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A Single-Wire Method of Coupling Interface in Capacitive Power Transfer for Electric Vehicle Wireless Charging System

Aam Muharam[1, 2, *], Tarek M. Mostafa[1], Asep Nugroho[2], Abdul Hapid[2], Reiji Hattori[1]
[1]*Dept. of ASEM, Interdisciplinary Graduate School of Engineering and Sciences, Kyushu University*
Kasuga, Japan
[2]*Research Centre for Electrical Power and Mechatronics, Indonesian Institute of Sciences (LIPI)*
Kampus LIPI Jalan Sangkuriang, Bandung, Indonesia
*aam.muharam.101@s.kyushu-u.ac.jp

***Abstract*— This paper proposes a new approach of coupling interface configuration on capacitive power transfer (CPT) for electric vehicle wireless charging system. CPT has several advantages in use of wireless charging system for short range application such as electric vehicle. One of the advantages is flexibility of coupling interface. Two-pairs of plate usually used to acquire electric field work in order to deliver some amount of designated power. This paper studies a single-wire coupling interface for EV charging system. Simulation has been done in SPICE software with the consideration of parasitic components appearing in the system. As the result, at 3.3 kW output power delivered, the coupling voltage and chassis voltage were measured at 24,720 V and 114V, respectively. This level is obtained when the coupling and chassis capacitances are 1.1 pF and 442 pF, correspondingly. The values are extracted by the electric field simulation on a normal size car.**

Keywords—wireless power transfer, single-wire coupling, capacitive power transfer, capacitive coupling, electric vehicle wireless charging

I. INTRODUCTION

Electric vehicle (EV), nowadays becomes more intensively developed by the world. The environment conditions and dependency of fuel are the crucial issues to bring into view. The trend is usually accelerating because of the rules introduced by the local government that limits the emission level from combustion engine driven vehicle in their city.

The important point of EV is charging infrastructure to cover the energy needed by the EV to run [1]. The wired charging can be found easily around in the big city. Moreover, it provides power through a pair of plug connected by the wire. Even it was efficient, the charger has several issues. There are related to the plug electrode deterioration, high crack possibility of old cable, electric shock risk when rainy or snowy. Wireless power transfer (WPT) for EV charging system is better option to overcome the issues. Research on this area has been conducted by the scientists and industries[2]–[6].

Inductive power transfer (IPT), as a popular one, is a method of transferring power through electromagnetic field by using a pair of coil. Comparative research on traditional IPT has been conducted [7], in line with the study on static and dynamic charging for EV using IPT [8]-[9]. Even IPT is a proofed method to deliver a high power without contacting metal, IPT has disadvantages related to poor power delivered when misalignment in coil pad position, electromagnetic interferences (EMI), and influenced by metal barrier [10].

Capacitive power transfer (CPT), as a new challenge, is using electric field rather than magnetic field to deliver power from primary side to the load in the secondary side. Currently, many scientists tried to find best approach of CPT system that match to the application needed in the market. Previous research in low power [11]–[14] and high power [15] application of CPT has been conducted with efficiency was reported more than 90%. Two pair of plate, normally construct the wireless coupling interface between source and load. A new approach of coupling structure has been introduced to make an interface more simple, efficient and safe [16]–[19].

This paper will provide an equivalent circuit model analysis of a single-wire coupling structure in EV wireless charging system. Sinusoidal approach will introduce to analyze the system using LTSpice simulation software. Finite element analysis (FEA) by Quickfield will give an electric field analysis and safety of the single-wire coupling structure. The simulation result shows the possibility of the proposed system to deliver a power at 3.3 kW with the electric field around the plate bellow 614 V/m which meet the safety regulation from the IEEE [20].

The remaining part of the paper proceeds as follows: The proposed system is explained in Section II. This section also describes the capacitive coupling interface and the compensation circuit topology. The design example and simulation results are provided in Section III, with analysis of electric field and comparison both of the coupling structure. At the end, Section IV will notice the conclusion of this research.

