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Wireless Power Transfer System for an Autonomous Electric Vehicle

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***Abstract*— KAIST (Korea Advanced Institute of Science and Technology) and KU (Khalifa University) in UAE have been progressing joint research of the semi-dynamic wireless power transfer system for autonomous electric vehicle from year 2018. The presented semi-dynamic wireless system consists of short length (1.5m) of power line for static charging and long length (5m) of power line for dynamic charging around vehicle stop. In this paper, several important system parameters are obtained through the magnetic simulation and the prototype system is implemented in the laboratory. Finally, the performance of the presented system is verified through test result, that is, the maximum power efficiency is 90.8% for static charging and is upper 85% for dynamic charging.**

Keywords—Wireless power charging, Semi-dynamic, Autonomous, Electric vehicle

I. Introduction

Since 2009, KAIST Wireless Power Transfer Research Center(WPTRC) have been applying wireless power transfer technology to various electric vehicles including electric bus, electric TRAM and small electric car. In case of wireless charging electric bus, we used 20kHz switching frequency [1], [2]. However, 85kHz of switching frequency have been international standard in case of SAE wireless charging of small vehicle below 11kW output power.

This paper aims to develop semi-dynamic wireless charging system for autonomous electric vehicle through KAIST-KU Joint Research.

II. Overall Syetem and Theory

Below is the schematic diagram of the presented overall system, which comprises of the primary side including power inverter with power line and the secondary side with pick-up module with rectifier. Power inverter converts low frequency 60Hz ac voltage to high frequency current and high frequency magnetic field is generated through high frequency coil in power line. Pickup module and rectifier converts this high frequency field to DC voltage.

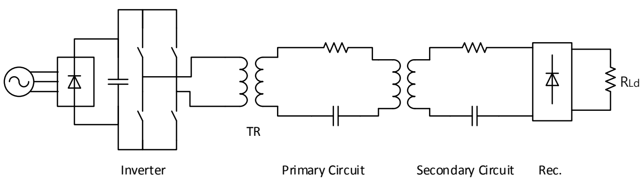

Figure 1. The schematic circuit of overall system

We can use below simple equivalent circuit to obtain the related equations, where R1, L1, C1, R2, L2, C2 are the power loss, self-inductance and resonant capacitance of the primary and secondary side respectively. And M is the mutual inductance between the primary and secondary coil.

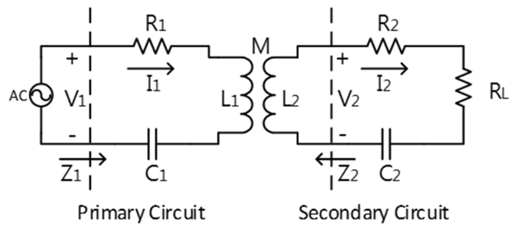

Figure 2. Equivalent circuit considering each circuit parameters

Z1 is the total impedance of primary circuit and Z2 is the total impedance of secondary circuit. Then,

$$V_1 = \left(R_1 + j\omega L_1 + \frac{1}{j\omega C_1}\right) I_1 + j\omega M I_2 \quad (1)$$

$$V_2 = j\omega M I_1 = \left(R_L + R_2 + j\omega L_2 + \frac{1}{j\omega C_2}\right) I_2 \quad (2)$$

$$Z_2 = R_L + R_2 + j\omega L_2 + \frac{1}{j\omega C_2} \quad (3)$$

$$I_2 = \frac{j\omega M}{Z_2} I_1 \quad (4)$$

$$V_1 = \left(R_1 + j\omega L_1 + \frac{1}{j\omega C_1} - \frac{\omega^2 M^2}{Z_2}\right) I_1 \quad (5)$$

$$Z_1 = R_1 + j\omega\left(L_1 - \frac{1}{j\omega^2 C_1}\right) - \frac{\omega^2 M^2}{{Z_2}^2} {Z_2}^* \quad (6)$$

$$Z_{1,real} = R_1 - \frac{\omega^2 M^2 (R_L + R_2)}{{Z_2}^2} \quad (7)$$

$$Z_{1,imag.} = j\omega\left\{\left(L_1 - \frac{1}{j\omega^2 C_1}\right) + \frac{\omega^2 M^2}{{Z_2}^2}\left(L_2 - \frac{1}{j\omega^2 C_2}\right)\right\} \quad (8)$$

If, the frequency ω is same with resonant frequency of each circuit,

$$\omega = \omega_{res.} = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \quad (9)$$

Then, Imaginary parts of Z1 and Z2 are eliminated.

$$Z_1 = Z_{1,real} = R_1 - \frac{\omega^2 M^2}{R_L + R_2} \quad (10)$$

$$Z_2 = Z_{2,real} = R_L + R_2 \quad (11)$$

Output power and power efficiency etc. can be calculated by using Z1 and Z2.

