

Article

Compensation Parameters Optimization of Wireless Power Transfer for Electric Vehicles

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Abstract: For wireless charging of electric vehicles (EVs), increasing the output power level is particularly important. In this paper, the purpose of improving the output power while maintaining optimal transmission efficiency is achieved by optimizing the parameters of the compensation topology under the premise that the coupled coils of the system does not need to be redesigned. The series-series (SS) and hybrid-series-parallel (LCC, composed by an inductor and two capacitors) compensation topology are studied. The influence factors of load resistance to achieve optimal efficiency, the influence of LCC compensation parameters on the power output level, and the influence of parameter changes on system safety are analyzed. Theoretical results show that by rationally designing the LCC compensation parameters, larger output power and optimal transfer efficiency can be achieved under different load resistance by adjusting the inductances of the primary and secondary compensation circuits. The output power of the optimized system with adjusted LCC compensation topology is increased by 64.2% with 89.8% transfer efficiency under 50 ohms load in experiments. The correctness and feasibility of this parameter design method are verified by both theoretical and experimental results.

Keywords: Wireless Power Transfer (WPT); compensation topology; optimal load; output power level; electric vehicle (EV)

1. Introduction

Since the concept of magnetic coupled resonant wireless power transfer (MCR-WPT) was proposed by MIT in 2007, the technology has developed rapidly and has been widely applied in implantable medical devices, home appliances, mobile devices and electric vehicles [1–8]. Increasing transmission power is particularly important for wireless charging of electric vehicles. The main ways to improve power levels are: (1) power supply parallel topology, which uses multiple parallel power supplies for power distribution, but the parallel topology is too redundant [9]; (2) multi-phase parallel, there are shortcomings of current imbalance between phases and serious coil loss. In addition, the compensation topology also has a great impact on the output power level.

At present, the basic compensation topologies are series-series (SS), series-parallel (SP), parallel-series (PS), and parallel-parallel (PP) [10,11]. The most widely used is the SS topology, but this topology has inherent disadvantages: once coil parameters are determined, the rated output power can be regulated only by the input voltage. In addition to the four basic resonance topologies described above, hybrid-series-parallel (LCC, composed by an inductor and two capacitors) compensation topology has been extensively studied for its excellent performance. It can implement zero phase angle (ZPA) and zero voltage switching (ZVS), and its output current is independent of the load [12–17].

Most of the current studies on WPT compensation topology focus on improving the output performance by adopting complex control strategies. However, the load resistance to achieve optimal efficiency of SS topology WPT system is unchangeable after the coil-parameters are fixed whereas the one of LCC topology can be adjusted according to the parameters of compensation topology. In this paper, the WPT system is modeled and the transfer performance is analyzed. Methods are proposed to increase output power level while maintaining optimal transmission efficiency without redesign of the coupled coils by optimizing the parameters of LCC compensation topology. Both theoretical and experimental results indicate that the proposed parameter optimization strategy is effective in improving transfer efficiency and adjusting output power under different load resistances. It avoids the disadvantages of redesigning the coil due to power level changes to maintain high transmission efficiency. At the same time, it has obvious advantages in safety under the condition of output short circuit.

2. Theoretical Analysis

2.1. System Analysis

Figure 1 shows the schematic diagram of the magnetic coupled wireless power transfer system, where AC power on the grid side is rectified to form DC power, the high-frequency inverter is composed of H-bridge, and the direct current is converted by inverter circuit into alternating current with a system rated frequency, which flows through the transmitter end and transmits the power to the receiver coil. The primary and secondary compensation circuit is composed of SS or LCC compensation topology. The transmitter and receiver coils are planar spiral coils designed in Section 3, and the receiver end is connected to electric vehicle battery through a rectifier circuit.

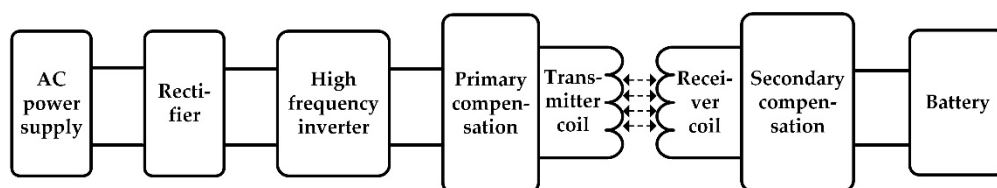


Figure 1. The structure diagram of wireless power transfer system.

