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Receiver Protection from Electrical Shock in Vehicle Wireless Charging Environments

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Abstract
This paper deals with the electrical shock that can occur in a car wireless charging system. The recently released the Wireless Power Consortium (WPC) standard specifies that the receiver must be protected from the radio power generated by the transmitter and presents two scenarios in which the receiver may be subjected to electrical shock due to the wireless power generated by the transmitter. The WPC also provides a hardware approach for blocking the wireless power generated by the transmitter to protect the receiver in each situation. In addition, it presents the hardware constraints that must be applied to the transmitter and the parameters that must be constrained by the software. In this paper, we analyze the results of the electric shock in the vehicle using the WPC certified transmitter and receiver in the scenarios presented by WPC. As a result, we found that all the scenarios had electrical shocks on the receiver, which could have a significant impact on the receiver circuitry. Therefore, we propose wireless power transfer limit (WPTL) algorithm to protect receiver circuitry in various vehicle charging environments.

Keywords
Battery Charging, Electrical Shock, Vehicle Charging System, Wireless Charging System, WPC

1. Introduction

The Wireless Power Consortium (WPC) [1-3] was established in 2008 to establish standards for wireless charging centered on European countries. The WPC released the world's first 5W transmitter and receiver in 2011; Qi, a wireless charging certification standard. At the same time, the smartphone manufacturers began selling a separate smartphone wireless charging case with a wireless charging receiver, and finally the wireless charging market has begun. However, initial popularization failed because of the hassle of installing a separate case and the low awareness of wireless charging. However, in 2015, Samsung Electronics launched the world's first "Galaxy S6" and "Galaxy S6 edge" models with a receiver for wireless charging without a separate case. Apple, which has the world's largest smartphone users, also has a built-in wireless charging receiver in the iPhone 8 and iPhone x launched in September 2017. In response to this trend, vehicle manufacturers also began introducing smartphone wireless charging systems in their vehicles.

In recent years, due to the growing interest in wireless charging, many studies have been conducted on wireless charging systems. Frohlich et al. [4] presented experimental results on magnetic field exposure

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in a wireless charger. Wu et al. [5] developed a system combining the transceivers of solid-state wireless energy systems using magnetic resonance technology and measured the efficiency. Gnanasegaran et al. [6] developed a Class E inverter that converts DC to AC for wireless charging. Dhungana et al. [7] investigated the potential of peer-to-peer energy sharing using charging skip optimization. Zhang et al. [8] proposed a wireless battery charging system in which the power transfer position is automatically changed to the optimal charging placement. Hassan et al. [9] presented a multiple receiver wireless power transfer system for charging mobile phone batteries. Riehl et al. [10] demonstrated a family of wireless power devices that operate in a variety of operating modes. Wu et al. [11] presented RF interference from switching electronics in a wireless charging pad, and proposed a frequency-selective surface (FSS) technique to reduce this.

However, unlike other research focusing on a general charging system that charges in a fixed location, we deal with a charging station problem equipped with vehicles. As the vehicle moves, sudden changes in position may occur due to the nature of the vehicle that changes its position in real time. If this occurs, the alignment of the transmitter and the receiver in the wireless charging state becomes unstable, which can adversely affect stable wireless charging. A receiver exposed to such a situation may lose its wireless charging function due to an electric shock due to a strong magnetic field generated in transmission. In this paper, we investigate the effect of electric shock condition on the equipment that can occur in the car wireless charging system. Therefore, our work focuses on adaptively limiting the wireless power transfer to protect a receiver circuitry in various vehicle environments.

2. Self-Inductive Wireless Charging

As shown in Fig. 1, the self-inductive wireless charging system consists of a transmitting coil for transmitting radio power and a receiving coil for receiving radio power.

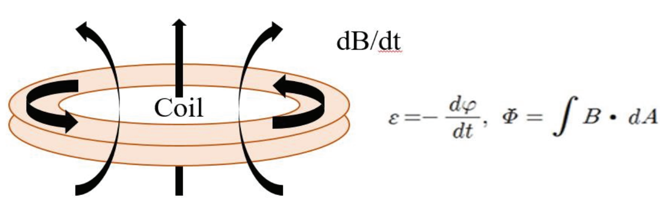


Fig. 1. Fundamental theory of self-inductive.

