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A Study of Electric Vehicle Wireless Charging System Integration and Vehicle Alignment Optimization

Jaeyong Seong[1], Jinsoo Jang, Youngcheol Koh

[1]*Hyundai Motor Group, 150 HyundaiYeonguso-ro Hwaseong-si Gyeonggi-do Republic of Korea,*
jyseong@hyundai.com

Summary

This paper aims to develop a verification and evaluation method of 3.3 kW wireless charging system installed in SOUL EV while minimizing modifications to the vehicle. we propose a primary coil recognition and vehicle alignment verification method using digital and analog signals in the vehicle.

Keywords: Wireless Power Transfer, Electric Vehicle, Integration, Alignment, Positioning

1 Introduction

At the end of the 1800's, wireless power transfer (WPT) first experimented by Nikola Tesla is the technology for transmitting electric energy through air without using wires [1]. The early days of WPT has not been commercialized except for the non-contact type inductive coupling method because of technological limitations and harmfulness to the human body. However, in 2007 MIT's Professor Marin Soljacic proposed a non-radiated magnetic resonance method [2] wireless power transfer which was a new method, since then various methods of WPT technology have researched and developed. Recently, in the field of electric mobile devices including smartphones, the demand for wireless charging is rapidly increasing and wireless charging market is also rapidly growing [3].

Research and development on WPT technology is underway in the automotive field. Since the beginning of the 2000s, in order to respond to the strengthening of environmental regulations in the automotive division, consideration for the environment has increased interest in low-carbon vehicle. In keeping pace with this, developed countries began to mass product eco-friendly cars. Thus, the paradigm of the global automotive market is changing from internal combustion engines to environmental vehicles focussed on electric vehicles. As electric vehicles are puts into commercialization, offering convenience of charging, and the interest of wireless charging for electric vehicles that is safe due to short-circuiting and disconnection of charging cables has also increased. Society of Automotive Engineers (SAE) and International Electrotechnical Commission (IEC) are working to standardize wireless charging of electric vehicles [4, 5].

This paper aims to develop a verification and evaluation method of 3.3 kW class wireless charging system installed in SOUL EV while minimizing modifications to the vehicle. Also, in order to improve the evaluation ability at the vehicle level, we propose a primary coil recognition and vehicle alignment method using digital and analog signals in the vehicle.

2 Overview of Wireless Power Transfer

2.1 History of Wireless Power Transfer

In 1820, Hans Christian Oersted founded that electric currents create magnetic fields, now known as Oersted's law [6]. Oersted discovery was the first connection found between electricity and magnetism. The first of two laws that link the two; one is Ampere's circuital law showing that electric current produces a magnetic field, the other is Faraday's law of induction the electromotive force driving a current in a conductor loop by a time-varying magnetic flux. The fact that electrical energy could by transmitted at a distance without wires was observed by many inventors and experimenters [7]. These two laws became part of the equations that govern electromagnetism, Maxwell's equations. Since then, electricity and magnetism are known to regulate by the same force. These historic progresses were established the modern theoretic foundation of electromagnetism.

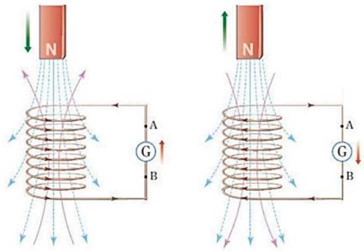

Figure1: Electromagnetic induction

2.2 Classification of Wireless Power Transfer

The wireless power transmission method can be classified into three types according to the transmission method of the energy and the transmission distance.

Inductive coupling [8] is based on Ampere's circuital law and Faraday's low of induction. Ampere's circuital law describes that the circulation of the magnetic field intensity around any closed path is equal to the free current flowing through the surface bounded by the path. Faraday's law of electromagnetic induction describes that the electromotive force induced in a stationary closed circuit is equal to the negative rate of increase of the magnetic flux linking the circuit. The electric power carried through the magnetic field between two coils. Fig. 2 shows the reference model [9]. The efficiency of wireless power depends on the coupling coefficient. Therefore, the wireless energy cannot be carried over a distance longer than a few millimetres, and the frequency used in inductive coupling is below some mega Hertz range.

