Sensorless Vehicle Detection Using Vehicle Side Voltage Pulses for In-motion WPT

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***Abstract*—In order to put in-motion wireless power transfer to practical application, it is necessary to establish the technology of detecting the vehicle side coil from the road side coil. Search pulse method is one of the previous methods that can detect the vehicle side coil by measuring the current of the road side coil. However, in the conventional method, the road side coil emits search pulses continually even when vehicles rarely pass over the road side coil. Here the authors have proposed a new method that search pulses are emitted from the vehicle side coil, and verified by simulation and experiments that the proposed method is superior to the conventional method in terms of the standby power and the sensitivity of detection.**

***Index Terms*—wireless power transfer, in-motion charging, search pulse, detection**

I. Introduction

Recently, wireless power transfer (WPT) has been researched widely. In particular, magnetic resonant coupling, which MIT published in 2007, has attracted a lot of attention because it can transfer large power with high efficiency. Furthermore, it has a characteristic that it maintains high efficiency even with wide air gap or misalignment [1].

One application of the technology is wireless power supply to Electric Vehicles (EVs). EVs do not emit CO2 during traveling, and various countries promote the shift from gasoline-engined cars to EVs. However, they have not yet become widely used. This is due to the shorter range, higher vehicle price, and longer charging time compared to those of gasoline-engined cars. These problems are resolved by in-motion wireless power transfer. If the road side coils are installed to intersections in cities or on highways, power can be transferred from the road side coil to the vehicle side coil. As a result, the cruising range can be extended significantly as long as the vehicles run in the area with road side coils, and the drivers do not need to wait a long charging time. Moreover, the price of EVs is expected to fall because the amount of battery on EVs can be reduced. [2] [3] [4].

As mentioned above, problems which prevent the spread of the EVs can be resolved by in-motion WPT. However, there are some problems in WPT. One of them is radiation noise [5] [6] [7]. The optimazation of the allocation of road side coils has also been researched recently [8]. In addition to these problems, there are problems that WPT during stopping does not have in order to realize in-motion WPT.

It is necessary for road side coils to detect vehicle side coils and start power transfer quickly. When a one-meter-long road side coil transfers power to a vehicle moving at $100\,\mathrm{km/h}$ on the highway, the staying time of the vehicle on each road side coil is only $36\,\mathrm{ms}$. During the $36\,\mathrm{ms}$, the road side coil has to detect a vehicle, and transfer enough power. Therefore, the vehicle detection is very important.

Fig. 1. The vehicle used in the experiment of the conventional sensorless detection method.

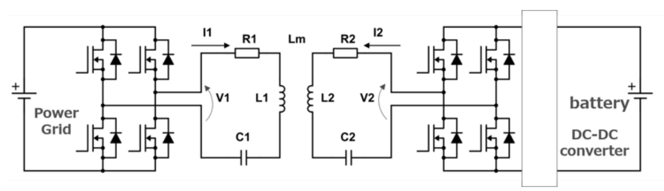


Fig. 2. S-S type resonance circuit.

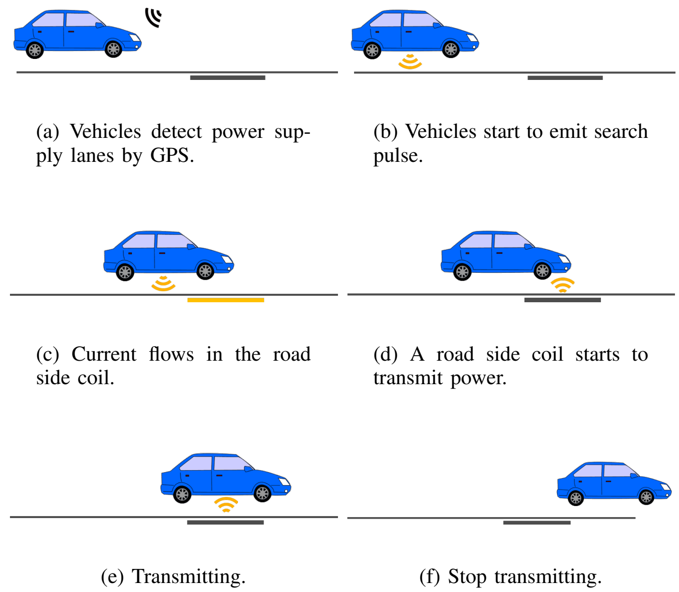
Until now, various vehicle detection methods have been researched. They can be divided into two groups: methods with external sensor, and sensorless methods. Some studies use magnetic sensors [9] [10]. It is simple to detect vehicles with external sensors. However, the cost gets high with additional hardware, and it also leads to the decline of the reliability. Therefore, the vehicle detection without sensors have been suggested. In this method, a coil for power supply is used for detection [11] [12] [13]. The authors studied the search pulse method, and an experiment with a real vehicle is already conducted [12]. Fig. 1 shows the vehicle used in the experiment of the search pulse sensorless detection method.