Because the resonance part of wireless power transfer system has the characteristics of band-pass filtering, only the fundamental wave component is considered later, and the square wave generated by the full-bridge inverter can be equivalent to an AC voltage source for theoretical analysis. The square wave is expanded according to the Fourier series, the duty cycle is set to D , and the fundamental wave of the square wave whose amplitude is U_d is as follow:

$$f_t = \frac{4U_d}{\pi} \sin(\pi D) \cos(\omega t - \pi D) \quad (1)$$

The battery is a typical non-linear load. With the use of battery, the battery charging current and the state of charge are different, and different external load characteristics are displayed. In order to simplify the difficulty of system analysis, the battery is generally equivalent to a resistive load according to the ratio of charging voltage and current of battery and then analyzed. Therefore, the battery and its management system are equivalent to a load in this paper.

2.2. Theoretical Analysis of SS and LCC Compensation Topology

Modeling and analysis of SS-type and LCC-type compensation topologies are shown below. Figures 2 and 3 show simplified topologies of SS-type and LCC-type resonant circuits, respectively. The parasitic resistance of inductors and capacitors are much smaller than the internal resistance of

coil, so it can be ignored. The subsequent experimental results show that this approximate analysis does not affect the accuracy of experiment.

2.2.1. Analysis of SS-type Resonance Circuit

The SS topology is the most basic resonance structure. Both primary and secondary side use series resonance. The equivalent circuit is shown in Figure 2, where U_s is a voltage-stabilized source, the source internal resistance is ignored, M is the mutual inductance between two coils.

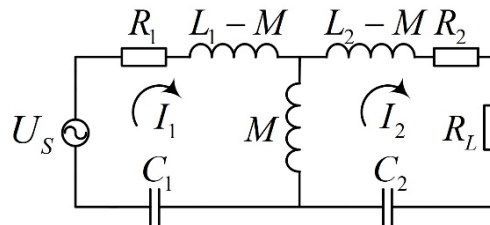


Figure 2. The equivalent circuit model of SS-type.

According to Figure 2 and Kirchhoff voltage law (KVL), we can obtain:

$$\begin{cases} (R_1 + j\omega L_1 + \frac{1}{j\omega C_1})I_1 - j\omega M I_2 = U_s \\ (R_2 + R_L + j\omega L_2 + \frac{1}{j\omega C_2})I_2 - j\omega M I_1 = 0 \end{cases} \quad (2)$$

When the system meets the resonance conditions:

$$f_0 = \frac{1}{2\pi \sqrt{L_1 C_1}} = \frac{1}{2\pi \sqrt{L_2 C_2}} \quad (3)$$

When R_L is much greater than R_1 and R_2 , R_1 and R_2 can be ignored, the currents are as follows:

$$\begin{cases} I_1 = \frac{U_s R_L}{(\omega M)^2} \\ I_2 = \frac{U_s}{\omega M} \end{cases} \quad (4)$$

The transmission power and efficiency of the system are:

$$P_{ss} = \frac{U_s^2 R_L}{(\omega M)^2} \quad (5)$$

$$\eta_{ss} = 1 - \frac{R_L R_1}{(\omega M)^2} - \frac{R_2}{R_L} \quad (6)$$

The maximum efficiency and corresponding load value are:

$$\eta_{ss_max} = 1 - \frac{2\sqrt{R_1 R_2}}{\omega M} \quad (7)$$

$$R_{ss} = \sqrt{\frac{R_2}{R_1}} (\omega M)^2 \quad (8)$$

Due to the inverse relationship between distance and mutual inductance, in practical applications, it is common for charging object to be far away from primary coil. It can be seen from (4) and (5) that when the secondary side is open, the primary current will increase sharply; when a short circuit occurs on the secondary side, the primary current and transmission power will decrease. On the other hand,

in the case of the SS structure with constant coil parameters, the load resistance to achieve optimal efficiency is unchangeable.

2.2.2. Analysis of LCC-type Resonance Circuit

The LCC structure is a new type of composite resonant structure. As shown in Figure 3, L_{f1} , C_1 , C_{p1} and L_{f2} , C_2 , C_{p2} are the corresponding resonant circuit units of primary and secondary coils, respectively.

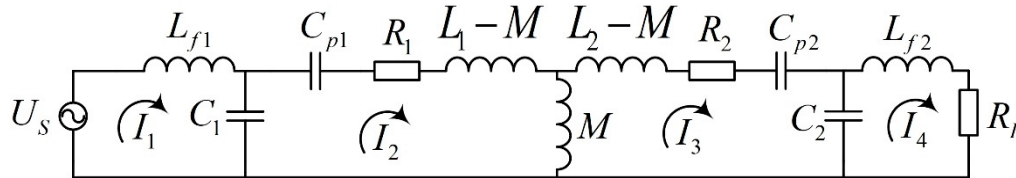


Figure 3. The equivalent circuit model of LCC-type.

