

Compensation Optimization of the Relay Coil in a Strong Coupled Coaxial Three-Coil Wireless Power Transfer System

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Abstract—With regards to wireless power transfer (WPT) systems with relay coils, the power transfer distance, efficiency, and capacity can be effectively improved by tuning the relative position of the relay coil compared with a common two-coil WPT system. However, the cross-coupling between nonadjacent coils can cause the system to no longer resonate even when the compensation capacitors resonant with the corresponding coils. This will cause an increase in reactive power and additional losses in the coils. In this article, the optimal operating conditions of the coaxial fully resonant three-coil WPT system are analyzed first for achieving higher efficiency compared with the two-coil WPT system with the same load and the same power transfer distance, by adjusting the relative location of the source coil and relay coil. An optimization design method for further improving the efficiency of the three-coil WPT system by tuning the compensation capacitor of the relay coil is proposed subsequently. The experimental results show that for a given load ($10\ \Omega$ in this article), the efficiency of the three-coil WPT system can be improved from 88.8% to 92.3% compared with the two-coil WPT system, and be further improved to 93.3% when the relay compensation capacitor is optimized.

Index Terms—Efficiency optimization, power transfer efficiency, three-coil system, wireless power transfer (WPT).

I. INTRODUCTION

WIRELESS power transfer (WPT) can transfer electric energy across an air gap without any direct electrical contact from a power source to a load, which has attracted more and more attention from both academia and industry [1], [2]. The main research objectives of WPT include improving the power transfer distance, efficiency, and capacity [3], [4]. For a two-coil WPT system with one source coil and one load coil, the power transfer efficiency is inversely proportional to the power transfer distance, which seriously limits its application in the field of long-distance conditions [5]. Consequently, a lot of research efforts have been directed towards studying the relay

coil to increase the power transfer distance. And it has been proven that with the relay coils, the power transfer distance and efficiency of the WPT system can be effectively improved and the load voltage can also be controlled by tuning the relative position of the relay coil to the source or load coils with specific purposes [6]–[9].

In [10], a relay coil is added in the same plane as the source coil, which proved that the relay coil can help increase the apparent self-inductance of the source coil and the mutual coupling between the source and the load coils. Hence, the efficiency of the three-coil WPT system can be greatly improved compared to the two-coil WPT system. In [11], the relay coil is placed in the same axial as the source and load coils. The self-resonance of the source, relay, and load coils are optimized against load variation, respectively, based on the analysis of the effects on the power transfer efficiency caused by the driving frequency and the resonant frequency of the three-coil WPT system. With the proposed optimization method of different coils' resonant frequencies, the power transfer efficiency can be effectively improved against various load resistance. To improve the misalignment tolerance for the WPT system, a relay coil is reversely connected with the primary coil [12]. The results show that with the added relay coil, the system efficiency and load power can both be nearly held constant with 40% misalignment. As the three-coil WPT system with a relay coil is derived from the two-coil WPT system, the conditions for obtaining higher efficiency of the three-coil structure over its two-coil counterpart are analyzed in [13]. It is found that as long as the mutual inductance between the source and relay coils is large enough, the power transfer efficiency can be effectively improved compared with the two-coil WPT system with the same source and load coils. Therefore, it is suggested that the relay coil can be placed coplanar with the source coil.

Furthermore, for a three-coil WPT system, the coaxial structure of the source, load, and relay coils can also help achieve maximum power tracking, output voltage or current control, etc., compared with the coplanar structure. For example, Abatti *et al.* [14] investigate the maximum efficiency and power tracking of the three-coil WPT system. It shows in [14] that for the three-coil WPT system, the maximum power transfer efficiency and capacity are only related to the mutual inductance between the source and relay coils and can be both achieved by adjusting the mutual inductance between the relay and load coils by tuning the location of the relay coil.

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For a typical multicoil WPT system, the system operating frequency and compensation capacitance are usually used as control variables to improve the power transfer efficiency and capacity [15]–[18]. It is found in [15] that the operating frequency corresponding to the maximum power transfer efficiency of the three-coil WPT system changes when the coupling between the source and relay coils changes. Therefore, the operating frequency can be adjusted to get maximum power transfer efficiency. In [16], it is proven that when the coils are too close to each other, the mutual coupling between nonadjacent coils cannot be neglected anymore. And the compensation capacitors can be tuned to eliminate the cross-coupling to improve the system performance. In [17], a continuously adjustable capacitor array to match the impedance network in a multicoil WPT system is proposed, and the system performance can be effectively improved when the operating frequency changes. In [18], a compensation capacitor selecting method is proposed for a four-coil WPT system. Four different compensation capacitors can be chosen according to the system operating conditions to improve the power transfer efficiency when misalignment occurs. It can be found out from the above researches that the compensation capacitors of the multicoil WPT system can be effectively utilized to improve the system performance.

However, most existing studies neglected the mutual inductance between nonadjacent coils (source and load coils) to simplify the theoretical analysis for coaxial three-coil WPT systems. To obtain higher efficiency, the distance between the source and relay coils should be as close as possible as stated in [13], which means that the value of mutual inductance between nonadjacent coils cannot be neglected anymore. As studied in [19], with the consideration of the mutual inductance between nonadjacent coils, the power transfer efficiency and capacity are both affected when the mutual inductance between nonadjacent coils changes. Therefore, a lot of studies are carried out to eliminate the impacts caused by the mutual inductance between the source and load coils. For example, in [20], an adjustable compensation capacitor is designed to completely eliminate the cross-coupling between two load coils in a three-coil WPT system, which greatly improves the performance of the multiloading WPT system. Based on a normalized equivalent circuit model, Bin *et al.* [21] analyzed the effects of cross-coupling between the source and load coils on the power transfer efficiency and capacity of the three-coil WPT system with one relay coil. It proposed a method to eliminate the cross-coupling by inserting a series reactance circuit in the load circuit. However, the design of the whole system is too complex, and the overall efficiency of the system decreased. As a consequence, there should be more works carried out to analyze the impacts caused by the cross-coupling on the system performance and find a suitable optimization method for a common coaxial three-coil WPT system. The differences of these studies by tuning the compensation parameters are summarized in Table I, where C_S , C_R , and C_L are the compensation capacitors of the source, relay, and load coils, respectively.

It can be seen in Table I that compared with the existing studies, the proposed optimization method for the three-coil WPT system in this article can achieve higher power transfer

TABLE I
COMPARISON OF DIFFERENT RESEARCH ON COMPENSATION CAPACITOR OPTIMIZATION METHODS

Reference	[21]	[22]	[23]	This paper
Power (W)	N/A	N/A	<10	>60
Efficiency	88.5%	88%	<70%	>93%
Frequency (MHz)	13.45	13.56	0.262	0.2
Change C_S	Yes	No	No	No
Change C_R	Yes	Yes	Yes	Yes
Change C_L	Yes	Yes	Yes	No
Compare to two-coil WPT system	No	No	No	Yes

efficiency by tuning the least system parameters. Besides, the system performance is effectively improved compared to the two-coil WPT system with the same source and load coils.

Therefore, this article studies the impacts caused by the nonadjacent coupling between the source and load coils of the three-coil WPT system in detail first. The condition that the efficiency of the coaxial three-coil WPT system is higher than that of the two-coil structure at the same power transfer distance is proposed subsequently. Then, the effect of the relay compensation capacitor on the power transfer efficiency and capacity of the three-coil WPT system is analyzed. And an optimization design method by tuning the relay compensation capacitor is presented. Finally, the experimental setups of the two-coil and three-coil WPT systems are built to validate the proposed theoretical analysis and system optimization methods.