It uses magnetic induction between two coils, and power transmission is possible when the transmitting coil and the receiving coil are in close contact within a distance of up to 4 cm [1]. As shown in Fig. 2, the magnetic induction method of coils is the most basic technology of wireless power transmission technology and was discovered by Micheal Faraday in 1931. When the receiving coil is located in the magnetic field region where the transmitting coil is generated, an induced current is generated in the receiving coil. The voltage generated by the induced current is the AC voltage. The AC voltage is rectified to a DC voltage through the rectifier circuit of the receiver to charge the battery. The closer the contact distance between the two coils is, and the closer the coils are in contact with each other, the closer to 1:1, the more efficient power transmission becomes possible.

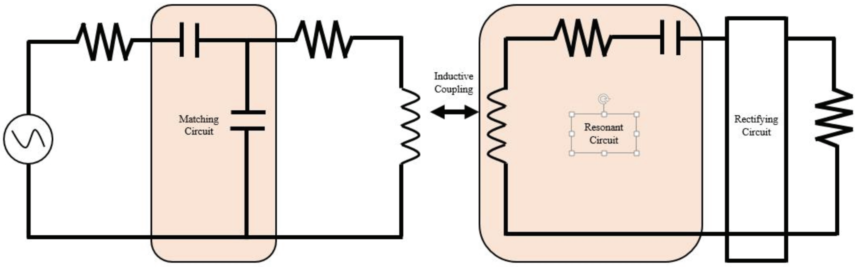


Fig. 2. Wireless power transmission circuitry.

The magnetic induction method has the same structure as our common transformer and the same principle of operation as described in [12]. Efficient wireless power transmission is possible by adjusting various variables such as the number of turns of the coil, the thickness of the coil, and the contact interval of the two side coils. This hardware structure is specified in WPC Part 4 reference designs [2].

3. Electrical Shock Issues by WPC

The Part 1 and Part 2 in WPC 1.2.2 Section 3.2.4 state that the transmitter must protect the receiver from the generated wireless power. The protection criteria shall not cause the rectifier circuit output voltage of the receiver to exceed 20 V. The scenario suggested by WPC is as follows. First, a receiver that is charging may move from a poor coupling position to a strong coupling position. In fact, when the user places the receiver on the transmitter for a charging attempt, it may not be placed in an aligned position, or when the receiver is lifted or lowered (Fig. 3).

Fig. 3. Case 1: displacement of the receiver.

Second, there is no alignment between the transmitter and receiver coils, the coupling is poor, and charging begins at a position where communication is possible. The receiver may also start charging at a higher rectified voltage of 12 V or higher to charge the battery. The V-rail voltage of the transmitter is controlled to a high level to obtain a rectified voltage of 12 V or more.

This situation is very likely to occur during driving. Due to the nature of the vehicle driving in which the position and direction change in real time, the receiver cannot avoid the influence on the inertia. Changes in the position of the receiver being charged on the transmitter due to inertia can occur very frequently. Fig. 4 shows the change in transmitter output when a position change occurs in a wirelessly charging receiver.

The first scenario is that the coupling between the transmitter and receiver coils is poor, so the receiver cannot get enough energy to charge the battery. Thus, the receiver raises the V-rail voltage of the transmitter through the CEP (control error packet) to obtain the energy required to charge the battery. V-rail voltage rise causes a high current to flow through the transmitting coil, resulting in a strong magnetic field. When the receiver suddenly moves to a good position, the receiver cannot control the V-rail voltage of the transmitter. This allows the output voltage of the transmit coil to increase to tens of volts.

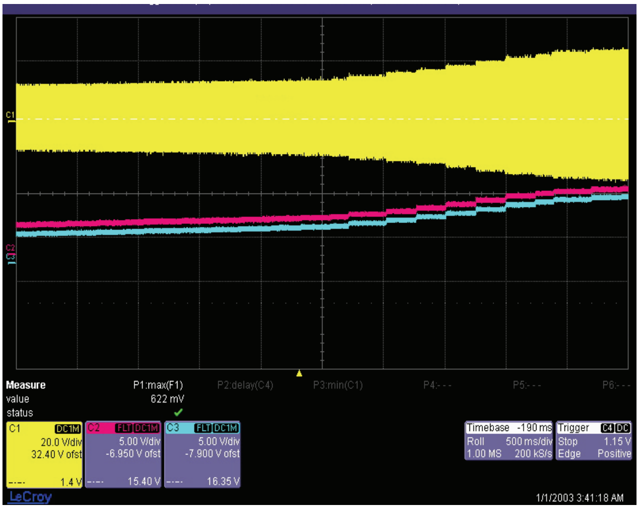


Fig. 4. Transmitter output variation with receiver position change.