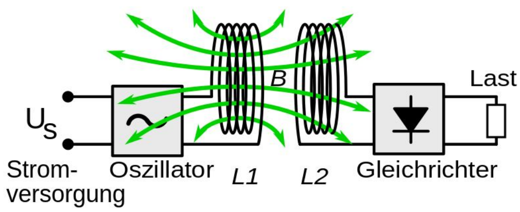

Figure2: Inductive coupling reference model

Magnetic resonance coupling [2] is based on evanescent mode wave coupling which generates and transfers electrical energy between two resonant coils through varying or oscillating magnetic fields. A resonator is formed by adding capacitance on an induction coil. As magnetic resonance coupling typically uses in the kilo Hertz to mega Hertz frequency range, the quality factors are normally high. With the increase of charging distance, the high-quality factor helps to mitigate the sharp decrease in coupling co efficiency, and thus charging efficiency. Consequently, extending the effective power transfer distance to meter range is possible. Fig. 3 shows the reference model [10].

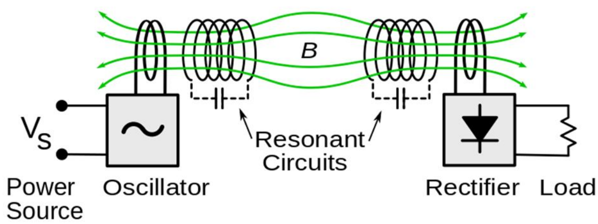

Figure3: Magnetic resonance coupling reference model

Microwave power transmission is the use of microwave to transmit power through outer space or the atmosphere without the need for wires [11]. Microwave propagates over space at the speed of light, normally in line-of-sight. The typical frequency of microwave ranges from 300MHz to 300GHz. The energy transfer can use other electromagnetic waves such as infrared and X-rays. However, due to the safety issue, they do not widely used. Fig.4 shows an example of a microwave power transmission [12].

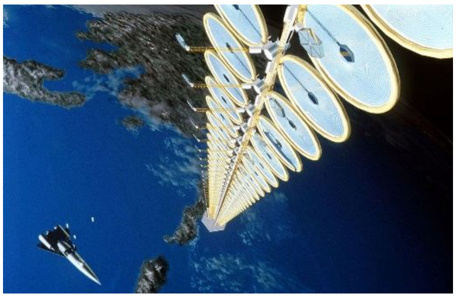

Figure3: An example of a microwave power transmission

2.3 Operating Principle for Wireless Charging Electric Vehicle

In the information report of the wireless power transfer for light-duty plug-in electric vehicles (xHEV) and alignment methodology [13] of the recently published, the basic principle behind magnetic resonance coupling wireless power transfer is that of a two-part gapped core transformer in which the two halves of the transformer, the primary and secondary coils are physically separated from one another. WPT systems consist of a Ground Assembly (GA) and a Vehicle Assembly (VA). Fig. 4 shows a block diagram. The GA broadly consists of a main connected Power Factor Correction (PFC) converter, followed by a DC-AC inverter, a filter and impedance matching network (IMN) that is connected to the primary coil. The magnetic energy created by the primary coil is coupled to the secondary coil. The VA consists of the secondary coil connected to an IMN and filter, a rectifier and an optional impedance converter that produces suitable voltages and currents to the connected battery. The GA and the VA must share a communication system that allows the GA to know the state of the VA and for the GA to receive and respond to messages from the VA. It is critical that power transfer is not initiated until the GA determines that a vehicle with a compatible VA is in place and properly aligned. The following steps describe the high-level operation of the closed-loop charging system: (1) within the VA, the current desired to charge the battery is determined; (2) the request for power is communicated over the wireless communication channel from the VA to the GA; (3) the GA recognizes the request, draws power from the grid, converts it to high frequency AC and sends it to the primary coil; (4) the high frequency AC couples to the secondary coil, is rectified and processed in the VA and charges the batteries; (5) this process continues until the VA signals a different power level requirement, including no power required, as would be the case when the batteries are adequately charged.