Similarly, we can formulate KVL equation according to Figure 3:

$$\begin{cases} (j\omega L_{f1} + \frac{1}{j\omega C_1})I_1 - \frac{1}{j\omega C_1}I_2 = U_s \\ (R_1 + j\omega L_1 + \frac{1}{j\omega C_1} + \frac{1}{j\omega C_{p1}})I_2 - \frac{1}{j\omega C_1}I_1 - j\omega M I_3 = 0 \\ (R_2 + j\omega L_2 + \frac{1}{j\omega C_2} + \frac{1}{j\omega C_{p2}})I_3 - \frac{1}{j\omega C_2}I_4 - j\omega M I_2 = 0 \\ (R_L + j\omega L_{f2} + \frac{1}{j\omega C_2})I_4 - \frac{1}{j\omega C_2}I_3 = 0 \end{cases} \quad (9)$$

The resonance conditions are as follows:

$$\begin{aligned} C_1 &= \frac{1}{\omega^2 L_{f1}}, C_{p1} = \frac{1}{\omega^2 L_1 - \frac{1}{C_1}}, \\ C_2 &= \frac{1}{\omega^2 L_{f2}}, C_{p2} = \frac{1}{\omega^2 L_2 - \frac{1}{C_2}} \end{aligned} \quad (10)$$

The currents of the loops are:

$$\begin{cases} I_1 = \omega^6 C_1^2 C_2^2 M^2 R_L U_s \\ I_2 = -\omega C_1 U_s \\ I_3 = \omega^4 C_1 C_2^2 M R_L U_s \\ I_4 = -\omega^3 C_1 C_2 M U_s \end{cases} \quad (11)$$

The transmission power and efficiency of the system are:

$$P_{LCC} = \frac{M^2 U_s^2 R_L}{\omega^2 L_{f1}^2 L_{f2}^2} \quad (12)$$

$$\eta_{LCC} = 1 - \frac{R_1 L_{f2}^2}{R_L M^2} - \frac{R_2 R_L}{\omega^2 L_{f2}^2} \quad (13)$$

The maximum efficiency and corresponding load values are:

$$\eta_{LCC_max} = 1 - \frac{2\sqrt{R_1 R_2}}{\omega M} \quad (14)$$

$$R_{LCC} = \sqrt{\frac{R_1 \omega^2 L_{f2}^4}{R_2 M^2}} = \frac{R_1 L_{f2}^2}{R_2 M^2} R_{SS} \quad (15)$$

It can be known from (11) that when the mutual inductance decreases, the currents of primary and secondary coils decrease, which is a safe working condition. And when the system coil-parameters are fixed, the load resistance to achieve optimal efficiency can be adjusted by the inductance of the secondary resonance circuit L_{f2} . C_2 also needs to be adjusted to keep resonant according to (10). Compared with the SS structure, it avoids the disadvantages of redesigning the coil parameters to maintain efficient operation when the system's rated parameters are changed, which makes the system design more flexible and reduces the manufacturing cost.

3. Parameter Design

3.1. Effect of Coil Design on Optimal Efficiency Load

When a WPT system is actually designed, some parameters are fixed due to the limitation of frequency or coil size. At this time, choosing a specific resonance mode to obtain better transmission efficiency according to the existing parameters becomes the key to the design.

This paper presents a design scheme of planar spiral coil [18] that optimizes the system transmission efficiency. The core idea of designing a high-efficiency MCR-WPT system is to maintain the system's high-efficiency operating state by adjusting the other coil parameters (mainly turn number, wire diameter, turn pitch, etc.) when the rated load is the optimal load to achieve maximum efficiency.

Figure 4 is a schematic diagram of planar spiral coil. The internal resistance R , self-inductance L and mutual inductance M between the coils [19–21] can be obtained by:

$$\begin{cases} R = \sqrt{\frac{\rho \mu_0 \omega}{2}} \frac{N r_{avg}}{a} \\ L = \mu_0 N^2 r_{avg} c_1 [\ln(c_2 / \lambda) + c_3 \lambda + c_4 \lambda^2] \\ M = \frac{\mu_0 \pi N_1 N_2 \left(\frac{r_{1_avg}}{2}\right)^2 \left(\frac{r_{2_avg}}{2}\right)^2}{2[h^2 + \left(\frac{r_{1_avg}}{2}\right)^2]^{1.5}} \end{cases} \quad (16)$$

where ρ is the conductor resistivity, μ_0 is the vacuum permeability, ω is the current angular frequency, N is the number of coil turns, r_{min} is the inner radius of coil, d is the turn spacing of coil, $r_{avg} = r_{min} + (N - 1)d/2$ is the average radius of coil, a is the conductor radius, c_1 , c_2 , c_3 and c_4 are fitting coefficients, for circular coils they are 1, 2.46, 0 and 0.2, respectively, $\lambda = (N - 1)d/(2^*r_{avg})$, h is the transmission distance.

