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전계결합 무선전력전송의 수신부 감지 방법

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A Novel Receiver Sensing Scheme for Capacitive Power Transfer System

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Abstract

Wireless power transfer systems require an algorithm to determine the presence of the target object for mitigating standby power and safety issues. Although many schemes that sense various external objects have been actively proposed for inductive power transfer systems, not many studies on capacitive power transfer systems have been conducted compared with those on inductive power transfer systems. This study proposes a target object detection algorithm by monitoring the capacitance in transmitter-side electrodes without additional pressure sensors or distance sensors. The proposed algorithm determines the presence of a target object by monitoring the change in capacitance in transmitter-side electrodes using the step pulse of the microcontroller unit. The algorithm is verified by two step processes. First, the performance in capacitance measurement is compared with that of an LCR meter. Then, the verification is conducted in a 5-W capacitive power transfer hardware. Experimental result shows that the interelectrode capacitance increases by 6 times when the target object is fully aligned. Thus, the proposed scheme can successfully detect the presence of the target object.

Key words: Capacitance measurement, CPT(Capacitive Wireless Power Transfer), Receiver detection method

1. Introduction

In wireless power transfer system, operation of the transmitter power circuit in the absence of receiver is a waste of standby power, and in the case of the capacitive power transfer(CPT), it can be dangerous because a voltage exist between the transmitter electrodes. Therefore, an algorithm is needed to operate the transmitter only when the receiver is able to transfer power.

Several target detecting techniques have been presented in the literature[1]-[2]. Firstly, analog ping in Qi standard periodically injects a few cycles of sinusoidal current waveforms at a specific frequency into the primary coil to detect the receiver. The specific frequency is equal to the resonant frequency when the receiver is not present. Therefore, the receiver approaches, it senses the receiver through a decreasing current[1]. As this resonance shift technique requires the entire power stage to be energized regularly to detect the target object. To solve this issue, literature[2] proposed impulse injection method, where it senses the decay time in the transient waveforms of the injected current to detect the receiver.

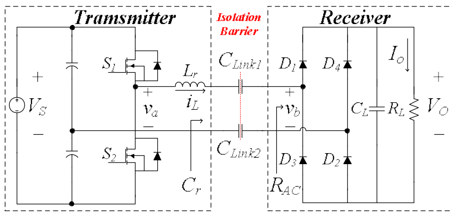

Fig. 1. A typical CPT system converter.

It is clear that even though various target object detection schemes have been investigated so far in inductive power transfer system, such a study is still not so active for CPT system. Therefore, this paper

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presents an effective target object detecting algorithm by monitoring the change of the capacitance between the transmitter-side electrodes in the CPT system.

2. Principle of Receiver Detection

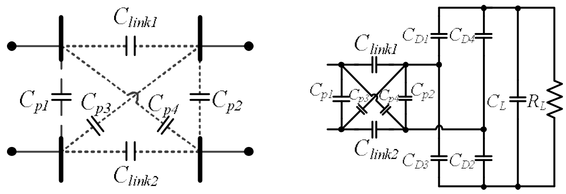
2.1 Capacitive wireless power transfer

CPT system contains electrodes in both a transmitter and a receiver, and performs wireless power transfer using the displacement current through the link capacitors[3]. Fig. 1 shows a half-bridge series resonant converter. The transmitter circuit converts the DC input voltage to the AC voltage through the switching of the MOSFETs S_1 and S_2 and transfers the power through the link capacitors. In the receiving part, the DC voltage is recovered through the full-wave rectifying diodes D_1 to D_4.

2.2 Alteration of equivalent capacitance due to receiver presence

Link capacitors are modeled by six different capacitors ($C_{link1,2}$, C_{p1} to C_{p4}) including the cross coupling as shown in Fig. 2(a)[4]. When the receiver is separated from the transmitter, the equivalent capacitance C_{eq} of the two electrodes 1 and 2 is equal to C_{p1} as shown in (1). If the receiver is fully aligned to the transmitter, circuit seen from the transmitter is Fig. 2(b), where C_{D1} to C_{D4} are the equivalent capacitances of the rectifying diodes, D_1 to D_4. In other words, the capacitors of the four electrodes ($C_{link1,2}$ and C_{p1} to C_{p4}), the equivalent capacitors of the rectifying diodes (C_{D1} to C_{D4}), the output filter (C_L) and the load resistance (R_L) can be seen in the two electrodes of the transmitting part. By measuring the capacitance seen from the transmitter electrodes, system can detect the presence of the receiver.

As will be described in the following paragraphs, if the step voltage tests is conducted to detect the receiver, the C_L can be regarded as a short circuit because the output filter capacitance is much larger than the equivalent capacitances C_{D1} to C_{D4} of the rectifying diodes. Since C_L is shorted-circuited, R_L can be ignored and it is verified by circuit simulation. Furthermore, in fully aligned condition, $C_{link1,2}$ are dominant, and thus $C_{p3,4}$ are negligible. Assuming that C_{D1} to C_{D4} are identical as C_D, and $C_{link1,2}$ have the same value as C_{link}, the equivalent capacitance C_{eq} seen from electrodes 1 and 2 is given by the series-parallel combination of C_{link}, $C_{p1,2}$ and C_D and thus is represented as (2).