The second scenario would be the same as in the first scenario if the receiver and receiver coils were well aligned due to sudden positional movements of the receiver. Smartphones that are charging wirelessly in the vehicle interior are very likely to be moved to upper and lower, left and right positions with poor coupling due to inertia due to the external environment.

A large amount of induced current is generated in the receiving coil due to a strong magnetic field generated in the transmitting coil. Therefore, the rectified voltage output of the receiver rises sharply. If the magnitude of the rectified voltage outputted at this time cannot withstand the receiver control unit, the receiver control unit will lose its function.

To protect the receiver from excessive transmit coil output voltages, the WPC imposes some restrictions on the transmitter and presents a more detailed approach.

To protect the receiver, the power consumption of the transmitter must be limited. The maximum average power is specified as 24W. The power limitation method suggests two ways to limit the current.

The first method is to limit the maximum value of the current flowing in the transmitting coil to 3 A (ampere). The second method is to limit the transmitter current to 0.75 A (RMS) in the idle state with no transmit power, and to about 2.7 A (RMS) at the maximum radio power transmission state that the transmitter can transmit. Limitations of the transmitter system design should also be applied to the design of the vehicle wireless charging system. Since the battery voltage of the vehicle is maintained at 12–14 V, the system power of the transmitter must be limited properly. The maximum current that can be applied in a car wireless charging system is 1.714 A. Fig. 5 shows the measured power consumption of the transmitter according to V-rail voltage.

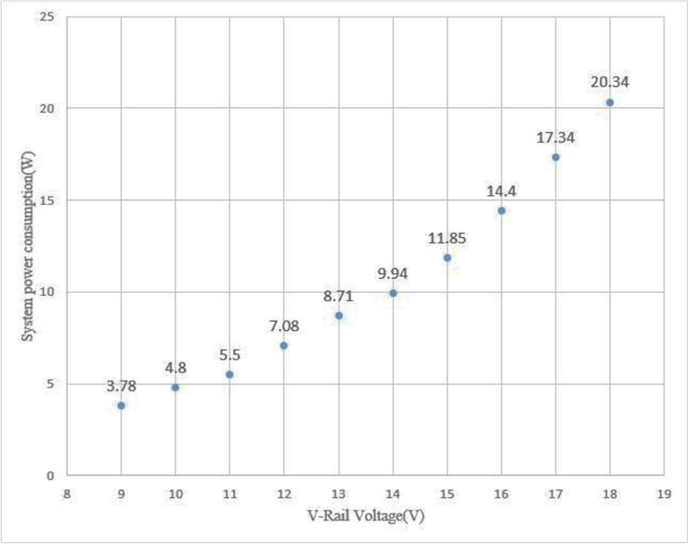


Fig. 5. Power consumption of the transmitter according to V-rail voltage.

4. Experimental Study on Effect of Electrical Shock

The transmitter used for the experiment is the WCT-5WTXAUTO model using NXP's MWCT1003A MCU. It is a model released for the interior of the vehicle, and it has a wide charging area compared with the conventional transmitter using three transmission coils. For the receiver, we used the iPhone exclusive receiver. The receiver is a Qi certified product of the WPC 1.2 standard. The distance between the transmitting coil and the receiving coil was 7 mm. Fig. 6 shows the experimental environment.

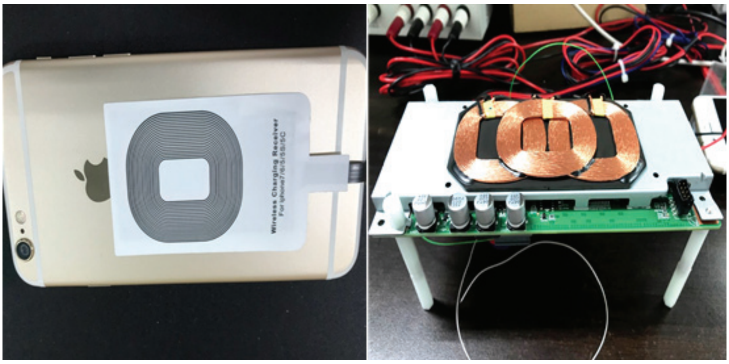


Fig. 6. Experimental environment.