II. A PROPOSED SYSTEM

A. Working Principle

Fig. 1 shows the structure of CPT system proposed for EV charging application. It divided into 3 parts, there are: primary side, coupling interface, and secondary side. First, the primary side consists of the switching network that converts the DC voltage to AC sine wave voltage working in a high frequency. Thus to reach higher voltage, a step-up transformer is connected through the output of switching network. A compensation network is needed to cancel the reactance *C* in coupling interface. Secondly, single-wire

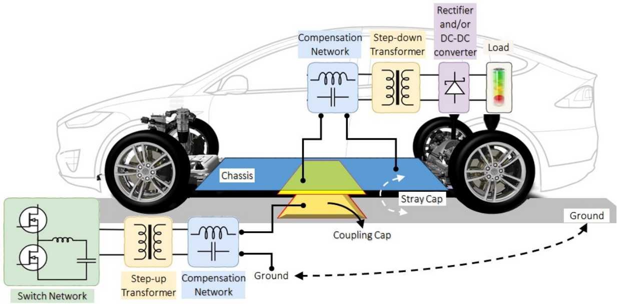


Fig. 2. Structure of single-wire coupling interface of CPT system proposed for EV charging system. (outline car and wheel pictures are from Google)

coupling plate interface topology [16],]17],[21] is used in this research. One wire connection is established from output of the resonant network to the ground. Moreover, a chassis of car will make another coupling interface through the stray capacitance appearing to the ground. Lastly, the secondary side consists of a step-down transformer which will convert the high AC voltage to the low DC voltage, as needed by the load, through the diode bridge or DC/DC converter.

The circuit diagram of CPT system proposed for EV charging system is illustrated in Fig. 2. A half bridge inverter is used to obtain high-voltage high-frequency signal. The duty cycle, amplitude and operating frequency is controlled by using a signal generator.

B. Capacitive Coupling Interface

CPT works with crossing voltage between, usually, two pairs of coupling plates which produced electric field around the interface. The capacitance of coupling plate C_C can be modeled and calculated as [22]:

$$C_C = \frac{\varepsilon_0 \varepsilon_r A_C}{d_C}, \tag{1}$$

where ε_0, ε_r, A_C and d_C denote the dielectric constant in vacuum ($8.854\text{x}10^{-12}$ F/m), relative dielectric constant of material used between the plates, the coupling area of the plate (m^2), and the gap distance between the plate in vertical (m), respectively. The voltage across the coupling capacitance, V_C, at the angular frequency, ω, can be expressed as:

$$V_C = \frac{I}{\omega C_C}, \tag{2}$$

where I is the current flowing the capacitance. On the other hand, V_S (the voltage across the stray capacitance, C_S) can be expressed as:

$$V_S = \frac{I}{\omega C_S}. \tag{3}$$

In EV, A_S is assumed with the area of the chassis underbody of the EV. From (1) to (3), the ratio of coupling capacitance and stray capacitance can be written:

$$\frac{C_C}{C_S} = \frac{A_C d_S}{A_S d_C}, \tag{4}$$

substituting (3) to (4), V_S is can be expressed as:

$$V_S = \left(\frac{A_C d_S}{A_S d_C}\right) \times V_C. \tag{5}$$

From (5), V_S is affected by the ratio area of coupling plate A_C and A_S. The higher ratio will give the lower V_S. The vice versa for lower ratio that will result in higher V_S. Notice that V_S corresponds to the voltage to the ground because of C_S appearing from the car chassis to the ground.

Parasitic components are included as parameters affecting the calculation of capacitive coupling interface [19],[23]. Fig. 3 shows the equivalent model of coupling interface with cross capacitances. C_{P1G}, C_{P1S}, C_{P2G}, and C_{P2S} are the parasitic capacitance from plate 1 (on the surface) to the earth ground, parasitic capacitance between plate 1 to the vehicle chassis, parasitic capacitance from plate 2 (in the vehicle) to the earth ground, and the capacitance appear from plate 2 to the vehicle chassis, respectively. All the capacitances will be included to the calculation of compensation network.

C. Compensation Circuit Topology

Due to reactance component of the circuit, the system needs to compensate it. The *LC* simple resonant topology is used in this research. Four compensation inductors L_{r1}~L_{r4} are implemented on the primary and secondary sides, in both upper and lower sides.

