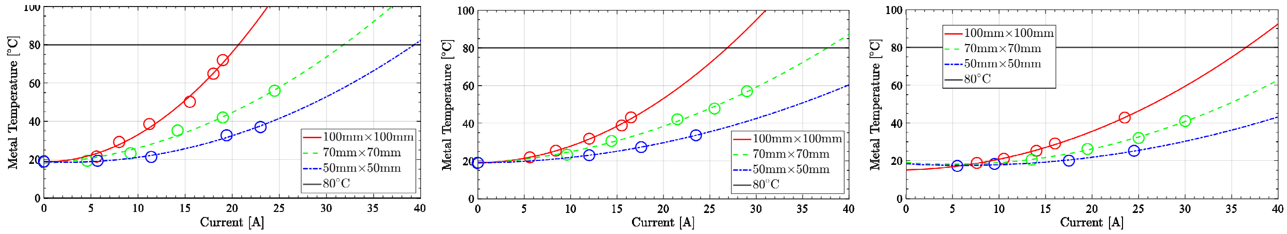

Fig. 8. Graphs of surface temperature of metal objects versus transmitter current value. The left figure shows result of Case1, the center figure shows Case2, and the right figure shows Case3. The circles are the actual temperatures, and the lines are extrapolated by the least-squares method based on the measurements.

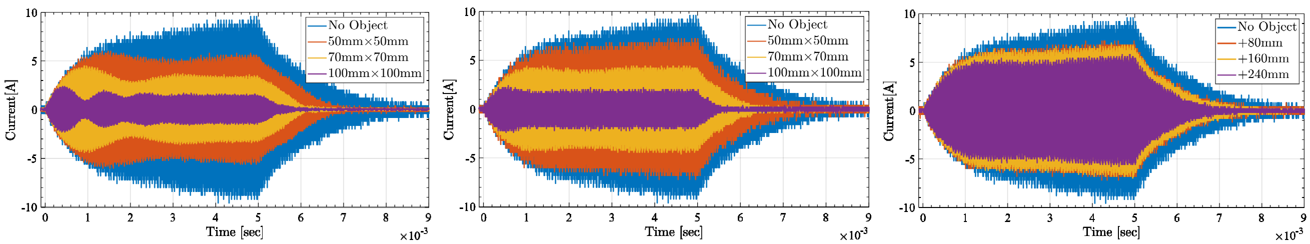

Fig. 9. Current waveforms of the detection experiment. The left figure shows result of aluminum plate, and the center figure shows result of steel sheet. Both of metals are on the center of transmitter coil. The right figure shows the results when the steel sheet (50 mm × 50 mm) is displaced in the longitudinal direction on the transmitter coil. The value of distances in legends are measured from the center of transmitter coil.

This work was partly supported by JST-Mirai Program Grant Number JPMJMI17EM, JSPS KAKENHI Grant Number JP18H03768, JST CICORP Grant Number JPMJSC17C4, Japan.

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