The main works and contributions of this article are as follows, 1) the impacts of the position of the relay coil on the coaxial three-coil WPT system are analyzed in detail, which can help the three-coil WPT system achieve higher efficiency compared to the two-coil WPT system with the same source and load coils, the same load, and the same power transfer distance. It has been found in this article that the shorter the distance between the relay coil and source coil, the higher the power transfer efficiency can be obtained from the three-coil WPT system. 2) A method for optimizing the relay compensation capacitance of the coaxial three-coil WPT system is proposed, which can effectively improve the power transfer efficiency and capacity simultaneously compared with the perfectly resonant three-coil WPT system. It has been found in this article that by tuning the relay compensation capacitance a little away from the resonant capacitance, both the power transfer efficiency and capacity can be effectively improved. The detailed relay compensation capacitance optimization method is also given in this article.

The rest of this article is organized as follows. In Section II, the mathematical model of the three-coil WPT system with series compensations is established, and the impacts caused by the mutual inductance between the source and load coils on the system performance are analyzed in detail. In Section III, the conditions for achieving higher efficiency of the three-coil WPT system than the two-coil structure are proposed. And the influence of the relay compensation capacitor on the three-coil WPT system is analyzed. Based on the theoretical analysis, an optimization method to improve the power transfer efficiency and capacity of the resonant operating three-coil WPT system is also given in this section. The correctness of the analysis and

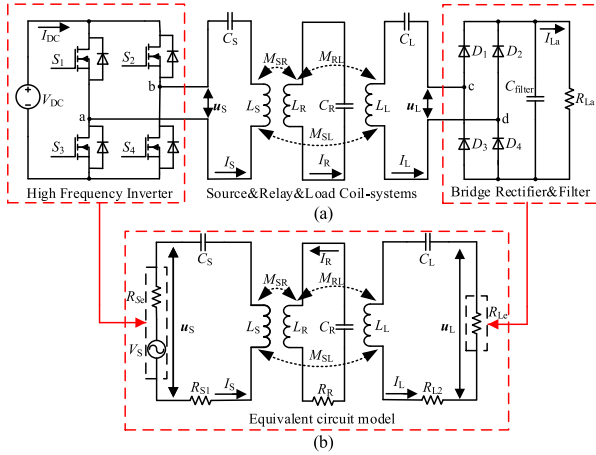


Fig. 1. Three-coil WPT system. (a) Whole system. (b) Simplified model.

the effectiveness of the proposed system optimization method is experimentally validated on a 200 kHz, 80-W WPT system, and the results are given in Section IV. Finally, Section V concludes this article.

II. THEORETICAL ANALYSIS OF THE THREE-COIL WPT SYSTEM

The equivalent circuit diagram of a common three-coil WPT system with series compensated capacitors is shown in Fig. 1(a), and the simplified model is shown in Fig. 1(b). As shown in Fig. 1, L_S , L_R , and L_L are the self-inductance of the source, relay, and load coils, respectively. C_S , C_R , and C_L are the compensation capacitors accordingly, and they are all resonating with the source, relay, and load coils at the same frequency. Besides, the compensation topology adopted in this work is the most basic and common series-series (SS) compensation topology for the general purpose of the study, ω_r is the resonant angular frequency of the system, and it has been defined as (1). If the compensation topology adopts high-order topologies, the power transfer efficiency and amount can be further improved

$$\omega_r = 1/\sqrt{L_S C_S} = 1/\sqrt{L_R C_R} = 1/\sqrt{L_L C_L}. \quad (1)$$

Besides, R_{S1} , R_R , and R_{L2} are the parasitic resistance of the corresponding circuits. M_{SR} , M_{SL} , and M_{RL} are the mutual inductance of these three coils. V_s in Fig. 1(b) is the equivalent ac source of the dc power and dc-ac inverter in Fig. 1(a), and R_{Se} is the equivalent resistance of the ac source. U_s stands for the output voltage of the dc-ac inverter. Therefore, the relationship between V_s and I_S can be shown as (2). R_{Le} in Fig. 1(b) is the equivalent load resistance of the rectifier, filter and actual load R_{La} in Fig. 1(a), and the relationship between R_{Le} and R_{La} can be shown as (3)

$$V_S = U_S + R_{Se} I_S \quad (2)$$

$$R_{Le} = \left(2\sqrt{2}/\pi\right)^2 R_{La}. \quad (3)$$

Besides, the voltage and current directions are the reference directions for calculating the actual currents flowing in each coil and their phase relations.

With the lumped-element circuit shown in Fig. 1(b), the three-coil WPT system can be expressed in the matrix form according to Kirchhoff voltage law (KVL) as follows:

$$\begin{bmatrix} \vec{V}_S \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Z_S & j\omega_d M_{SR} & j\omega_d M_{SL} \\ j\omega_d M_{SR} & Z_R & j\omega_d M_{RL} \\ j\omega_d M_{SL} & j\omega_d M_{RL} & Z_L \end{bmatrix} \begin{bmatrix} \vec{I}_S \\ \vec{I}_R \\ \vec{I}_L \end{bmatrix} \quad (4)$$

where

$$Z_S = R_{Se} + R_{S1} + j\omega_d L_S - j/(\omega_d C_S) \quad (5)$$

$$Z_R = R_R + j\omega_d L_R - j/(\omega_d C_R) \quad (6)$$

$$Z_L = R_{L2} + R_{Le} + j\omega_d L_L - j/(\omega_d C_L) \quad (7)$$

where \vec{V}_S is the voltage vector of the equivalent ac input power supply, and \vec{I}_S , \vec{I}_R , \vec{I}_L are the current vectors of the three coils respectively. Z_S is the impedance of the source circuit; Z_R is the impedance of the relay circuit; Z_L is the impedance of the load circuit.

Therefore, the currents flowing in different coils can be expressed as

$$\vec{I}_S = \frac{(k_{RL}^2 + q_R q_L) \vec{V}_S}{X_0 - j(2k_{SR} k_{SL} k_{RL})} \frac{1}{\omega_d L_S} \quad (8)$$

$$\vec{I}_R = -\frac{k_{SL} k_{RL} + j k_{SR} q_L}{k_{RL}^2 + q_R q_L} \sqrt{L_S/L_R} \vec{I}_S \quad (9)$$

$$\vec{I}_L = -\frac{k_{SR} k_{RL} + j k_{SL} q_R}{k_{RL}^2 + q_R q_L} \sqrt{L_S/L_L} \vec{I}_S \quad (10)$$

where

$$X_0 = k_{SR}^2 q_L + k_{SL}^2 q_R + k_{RL}^2 q_S + q_S q_R q_L \quad (11)$$

$$k_{ab} = M_{ab} / \sqrt{L_a L_b} \quad (12)$$

$$q_a = Z_a / \omega_d L_a \quad (13)$$

where a, b represent S, R , and L , and a is not the same as b .

With (4)–(13), the efficiency of the three-coil WPT system can be derived as (14) when the system operates at the resonant condition (driving frequency equals resonant frequency)

It can be seen from (8)–(14) that the formulae of the three-coil WPT system are very comprehensive when the cross-coupling is considered, but it can be easily calculated with the help of a mathematical calculation tool such as MATLAB. Besides, it can also be found out from (8) that even all the compensation capacitors are resonant with the corresponding coils and the system operates at the resonant condition, the current flowing in the source coil is not in phase with the voltage. This is caused by the cross-coupling between the source and load coils k_{SL} . Besides, regarding the system efficiency (14), k_{SL} also has a non-negligible impact on it.