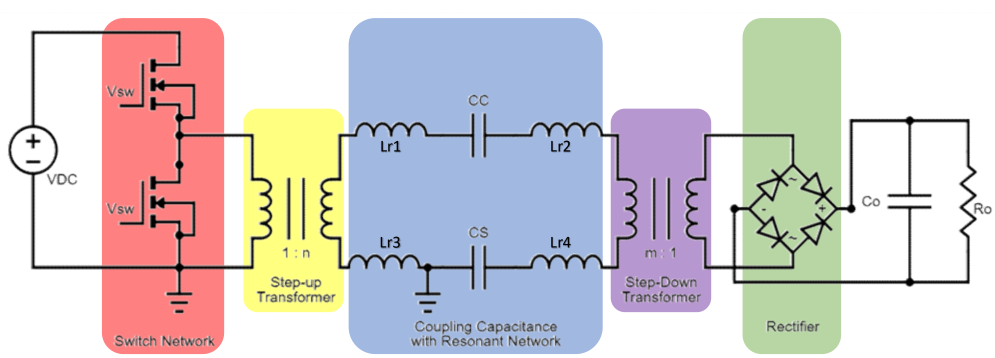


Fig. 1. Circuit diagram of CPT system proposed for EV charging system.

$$C_{equiv1} = C_{P1G} + \frac{(C_S + C_{P2G}) \times (C_{P1S} + C_C)}{C_S + C_C + C_{P1S} + C_{P2G}} \quad (6)$$

$$C_{equiv2} = C_{P2S} + \frac{(C_S + C_{P1S}) \times (C_{P2G} + C_C)}{C_S + C_C + C_{P1S} + C_{P2G}} \quad (7)$$

where C_{equiv1} denotes the equivalent capacitance that calculated when the secondary side is short circuited. C_{equiv2} means the equivalent capacitance when primary circuit is short circuited. The coupling capacitance C_{P1S} and C_{P2G} are usually much smaller than C_C and C_S, then the equivalent capacitance calculation can be more simplified.

The total resonant inductors in primary side are influenced by the equivalent capacitance and the leakage inductance in the primary side. The resonant inductors in the primary side can be expressed as:

$$L_{rp} = \frac{1}{\omega^2 C_{equiv1}} \quad (8)$$

$$L_{rp} = \sum_{i=1,3} L_{ri} + L_{Leakp}, \quad (9)$$

and the total resonant inductors in the secondary side are:

$$L_{rs} = \frac{1}{\omega^2 C_{equiv2}} \quad (10)$$

$$L_{rs} = \sum_{i=2,4} L_{ri} + L_{Leaks} \quad (11)$$

where $\omega = 2\pi f_r$, f_r is the resonant frequency, L_{Leakp} and L_{Leaks} are the leakage inductance from the primary and the secondary side of transformer, respectively.

III. Design and Simulation Results

A. Design Example

As an example, the Tesla model X series will be used in this design. The chassis area and the ground clearance of the vehicle is 500 cm × 200 cm and 21 cm, respectively [24]. A 3.3 kW of power is chosen for the designated system. The size of plate coupling structure is 15 cm × 15 cm, with the plate distance is 19 cm. The capacitance of each coupling C_C and C_S, and also the parasitic capacitances of C_{P1G}, C_{P1S}, C_{P2G}, and C_{P2S} can be calculated by using (1).

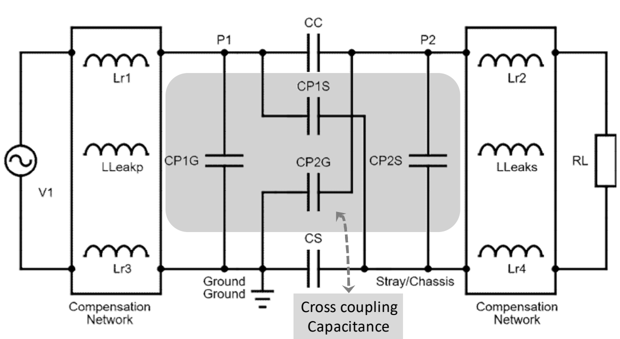


Fig. 3. Equivalent model of coupling interface with cross-capacitances.