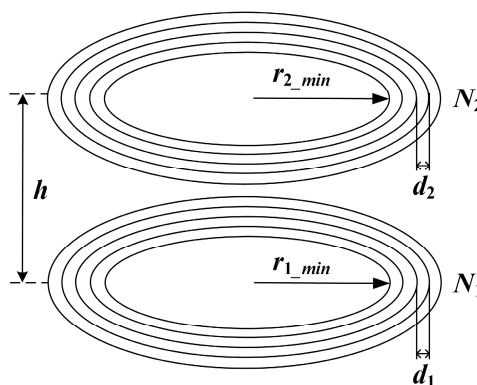


Figure 4. Schematic diagram of planar spiral coil.

According to the actual application scenario, some parameters of the system can be determined. In this paper, the transmission distance $h = 20\text{cm}$, the inner radius of the transmitter and receiver coil $r_{1_min} = r_{2_min} = 2\text{ cm}$. In the case of tightly wound, the conductor diameter and turn spacing are not considered, the influence of coil turns on transmission efficiency occupies the main factor. Where the load resistance R_L is optimal to realize maximum transmission efficiency, the coupling coefficient $k = M/\sqrt{L_1 * L_2}$, self-inductance L_1 and L_2 , the coil internal resistance R_1 and R_2 , and the optimal load R_L are all related to the turn number of primary coil N_1 and secondary coil N_2 :

$$\begin{cases} P_L = \varsigma(k(N_1, N_2), L_1(N_1), L_2(N_2), R_1(N_1), R_2(N_2), R_L(N_1, N_2)) \\ \eta = \xi(k(N_1, N_2), L_1(N_1), L_2(N_2), R_1(N_1), R_2(N_2), R_L(N_1, N_2)) \end{cases} \quad (17)$$

(17) shows that the transmission power P_L and efficiency η are quantities related to the coupling coefficient, load value, self-inductance, and coil internal resistance. Under the tightly winding condition, the independent variable is mainly affected by the turn number of the coils. Therefore, the ultimate optimization goal of this paper can be expressed as finding the optimal coil turn number while meeting the rated power value of the system design, that is, to find $\max(\eta(N_1, N_2))$.

Figure 5 can be made by Equation (16). It can be seen from Figure 5a that the transmission power decreases with increasing turns; from Figure 5b, the efficiency increases quickly first, then slowly increases as the turn number increases, only when the turn number of primary and secondary coils reaches a critical point can the efficiency be maintained at a higher level. Finally, the iterative method is used to obtain the number of turns, and the coil parameters are reasonably designed to achieve a high-efficiency transmission system that meets the power requirements. The specific design process is shown in Figure 6.