(a) Capacitances between the electrodes (b) Equivalent circuit of receiver

Fig. 2. Detailed circuit modeling of CPT link capacitors.

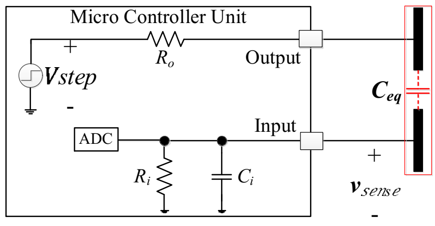


Fig. 3. Capacitance measuring circuit.

$$C_{eq(seperated)} = C_{p1} \tag{1}$$

$$C_{eq(aligned)} = C_{p1} + \frac{C_{link}}{2} \parallel (C_{p2} + C_D) \tag{2}$$

2.3 Capacitance measurement by MCU

Fig. 3 shows the circuit of the micro controller unit (MCU) measuring the capacitance of transmitter electrodes. The output and the input ports are connected to the two electrodes, respectively. In the proposed method, MCU applies a step voltage, V_{step} into the output node and read the V_{sense} value using analog to digital converter(ADC) of the input port. Because the MCU output and input ports have the internal resistances and capacitances, the step response of V_{sense} shows the exponential decaying behavior with R-C time constant and is derived as (3) using the transfer function analysis. R_O is the internal resistance in the output port, R_i and C_i are the internal resistance and capacitance in the input ADC port of the general MCU. In the general MCU, R_O is very small compared to R_i and can be omitted. Since the V_{sense} is read from the input port immediately after outputting V_{step}, the scaling coefficient of the exponential function in (3) is directly measured as the time axis value of the exponential function portion is taken as $t=0^+$. By rearranging (3), the capacitance C_{eq} between the transmitter-side electrodes is obtained by (4). In (3) and (4), V_{step} is the height of the step excitation.

$$V_{sense}(t) = V_{step} \frac{C_{eq}}{C_{eq} + C_i} e^{-\frac{t}{R_i(C_{eq}+C_i)}} \tag{3}$$

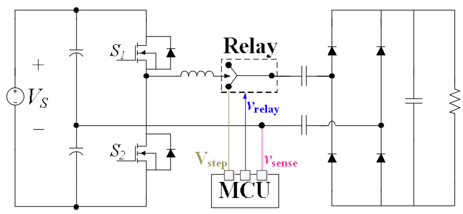


Fig. 4. CPT circuit with relay switch.

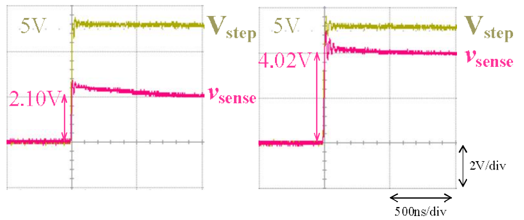


Fig. 5. Capacitance measurement waveforms by MCU.

$$C_{eq} = C_i \frac{V_{sense}(0^+)}{V_{step} - V_{sense}(0^+)} \tag{4}$$

To apply the proposed capacitance measurement circuit to the CPT system, the MCU must be disconnected from the transmitter electrodes when the power transfer circuit is in operation. Fig. 4 shows how the proposed capacitance measurement method is applied to existing CPT circuits connecting the MCU to the front of the transmitter electrodes using the relay switch.

3. Verification with Prototype Hardware

3.1 Comparison of measurement results between LCR meter and MCU

In order to study the feasibility of the proposed detection method, change in the equivalent capacitance value according to the receiver position has been cross-checked by LCR meter with Kelvin clip. (Agilent Technologies, 4263B with 16089A) and MCU method. The lateral dimensions of the transmitter electrodes and receiver electrodes used for hardware verification are 13 cm x 9.5 cm and 13 cm x 9.0 cm, respectively. The glass(dielectric constant ϵ_r=3, separation distance of 1.60mm) was inserted between the electrodes to increase the link capacitance.

Using LCR meter, the capacitance of C_{p1} and C_{p2} were measured as 10pF and 5pF, respectively, and the averaged C_{link} was measured as 274pF. C_D was obtained 550pF by the Schottky diode datasheet[5]. Resultingly, $C_{eq(seperated)}$ and $C_{eq(aligned)}$ have been calculated to be 10pF and 120pF by (1) and (2), and measured to be 10pF and 110pF respectively.

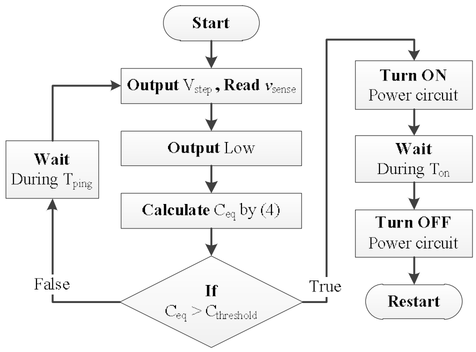


Fig. 6. Receiver detection flowchart.