In this paper, the authors propose a new vehicle detection method with no additional sensors or coils. It can reduce the standby power and increase the sensitivity of the detection. Chapter 2 introduces the search pulse method as the conventional sensorless vehicle detection method, and proposes a

TABLE I
MEANING AND VALUES OF THE PARAMETERS OF THE COILS

Parameter	Meaning	Value
C_1	Capacitance of road side coil	7.48 nF
C_2	Capacitance of vehicle side coil	8.50 nF
R_1	Resistance of road side coil	0.53 Ω
R_2	Resistance of vehicle side coil	0.40 Ω
L_1	Inductance of road side coil	42.9 mH
L_2	Inductance of vehicle side coil	37.7 mH
ω_0	Operating angular frequency	88.1 kHz

new method which resolves the problems of the conventional method. Chapter 3 analyzes the proposed method from the perspectives of the detection sensitivity and the standby power. Chapter 4 introduces the experiment result of the detection sensitivity. Chapter 5 shows the experiment of switching from detection to power supply, and confirms that the proposed method can receive power even at the negative coupling region.



(a) Vehicles detect power supply lanes by GPS. (b) Vehicles start to emit search pulse. (c) Current flows in the road side coil. (d) A road side coil starts to transmit power. (e) Transmitting. (f) Stop transmitting.

Fig. 3. The proposed method in which search pulses are transmitted from the vehicle side coil.

II. METHOD FOR SENSORLESS VEHICLE DETECTION

A. WPT Circuit and the conventional method

First of all, the authors introduce the search pulse method as a conventional sensorless vehicle detection method [12]. For explaining this method, it is necessary to derive the road side coil current of the magnetic resonant coupling. Fig. 2 shows S-S type magnetic resonant coupling circuit. In the detection mode, the vehicle side coil is shorted by turning on the lower SiCs (Short mode). V_1 is the voltage of the road side coil. k is the coupling coefficient, and can be described as follows: $k = \frac{L_m}{\sqrt{L_1 L_2}}$. L_m is the mutual inductance. The meanings of the other parameters are Table. I. In short mode, the road side current I_1 is described as the following equation:

$$I_1 = \frac{R_2}{R_1 R_2 + \omega_0^2 k^2 L_1 L_2} V_1. \tag{1}$$

Now the authors introduce the procedure of the conventional search pulse method. The vehicle side coil waits in the short mode. The road side coil emits pulses at regular time intervals. The pulse is called search pulse. The duty ratio of the pulse is lower than that at the power transfer mode. When a vehicle is not around the road side coil, the coupling efficient k is very close to 0. Therefore, according to the (1), I_1 is large. When a vehicle comes on the road side coil, I_1 becomes small. The road side coil detects the existence of the vehicle by monitoring the I_1. Then, the road side coil starts to transmit power, and the vehicle side coil detects it from its own current, and turning off the all SiCs (Rectification Mode).

However, this conventional method has a problem. In this method, the road side coil needs to emit searching pulses at regular time intervals even when vehicles are not around the road side coil. This is not good from the viewpoint of the standby power.