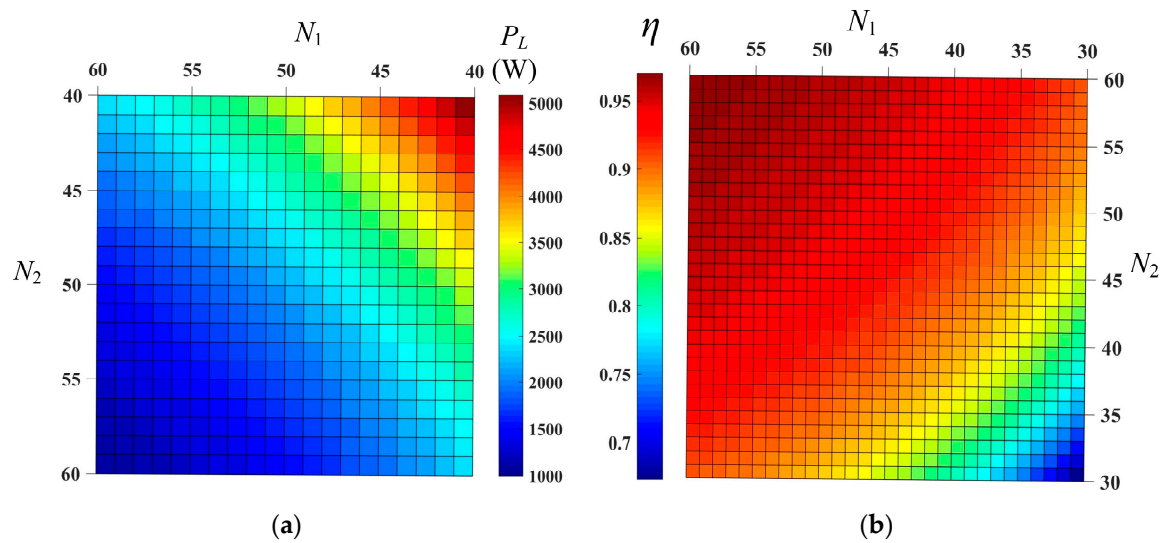


Figure 5. (a) Transmission power and (b) efficiency with respect to the turn number of coil.

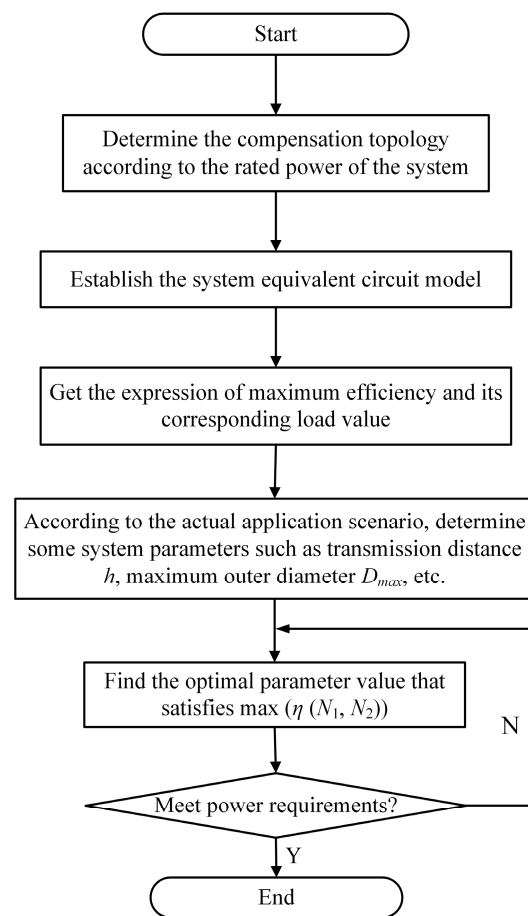


Figure 6. Flow chart of system design.

The following Table 1 shows the optimized resonant parameters of SS compensation topology designed to the load (50Ω) corresponding to optimal efficiency point.

Table 1. The resonant circuit parameters of SS-type.

Parameter	Value	Unit
resonance inductance L_1	477.4	μH
resonance inductance L_2	426	μH
primary coil turns N_1	50	-
secondary coil turns N_2	48	-
resonance capacitor C_1	7.34	nF
resonance capacitor C_2	8.23	nF
input voltage	300	V
output power	2	kW

3.2. Selection of LCC Resonance Parameters

By optimizing the coil design, for the SS resonance structure, the system is in an optimal efficiency condition when the load is 50 ohms. According to (15), after the coil parameters of LCC resonance structure are determined, the optimal efficiency load value is only related to the parameter L_{f2} . The optimal efficiency load of LCC resonance structure can be determined by designing the inductance L_{f2} . From (5) and (12), we have:

$$P_{LCC} = \frac{M^4}{L_{f1}^2 L_{f2}^2} P_{SS} \quad (18)$$

For the LCC resonance structure, since the load and coil parameters have been determined, it can be known that by adjusting the value of L_{f1} , the level of rated output power can be changed. The parameter configuration method is as follows: (1) Firstly, according to the design parameters of SS compensation structure system, the value of L_{f2} is obtained by Equation (15); (2) Secondly, according to the rated power of system, determine the value L_{f1} through Equation (18); (3) Finally, determine the remaining parameter values according to Equation (10).

As the rated output power of SS resonant structure is 2 kW, a margin of 0.85 is taken, and the rated output power of LCC resonant structure is 2.45 kW, so the values of two inductors L_{f1} and L_{f2} can be determined. The specific parameter values are as follows in Table 2.

Table 2. The resonant circuit parameters of LCC-type.