In this article, for determining the self-inductance of the coils, it is assumed that the coupling coefficients among these three coils are constant as the coupling can be easily adjusted

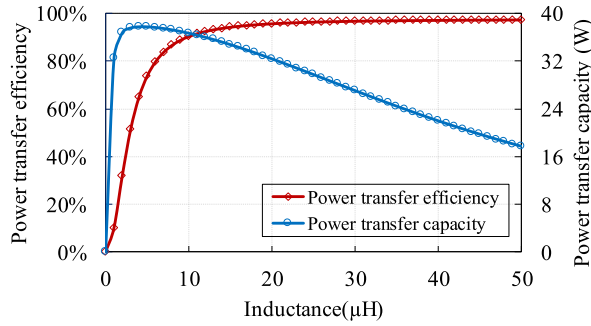


Fig. 2. Power transfer efficiency and capacity with various self-inductances.

by carefully designing the coil structure [24]. And these three couplings are 0.6 (source coil to relay coil), 0.3 (relay coil to load coil), and 0.2 (source coil to load coil), respectively. These values are the empirical values [3], [10], [13], [24]. Besides, these three coils are the same as each other to simplify the theoretical analysis, which is a common method in the analysis of the WPT systems. As a result, it can be seen from Fig. 2 that with the increase of self-inductance, the system efficiency increases as well. On the other hand, the power transfer capacity of the system increases first and then decreases. As the power transfer efficiency and capacity are the two equally important indicators of a WPT system, with a comprehensive consideration of these two indicators, the self-inductance is set to be $14 \mu\text{H}$ in this article to achieve a relatively higher power transfer efficiency and capacity simultaneously.

Fig. 3 illustrates the power transfer efficiency and capacity under different conditions with and without considering k_{SL} . The self-inductance of all three coils is $14 \mu\text{H}$ and the resonant frequency is set to be 200 kHz. The dc input voltage (V_{DC}) is held constant at 50 V. 5Ω and 10Ω loads are adopted to provide different load conditions. Besides, the source and relay coils are taken as the primary side, the load coil is taken as the secondary side. The vertical distance from the relay coil to the load coil (d_{RL}) is set at 30 mm. And the distance between the source and relay coils (d_{SR}) can be adjusted to provide different k_{SR} as shown in Fig. 4.

As shown in Fig. 3, when the cross-coupling is neglected, k_{SL} is set to be zero, and when the cross-coupling is considered, k_{SL} will not be equal to zero. It can be seen from Fig. 3 that the theoretical calculated system efficiency without considering k_{SL} is always higher than that when considering k_{SL} under various load conditions, and the error of the power transfer efficiency stays constant with varied d_{SR} . The absolute error is about 0.4%. Regarding the power transfer capacity, the impact caused by k_{SL} is more obvious particularly when the cross-coupling is weak. It can be seen that the larger the d_{SR} is, the larger the error on the power transfer capacity will be, as k_{SL} is not considered. The

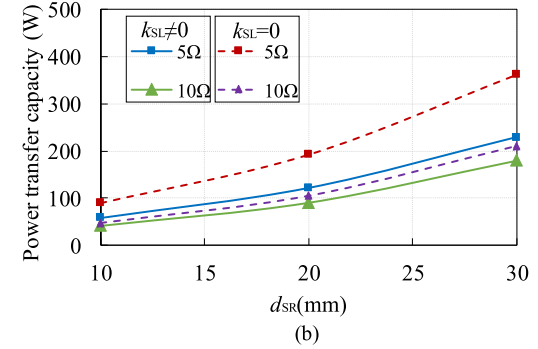
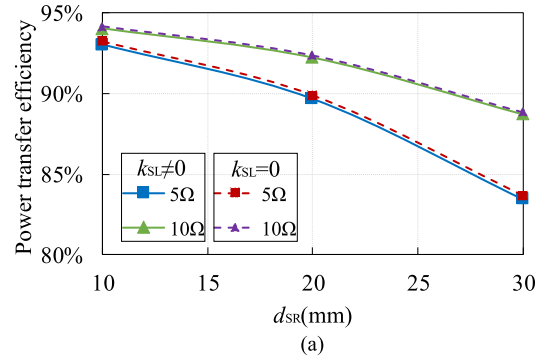
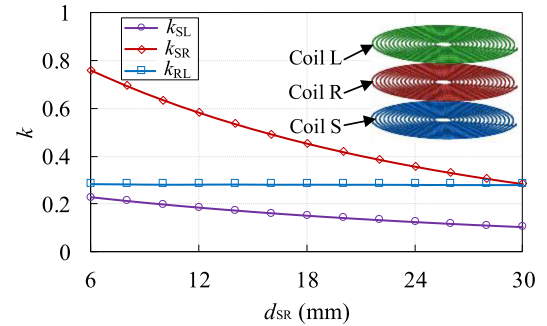


Fig. 3. Power transfer efficiency and capacity under various conditions. (a) Power transfer efficiency. (b) Power transfer capacity.


 Fig. 4. Coupling coefficient against various d_{SR} and constant d_{RL} (30 mm).

error of the power transfer capacity increases with the increase of d_{SR} , and the maximum absolute error is about 36% when d_{SR} is 30 mm with a 5Ω load.

Besides, it can be seen from Fig. 4 (which is derived from ANSYS Maxwell) that, when the distance between the relay coil to the load coil (d_{RL}) is 30 mm, the cross-coupling between the source and load coils (k_{SL}) can be as high as 0.23 when the distance between the source and relay coils (d_{SR}) is 10 mm. And k_{SL} can still be larger than 0.1 even d_{SR} reaches 30 mm ($d_{\text{SR}} = d_{\text{RL}}$). This means that the cross-coupling k_{SL} has reached the range of the coupling coefficient of the middle-range systems

$$\eta_3 = \frac{(k_{\text{SR}}^2 k_{\text{RL}}^2 + k_{\text{SL}}^2 q_{\text{R}}^2) R_{\text{Le}}}{(\omega_{\text{d}}^3 L_{\text{R}} L_{\text{L}}^2) (k_{\text{RL}}^2 + q_{\text{R}} q_{\text{L}}) \sqrt{X_0^2 + (2k_{\text{SR}} k_{\text{SL}} k_{\text{RL}})^2}} \quad (14)$$

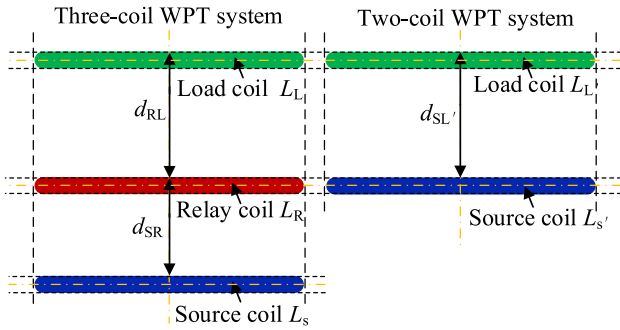


Fig. 5. Schematic diagram of three-coil and two-coil WPT systems.

TABLE II
DESIGN PARAMETERS OF THE COILS

Coil design parameters	Value
Line diameter	2 mm
Inner radius	5 mm
Outer radius	56 mm
Turn spacing	1 mm
Coil turns	17

[26]. Therefore, the cross-coupling cannot be neglected in the condition that the distance between the source and load coils (d_{SL}) is not large enough.

The two-coil WPT system consisting of the same source and load coils as the three-coil WPT system is taken as the basis to optimize the power transfer efficiency of the coaxial three-coil WPT system. Meanwhile, to make the design of the three-coil WPT system more meaningful, the power transfer distance of the three-coil WPT system is the same as the two-coil WPT system, which is shown in Fig. 5. It should be noted that the coils used in this article are flat spiral coils, and each turn of the coil has the same line diameter. And the design parameters of the coils are listed in Table II. The flat spiral coil is different from the solenoid coil as adopted in [26], so there are no vertical extensions of the coils.

III. OPTIMIZATION OF THE COAXIAL THREE-COIL RESONANT WPT SYSTEM

For a two-coil WPT system, the maximum power transfer efficiency can be obtained when the driving frequency equals the resonant frequency [27]. Meanwhile, when the two-coil WPT system operates at resonant condition, the output voltage and current of the dc-ac inverter is in phase with each other. While as can be seen in (8), for the three-coil WPT system, even when the driving frequency equals the resonant frequency of each coil, the output voltage and current of the dc-ac inverter cannot be in phase because of the cross-coupling between the source and load coils (k_{SL}). It can also be found out from (14) that k_{SL} also has a non-negligible impact on the power transfer efficiency of the three-coil WPT system. Consequently, the study on the relay coil and its compensation capacitor are necessary, as only the relay coil and its compensation capacitor are added compared with the two-coil WPT system.

