Improvement of 85 kHz Self-resonant Open End Coil for Capacitor-less Wireless Power Transfer System

Koichi FURUSATO†, Takehiro IMURA††, and Yoichi HORI†††

† The University of Tokyo

5-1-5, Kashiwanoha, Kashiwa, Chiba, 277-8561, Japan

E-mail: †furusato15@hflab.k.u-tokyo.ac.jp, ††imura@hori.k.u-tokyo.ac.jp, †††hori@k.u-tokyo.ac.jp

Abstract The characteristics of a wireless power transfer system depend on the coils. Resonant coil is used for wireless power transfer in the case of magnetic resonant coupling type. Resonant capacitor used for compensation has to withstand high voltage, which is applied to resonant capacitor because of high Q coil, and can cause breakdown accident. Capacitor-less wireless power transfer can prevent this accident. In case of wireless power transfer for electric vehicles, 85 kHz is used as resonant frequency. In this paper, design method of self-resonant open end coil which resonate at 85 kHz is proposed. Characteristics of the proposed coil are verified by experiment.

Key words Wireless power transfer, Open end coil, Short end coil, Resonant capacitor, Stray capacitance

1. Introduction

After André Kurs *et al.* (MIT) proposed magnetic resonant coupling type wireless power transfer(WPT) [1] in 2007, WPT has been popular research topic in recent years. WPT is the transmission of electrical energy from a power source to the load, without using any conductors. It is expected that WPT is applied to mobile devices, home appliance and industrial applications [2]. Magnetic resonant coupling type WPT is superior to magnetic induction type in terms of long distance, efficiency and transmission power [3]. As theoretical research, filter theory was used for explanation [4], maximum efficiency of WPT system is expressed by using kQ product [5], Unified Theory of Electromagnetic Induction and Magnetic Resonant Coupling was discussed [3].

Research on wireless charging for EVs is popular in recent years [6] [7] [8]. More than one coil are used in transmitter side and receiver side respectively for magnetic resonant coupling type wireless power transfer. This paper focuses on transmitter coil under the ground in wireless charging for EVs. The transmitter coils are used in high frequency, therefore, miniaturization of coils and high efficiency WPT system can be achieved [5]. As other research, coupling coefficient was improved by using the DD coil [9], [10], the coil shape was optimized for magnetic field leakage reduction [11], auxiliary coil position was considered for simplification of transmitter side WPT system [12]. Coils for WPT are categorized as two types: open end coil and short end coil. The open end coil has not ever been applied as transmitter coil under the ground. Additionally, comparison with open end coil and short end coil, considering the breakdown of resonant capacitor, have not been discussed enough.

In this paper, capacitor-less underground resonant coil system using open end coil is proposed. The open end coil can resonate at self-resonant frequency with stray capacitance, and using proposed method in this paper, a transmitter coil which resonating at 85 kHz is designed.

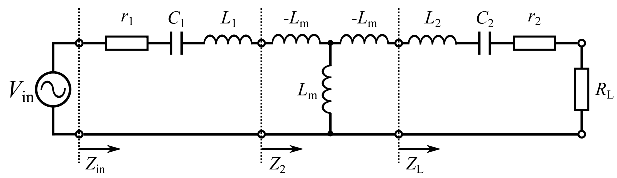


Fig. 1 Equivalent circuit of S/S type wireless power transfer system

2. Structure of under ground system

2.1 Withstand voltage of resonant capacitor

As a resonator, short end coil and resonant capacitor are needed in magnetic resonant coupling type WPT [3]. Based on equivalent circuit of typical S/S type magnetic resonant coupling WPT, shown in Fig. 1, this paper focuses on withstand voltage of resonant capacitor in transmitter side.