Parameter	Value	Unit
resonance inductance L_{f1}	64.9	μH
resonance inductance L_{f2}	93.6	μH
resonance capacitor C_1	54.0	nF
resonance capacitor C_2	37.5	nF
resonance capacitor C_{p1}	9.1	nF
resonance capacitor C_{p2}	10.5	nF
output power	2.45	kW

4. Simulation and Experimental Verification

4.1. Magnetic Simulation

For the coil designed in Section 3, the finite element simulation software ANSYS EM was used for simulation, and the vertical distance between two coils was 200 mm, the remaining parameters are shown in Tables 1 and 2. The 3D finite element model is shown in Figure 7a, the boundary condition is radiation, the excitation currents $I_p = 7\text{ A}$ and $I_s = 7\text{ A}$, the maximum mesh element lengths of solution region, transmitter and receiver coil are 75 mm, 40 mm and 40 mm, respectively. Figure 7b is the distribution diagram of magnetic field strength around the system. It can be seen that the magnetic field distribution around the system is evenly distributed, mainly concentrated near the coils, and has little effect on the surrounding environment.

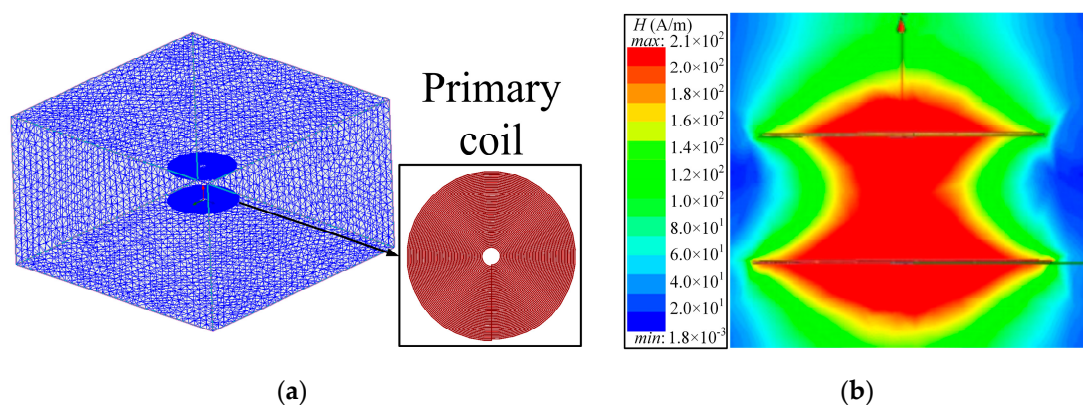


Figure 7. (a) Simulation setup and (b) magnetic field strength distribution.

Another purpose of simulation is to obtain the self-inductance, mutual inductance and coupling coefficient of the coil. There are many theoretical calculation methods for calculating these parameters, which will not be repeated here. They can also be obtained by actual measurement. According to the SAEJ2954 standard [22], the actual measured coupling coefficient formula is:

$$k = \sqrt{V_{oc}I_{sc}/V_1I_1} \quad (19)$$

where, V_1 and I_1 are the voltage and current of primary coil respectively, V_{oc} and I_{sc} are the open circuit voltage and short circuit current of secondary coil, respectively.

The actual mutual inductance value can be obtained by “open circuit and short circuit test”. This method needs to measure three quantities, L_{p1} is the measured primary inductance when the secondary circuit is open, L_{s1} is the measured secondary inductance when the primary circuit is open, and L_{p2} is the measured primary inductance when the secondary circuit is shorted, as follow:

$$M = \sqrt{(L_{p1} - L_{p2})L_{s1}} \quad (20)$$

Table 3 shows the theoretical, simulated and actual measured parameter values of the system under rated parameters. It can be seen from Table 3 that the deviation of the theoretical, simulated and actual value of the primary and secondary coil self-inductance can be ignored.

Table 3. System parameter values.

Parameter	Theoretical Value	Simulation Value	Measured Value
primary coil self-inductance (μH)	477.4	481.5	475.2
secondary coil self-inductance (μH)	426.1	428.3	423.1
mutual inductance (μH)	82.0	82.6	81.2
coupling coefficient	0.18	0.18	0.18

4.2. Experiment

The experimental setup is shown in Figure 8, the experimental parameters of compensation circuit are generally consistent with Tables 1 and 2. The coils are planar spiral coil wound by Litz wire, and tightly wound with the turn spacing $d = 2a$, the conductor radius $a = 1.8$ mm, the inner radius of the transmitter and receiver coil $r_{1_min} = r_{2_min} = 2$ cm, the out radius of the transmitter $r_{1_max} = 20$ cm, the out radius of the receiver $r_{2_max} = 19.28$ cm. The quality factor of the transmitter and receiver coil are 612 and 623, respectively. The gate drive signal of full-bridge inverter circuit can achieve frequency adjustment, and its duty cycle is 0.5. In the resonance state, the input power can be obtained from the input voltage value and input current value of rectifier bridge. The output power is obtained by measuring the load voltage with a differential probe and measuring the output current with a current probe. Considering that the voltage on the capacitor at resonance is Q (quality factor) times the voltage on the circuit, the tuning capacitor is composed of CBB capacitor series and parallel.