TABLE I. Parameter of Designated 3.3 kW CPT System for EV Wireless Charging Application

Parameter	Component		
	Symbol	***Value***	***Unit***
Vehicle stray area	A_S	1e5	cm^2
Vehicle stray distance	d_S	20	cm
Vehicle stray capacitance	C_S	442	pF
Coupling plate area	A_C	225	cm^2
Coupling distance	d_C	18.5	cm
Coupling capacitance	C_C	1.1	pF
Parasitic C P1 to ground, C P2 to chassis	C_{P1G}, C_{P2S}	27	pF
Parasitic C P1 to chassis, C P2 to ground	C_{P1S}, C_{P2G}	1	pF
Resonant inductance primary side	L_{rp1}, L_{rp3}	442	µH
Resonant inductance secondary side	L_{rp2}, L_{rp4}	442	µH

After the value of all capacitances are obtained, the inductors for compensate the network can be calculated by using (6) to (11). In transformer implementation, the leakage inductance of primary and secondary transformer is need to be considered in the calculation. Table I shows the parameter of the designated 3.3 kW CPT system for EV wireless charging application.

B. Simulation

Simulation of the proposed system is conducted by using SPICE software. A sinusoidal approximation is used to simplify the real complex system, based on the result from designed system. The output power delivered, voltage stress at coupling interface and also electric field appearing in chassis of vehicle will be considered in this paper. 1 MHz resonant frequency is applied with 1,000 V high input voltage. To obtain the range of operation load and voltage, then those parameters are marked as a sweep parameter. The system designed to deliver 3.3 kW power through the coupling structure interface. The SPICE simulation result for power delivered is shown in Fig. 4. From 100 Ω to 240 Ω load resistance, it can be seen that at the load 230 Ω will give a 3.3 kW output power range. The higher load will give higher output power as shown in Fig. 4.

The level of voltage across the coupling interface and the chassis of vehicle is shown in Fig. 5. It can be seen that the coupling voltage is much higher than the chassis voltage. This is related to the size area of each coupling interface. As shown in (5), the voltage across will depend on the size and distance of the coupling plate. The simulation shows that the coupling voltage and the chassis voltage, when the load operated at 230 Ω, is leveled at 24,720 V and 114 V, respectively. In order to meet the maximum RMS voltage at 8.35 V on the car chassis, based on IEEE standard [20], the ratio of coupling capacitance and chassis stray capacitance can be more increased. However, the size of coupling plate should be well maintained due to the plate placement and the misalignment consideration.