A. Characteristic Analysis of the Position of the Relay Coil on the Coaxial Three-Coil WPT System

In this section, it should be noted that the power transfer distance of the three-coil WPT system is defined as the distance between the relay coil and the load coil. Both the two-coil and three-coil WPT systems adopt SS compensation topology, as the SS compensation topology is the most basic and common topology for the WPT systems [26]. Meanwhile, the coils are perfectly aligned, and the power transfer distance will be adjusted to provide different coupling conditions in this work [28]. Besides, resistive loads are used as the load, and the load resistance varies from 1 to 50 Ω to simulate the battery as the equivalent resistance of the battery will change with the charging process [11].

If keeping the distance between the source and load coils constant, the actual power transfer distance is reduced compared to the two-coil WPT system as a relay coil is added between the source and load coils. Besides, the power transfer efficiency of the three-coil WPT system is desired to be higher than the two-coil WPT system with the same load conditions.

Similar to the mathematical analysis on the three-coil WPT system, the efficiency of the two-coil WPT system can also be derived from its voltage and current matrix as (15) [13]. For the two-coil WPT system, the position of the load coil is as same as the three-coil WPT system. The location of the source coil used in the two-coil WPT system is as same as the relay coil used in the three-coil WPT system to provide the same power transfer distance. Besides, it can be found out from (15) that when the driving frequency is equal to the resonant frequency, the efficiency of a specific two-coil WPT system is only related to the coupling coefficient between the source and load coils for a fixed load

$$\eta_2 = \frac{k_{SL'}^2}{q_{S'}q_{L'} + k_{SL'}^2} \frac{R_{Le'}}{R_{L'}} \quad (15)$$

To achieve higher efficiency of the three-coil WPT system than the two-coil WPT system, inequation (16) should be satisfied

$$\eta_3 > \eta_2. \quad (16)$$

Therefore, the followed inequation (17) can be derived by substituting (14) and (15) into (16)

$$\begin{aligned} & (k_{RL}^2 + q_R q_L + R_{Se} q_L / \omega_d L_R) (k_{SR}^2 + k_{SL}^2 q_R^2 / k_{RL}^2) q_L \\ & > (k_{RL}^2 + q_R q_L) \sqrt{X_0^2 + (2k_{SR} k_{SL} k_{RL})^2} \end{aligned} \quad (17)$$

where $R_{S'} = R_R$, $R_{Se'} = R_{Se}$, $R_{L'} = R_L$, and $k_{SL'} = k_{RL}$.

As can be seen from (17), it is too complex to derive the optimization location of the relay coil through the mathematical calculation, as the location of the relay coil will not only affect k_{SR} but also has a non-negligible impact on k_{SL} . Therefore, the mathematical calculation tool (MATLAB) can be adopted to derive the comparison of the power transfer efficiency of the two-coil and three-coil WPT systems under various conditions. The power transfer efficiency of the two-coil and three-coil WPT systems under various load conditions can thereby be derived as shown in Fig. 6.

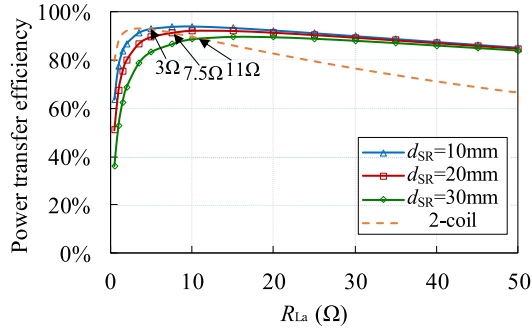


Fig. 6. Power transfer efficiency of two-coil and three-coil WPT systems with various R_{La} .

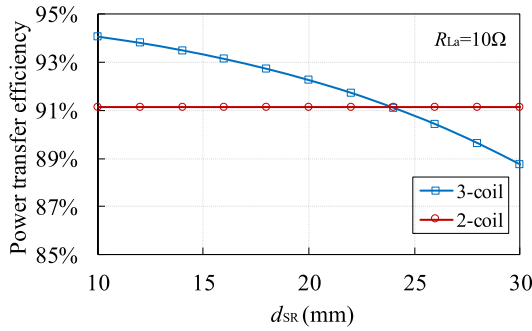


Fig. 7. Power transfer efficiency of two-coil and three-coil WPT systems with various d_{SR} .

As can be seen in Fig. 6, there is always an optimal range of load resistance for the three-coil WPT system to achieve higher efficiency than the two-coil WPT system regardless of d_{SR} . And the larger the d_{SR} is, the larger the critical load resistance will be. Besides, the decline rate of the efficiency of the three-coil WPT system is much smaller than that of the two-coil WPT system with the load resistance increased, which means that the three-coil WPT system is more applicable to the equipment with a larger range of load resistance compared with the two-coil WPT system. Meanwhile, as can be seen in Fig. 6 that when the load resistance is larger than 11 Ω , the power transfer efficiency of the three-coil WPT system can always be higher than that of the two-coil WPT system.

Therefore, to more clearly investigate the relationship between the power transfer efficiency and d_{SR} , the load resistance is set to be 10 Ω , and the system efficiency is plotted under various d_{SR} as shown in Fig. 7, and the power distributions are shown in Table III.

It can be seen in Fig. 7 that for a given load resistance, as long as d_{SR} is small enough, the power transfer efficiency of the three-coil WPT system can be higher than the two-coil WPT system. Besides, the smaller the d_{SR} is, the higher the three-coil WPT system efficiency will be. In conclusion, shortening d_{SR} as much as possible can effectively help to improve the power transfer efficiency of the coaxial three-coil WPT system. Meanwhile, Table III presents the power losses measured with fixed equivalent load resistance (10 Ω). In the theoretical calculations, the power

TABLE III
POWER DISTRIBUTION IN EACH COMPONENT

Component	Two-coil system	Three-coil system (10 mm)	Three-coil system (20 mm)
Inverter (W)	2.654(3.81%)	0.381(1.01%)	1.950(2.31%)
Source coil (W)	2.654(3.81%)	0.076(0.2%)	0.390(0.46%)
Relay coil (W)	N/A	1.507(4.01%)	3.354(3.96%)
Load coil (W)	0.636(0.92%)	0.353(0.94%)	0.782(0.92%)
Load power (W)	63.624(91.46%)	35.309(93.84%)	78.157(92.35%)

losses are generated at the dc–ac inverter, coil circuits including the coils and the compensation capacitors. The ac–dc rectifier, capacitor filter, and the actual load are treated as equivalent load (R_L). For calculating the power losses on the dc–ac inverter and the coil circuits, the equivalent resistance of each component should be get first. The equivalent resistance of the inverter (R_{Se}) is derived by adding the ON-state resistance and equivalent resistance of the switching losses. It should be noted that the equivalent resistance of the switching losses is an empirical value, as the switching losses will vary in a practical system. The equivalent resistances of the coil circuits ($R_{S1}/R_R/R_{L2}$) are measured at 200 kHz by an impedance analyzer. Then, the power losses can be calculated with the following equation:

$$P_{\text{loss}} > I^2 R \quad (18)$$

where P_{loss} is the power loss of each component, I is the current of each component, and R is the equivalent resistance of each component.

It can be found from Table III that the losses on the coils are the main losses in the WPT system for both the two-coil and three-coil WPT systems. Therefore, to effectively improve the power transfer efficiency of the WPT system, the research should be focused on optimizing the coil-to-coil efficiency.

B. Impacts of the Relay Compensation Capacitance on the Power Transfer Efficiency and Capacity

It has been analyzed that for the two-coil WPT system, when the system operates at the resonant condition, the maximum power transfer efficiency can be achieved, and the output voltage of the dc–ac inverter is in phase with the output current. While for the three-coil WPT system, even though the system operates at the resonant condition, the current flowing in the source coil is not in phase with the voltage, and the system efficiency is also impacted by the non-negligible cross-coupling between the source and load coils (k_{SL}). Therefore, in this section, the compensation circuit of the relay coil will be studied to suppress the impacts caused by k_{SL} .