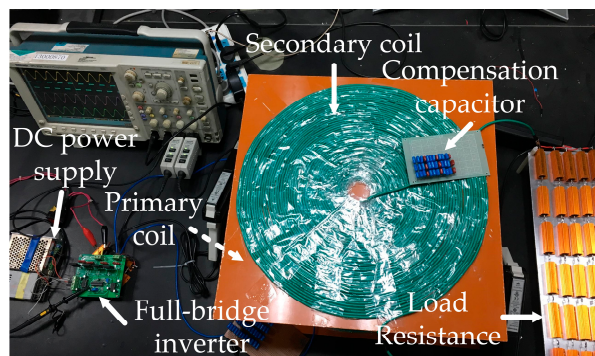


Figure 8. Experimental set up.

A comparative experiment is performed for SS and LCC compensation topologies. Figure 9 shows the experimental waveforms of SS and LCC under the system's optimal efficiency load. In Figure 9b, the primary current shows wonky parts. This is because LCC compensation topology is more complicated than SS, and the coil winding and capacitance matching errors are larger, which results

in the failure to realize ideal resonance at the rated frequency. Therefore, the I_p waveform of LCC structure is not as stable as the SS structure.

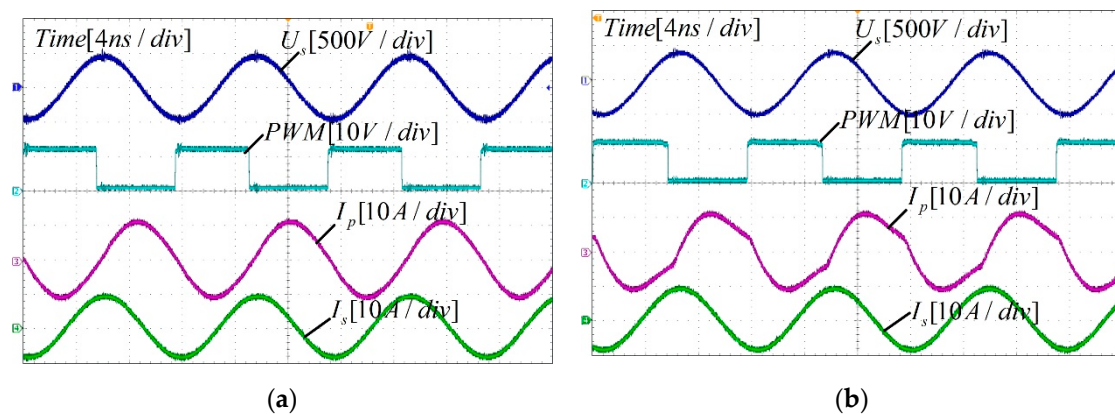


Figure 9. The input and output waveform of optimal state, (a) SS-type; (b) LCC-type.

As can be seen from Table 4, the actual system operating efficiency and output power are basically consistent with the design goals. It illustrates the correctness of the above design method. The error between experimental results and simulation values is due to the fact that the actual system cannot fully work in the ideal state, the coil and resonant capacitor cannot be perfectly matched at the rated frequency in experiment. It is verified through experiments that the output power is increased by 13.5% under the same input voltage without a significant decrease in efficiency.

Table 5 shows the experimental data of the power and efficiency of the SS and LCC compensation topology under different loads. It can be seen from Table 5 that both SS and fixed LCC compensated WPT system achieve maximum efficiency at 50 ohms load, which is consistent with theoretical analysis. By adjusting the parameters of LCC compensation topology according to the load resistances, the output power and transfer efficiency of the adjusted LCC compensated WPT system are improved and more stable under different loads.

Table 4. System experimental results and simulation values.

Parameter	SS Simulation	SS Experiment	LCC Simulation	LCC Experiment
input voltage	300 V	300 V	300 V	300 V
input current	7.2 A	7.56 A	8.857 A	8.52 A
input power	2.161 kW	2.268 kW	2.657 kW	2.556 kW
load voltage	316 V	319 V	352.1 V	339.6 V
output power	1.994 kW	2.011 kW	2.475 kW	2.282 kW
efficiency	92.26%	88.67%	93.14%	89.28%

Table 5. System power and efficiency under different load resistances.