B. Proposed method

The authors propose a new method in which search pulses are emitted not from the road side but from the vehicle side. This proposed method can resolve the problem of standby power. In proposed method, road side coil stands by in short mode. In short mode, road side coil only needs to monitor the current. Therefore, the standby power can be greatly reduced in comparison with the conventional method in which the search pulse is continuously emitted periodically. The flow of detection of the proposed method is Fig. 3. First, vehicles detect the approach to the wireless power supply section by positioning system like GPS. When vehicles detect the approach, vehicles start to emit search pulses. As vehicles approach to the road side coil, current starts to flow in the road side coil. The road side coil detects the current, and starts to supply power to the vehicle. The road side coil stops power supply by detecting the reduction of the current when the vehicle passes over the coil.

III. SIMULATION ABOUT STANDBY POWER

A simulation about standby power was conducted. In the simulation, the power supply coils were installed one lane each in half of the sections between the interchanges (ICs) of the Tomei Expressway in Japan. The circumstances of the simulation are based on Table II. The distance between ICs, the number of lanes, the amount of traffic, and the average speed of vehicles are based on the Consensus of Ministry of Land, Infrastructure, Transport and Tourism [14].

Fig. 7 shows the standby power of conventional and proposed methods per day. The proposed method can reduce standby power by 99 % compared to the conventional method.

This result comes from the difference of the standby time of the both methods. In the conventional method, the standby time depends on the inter-vehicle distance. According to the Consensus [14], the inter-vehicle distance of Tomei Expressway in Japan is about $65\,\mathrm{m}$ to $300\,\mathrm{m}$, and the size of the vehicle side coil is about $1\,\mathrm{m}$. Therefore, the road side coil waits $99\,\%$ of the day.

On the contrary, the standby time of the proposed method depends on the span of the road side coil. It is debatable, but it may fits in the range of about 0.5 to 3 times of the size of the road side coil. This means that the vehicle side coil emits the search pulses during about 33% to 75% of the driving time. So, the standby time in the proposed method is shorter than that in the conventional method.

Another factor is the difference of the number of the equipment which emits the search pulses. In the conventional method, the road side coil emits the search pulses, and the number of them is 66,500 if the span of road side coil is $2.6\,\mathrm{m}$ (that is 2 times of the road side coil) and they are installed one lane each in half of the sections between the interchanges (ICs) of the Tomei Expressway in Japan. In the proposed method, the vehicle side coils emit the search pulses. The number of vehicle can be calculated from the traffic, and average speed. According to the Consensus, the number of vechiles is 3,184 in daytime, and 2,040 in nighttime.

As above, in the proposed method, the ratio of the standby time is low and the number of equipment which emits the search pulses is small. So, the total standby power of the proposed system is smaller than that of the conventional system.

As shown in Fig. 8, the standby power of conventional method is 19.2 % of the power supply from road side to vehicle side in daytime, and 30.1 % of the power supply from road side to vehicle side in nighttime. The standby power is enough large compared to the supplied power. So, it is significant to reduce the standby power.

The proposed method uses the battery of the vehicle to emit the search pulses. According to the Fig 9, the standby power of the proposed method is sufficiently small compared to the battery consumption for cruising.

Fig. 10 shows the power consumption of the whole system. The standby power of the conventional method is comparatively large, so it is worth reducing the standby power by using the proposed method. The proposed method can reduce the whole consumption power by 10.8% in daytime, and 16.0% in nighttime.

Therefore, it can be concluded that the proposed method can reduce more standby power compared to the conventional method, and the effect is large.

IV. Sensitivity of Detection

In both conventional and proposed methods, the current of the road side coils was monitored to detect the vehicles. When vehicles pass over the road side coils, the coupling coefficient k changes gradually. In the conventional method, the road side emits search pulses, and the vehicle side waits in the short mode. On the other hand, in the proposed method, the road side waits in the short mode, and the vehicle side emits search pulses. Therefore, the current of the road side coil is described in the different ways in the conventional and proposed methods. V_2 is the voltage of the vehicle side coil. (1) is the conventional method, and (2) is the proposed method.

$$I_1 = \frac{\omega\sqrt{L_1 L_2}k}{R_1 R_2 + \omega_0^2 k^2 L_1 L_2} V_2. \tag{2}$$

Fig. 4 shows the relation between the coupling coefficient and the current of road side coil. The parameters are based on Table I. In the simulation of the conventional method, the voltage of the road side coil V_1 is $10\,\mathrm{V}$, and the voltage of the vehicle side coil V_2 is $0\,\mathrm{V}$. In the simulation of the proposed method, V_1 is $0\,\mathrm{V}$, and V_2 is $10\,\mathrm{V}$. When vehicles pass over the coils, k increases from 0. Therefore, the authors focus on the range that k is from 0 to 1×10^{-4}. In this range, the current changes from $37\,\mathrm{A}$ to $30\,\mathrm{A}$ in the conventional method. In the proposed method, it changes from $0\,\mathrm{A}$ to $17\,\mathrm{A}$. The change of the current in the proposed method is larger than that of the current in the conventional method.