4.1 Effect on Electrical Characteristics in Vehicle Environment

Fig. 7 shows the V-rail voltage and output change of the transmitter coil when the receiver is moving away from the transmitter during normal charging. If the charging is performed without changing the position of the receiver, the charging state will be stable. However, when the receiver moves away from the transmitter and the coupling moves to a poor position, the receiver raises the V-rail voltage through the CEP. The V-rail voltage and the transmit coil output after the A point rise due to the CEP as shown in Fig. 7. In this case, if the receiver moves quickly to a good position with the transmitter, the V-rail voltage cannot be controlled. If the coupling is good due to the movement of the receiver when the V-rail voltage cannot be lowered, a strong induction current will be generated in the receiving coil. Due to the induced current, the rectified voltage output of the receiver instantaneously exceeds 20 V.

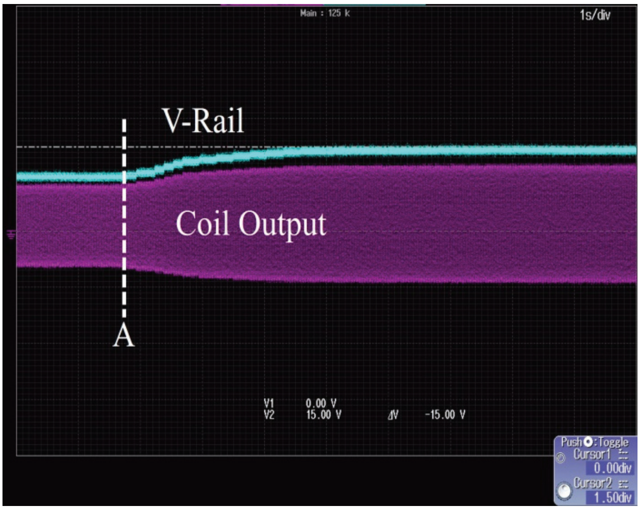


Fig. 7. V-rail voltage output in the first scenario presented by WPC.

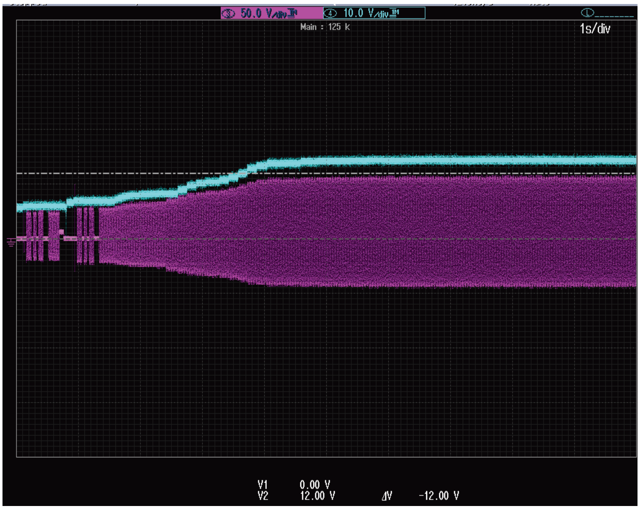


Fig. 8. V-rail voltage output in the second scenario presented by WPC.

Fig. 8 shows V-rail voltage and transmission coil output when charging is in progress by poor coupling due to bad alignment between transmitting and receiving coils. Since the output of the transmitting coil is strong but the coupling is poor, the amount of current induced in the receiving coil is a level of current suitable for battery charging. If there is no change in the position of the receiver, normal charging will proceed. However, if the receiver position changes, the same phenomenon as the first scenario will occur in the receiving coil.

Fig. 9 shows the change in receiver rectifier circuit output when the two situations described above occur. A rectified voltage output of 20 V or more can be confirmed. An electric shock is applied to the receiver control unit due to an excessive rectified voltage output.

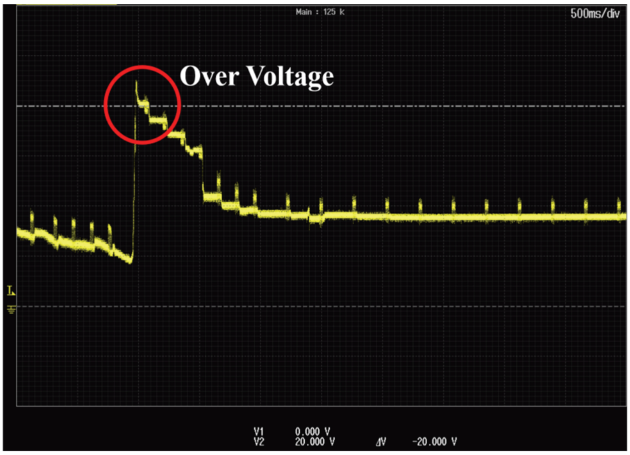


Fig. 9. The rectifier circuit output voltage at which electrical shock is applied to the receiver.