As Fig. 1, calculation was done by dividing equivalent circuit. Impedance of load side with mutual induction circuit Z_L is shown as

$$Z_L = j\omega L_2 + \frac{1}{j\omega C_2} + r_2 + R_L$$

where ω is angular frequency, L_2 is self-inductance of coil in secondry side, C_2 is capacitance of resonant capacitor in secondry side, r_2 is wire resistance of coil in secondry side and R_L is load resistance respectively. In case that S/S type resonant condition $\omega L_2 = 1/\omega C_2$ is adopit, Z_L is modified as

$$Z_L = r_2 + R_L.$$

therefore, impedance of load side Z_2 with mutual induction circuit is calculated as

$$Z_2 = -j\omega L_m + \frac{j\omega L_m\{-j\omega L_m + Z_L\}}{j\omega L_m - j\omega L_m + Z_L} = \frac{\omega^2 L_m^2}{Z_L}$$

where L_m is mutual inductance. Total input impedance Z_{in} shown as

$$Z_{\mathrm{in}} = r_1 + Z_2 + \frac{1}{j\omega C_1} + j\omega L_1.$$

where L_1 is self-inductance of coil in primary side, C_1 is capacitance of resonant capacitor in primary side and r_1 is wire resistance of coil in primary side respectively. From the Kirchhoff's law,

$$V_{\mathrm{in}} = I_{\mathrm{in}} \left\{ (r_1 + Z_2) + j\left(\omega L_1 - \frac{1}{\omega C_1}\right) \right\}$$

In case that S/S type resonant condition $\omega L_1 = 1/\omega C_1$ is adopted, $V_{\mathrm{in}} = I_{\mathrm{in}}(r_1 + Z_2)$ will be established. Ratio of input constant voltage V_{in} to voltage in road side capacitor V_{C_1} is shown as

$$\frac{V_{\mathrm{C_1}}}{V_{\mathrm{in}}} = \frac{\frac{I_{\mathrm{in}}}{j\omega C_1}}{V_{\mathrm{in}}} = \frac{\frac{I_{\mathrm{in}}}{j\omega C_1}}{I_{\mathrm{in}}(r_1 + Z_2)} = \frac{-j}{\omega C_1 \left(r_1 + \frac{\omega^2 L_{\mathrm{m}}^2}{r_2 + R_{\mathrm{L}}}\right)} \quad (1)$$

From (1), in case that R_{L} is very large, and in case of L_{m} is very small, (1) is re-written as

$$\frac{V_{\mathrm{C_1}}}{V_{\mathrm{in}}} = \frac{-j}{\omega C_1 r_1} = -jQ_C, \quad Q_C \equiv \frac{1}{\omega C_1 r_1}. \quad (2)$$

As (2), very high voltage which is Q times than input voltage is applied to resonant capacitor.

Ratio of input constant voltage V_{in} to voltage in receiving side capacitor V_{C_2} is given as

$$\frac{V_{\mathrm{C_2}}}{V_{\mathrm{in}}} = \frac{L_{\mathrm{m}}}{r_1 C_2 (r_2 + R_L) + \omega^2 L_{\mathrm{m}}^2 C_2} \quad (3)$$

Efficiency get higher in magnetic resonant coupling type WPT as kQ product get higher [5]. Therefore, when high power is transferred with high Q coil, very high voltage is applied to resonant capacitor. Here, under the condition in Table 1, mutual inductance L_{m} get smaller, (1) get closer to (2). As a result, by using circuit simulator LTSpice, it is confirmed that very high voltage which is Q times than input voltage is applied to resonant capacitor.

Fig. 2(a) shows that voltage about 120 kV applied to resonant capacitor when mutual inductance L_{m} between road side coil and receiving side coil is very small.

Fig. 2(b) shows that voltage about 60 kV applied to resonant capacitor when mutual inductance L_{m} and load resistance are very small.

As above, from view point of applied voltage, higher voltage is applied to road side resonant capacitor rather than receiving side. Supposing wireless charging for EVs, coupling between two coils are changed dynamically. As a result, road side resonant capacitor has more denger risk than receiving side resonant capacitor.

In this paper, it is proposed that open end coil [13] [14] which resonate with stray capacitance is applied to capacitor-less WPT system.