While studying the relationship between the power transfer efficiency of the three-coil WPT system and the relay compensation capacitance, (14) is not applicable anymore because the imaginary part of Z_R cannot be omitted anymore. Therefore, the power transfer efficiency of the three-coil WPT system can be expressed as (19) in this case

$$\eta_3 = \frac{k_{SL}^2 q_X^2 - 2k_{SR} k_{SL} k_{RL} q_X + k_{SL}^2 q_{R1}^2 + k_{SR}^2 k_{RL}^2 R_{Le}}{(k_{SL}^2 q_L + q_S q_L^2) q_X^2 - 2k_{SR} k_{SL} k_{RL} q_L q_X + X_1 \omega_d L_L} \quad (19)$$

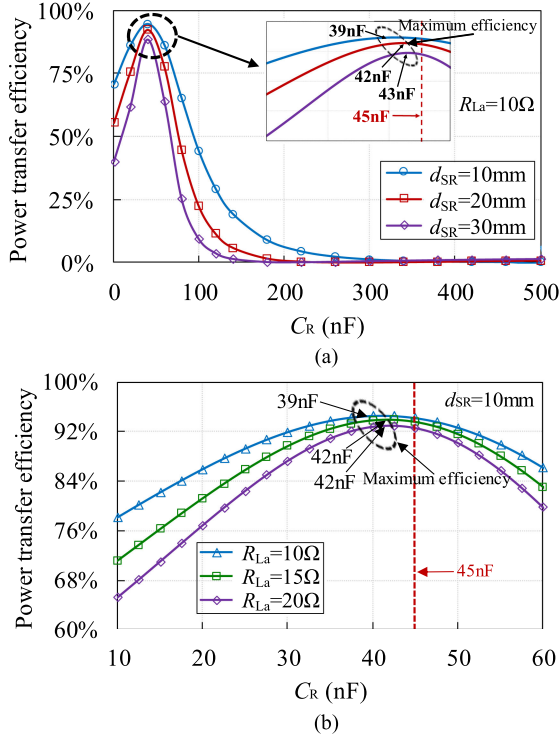


Fig. 8. Power transfer efficiency with varied C_R . (a) Fixed load resistance and various d_{SR} . (b) Fixed d_{SR} and various load resistance.

where

$$X_1 = k_{SR}^2 q_L + k_{SL}^2 q_{R1} + k_{RL}^2 q_S + q_S q_{R1} q_L \quad (20)$$

$$q_{R1} = R_R / \omega_d L_R \quad (21)$$

$$q_X = \frac{\text{Im}(Z_R)}{\omega_d L_R} = 1 - \frac{1}{\omega_d^2 C_R L_R}. \quad (22)$$

The power transfer efficiency of the three-coil WPT system with different relay compensation capacitance is shown in Fig. 8. In this work, the resonant frequencies of the three coils are all set to be 200 kHz. Therefore, the corresponding resonant capacitances of each coil are all 45 nF. Besides, the operating frequency is also set to be 200 kHz.

It can be seen from Fig. 8(a) that with a fixed load resistance, the power transfer efficiency achieves maximum when the relay compensation capacitor is a little smaller than the resonant capacitance, which is consistent with the theoretical analysis in Section II that the power transfer efficiency cannot be maximum at the resonant condition. Besides, it can also be found that with the increase of the distance between the source and relay coils, the relay compensation capacitor corresponding to the maximum efficiency is getting closer and closer to the resonant capacitance. While when the distance between the source and relay coils (d_{SR}) is fixed at 10 mm [see Fig. 8(b)], the maximum efficiency also appears when the relay compensation capacitor is a little smaller than the resonant capacitance in the condition of different load resistances.

Regarding the power transfer capacity, as shown in Fig. 9, the power transfer capacity of the three-coil WPT system can also

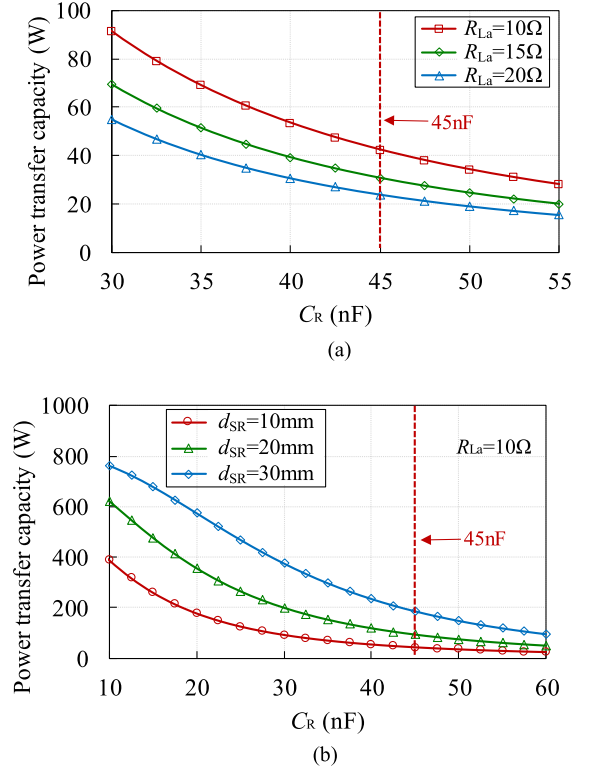


Fig. 9. Power transfer capacity with varied C_R . (a) Fixed d_{SR} and various load resistance. (b) Fixed load resistance and various d_{SR} .

be effectively improved when the relay compensation capacitor is tuned down from the resonant capacitance, regardless of different load resistance [see Fig. 9(a)] or different distance from the source coil to the relay coil [see Fig. 9(b)]. In conclusion, it is feasible to improve the power transfer efficiency of the three-coil WPT system by tuning the relay compensation capacitor C_R to a suitable value according to the load resistance and the distance between the source and relay coils.

C. Optimization of the Relay Compensation Capacitance

As analyzed in Section III-B, the relay compensation capacitor can be tuned to improve the power transfer efficiency and capacity of the three-coil WPT system. And it can also be found out from Fig. 8(a) that there is always an optimal C_R that can make the efficiency of the three-coil WPT system maximization. Therefore, the optimization capacitance of C_R can be derived by taking the derivative of η_3 concerning q_X as follows:

$$\frac{d\eta_3}{dq_X} = \frac{2k_{SR}k_{RL}q_Sq_L^2q_X^2 + (X_1k_{SL} - X_2X_3)q_X + X_3k_{SR}k_{RL}q_L}{[X_2q_X^2 - 2k_{SR}k_{SL}k_{RL}q_Lq_X + X_1]^2 \frac{\omega_d L_L}{2k_{SL}R_{Le}}} \quad (23)$$

where

$$\begin{cases} X_2 = k_{SL}^2 q_L + q_S q_L^2 \\ X_3 = k_{SL}^2 q_R^2 + k_{SR}^2 k_{SL}^2. \end{cases} \quad (24)$$

When $d\eta_3/dq_X = 0$, the extreme value of the system efficiency can be obtained. It can be seen from (23) that either the following

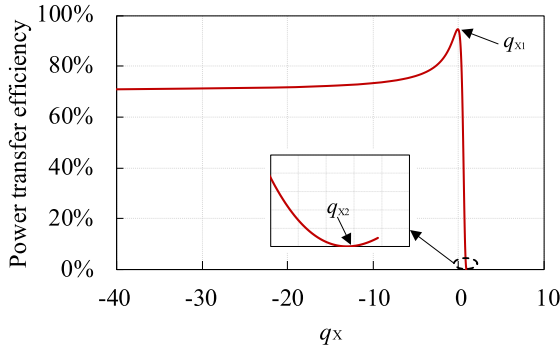


Fig. 10. Relationship between power transfer efficiency and q_X .