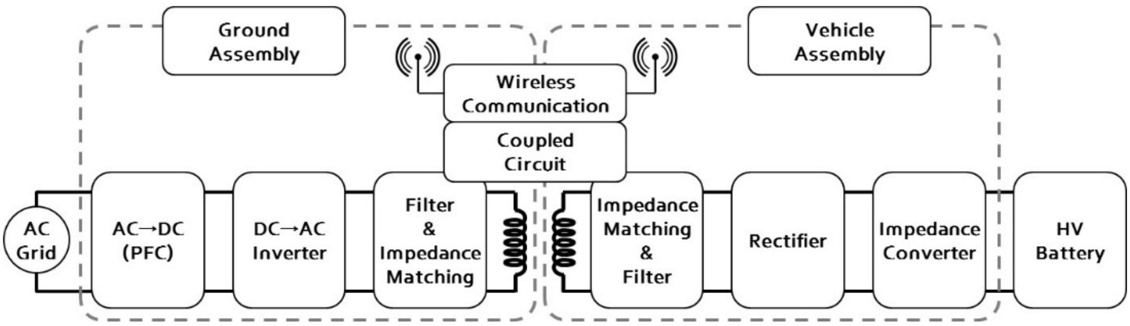

Figure4: Block diagram of WPT for EV

3 Integration of Wireless Charging System

3.1 Implementation of Proto-type WPT in SOUL EV

In order to develop a verification and evaluation method of wireless charging system, a prototype of a 3.3 kW wireless charging system was installed on SOUL EV by adding the secondary coil and output power controller, as shown in Fig. 5. The basic components of the prototype were similar to those described in SAE J2954 information report [13]. Table 1 describes the comparison between the physical characteristics of the prototype and those of the WPT1-Z2 class as reported in SAE J2954 information report. Compared with the WPT1-Z2 class, the primary and secondary coil size of our prototype are 20% and 30% smaller, respectively, while the charging efficiency of our prototype was 6.5% higher.

Figure5: Integration of WPT in SOUL EV

Table 1: Physical characteristics of the prototype wireless charging system

	Primary coil size (mm)	Secondary coil size (mm)	Z-height (mm)	Input power (kW)	Efficiency (%)
Prototype	650×470×60	250×250×20	165	3.7	90.6
WPT1-Z2	675×590×60	355×355×20	140–210	0–3.7	>85

3.2 Implementation of Primary Coil Recognition and Position Alignment System

Unlike conductive charging of electric vehicles, in wireless charging the alignment between the primary and secondary coil is important for maximizing charging efficiency. In order to achieve the maximum possible efficiency, it is critical to provide the user with a simple, user-friendly environment for accurately aligning the vehicle with the primary coil. We have developed a system to recognize the primary coil by using the front camera in the vehicle as well as a support system to inform the user the relative position information of the primary coil even when the coil is covered with the vehicle body and thus not detected with the camera. Fig. 6 shows a block diagram of recognition and position alignment system.

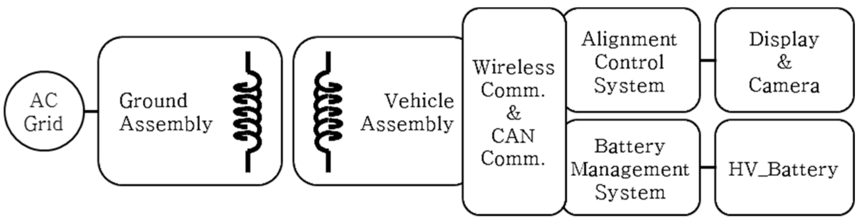

Figure6: Block diagram of recognition and alignment system in SOUL EV

The sequence of the primary coil recognition algorithm is as follows. First, the distortion of the digital image obtained with the front camera is removed and a top-view image is generated. Second, the parking slot as well as the primary coil within the slot are detected. Then, in order to localize the primary coil with a high precision, the logic that compares the current image with the images stored in the local database is performed. Fig. 7 shows the first sequence of the primary coil recognition