TABLE II
Parameters of the simulation of standby power

Parameter	Value
Power consumption during power supply	30 kW
Power consumption during standby	70 W
Size of coil	1.3 m
Distance between coils	1.3 m
Electricity consumption of EVs	8 km/kWh
Unit price of electricity	27 Yen/kWh

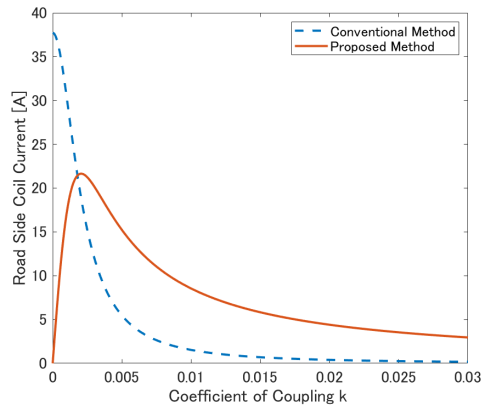


Fig. 4. Standby power.

V. Experiment of the Sensitivity of Detection

In order to confirm the superiority of the proposed method in the sensitivity of the detection, the authors carried out an experiment about sensitivity. A bench that can change the position of the vehicle coil to the driving direction with keeping the gap between the vehicle and road side coils like

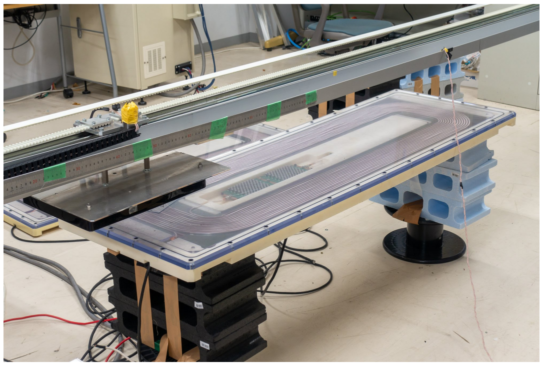


Fig. 5. Bench for experiment.

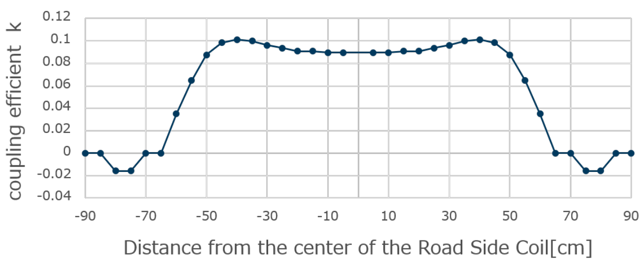


Fig. 6. The value of k at each position.

Fig. 5 was used. The coils used in this experiment are the same ones which are used in the vehicle in Fig. 1. Parameters are same as the ones in the simulation. In the experiment of the conventional method, an inverter was connected to the road side coil, and the vehicle side coil was shorted. In the experiment of the proposed method, an inverter was connected to the vehicle side coil, and the road side coil was shorted.

The center of the road side coil was defined as $0\,\mathrm{cm}$, and the traveling direction of vehicles was defined as positive. In both experiments, the vehicle side coil was fixed at $-65\,\mathrm{cm}$, $-85\,\mathrm{cm}$, and $-105\,\mathrm{cm}$, respectively. The size of the road side coil is $130\,\mathrm{cm}$, so the center of the vehicle side coil is just on the edge of the road side coil when it is fixed at $-65\,\mathrm{cm}$. The gap between vehicle and road side coils was $10\,\mathrm{cm}$. The inverter outputted rectangular waves, and the authors measured the voltage of inverter, the current of the road and vehicle side coil.