III. SIMULATION

A. Magnetic Field Simultaion

Below figure is the magnetic simulation environment for obtaining circuit parameters in the presented wireless power system, where the pick-up module is placed over the center position of the power line and the air gap between primary and secondary coil is 23cm.

Power line and pickup module are composed of ferrite cores and high frequency coil. In this case, the width and length of the power line is 0.72m and 5m respectively.

From this simulation result, 250A·turn (rms) is needed to flow into the power line to get about 360Vdc of the rated pickup output voltage on the condition of 85kHz switching frequency.

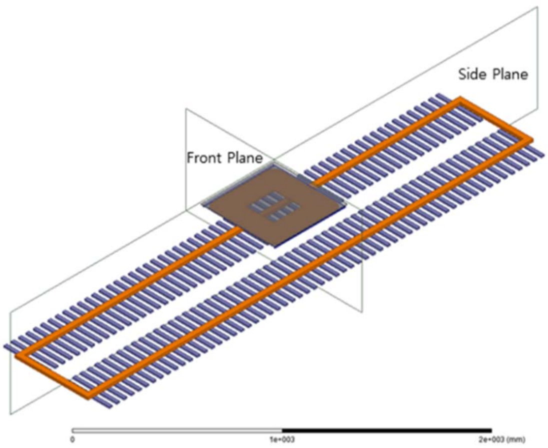

Figure 3. Magnetic simulation environment

Below figure is the magnetic field distribution seen from the front plane, where magnetic field is generated by the alternating current flowing in the transmitter coil. Red zone is the region that the magnitude of the magnetic field is higher than 1.5mT, which is distributed around the transmitter coil or near the wing of the ferrite core in the pick-up module. Green zone means that the magnitude of the magnetic field is under 1.0mT. In this case, magnetic field is distributed in the space between the power line and the pick-up module, from which power from the power line to the pick-up module can be transferred wirelessly. The zone over the pick-up module and under the power line show blue since the ferrite core absorbs the magnetic field and modifies the magnetic path.

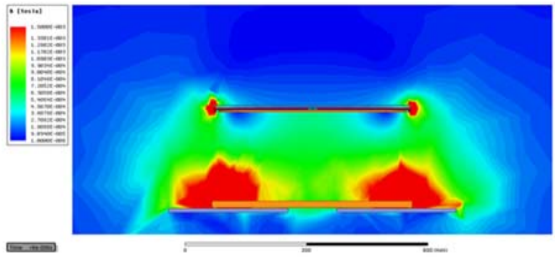

Figure 4. Magnetic field distribution seen from the front plane

Below figure is the magnetic field distribution seen from the side plane. In this case, the magnetic field seen as green zone is distributed constantly toward longitudinal direction except the front and the end edge of the power line, which means that the length of power line does not give dominant effects to wireless charging.

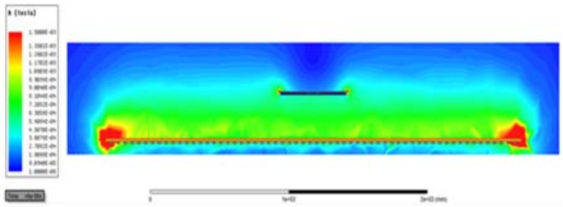

Figure 5. Magnetic field distribution seen from the side plane

B. Circuit Simulation

Circuit simulation corresponding to schematic circuit shown in figure 1 was carried out on the condition of 85kHz switching frequency and 730Vdc of dc link voltage. Also, each of mutual inductance M, resonant frequency of the primary and secondary side were about 12uH, 81kHz and 85kHz.

Below is the waveform of output voltage and current in case of power inverter, which phase shift method was applied to control output voltage of power inverter. Also, we used constant current control method in case of power inverter to obtain the constant output rectifier voltage.