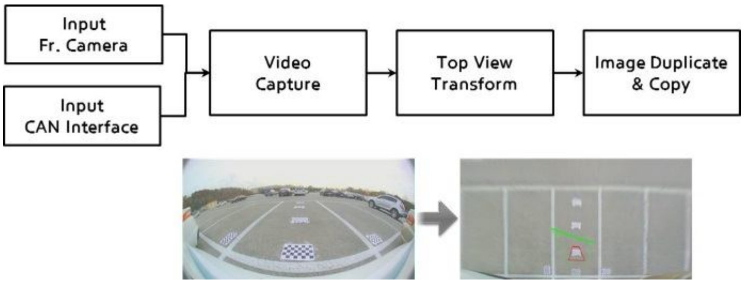

Figure7: The first sequence of the primary coil recognition

In order to improve the primary coil recognition performance, the position alignment system preferentially recognizes the parking slot. Then, when a parking slot was recognized, an algorithm for recognizing the primary coil was applied. In addition, this system took into consideration the various environment conditions of the parking slot. This algorithm is to prevent the primary coil from being recognized by owing to the environmental condition in which the primary coil is mounted. Fig. 8 shows the steps of the parking slot and the primary coil recognition algorithm. When the vehicle enters the parking slot, there occurs a moment when the front camera no longer detects the primary coil as the coil is positioned underneath the vehicle body. In order to solve this problem, the position calculation between the primary and secondary coil and the position tracking algorithm was applied. In order to calculate the distance between the primary and secondary coil, this algorithm wad calculated the change amount of the frame of the video signal of the center point of the primary coil displayed in the top view image. In order to calculate the degree of deviation between the primary and secondary coil, the center of rotation and the rotation angle of the vehicle were calculated, as shown in Fig. 8.

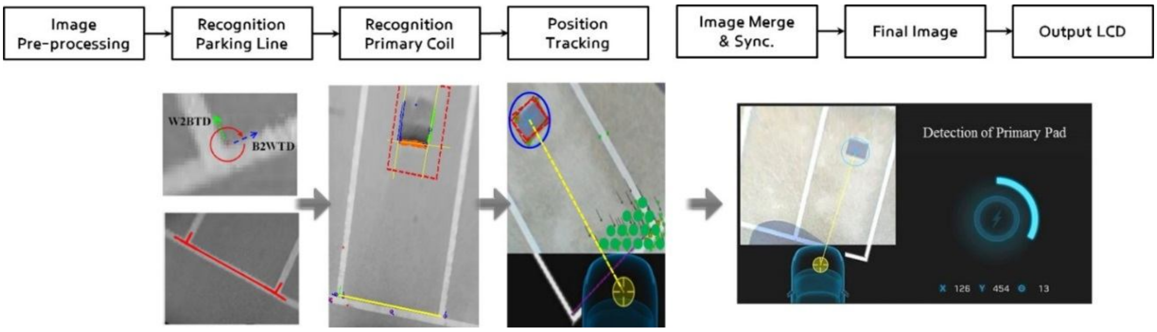

Figure8: The second sequence of the primary coil recognition

4 Experiment and Measurement Results

4.1 Test Result of Efficiency and Positioning Tolerance

The system must operate over a range in X and Y direction to account for expected misalignments in actual use. The maximum positioning deviation in the XY plane occurs when both X and Y offsets are maximum. A compliant GA-VA pair, whether matched or interoperable, must be able to meet the requirements of SAE J2954 information report as given in Table 2. Product VA's must meet the offset tolerances specified by the manufacturer for the specific vehicle implementation. Testing should utilize the three-dimensional reference system as defined by ISO 4130: (1) X = Positive in the Rearward direction; (2) Y = Positive to the Right Side; (3) Z = Positive in the Upwards direction; (4) X=0 and Y=0 are defined by the magnetic center of the primary Coil; (5) Z=0 is defined by the surface of the ground.

Table 2: Positioning tolerance requirements

	ΔX	ΔY	ΔZ
Value (mm)	(-)75–(+)75	(-)100–(+)100	$Z_{nom}-\Delta_{low}$–$Z_{nom}+\Delta_{high}$
Efficiency (%)	>85	>85	>85

Fig. 9 shows the vehicle level test results of the wireless charging efficiency and chargeable coverage of this system. For this evaluation, the SAE J2954 document standards and evaluation processes were applied. The charging efficiency when the primary and secondary pads are perfectly aligned is 90.6%, and this result satisfies the standard of SAE J2954. The efficiency measured result is the ratio of the AC grid input to the high voltage DC output of the vehicle.