The experimental result is shown in Fig. 11. In the conventional method, the current of the road side coil does not change so much when the position of the vehicle side coil changes. On the other hand, the current changes more in proposed method.

In order to make a quantitative analysis, the RMS variation of the road side coil current was checked. The RMS changed only 1.06 times in the conventional method. On the contrary, in the proposed method, the RMS changed 9.58 times.

Thus, it is shown that the proposed method has a superiority in the sensitivity of the detection through this experiment.

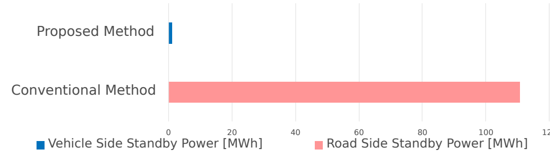


Fig. 7. Standby power per day.

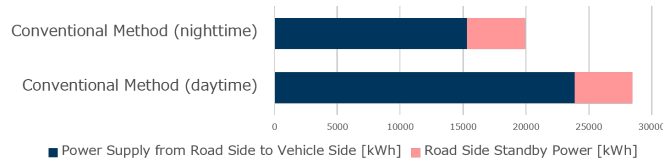


Fig. 8. Supplied power and standby power per hour.

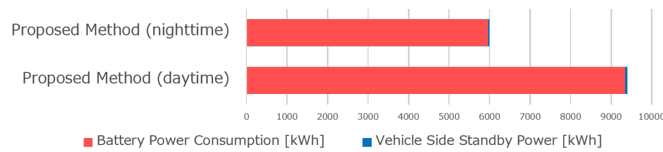


Fig. 9. Battery consumption for driving and standby power per hour.

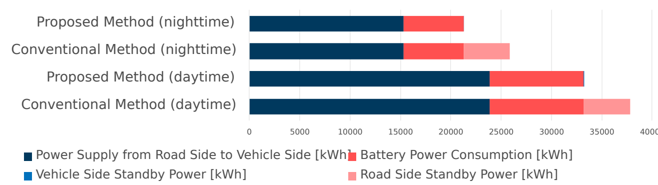


Fig. 10. Whole Power Consumption per hour.

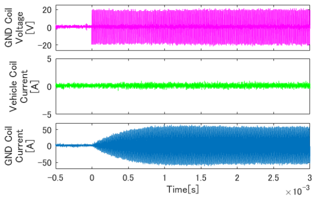
VI. Experiment of Detection and Power Supply

An experiment of the switching from the detection to the power supply have been conducted both by the conventional and the proposed method. The bench of Fig. 5 was used also in this experiment. The vehicle side coil passed over the road side coil at $4.7\,\mathrm{km/h}$.

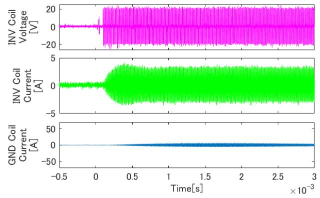
The voltage is set as following in both conventional and proposed methods. The DC input voltage of the road and vehicle side inverter is set to $20\,\mathrm{V}$. The effective voltage of the search pulses is set to $6\,\mathrm{V}$ by adjusting the duty.

The algorithm of switching mode is shown in Fig. 12.

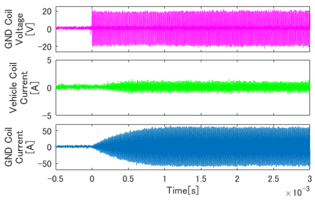
In the conventional method, the road side emits the search pulses for $1\,\mathrm{ms}$, and checks if the RMS current is under I_b. If so, the road side supposes that the vehicle side coil exists, and starts to transfer power. If not, the road side waits in the rectification mode for $3\,\mathrm{ms}$, then emits the search pulses again. On the contrary, the vehicle side waits in the short mode, and checks the RMS current continuously. If the current gets over I_a, the vehicle side supposes that the road side coil is around itself, and moves to the rectification mode.



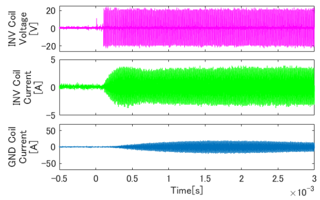
(a) Conv. Method at $-65\,\mathrm{cm}$.