2.2 Proposed system

About wireless charging for EVs, difference between open end coil and short end coil for underground coil is discussed.

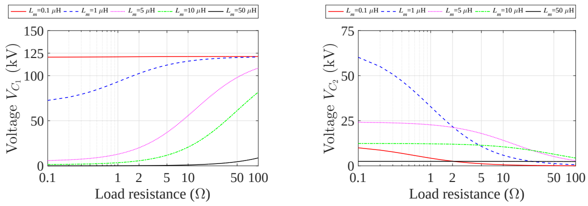
Fig. 3(a) shows conventional system using short end coil. Short end coil, resonant capacitor are main elements of the system. First resonant frequency of the short end coil cannot be used for WPT. Therefore, resonant frequency is made at lower than first resonant frequency (anti-resonant frequency) by using external resonant capacitor. If breakdown occur in external resonant capacitor, replacing capacitor is needed.

Fig. 3(b) shows proposed system structure using open end coil. Only open end coil is main element of the system. First resonant frequency of the open end coil can be used for WPT. For resonance, external resonant capacitor is not needed, because stray capacitance of open end coil is used. This coil can decrease cost of resonator. Additionally, if breakdown is occurrs the coil, replacing is not needed because the coil can self reset.

In this paper, self-resonant frequency of the open end coil, which is superior to the short end coil view point of external capacitor-less WPT is discussed, and design method in order to set its self-resonant frequency to 85 kHz is discussed.

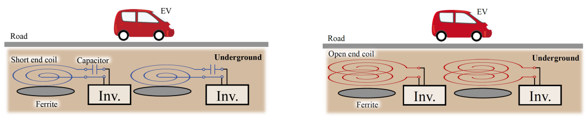
Table 1 Circuit parameter used in simulation

Parameter	Value
Input voltage V_{in}	500 V
Operating frequency	85 kHz
Self-inductance L_1, L_2	250 μH
Capacitance C_1, C_2	14 nF
Coil and Capacitor resistance r_1, r_2	0.5 Ω
Q value of the coils Q	267
Load resistance R_{L}	30 Ω



(a) V_{C_1} (b) V_{C_2}

Fig. 2 Applied capacitor voltage , coupling and load resistance



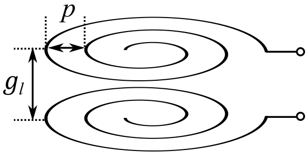
(a) Conventional system (b) Proposed system

Fig. 3 Diagram of conventional and proposed system

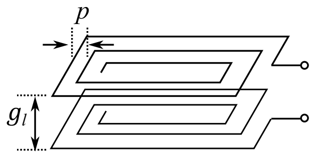
3. Design method of the underground open end coil

3.1 Resonant characteristics by changing coil shape parameter

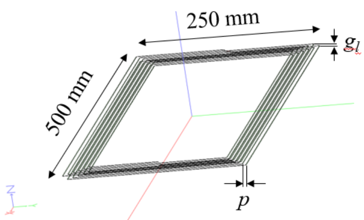
This paper proposed that capacitor-less WPT is achieved by setting self-resonant frequency of open end coil at 85 kHz. Based on input impedance of open end coil, required wire length l of the coil in order to self-resonate at 85 kHz is



(a) Circular coil



(b) Square coil



(c) Anaysis model of square coil

Fig. 4 Double layered open end spiral coil

shown as

$$\frac{\pi}{2} = \frac{\omega}{c} l = \frac{2\pi f}{c} l \tag{4}$$

$$l = \frac{c}{4f} = \frac{3 \times 10^8}{4 \times 85 \times 10^3} \cong 882.35 \text{ m}. \tag{5}$$

Calculated wire length is 882.35 m, and it is too long. In order to resonate by feasible wire length, double layered open end spiral coil is proposed shown in Fig. 4(a). Spiral structure makes near magnetic field increase, double layered structure increases stray capacitance. Therefore, the proposed structure can resonate even if wire length l is smaller than $c/4f$.