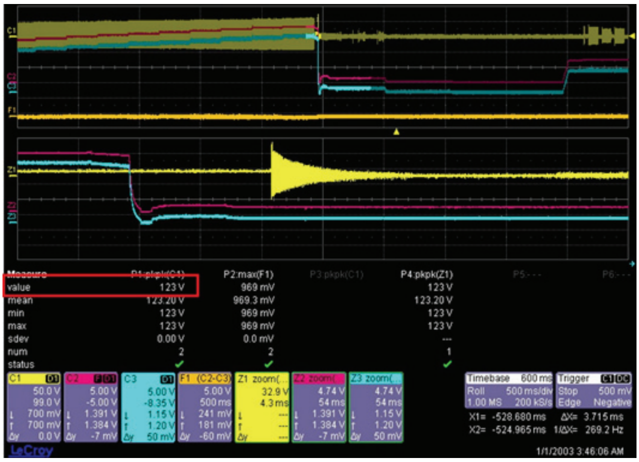


Fig. 10. Effect on the electrical shock onto the receiver.

4.2 Effect on Electrical Shock onto Receiver

When the V-rail voltage rises and the transmitter power consumption reaches the transmitter system power limit, the charging must be stopped. If charging is stopped without a power limit algorithm, a strong magnetic field is formed in the transmitting coil due to the current remaining in the V-rail as shown in Fig. 10, and if this situation persists, the receiver circuit may be damaged.

5. Wireless Power Transfer Limit

In this section, we propose a wireless power transfer limit (WPTL), a novel algorithm to minimize the damage in the receiver as confirmed by the previous experiments. In the proposed algorithm, excessive magnetic field is prevented from being formed on the transmission coil at the time of charging stop to prevent the instantaneous surge of the receiver voltage. Fig. 11 shows the overall flow chart of the WPTL algorithm. First, when the receiver moves away from the transmitter, the receiver sends a high CEP to the transmitter to get the current needed to charge the battery. The transmitter raises the V-rail voltage according to the CEP to form a strong magnetic field, which causes the system power to be greater than the power. At this time, the pulse width modulation (PWM) driver IC is turned off and the V-rail voltage is dropped to stop the wireless charging. However, when the wireless charging is stopped, a strong magnetic field is formed in the coil due to the current remaining in the V-rail. If the receiver is close to the transmitter and induction current is generated in the receiver coil, the rectifier voltage output of the receiver exceeds 20 V. In order to prevent this phenomenon, when the V-rail voltage drops below a certain voltage after stopping the wireless charging, the dummy load as shown in Fig. 12 is operated to discharge the current remaining in V-rail. It then waits until the V-rail voltage drops below the set value to discharge the remaining current on the V-rail through the dummy load. When the V-rail voltage drops below the point that is already set, the dummy load is reactivated to discharge any residual current on the V-rail. In this way, the proposed algorithm has the effect of blocking the magnetic field from forming in the transmitting coil. After this process, the V-rail voltage is set for the recharging attempt after stopping the charging, waiting for the stabilization time, and then the charging is tried again.

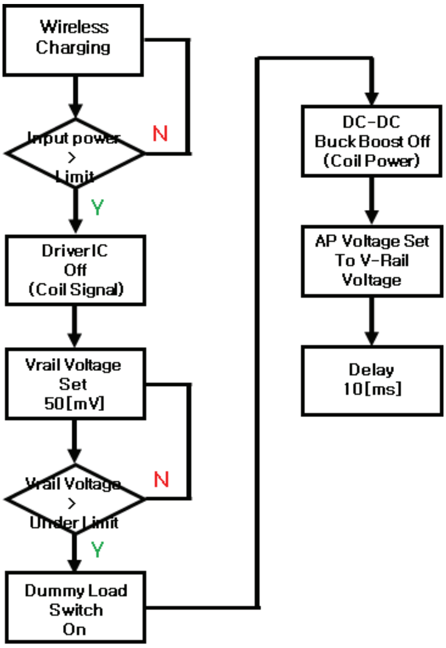


Fig. 11. WPTL flowchart.