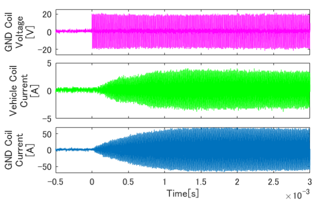
(d) Prop. Method at $-65\,\mathrm{cm}$.



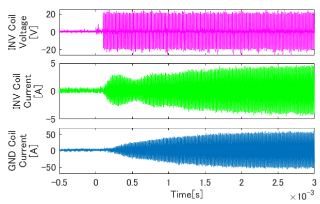
(b) Conv. Method at $-85\,\mathrm{cm}$.



(e) Prop. Method at $-85\,\mathrm{cm}$.



(c) Conv. Method at $-105\,\mathrm{cm}$.



(f) Prop. Method at $0\,\mathrm{cm}$.

Fig. 11. Evaluation of pulse sensitivity in experiments

In the proposed method, the vehicle side emits the search pulses for $1\,\mathrm{ms}$, and waits in the rectification mode for $3\,\mathrm{ms}$. Then, the vehicle side checks if the RMS current is over I_c. If so, the vehicle side supposes that the road side coil does not exist, and emits the search pulses again. If not, the vehicle side continues the rectification mode, and receives power. On the contrary, the road side waits in the short mode, and checks the RMS current continuously. If the current gets over I_d, the road side supposes that the vehicle side coil is coming, and starts to supply power.

The detection performance of the conventional and the proposed method depends on the configurable thresholds: I_a, I_b, I_c, and I_d. In the conventional method, the sensitivity of the detection increases when I_a gets smaller. However, too small I_a leads to the mis-detection by noise. The same trade-off goes for I_b. The sensitivity increases when I_b gets larger, but too large I_b leads to the mis-detection. As for the proposed method, the smaller I_c and I_d enhances the sensitivity of the detection, but too small I_c and I_d leads to the mis-detection.

To compare the sensitivity of the conventional and proposed method fairly, the thresholds were designed so that each method would be as sensitive as possible. Specifically, I_a, I_c, and I_d were adjusted to be as small as possible so that the system would not malfunction, and I_b were adjusted to be as large as possible. As the result, I_a, I_b, I_c, and I_d were setted as Table III.

TABLE III
PARAMETERS OF THE STATE TRANSITION

Parameter	Value
Vehicle side threshold current of conventional method I_a	$1\,\mathrm{A}$
Road side threshold current of conventional method I_b	$0.7\,\mathrm{A}$
Vehicle side threshold current of proposed method I_c	$0.05\,\mathrm{A}$
Road side threshold current of proposed method I_d	$0.05\,\mathrm{A}$

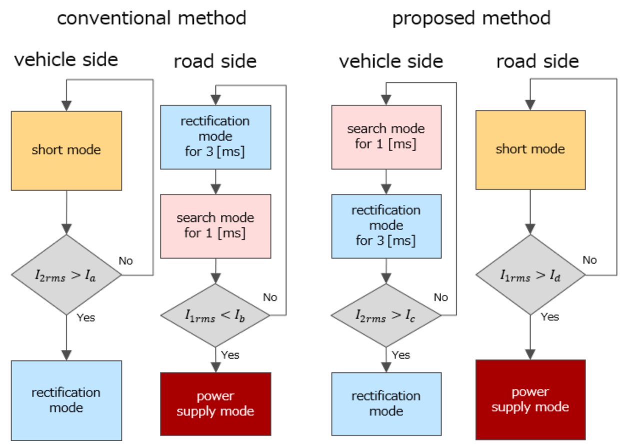


Fig. 12. State transition diagram of the conventional and proposed methods.

Fig. 13 shows the voltage and current of the conventional method. The road side coil emits the search pulses before the $-85\,\mathrm{cm}$ point. The road side coil detects the vehicle side at $-85\,\mathrm{cm}$ point, and start to supply power. The vehicle side coil detects the power supply from the road side coil immediately, and switches from the short mode to the rectification mode.