In case of double layered open end circular spiral coil, it was clear that resonant frequency can be adjusted by changing layer gap and wire pitch [15]. Hence, in order to clear relationship between coil shape parameter of double layered open end square spiral coil shown in Fig. 4(b) and resonant characteristics, analysis model shown in Fig. 4(c) is used for simulation. Square spiral coil is larger occupation area than circular coil, then square coil is more suitable for wireless charging, whose misalignment is only EVs direction. IE3D 15.1 (Mentor Graphics Inc.) is used for verification. Table 2 shows parameter of simplified analysis model.

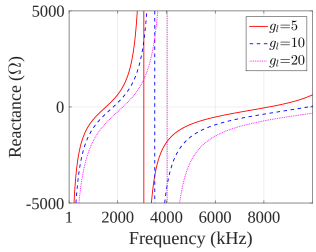
Fig. 5(a) shows the characteristics of reactance by changing layer gap g_l. Fig. 5(b) shows the characteristics of reactance by changing wire pitch p. From the result, layer gap g_l strongly affects resonant frequency, wire pitch l affects slightly resonant frequency, and wire pitch l affects only anti-resonant frequency.

Fig. 5(c) shows reactance characteristics when the number of turns is changed. If the number of turns of coil gets larger, it is confirmed that self-resonant frequency gets lower.

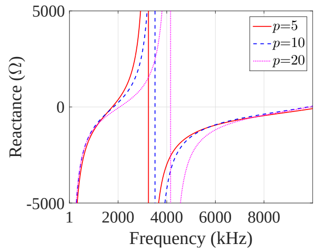
As above, the number of turns is decided approximately, because effect on resonant characteristics is large. After that, resonant frequency is adjusted by layer gap g_l, it is adjusted by wire pitch p precisely.

Table 2 Designed parameter of simplified coil model

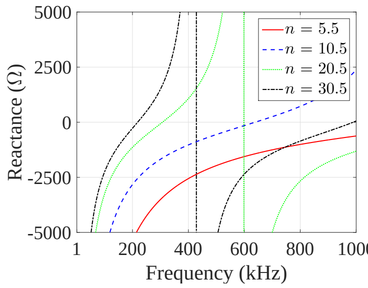
Parameter	Value
No. of turns n	5.5, 10.5, 20.5, 30.5
Coil outer Size	500 mm × 250 mm
Layer gap g_l	5, 10, 20 mm
Wire pitch p	5, 10, 20 mm
Wire diameter	2 mm



(a) Reactance vs. layer gap g_l



(b) Reactance vs. wire pitch p



(c) Reactance vs. No. of turns n

Fig. 5 Reactance characteristics of simplified coil model (simulation)

3.2 85 kHz self-resonant square open end underground coil

The self-resonant square open end underground coil resonating at 85 kHz is designed by using proposed open end coil coil. The electromagnetic simulator IE3D 15.1 (Mentor Graphics, Inc) was used for coil design. In order to achieve the self-resonant frequency at 85 kHz, l is should be longer.

First, the coil size is decided as 1280 mm × 390 mm supposing wireless charging for EVs. KIV wire (cross section : 3.5 mm^2) is used for making coil. Diameter of KIV wire is 2.5 mm, thickness of insulating coating is 0.8 mm.

Table 3 shows that designed data of the coil which resonates at 85 kHz. KIV wire was decided to use for coil making and its wire parameter was used for coil design. Fig. 6 shows analysis model on IE3D.

Based on Table 3, the actual coil was made by using KIV wire and vinyl chloride for layer gap. Fig. 7(a) shows overview of actual coil. As Fig. 7(b), vinyl chloride plate is in between a pair of coil layers.

Reactance characteristics of the coil was measured by using impedance analyser E4990A (Keysight Technology Inc.).

Fig. 8 shows reactance frequency plot of actual coil. The electromagnetic simulation result is sim., and exp. shows measured value. From Fig. 8, about resonant frequency, as simulation, it is achieved that self-resonant frequency is set at 85 kHz.