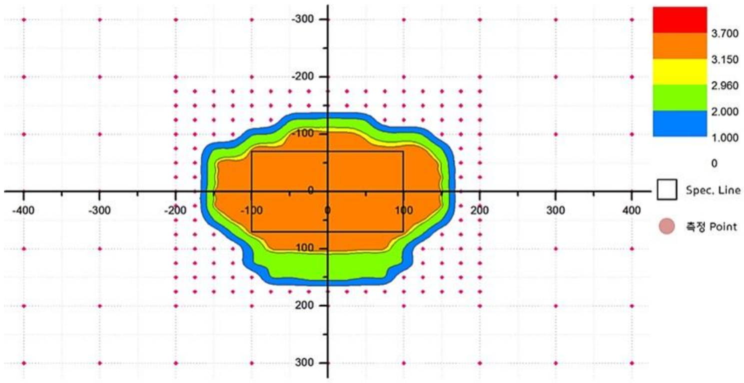

Figure9: Efficiency and coverage

4.2 Test Result of Primary Coil Recognition and Alignment

In order to confirm whether the camera correctly recognizes the primary coil and also whether the system accurately calculates the separation distance between the primary and secondary coil, an evaluation was carried out in two parts. The first part is the stage where the camera recognizes the primary coil. The second part is the high-precision alignment step that is performed during when the primary coil is covered by the vehicle body and no longer detected by the camera. In this case, only the position calculation process is performed using the vehicle steering angle and vehicle speed. For the analysis of the results, the actual distance of the primary and secondary coils and the accuracy of the coordinate values displayed on the screen measured. Fig. 10 shows the accuracy of the position alignment at the stage where the camera recognizes the primary coil. The accuracy in the step of recognizing the primary coil is about 94%. Fig. 11 shows the alignment accuracy when the primary coil is no longer detected. The recognition accuracy in the step of calculating the primary coil is about 91%.