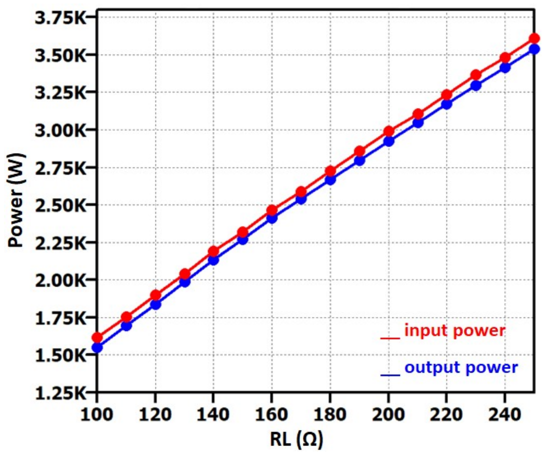


Fig. 4. Power delivered with range of operation load

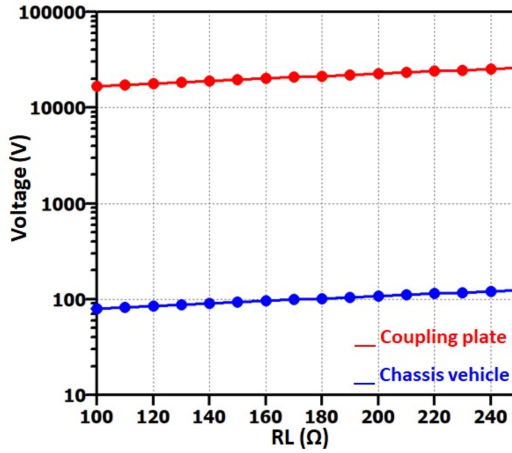
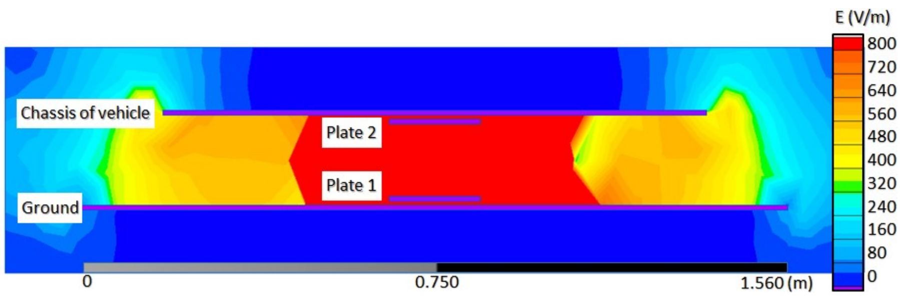
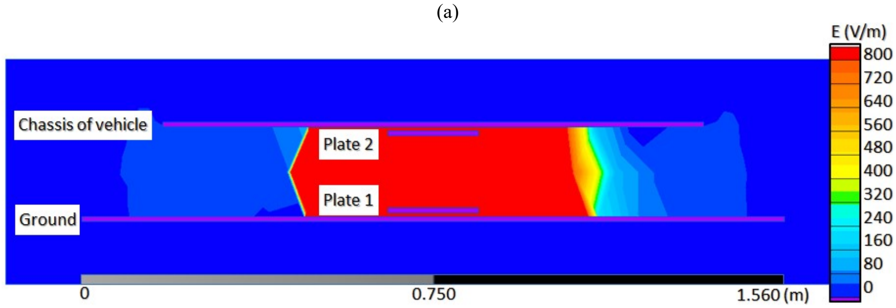


Fig. 5. The level of voltage across the capacitive interface



(a)



(b)

Fig. 6. The electric field emissions of the single-wire coupling interface of CPT: (a) an example design with 114 V chassis voltage, (b) 8 V chassis voltage

C. *Electric Field Analysis*

An analysis related to the electric field around the capacitive coupling interface is conducted by using Quickfield software. Fig. 6 shows the electric field emissions of the single-wire coupling interface. The single-wire coupling plate capacitor and the stray capacitor are placed in the simulation.

The red color denotes an electric field with equal or more than 800 V/m. The less value of electric field emission is represented by the darker color. It can be seen that the electric field are concentrated in the middle of coupling interface. Some of the electric field emission is appeared between chassis of the vehicle and the ground, however it is limited bellow 400 V/m with the distance of 0.25 m for the example design as shown in Fig. 6(a). The Quickfield simulation shows that the emission surround the chassis is still under the level standardized by IEEE [20], that the field strength emissions for any system should be lower than 614 V/m for 0.03 – 1.34 MHz. Compared to the 8 V of chassis voltage in Fig. 6(b), the emission of electric field is only appear surrounded the coupling interface.

IV. Conclusion

Capacitive wireless power transfer can be provided over single-wire coupling interface. The stray capacitance of car chassis is a main consideration of this research due the emission of electric field appeared in the CPT system. The ratio of coupling capacitance between the car chassis and the coupling plate is need to be maintained in order to obtain the lower emission in chassis body of vehicle. As SPICE simulation result, the designated CPT system can deliver a 3.3 kW of power by using the coupling interface size 225 cm^2 with the value of coupling capacitance and stray capacitance at 1.1 pF and 442 pF, individually.

The system has disadvantages related to the coupling size in order to obtain a small capacitance value. Future study will be needed on the impedance calculation of car chassis, insulation material between the coupling plate and car chassis, another resonant network topology, and shielding method to reduce the emission of electric field on CPT system.

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