matrix (25) or k_{SL} equals zero can make (23) equal to zero. However, k_{SL} cannot equal zero as d_{SR} should be as small as possible to improve the system efficiency as analyzed in Section III-A. Therefore, when $d\eta_3/dq_X = 0$, the following matrix (25) should be met

$$\begin{bmatrix} 2k_{SR}k_{RL}q_Sq_L^2 \\ X_1k_{SL} - X_2X_3 \\ X_3k_{SR}k_{RL}q_L \end{bmatrix}^T \begin{bmatrix} q_X^2 \\ q_X \\ 1 \end{bmatrix} = 0. \quad (25)$$

With (25), the optimal C_R corresponding to maximum system efficiency can be derived as follows:

$$C_{R-optimal} = \frac{1}{(1 - q_X)\omega_r^2 L_R}. \quad (26)$$

When C_R increases from zero to positive infinite, q_X increases from negative infinite to $\omega_r L_R$, so the monotonicities of C_R and q_X are the same. It should be noted that (25) is a quadratic equation, and the relationship between power transfer efficiency and q_X can be plotted as Fig. 10. It is clear that there are two real roots of (25). As can be seen from Fig. 10, when $q_{X1} < q_X < q_{X2}$, the system efficiency is reduced with q_X increases, so the power transfer efficiency around q_{X2} is much smaller than the efficiency obtained at q_{X1} . Hence, the optimal value of C_R for achieving maximum efficiency should be set with q_{X1} as shown in (26). Therefore, for a certain load, there will also be an optimal relay compensation capacitor, which can help to improve the power transfer efficiency.

However, for practical equipment such as a battery, the equivalent load resistance of the battery will vary with the charging process. When the load resistance varies, the optimal relay compensation capacitor corresponding to the maximum power transfer efficiency will vary too [see Figs. 8(b) and 9(b)]. While, for specific equipment with fixed parameters, the load resistance usually varies within a certain range. Therefore, a relative optimal capacitance can be derived which can satisfy the improvement both in the power transfer efficiency and capacity. For example, when the load resistance varies from 10 to 20 Ω , as can be seen in Fig. 8(b), when the load resistance is 10 Ω , the optimal relay compensation capacitance is 39 nF, and when the load resistance is 20 Ω , the optimal relay compensation capacitance is 42 nF. Meanwhile, the power transfer efficiency and capacity can also both be effectively improved when the

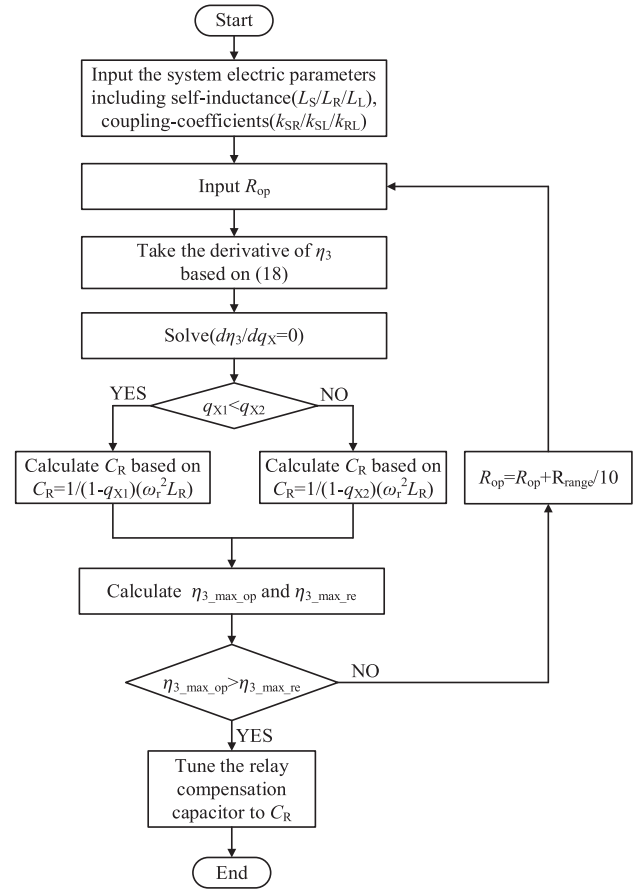


Fig. 11. Design flow of the relay compensation capacitor.

relay capacitance is 39 nF for a 20 Ω load resistance. Therefore, the relative optimal relay compensation capacitance is selected to be 39 nF. In this case, when the load resistance is 10 Ω , the power transfer efficiency is improved from 94.12% to 94.52%, and when the load resistance is 20 Ω , the power transfer efficiency can also be improved 0.21% from 92.56% to 92.77%. Therefore, when the load resistance varies from 10 to 20 Ω , the power transfer efficiency can be improved by 0.29% on average, and the power transfer capacity can be improved by 8.78 W on average.

According to the above-mentioned analysis, the design flow of the relay compensation capacitor C_R is shown in Fig. 11. The optimization method of the relay compensation capacitance can be summarized as follows.

Step 1: Determine the system electrical parameters including the self-inductance of the coils ($L_S/L_R/L_L$), and the coupling coefficients ($k_{SR}/k_{SL}/k_{RL}$).

Step 2: Derive the optimal load resistance R_{op} corresponding to the maximum power transfer efficiency in the given load resistance range.

Step 3: Derive the optimal relay compensation capacitance C_R at R_{op} .

Step 4: Calculate $\eta_{3_max_op}$ and $\eta_{3_max_re}$.

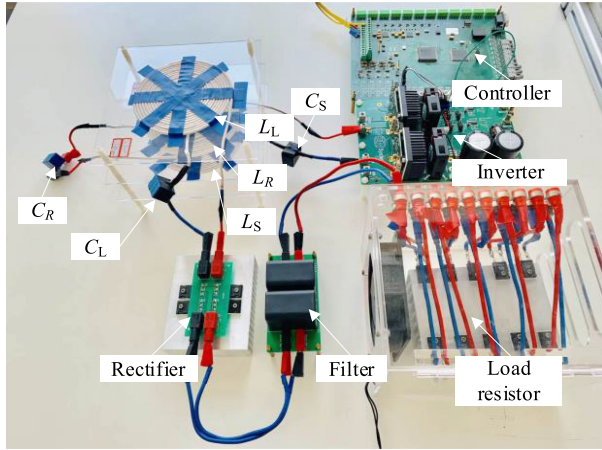


Fig. 12. Experimental platform of the WPT system.

Step 5: Compare $\eta_{3_max_op}$ and $\eta_{3_max_re}$, if $\eta_{3_max_op} \geq \eta_{3_max_re}$, C_R is selected as the optimal relay compensation capacitance. Otherwise, R_{op} should be increased until $\eta_{3_max_op} \geq \eta_{3_max_re}$.

In this design flow, $\eta_{3_max_op}$ is the power transfer efficiency of the system with the optimal relay compensation capacitance (C_R) at the maximum load resistance, $\eta_{3_max_re}$ is the power transfer efficiency of the system with the resonant relay compensation capacitance at the maximum load resistance, R_{range} is the load resistance range of the specific equipment.

It can be found out from Fig. 8(b) that the optimal relay compensation capacitance is smaller with load resistance reduces, and the power transfer efficiency decreases when C_R increase from the optimal relay compensation capacitance to the resonant relay compensation capacitance (45 nF). Therefore, (27) is always true, and only $\eta_{3_min_op}$ and $\eta_{3_min_re}$ need to be compared

$$\eta_{3_min_op} \geq \eta_{3_min_re} \quad (27)$$

where $\eta_{3_min_op}$ is the power transfer efficiency of the system with the optimal relay compensation capacitance (C_R) at the minimal load resistance, $\eta_{3_min_re}$ is the power transfer efficiency of the system with the resonant relay compensation capacitance (45 nF) at the minimal load resistance.