Load	SS Power	SS Efficiency	LCC with Fixed Parameters Power	LCC with Fixed Parameters Efficiency	LCC with Adjusted Parameters Power	LCC with Adjusted Parameters Efficiency	Adjusted L_{f1}	Adjusted L_{f2}
10 Ω	455.2 W	68.6%	478.7 W	73.7%	3295.1 W	89.0%	1.4 μH	18.7 μH
33 Ω	1331.8 W	82.8%	1559.5 W	87.7%	3323.5 W	89.3%	66.3 μH	61.8 μH
50 Ω	2011.0 W	88.7%	2282.1 W	89.3%	3302.1 W	89.8%	54.3 μH	93.6 μH
83 Ω	3170.0 W	85.6%	3210.7 W	86.7%	3313.0 W	89.5%	41.2 μH	155.4 μH

Based on the experiment of transmission distance change under SS and LCC structures, Figure 10 was produced. When the transmission distance changes, the system resonance frequency remains unchanged, so as to observe the vertical offset stability of the system under SS and LCC structures. It can be seen from Figure 10 that for the SS resonant topology, the input current and output current increase with distance; for the LCC structure, the input and output current decrease with distance. In practical applications, this positive correlation of the SS structure is very dangerous.

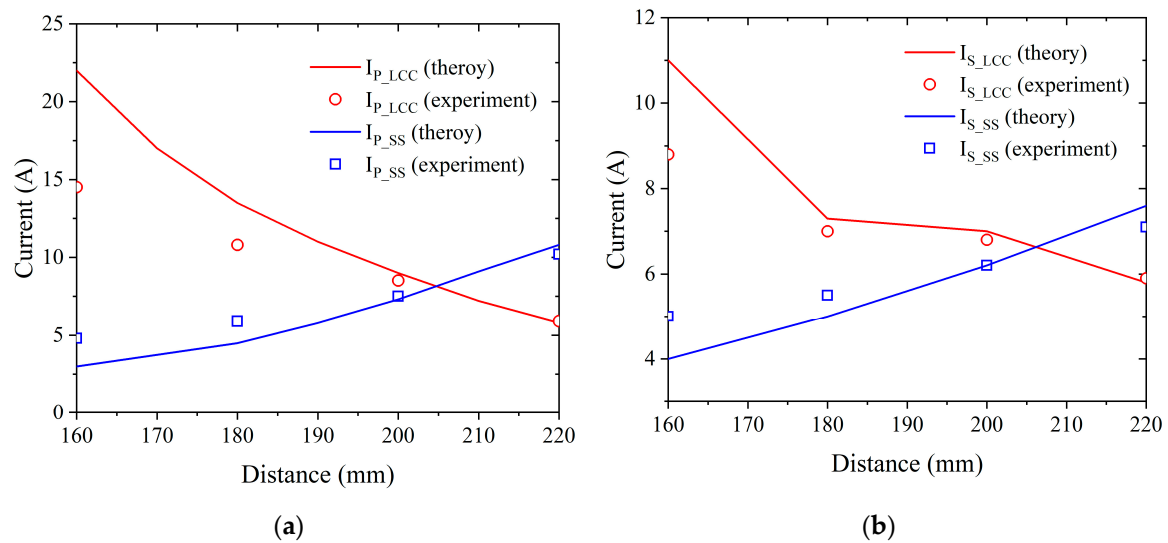


Figure 10. (a) Input current and (b) output current with respect to distance.

There is a deviation between the theoretical and experimental current values, the main reason is that the mutual inductance measured by the actual wound coil is smaller than the theoretical value. However, the current trend is basically the same.

5. Conclusions

In this paper, the optimal transfer efficiency of the WPT system under certain load resistance is achieved by optimizing the coil-turns number. Once the coupled coil-parameters are fixed, the load resistance to make the optimal efficiency can be adjusted and the output power can be increased by optimization design of the parameters of LCC compensation topology. The major contributions of this paper are as follows:

- (1) The method is proposed to keep the optimal transfer efficiency of the WPT system under different load resistances by adjusting the inductance value of the LCC compensate topology L_{f1} .
- (2) The method is proposed to increase the output power of the WPT system to satisfy more power requirements by adjusting the inductance value of the LCC compensate topology L_{f2} .
- (3) The optimized LCC compensated WPT system has significant advantages over the SS type. There's no need to redesign the coupled coils to maintain transmission power and efficiency under different power levels and transfer distance. When the load resistance equals 50Ω , the output power of the optimized WPT system is increased by 64.2% with 89.8% transfer efficiency.

Author Contributions: F.W. conceived and designed the study, and this work was performed under the advice of and regular feedback from him. X.C. and Q.L. was responsible for the models, simulations and X.C. wrote the article. W.G. was responsible for the experiments and data analysis. All authors have read and agreed to the published version of the manuscript.

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