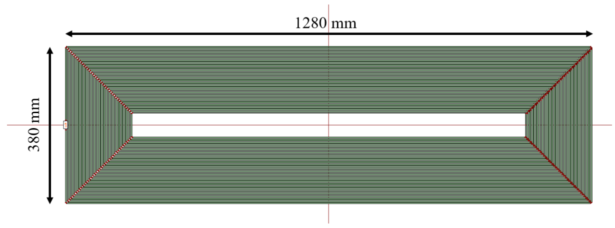
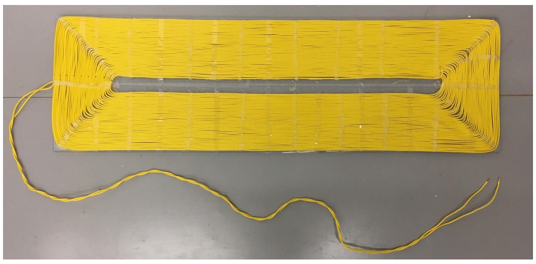


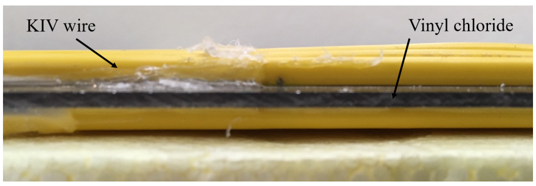
Fig. 6 Desined simulation model of 85 kHz self -resonant coil

Table 3 Desined parameter of 85 kHz self -resonant coil

Parameter	Value
No. of turns n	39.5
Coil outer size	1280 mm × 380 mm
Layer gap g_l	2 mm
Wire pitch p	1.6 mm
Wire diameter	2.5 mm



(a) Top view



(b) Side view

Fig. 7 85 kHz self-resonant open end coil (designed actual coil)

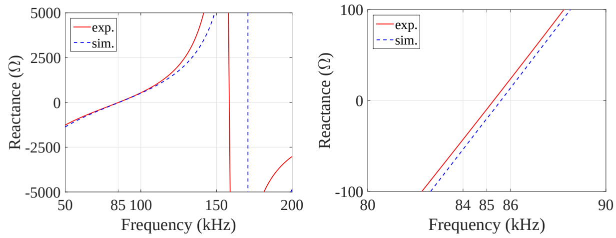
From the result, it is clear that self-resonant frequency can be set at 85 kHz by using proposed coil design method, and, feasibility of 85 kHz self-resonant open end coil is confirmed.

However, from Fig. 9, AC resistance (real part of impedance) is very large, about 60 Ω, and it is serious problem.

4. Reduction of AC resisnance

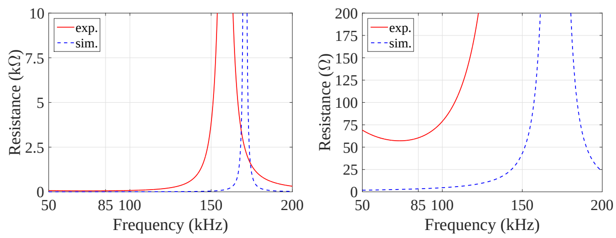
As Fig. 9, there is a problem that AC resistance is very high. Accordingly, in order to clarify increasing of resistance, relationship between coil shape and resistance is considered by electromagntic simulation using IE3D 15.0.

In consideration, open end coil is not suitable for resistance consideration because self-resonant frequency is also changed by coil shape change. Therefore, short end coil which does



(a) Imaginary part (b) Imaginary part (extended)

Fig. 8 Impedance frequency plots of 85 kHz self-resonant open end coil (Imaginary part)



(a) Real part (b) Real part (extended)

Fig. 9 Impedance frequency plots of 85 kHz self-resonant open end coil (Real part)

Table 4 Analysis condition

Parameter	Value
Coil type	Short type
Coil size	2000 mm × 1000 mm
Wire	3.5 mm^2 KIV wire
Layer gap	5, 10, 15, 20 mm
Wire pitch	5, 10, 15, 20 mm
No. of turns	20.5
Target frequency	85 kHz

not change self-resonant frequecy before anti-resonant frequency is used for simulation. AC resistance is simulated when layer gap g_l and wire pitch p is changed. Table 4 shows simulation condition.