Figure 6. Waveform of output voltage and current in case of power inverter

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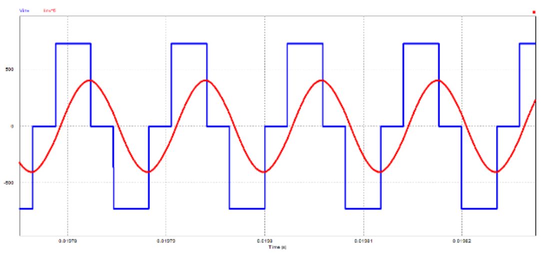

From the simulation results, we found that each of the rated output voltage and current was about 360Vdc and 35Adc, from which total output power was about 12.6kW.

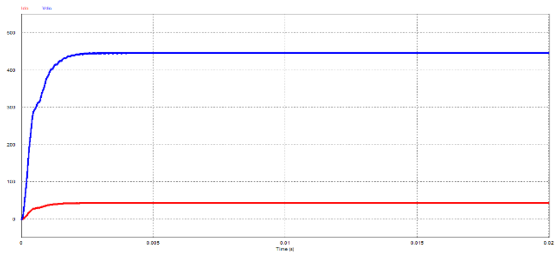

Figure 7. Output voltage and current of rectifier.

IV. Test Result

A. *Test Environment of the Semi-dynamic Wireless Charging System*

The presented semi-dynamic wireless charging system with power inverter, short and length of power line, pickup module and rectifier was implemented in laboratory as shown in below figure. Long and short power line is placed side by side and each power line can be connected to inverter output. Also, the current in power line was 250 Arms·turn and the length of long and short power line were 5m and 1.5m, respectively. Value of resonant capacitance in the primary side was chosen so that the primary resonant frequency is in the range of 81 ~ 83kHz considering the safety of FET in the inverter.

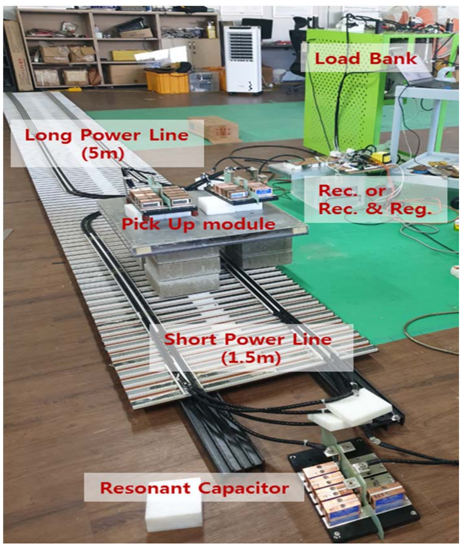

Figure 7. The presented semi-dynamic wireless system implemented in laboratory

However the resonant frequency of the secondary side was 85kHz in pick-up module to obtain the highest power efficiency. The air gap from primary coil to the pick-up coil was about 230mm.

B. *Test Result*

Input power of power inverter is measured at three phase 60Hz ac source of the inverter and output power at the output terminals of the rectifier. And the total power efficiency is calculated as the percentage of the output power divided by the input power.

Below table shows the input/output power and total power efficiency depending on lateral deviation and regulator. In this case, lateral deviation means the distance between center position of power line and pickup module. We determined the maximum lateral deviation as 10cm because the presented wireless charging system aim to apply to autonomous electric vehicle with slow speed approaching to vehicle stop. From this table, we obtained 90.8% of maximum power efficiency and 12.7kW output power on the center position in case of short length of power line for static charging and above 85% of power efficiency for long length of power line for dynamic charging. Therefore, the performance of the presented system was verified through these test results.

Table 1. Input/output power and total power efficiency depending on lateral deviation.

Type of power line	Lateral Deviation [cm]	Output Power [kW]	Input Power [kW]	Total Power Efficiency [%]	Comments
1.5 meter of power line	0	12.7	14.0	90.8	Without Regulator
	5	12.7	14.1	89.9	Without Regulator
	0	12.6	14.2	88.4	With Regulator
5 meter of power line	0	12.8	14.7	86.8	With Regulator
	10	10.2	12	85.2	With Regulator

Below is the waveforms of output voltage and current of power inverter in case of actual test, which is almost similar to the simulation waveform in Figure 6.

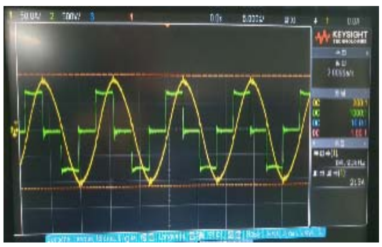

Figure 8. Waveform of output voltage and current of power inverter in case of actual test.

Acknowledgment

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