IV. EXPERIMENTAL VERIFICATION

For validating the theoretical analysis and the proposed optimization method for the coaxial three-coil WPT system in this article, the two-coil and three-coil WPT systems are both built up as shown in Fig. 12. The design parameters of the system are shown in Table IV. In this article, the source coil is the same as the load coil both in these two systems. Meanwhile, the relay coil in the three-coil WPT system also has the same design as the source and load coils to simplify the calculation and theoretical analysis.

In the experiments, a dc power supply (ITECH, IT6006D-800-20) is used to power up the whole system. The source coil and its compensation circuit receive the desired high-frequency

TABLE IV
PARAMETERS OF THE SYSTEM

Symbol	Value	Symbol	Value
f_d	200 kHz	R_{S1}	18.6 m Ω
V_{DC}	50 V	R_R	18.96 m Ω
L_S	13.78 μ H	R_{L2}	17.83 m Ω
L_R	13.76 μ H	C_S	45.11 nF
L_L	13.71 μ H	C_R	45.23 nF
R_{La}	1 Ω -50 Ω	C_L	45.15 nF

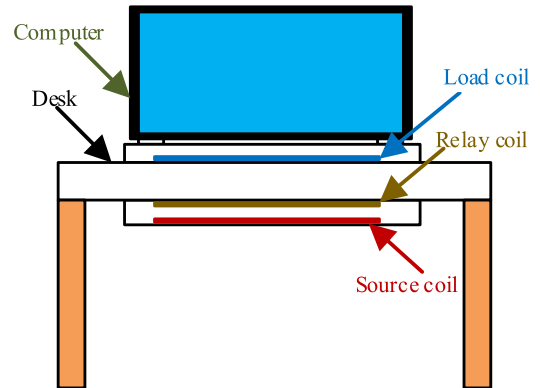


Fig. 13. Schematic diagram of desktop devices with wireless charging system.

power from the full-bridge inverter which consists of four GaN E-HEMTs S_1 - S_4 (GaN Systems, GS66516B), then the power is transmitted to the load side through the relay circuit, finally, the power is delivered to the load after being rectified by an H-bridge rectifier made by four SiC diodes (CREE, C4D20120). Besides, a power analyzer (Yokogawa, WT1800) is used to measure the power transfer capacity. 100 MHz voltage differential probes (Pico, TAO42) are used to measure the output voltage of the inverter and the input voltage of the rectifier. 100 MHz current probes (Keysight, N2783B) are used to measure the output current of the inverter and the input current of the rectifier. 200 MHz oscilloscope (Keysight, DSOX3024T) is used to capture the waveforms of voltage and current.

A. Verification of the Efficiency Characteristic of the Two-Coil and Three-Coil WPT Systems

To verify the theoretical analysis in Section III-B and the optimization design method for improving the power transfer efficiency of the three-coil resonant WPT system compared with the two-coil WPT system, the performance of the two-coil and three-coil WPT systems is compared first. In the experiments, the driving frequency is set to be 200 kHz according to Qi standards [29], and the desired load power is about 80 W for desktop devices (see Fig. 13). The load resistance is set to be 10 Ω according to [11], [22], which is a common value for the load in the WPT system. The power transfer distance is set to be 30 mm, which is the common thickness of a table. Therefore, the source side of the system can be installed under the table and power up the desktop devices put on the table. Besides, for this three-coil WPT system, d_{SR} is 10 mm to strengthen the cross-coupling.

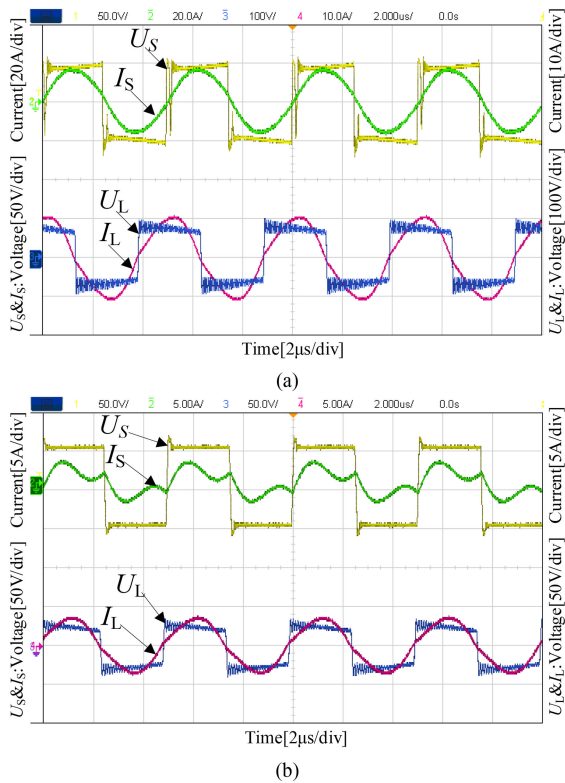


Fig. 14. Experimental waveforms. (a) Two-coil WPT system. (b) Three-coil WPT system. U_S and I_S : output voltage and current of the dc–ac inverter; U_L and I_L : input voltage and current of the ac–dc rectifier.

The measured waveforms of the input voltage and current of the source coil and output voltage and current of the load coil in the two-coil and three-coil WPT systems are shown in Fig. 14.

It can be seen that when the WPT system operates at the resonant condition, the output voltage and current of the load coil are always in phase with each other both in the two-coil and three-coil WPT systems. While the input voltage and current of the source coil, they are only in phase in the two-coil WPT system. For the three-coil WPT system, the voltage and current are not in phase anymore, which is consistent with the theoretical analysis in Section II. Besides, for the two-coil WPT system, there is a voltage pulse in the dead-time, which is caused by the energy absorption and release of the LC circuit in the dead-time.

Regarding the power transfer efficiency of these two systems, Fig. 15 plots the efficiency (load to the source) varies with the load resistance. It can be seen that the experimental results have the same trends as the theoretical calculation with small errors. The errors are caused by the parasitic parameters in the practical system including the stray resistance of the compensation capacitors, the leads, and connection nodes in the system, particularly caused by the errors of the ac resistance of coils under certain operating conditions because the current flowing in the coils will affect its proximity effect, but the influence on the veracity of trend analysis can be neglected. Besides, when d_{SR} is 10 mm, as can be seen from Fig. 15, when the load resistance is about 3 Ω , the efficiency of the two-coil WPT system is equal to that of the three-coil WPT system, while the theoretical critical

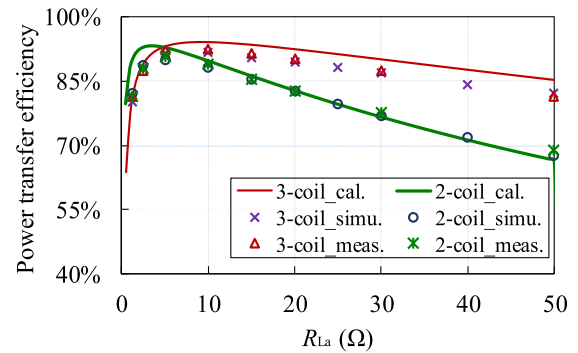


Fig. 15. Relationship between power transfer efficiency and $R_{L,a}$.

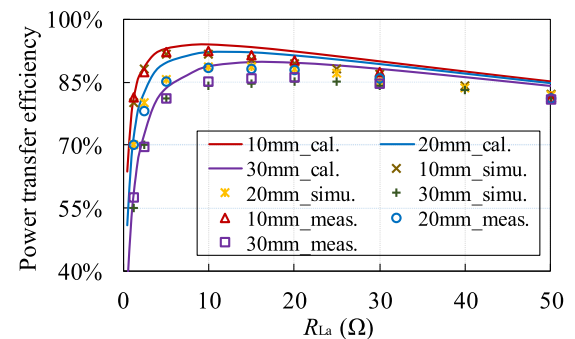


Fig. 16. Power transfer efficiency of the resonant three-coil WPT system with different d_{SR} .

value is 5 Ω . When the load resistance is smaller than 3 Ω , the efficiency of the two-coil WPT system is greater than that of the three-coil WPT system. And when the load resistance is larger than 3 Ω , the efficiency of the three-coil WPT system can exceed that of the two-coil WPT system. It can also be found out from the experimental results that the optimal load resistance of the three-coil WPT system is about 10 Ω , which is consistent with the theoretical calculation result. In conclusion, the three-coil WPT system is more suitable for charging batteries than the two-coil WPT system, as the usual equivalent resistance of the battery is around 1–50 Ω [23].