To verify the proposed capacitance measurement method, the capacitance of C_{eq} was measured using an MCU by (4). The MCU used in the hardware implementation is ATMega328P, and the equivalent circuit parameters in Fig. 3 of this MCU are R_O=50Ω, R_i=100MΩ and C_i=24pF[6]. Calculated capacitances by MCU are $C_{eq(seperated)}$=17pF and $C_{eq(aligned)}$=98pF, respectively. Fig. 5 shows the measured waveforms of V_{step} and V_{sense}. The capacitances of 17pF and 96pF were calculated by the measured $V_{sense}(0^+)$ of 2.10V and 4.02V, respectively.

3.2 Receiver detection flow chart

The MCU can detect the receiver by the change of the V_{sense}. In the standby state, the two electrodes of the transmitter are connected to the MCU, not the power transfer circuit by the relay switch in Fig. 4, and the MCU continues to measure the capacitance. When the V_{sense} is above the threshold voltage due to the capacitance increase in the presence of the receiver, the relay is operated to stop the measurement and start power transfer. The threshold voltage is determined by the degree of misalignment at which the CPT system can be driven.

Figure 6 is an algorithm flowchart of the receiver detection procedure of the MCU. The algorithm begins by outputting V_{step} to one of transmitter electrode. To utilize (4), $V_{sense}(0^+)$ is measured immediately from the other transmitter electrode. C_{eq} can be calculated through the measured $V_{sense}(0^+)$ and (4). If C_{eq} is lower than $C_{threshold}$, the measurement procedure will restart after a ping interval, T_{ping}. If C_{eq} is larger than $C_{threshold}$, the algorithm judges the receiver is aligned enough to transfer power. After the power transfer for a refresh period, T_{on}, the transmitter power circuit is turned off, algorithm goes back to the beginning and repeats the process to detect again. If a single foreign metal over a certain

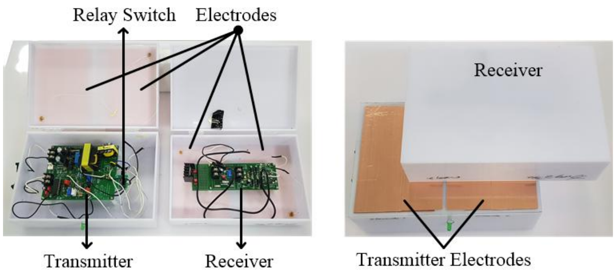
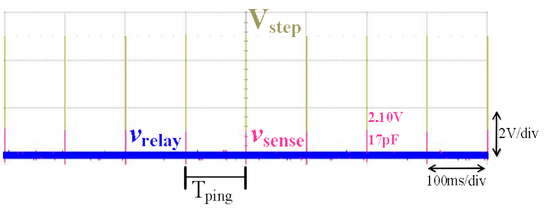
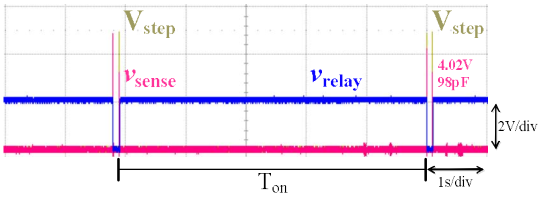


Fig. 7. Implemented hardware for verification.



(a) Separation condition



(b) Fully aligned condition

Fig. 8. System operation waveforms.

area is present across the transmitter electrodes, the transmitter may regard the foreign metal as the receiver. In this case, the algorithm should be assisted by additional identification scheme such as backscatter modulation method used in Qi standard[1].

3.3 Hardware test result

For hardware verification, a 5W wireless power system has been built in Fig. 7. The operating frequency of the half-bridge inverter is 429kHz. Fig. 8(a) and (b) are experiment waveforms of separation and fully aligned condition. In Fig. 8(a), the receiver is detected every 100msec, T_{ping} interval. The V_{relay} waveform which shows power stage turn on status is kept at low as it is in the separated condition. Fig. 8(b) shows waveforms in which the MCU repeatedly detects the receiver when the receiver is fully aligned. After every predetermined time, T_{on}, the transmitter suspends the power transfer, and then detects the receiver again. It should be mentioned that The proposed method is not suitable for high power applications such as wireless power transfer for EVs since the battery is charged with discontinuous current. However it is still effective for low power systems and is valid for the wake-up process.

4. Conclusion

In this paper, an algorithm to detect the presence of the receiver has been presented for CPT system. It applies a step voltage into the transmitter-side electrode to monitor the changes of capacitance. As the proposed method can be easily integrated into the digital PWM controller with ADC existing in the transmitter and does not require auxiliary sensing circuit, it is simple to implement and can be a low cost alternative of the conventional method with current sensors or position sensing circuitry. This method is especially useful for wake-up process with minimized stand-by power.

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