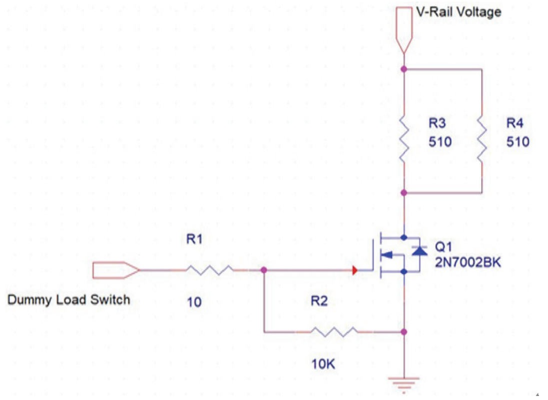


Fig. 12. Dummy load circuit.

6. Experimental Result

6.1 V-Rail Residual Voltage

Fig. 13 shows the variation of V-rail residual voltage with WPTL. The WPTL algorithm disables magnetic field formation in the transmit coil by discharging the current remaining on the V-rail through the dummy load. Therefore, it is possible to fundamentally block the cause of generating electric shock to the receiver without generating a strong induction current even if it comes in contact with the receiving coil.

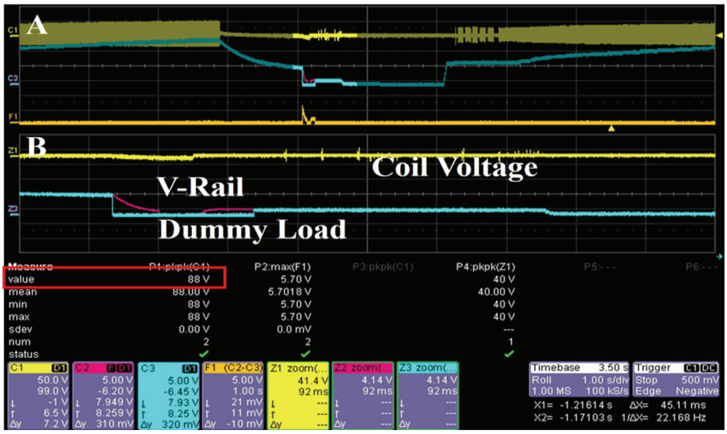
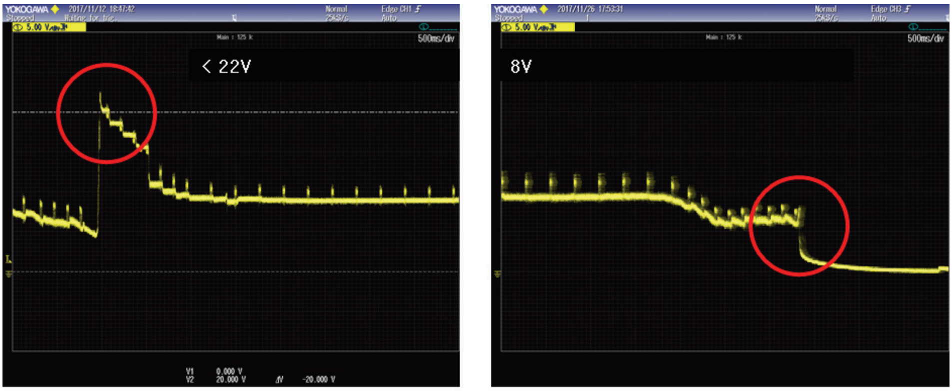


Fig. 13. V-rail residual voltage with WPTL.

6.2 Receiver Rectifier Voltage

Fig. 14 shows the comparison of the output of the receiver rectifier voltage before and after applying the WPTL algorithm. The WPC specification states that the rectifier circuit voltage output should not exceed 20V to safeguard the receiver IC. However, in the case of a system not using the proposed algorithm, it can be seen that the rectifier voltage of the receiver becomes more than 20 V. However, the system using the WPTL algorithm shows a rectified circuit voltage output of 8 V, which verifies that the receiver IC can be safely protected without electrical shock.



(a) (b)

Fig. 14. Receiver rectifying voltage comparison. (a) Rectifying voltage without WPTL. (b) Rectifying voltage with WPTL.

7. Conclusion

In this paper, we proposed an efficient method to solve the problems that may occur in the vehicle's wireless charging system. We first confirmed the problems that may occur during wireless charging in a vehicle environment, and showed that it is possible to solve this problem in a system using the proposed technique. In particular, the result proved that it is possible to fundamentally block the cause of generating electric shock to the receiver without generating a strong induction current even if it comes in contact with the receiving coil. In addition, we also verified that the system using the WPTL algorithm shows a rectified circuit voltage output of 8 V, which verifies that the receiver IC can be safely protected without electrical shock. This result is expected to be applied as an important development guideline in the future development of wireless charging system.

Acknowledgement

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