When d_{SR} varies, it can be seen from Fig. 16 that the shorter the d_{SR} , the higher the system efficiency can be obtained for the three-coil WPT system, which is also consistent with the theoretical analysis. Besides, it can be seen from Fig. 16 that the measured results agree well with the calculated results. In conclusion, the relay coil should be as close as possible to the source coil for the three-coil WPT system to obtain higher power transfer efficiency.

B. Verification of the Characteristic of the Three-Coil WPT System With Optimally Designed Relay Compensation Capacitors

To investigate the effectiveness and correctness of the optimization method for improving the power transfer efficiency and capacity of the three-coil WPT system, the voltage and current waveforms of the dc–ac inverter and rectifier with the optimal

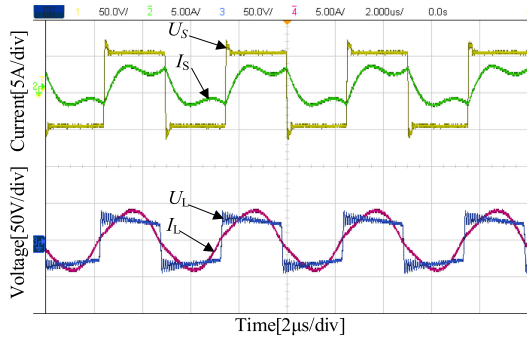


Fig. 17. Experimental waveforms with optimized relay compensation capacitor. U_S and I_S : output voltage and current of the dc-ac inverter; U_L and I_L : input voltage and current of the ac-dc rectifier.

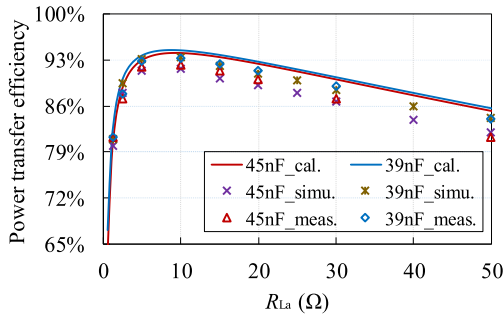


Fig. 18. Power transfer efficiency of the three-coil WPT system with different C_R .

relay compensation capacitance (39 nF, derived by Fig. 11) are measured as shown in Fig. 17. It can be found out in Figs. 14(b) and 17 that the input voltage and current of the rectifier are in phase. While the current distortion rate of the dc-ac inverter with the optimized relay compensation capacitor is much smaller than that with the resonant relay compensation capacitor. Besides, the phase angle between the output voltage and current of the dc-ac inverter is smaller than that in the resonant condition. Therefore, the power transfer efficiency and capacity of the three-coil WPT system can both be improved.

The power transfer efficiency of the three-coil WPT system with different load resistance is given in Fig. 18. First, it can be seen that the experimental results agree well with the theoretical calculation results. The trends of the power transfer efficiency of the three-coil WPT system with optimal C_R (39 nF) and resonance C_R (45 nF) are consistent with calculated results, and the error caused by the parasitic parameters in the practical system is small that can be neglected. Second, the power transfer efficiency can be effectively improved with the proposed relay compensation capacitor optimization method in a wide range of load resistance. And the maximum efficiency improvement is obtained at 50 Ω , which is 2.7%. The average improvement of the power transfer efficiency is 1.2%.

Regarding the power transfer capacity, as can be seen from Fig. 19, the power transfer capacity of the three-coil WPT system with optimal relay compensation capacitor (39 nF) is always higher than that with the resonant capacitor (45 nF). This is consistent with the analysis result of Fig. 17. Besides,

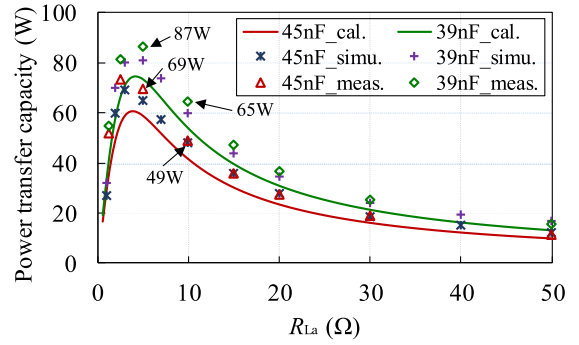


Fig. 19. Power transfer capacity of the three-coil WPT system with different C_R .

the measured and calculated results have the same trend with load resistance increasing from 1 to 50 Ω . The optimum load resistance to achieve maximum power transfer efficiency is about 10 Ω (see Fig. 6). For this load resistance, the power transfer capacity increases from 49 to 65 W when the capacitance of the compensation capacitor is changed from 45 to 39 nF. And the power transfer capacity is improved by about 32.65%. Besides, for the experimental setup used in this article, the maximum power transfer capacity is achieved at 5 Ω load (see Fig. 19). And the power transfer capacity increases from 69 to 87 W when the capacitance of the compensation capacitor is changed from 45 to 39 nF. Therefore, it is feasible to reduce the input dc voltage by tuning the relay compensation capacitor for a desired load power requirement, which is beneficial to reduce the voltage stress on the switching devices and passive devices in the WPT system.

It should be noted that there is a non-negligible difference existing in Fig. 19. This difference is mainly caused by the assumptions for deriving the simplified model [see Fig. 1(b)] from the whole system model [see Fig. 1(a)], as the dc power supply and the dc-ac inverter are seen as an ac voltage source, and the rectifier, filter, and the actual load are regarded as equivalent resistance. Meanwhile, the efficiency of the rectifier is assumed to be 100% in the calculation, but in the practical system, the efficiency of the rectifier cannot be 100%. Therefore, when the load resistance is 2.5 Ω , the equivalent resistance of the actual load, rectifier and filter is about 2.025 Ω in theory. But according to the measured input voltage and current of the rectifier, the equivalent resistance is about 2.7 Ω in practice. As a result, the differences in Fig. 19 cannot be neglected as the losses of the rectifier and inverter are not considered in the theoretical analysis. Nevertheless, the variation tendency of the calculated results agrees well with the experimental results.

V. CONCLUSION

In this article, the power transfer efficiency of a coaxial three-coil WPT system is compared to a two-coil WPT system with the same source and load coils, the same power transfer distance, and the same load. The effect of the position of the relay coil on the power transfer efficiency is analyzed to find the constraint that the power transfer efficiency of the three-coil

WPT system is higher than that of the two-coil WPT system based on the same power transfer distance. Subsequently, a novel optimization methodology for further improving the performance of the coaxial three-coil WPT system is proposed. The power transfer efficiency and capacity can both be improved in a wider range of load resistance variations by tuning the relay compensation capacitor according to the load condition and position. The detailed optimization process is also given in this article. The experimental results demonstrate that the performance of the three-coil WPT system can be effectively improved with the proposed approaches, the results showed that the power transfer efficiency can be improved by about 1.2% on average in the wide range of the load resistance, and the power transfer capacity can be improved 32.65% when the load resistance is 10 Ω .

Besides, it should be noted that the two-coil and three-coil WPT systems both have optimal load ranges for achieving higher efficiency. Given the background of this work is for wireless charging desktop devices, higher efficiency can be easily achieved by a three-coil WPT system. The studies on the two and three-coil WPT systems are both meaningful, and they have different application scopes and scenarios. And this article focuses on optimizing the power transfer efficiency and capacity of the three-coil WPT system at the same time.

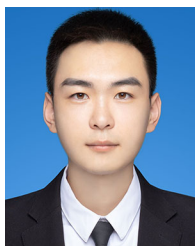
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