Fig. 14 shows the voltage and current of the proposed method. The vehicle side continuously emits the search pulses. The road side detects the search pulse at $-115\,\mathrm{cm}$, and start to supply power. However, the vehicle side cannot detect the power supply until the $-85\,\mathrm{cm}$ point due to the weekly coupling coefficient. The vehicle side detects the power supply at $-85\,\mathrm{cm}$, and switches from the search mode to the rectification mode. Fig. 6 shows the value of k at each position. According to these figures, the road side starts power supply earlier, and the vehicle side coil can receive power even before the negative coupling region by using the proposed method.

Fig. 15 shows the difference of the power supply start timing. By using the proposed method, the road side coil can detect vehicle side coil and start power supply earlier.

VII. Conclusion

In this paper, a novel method that search pulses are emitted from vehicle side was proposed. It was shown that the proposed method can reduce the standby power through the

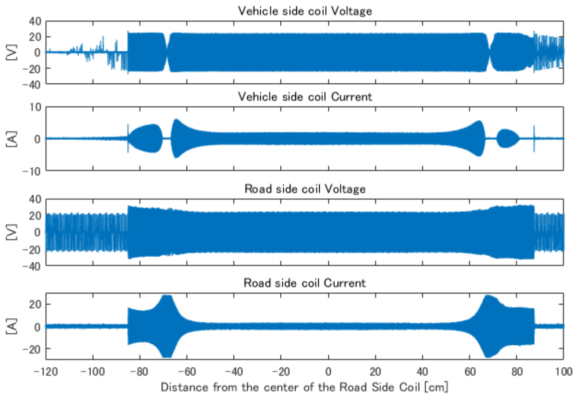


Fig. 13. The voltage and current of the conventional method.

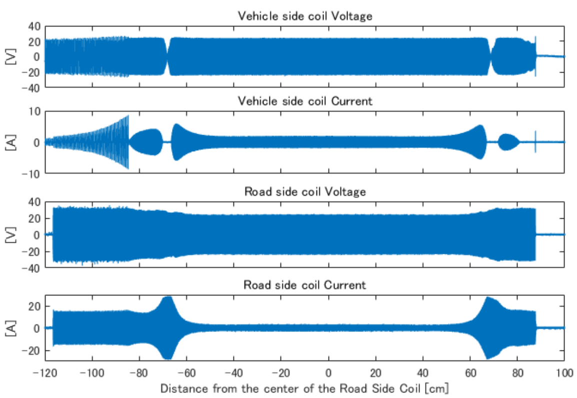


Fig. 14. The voltage and current of the proposed method.

simulation. Then, the experiment about the sensitivity of detection showed that the proposed method can rise the sensitivity. The experiment of switching from the detection to the power supply showed that it is possible to supply power even before the negative coupling region. This leads to the increase of the received power, and enables to keep the reduction of received power at high speed to a minimum.

VIII. Acknowledgment

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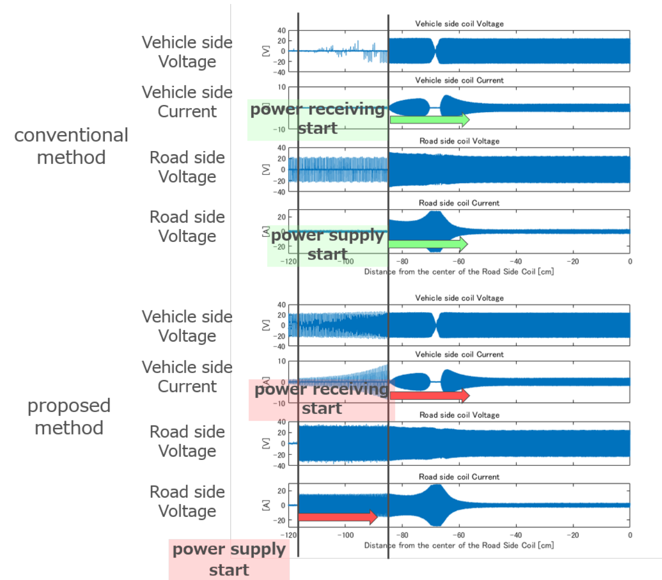

Fig. 15. The comparison of the power supply start timing

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