Table 5 shows simulation result of AC resistance at 85 kHz. Fig. 11 shows characteristics parameter plots.

From the result, it was clarified that AC resistance can be decreased by expanding layer gap g_l and wire pitch p. Most important point is that expansion of wire pitch p affects resistance reduction than layer gap g_l.

As a result, it is expected that AC resistance reduction can be achieved by expansion of wire pitch p.

5. Conclusion

In this paper, supposing wireless charging to EVs, capacitor-less wireless charging system using open end coil as underground coil is proposed. Main research purpose was that self-resonant frequency is set at 85 kHz. Open end coil can resonate only using stray capacitance, and double layered square spiral structure can resonate at lower kHz band

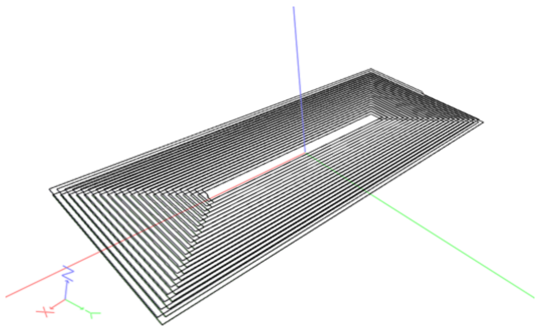


Fig. 10 Analysis model of short end coil on IE3D

Table 5 Simulated AC resistance at 85 kHz

		Wire pitch (mm)			
		5	10	15	20
Layer gap (mm)	5	34.23	18.89	11.58	8.011
	10	15.15	12.06	9.105	7.037
	15	11.76	10.11	8.209	6.643
	20	10.37	9.173	7.71	6.405

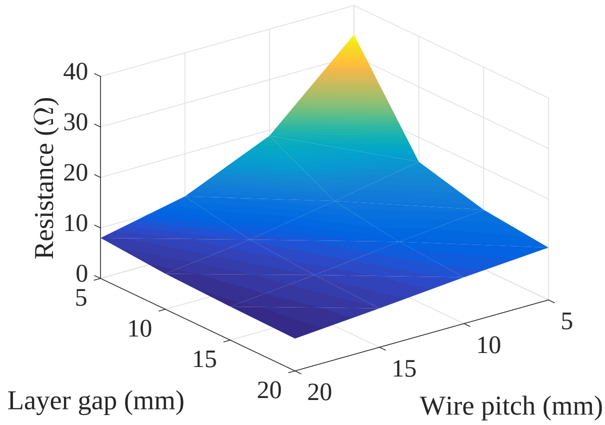


Fig. 11 AC resistance vs. coil parameter plot

easily. By clarifying relationship between coil shape and self-resonant frequency characteristics, design method is for adjusting self-resonant frequency by changing number of turs and layer gap is proposed. A open end coil resonating at 85 kHz is designed by using proposed design method. Measured resonant frequency using actual coil is around 85 kHz precisely. As a result, design of 85 kHz self-resonant open end coil is achieved and effectiveness of proposed method is confirmed. However, measured AC resistance is very high. From the result of simulation, expansion of wire pitch p affects resistance reduction more than layer gap g_l. As a result, it is expected that AC resistance reduction can be achieved by expansion of wire pitch p.

As a future research, an actual coil with more larger wire pitch than previous coil will be manufactured and discussed.

Aknowledgement

This work was partly supported by JSPS KAKENHI Grant Number 25709020 and 15H02232.

References

[1] A. Kurs, A. Karalis, R. Moffatt, J.D. Joannopoulos, P. Fisher, and M. Soljacic, "Wireless power transfer via strongly coupled magnetic resonances.," Science (New York, N.Y.), vol.317, no.5834, pp.83–86, 2007.