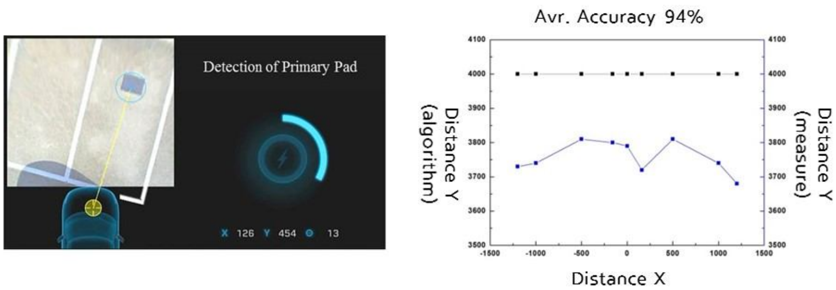

Figure10: Accuracy of camera recognition the primary coil

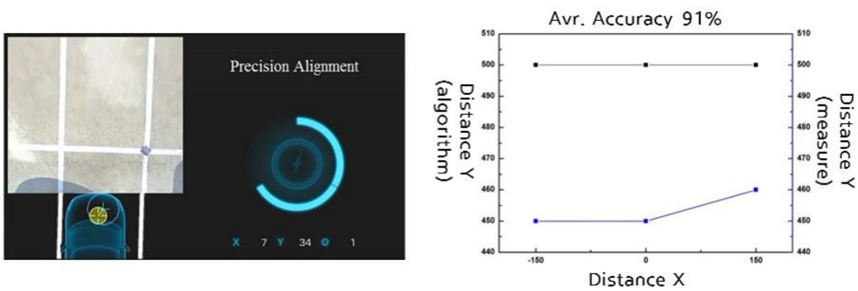

Figure11: Accuracy of position calculation process the primary coil

5 Conclusions

In this paper, we have installed a 3.3kW wireless charging system in SOUL EV while minimizing the modification of the vehicle and secured the ability of transmission coil recognition and position alignment evaluation technology through vehicle level evaluation. The results of this study are as follows: (1) The wireless power transmission method is classified into an electromagnetic induction method, a magnetic resonance method, and a microwave method according to a transmission method of energy and a transmission distance. However, a suitable method for electric vehicles is magnetic resonance coupling type, and many automakers are developing ahead for the electric charging of electric vehicles; (2) We have implemented a 3.3kW wireless charging prototype in a Soul EV to secure the capacity of evaluating the level of the electric vehicle charging car. The charging efficiency of the implemented wireless charging system is confirmed to satisfy the recently established SAE J2954 standard; (3) In order to achieve the maximum possible efficiency of the wireless charging of the electric vehicle and minimize the change range of the vehicle, a system for recognizing the primary coil using the in-vehicle front camera and a support system for indicating the transmission coil position information are implemented. We verified the primary coil recognition and the position alignment optimization through the implemented algorithm; (4) Development and evaluation of the actual vehicle evaluation criteria for primary coil detection were developed. Based on the derived evaluation items, the recognition rate of the actual vehicle evaluation result is more than 90%.

References

[1] D. H. Childress, *The Tesla papers*, Adventures unlimited press, 2000.

[2] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljaˇci c´, *Wireless power transfer via strongly coupled magnetic resonances Science*, Vol. 317, June 7, 2007, pp. 83-86.

[3] Proceedings of IEEE MTT-S international microwave workshop series (IMWPS) on innovative wireless power transmission: Technologies, systems, and applications (IMWS-IWPT), Kyoto, Japan, May, 2011.

[4] SAE, SAE Hybrid J2954 Wireless Charging Task Force. Available: www.sae.org/servlets/works/committeeHome.do?comtID=TEVHYB10, accessed on 2017.01.10

[5] IEC, IEC TC69/WG7 Electric vehicle wireless power transfer (WPT) systems. Available: www.iec.ch/dyn/www/f?p=103:14:11538666115355::::FSP_ORG_ID,FSP_LANG_ID:8538,25, accessed on 2017.01.10

[6] Brian, R.M. & Cohen, R.S. (2007). Hans Christian Ørsted and the Romantic Legacy in Science, *Boston Studies in the Philosophy of Science*, Vol. 241.

[7] T. K. Sarkar, Robert Mailloux, Arthur A. Oliner, M. Salazar-Palma, Dipak L. Sengupta, History of Wireless, John Wiley & Sons - 2006, pages 258-261.

[8] S. L. Ho, J. Wang, W. N. Fu, and M. Sun, "A Comparative Study Between Novel Witricity and Traditional Inductive Magnetic Coupling in Wireless Charging," IEEE Transactions on Magnetics, vol. 47, no. 5, pp. 1522-1525, May 2011.

[9] https://commons.wikimedia.org/wiki/File:Wireless_power_system_-_inductive_coupling_de.svg?uselang=ko.

[10] https://commons.wikimedia.org/wiki/File:Wireless_power_-_resonant_inductive_coupling.svg.

[11] Z. Popovic, "Cut the Cord: Low-Power Far-Field Wireless Powering," IEEE Microwave Magazine, vol. 14, no. 2, pp. 55-62, April 2013.

[12] https://commons.wikimedia.org/wiki/File:Suntower.jpg.

[13] SAE International - SURFACE VEHICLE INFORMATION REPORT - Wireless Power Transfer for Light-Duty Plug-In/ Electric Vehicles and Alignment Methodology, May, 2016, pp. 1-115.

Authors

Jaeyong Seong is a senior research engineer of Electric Energy Control Development Team at automotive division in Hyundai Motor Group. He is in charge of the development work of charging system for light-duty battery electric and plug-in vehicles and interests include wireless charging. He received the B.E. degree in electronic engineering and the M.E. in semiconductor from Kyung Hee University, Republic of Korea, in 2002 and 2005. He is currently working toward the Ph.D degree in department of electronics and computer engineering at Hanyang University, Republic of Korea.

Jinsu Jang is a senior research engineer of Electric Energy Control Development Team at automotive division in Hyundai Motor Group. He is in charge of the development work of conductive charging system for electric vehicle and interests include vehicle to grid communication. He received the B.S. and the M.S. degree in electronic engineering from Hanyang University, Republic of Korea, in 2006 and 2009.

Youngcheol Koh is a team leader of Electric Energy Control Development Team at automotive division in Hyundai Motor Group. He is in charge of the management work of 12V battery system and eco-friendly vehicle charging and control system.