[2] H. Shoki, "Trends of Wireless Power Transmission Technologies and Approaches for Commercialization," Technical report of IEICE(WPT2010-07), pp.19–24, 2010.

[3] T. Imura and H. Yoichi, "Unified Theory of Electromagnetic Induction and Magnetic Resonant Coupling," IEEJ Transactions on Sensors and Micromachines, vol.135, no.6, pp.697–710, 2015.

[4] I. Awai, "BPF Theory-Based Design Method for Wireless Power Transfer System by Use of Magnetically Coupled Resonators," IEEJ Transactions on Electronics, Information and Systems, vol.130, no.12, pp.2192–2197, 2010.

[5] T. Tohi, Y. Kaneko, and S. Abe, "Maximum Efficiency of Contactless Power Transfer Systems using k and Q," IEEJ Transactions on Industry Applications, vol.132, no.1, pp.123–124, 2012.

[6] J.M. Miller, O.C. Onar, C. White, S. Campbell, C. Coomer, L. Seiber, R. Sepe, and A. Steyerl, "Demonstrating dynamic wireless charging of an electric vehicle: The benefit of electrochemical capacitor smoothing," IEEE Power Electronics Magazine, vol.1, no.1, pp.12–24, 2014.

[7] L. Chen, G.R. Nagendra, J.T. Boys, and G.a. Covic, "Double-coupled systems for IPT roadway applications," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol.3, no.1, pp.37–49, 2015.

[8] d. Kobayashi, T. Imura, and Y. Hori, "Real-time maximum efficiency control in dynamic wireless power transfer system," IEEJ Transactions on Industry Applications, vol.136, no.6, pp.425–432, 2016.

[9] A. Zaheer, H. Hao, G.a. Covic, and D. Kacprzak, "Investigation of multiple decoupled coil primary pad topologies in lumped IPT systems for interoperable electric vehicle charging," IEEE Transactions on Power Electronics, vol.30, no.4, pp.1937–1955, 2015.

[10] Z. Wei, J.C. White, a.M. Abraham, and C.C. Mi, "Loosely Coupled Transformer Structure and Interoperability Study for EV Wireless Charging Systems," Power Electronics, IEEE Transactions on, vol.30, no.11, pp.6356–6367, 2015.

[11] H. Kim, S. Member, C. Song, D.-h. Kim, D.H. Jung, I.-m. Kim, Y.-i. Kim, J. Kim, S. Member, S. Ahn, S. Member, and J. Kim, "Coil Design and Measurements of Automotive Magnetic Resonant Wireless Charging System for High-Efficiency and Low Magnetic Field Leakage," IEEE Transactions on Microwave Theory and Techniques, vol.64, no.2, pp.383–400, 2016.

[12] T. Kan, T.D. Nguyen, J.C. Wjite, R.K. Malhan, and C. Mi, "A New Integration Method for an Electric Vehicle Wireless Charging System Using LCC Compensation Topology," IEEE Transactions on Power Electronics, pp.1–12, 2016.

[13] H. Hirayama, T. Amano, N. Kikuma, and K. Sakakibara, "A consideration of open- and short-end type helical antennas for magnetic-coupled resonant wireless power transfer," Proceedings of 6th European Conference on Antennas and Propagation, EuCAP 2012, pp.3009–3013, 2012.

[14] T. Imura, H. Okabe, T. Uchida, and Y. Hori, "Study on open and short end helical antennas with capacitor in series of wireless power transfer using magnetic resonant couplings," IECON Proceedings (Industrial Electronics Conference), pp.3848–3853, 2009.

[15] K. Furusato, T. Imura, and Y. Hori, "Design of Multi-frequency Coil for Capacitor-less Wireless Power Transfer using High Order Self-resonance of Open End Coil," IEEE MTT-S Wireless Power Transfer Conference 2016, no.78, pp.1–4, 2016.