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Optimization Method of Magnetic Coupling Resonant Wireless Power Transfer System with Single Relay Coil

Jianpo Li[1, *], Yang Lu[1], Fuxin Liu[2], Baochun Mu[3], Ziqi Dong[4], Songjun Pan[2], and Cong Zheng[2]

Abstract—In view of the dynamic wireless energy charging of electric vehicles, because of the different types or dynamic changes of carrying capacity, the distance between receiving coil at the chassis of electric vehicles and transmitting coil under the road will change dynamically. The unsuitable distance may make the system keep an under-coupling state and reduce the output power of energy transmission system. To improve the system output power, and a relay coil can be added between transmitting coil and receiving coil. But the system charging state may change from under-coupling state to over-coupling state directly because of the introduction of relay coil, and at the same time, the system may show frequency splitting phenomenon. These problems can be solved by adjusting the position of relay coil, the rotating angle of relay coil, and the load value. The experiment shows that the system output power can be improved obviously by increasing relay coil and suppressing frequency splitting. In order to obtain the optimal parameters about the position, rotation angle of relay coil, and load resistance, a genetic algorithm is introduced to improve the output power. At last, using the optimal system parameters, a magnetic coupling resonant wireless power transmission (MCRWPT) system is designed and manufactured, by which the effectiveness and advantage of this approach are verified by experiments.

1. INTRODUCTION

Wireless power transfer (WPT) is a new technology which can free people from annoying wires. Magnetic coupling resonance (MCR) mode is one of the ways of inductance contactless power transfer (ICPT). This technology is widely concerned because it has broad application prospects [1–3]. Compared with wired charging, the ICPT system makes it possible to charge the electric vehicles wirelessly to avoid safety issues and provide convenience to users. The ICPT system also has potential applications in the field of medical sciences, industrial loading machines, and battery charging.

Although the ICPT system has been applied successfully in electric vehicle charging, it still has many problems and challenges. References [4] and [5] optimize the electrical parameters involved in ICPT system. The presented algorithms can help us choose appropriate coil dimension and electrical parameter to cope with the issue of misalignment tolerance. The detailed analysis of different types of wireless charger topologies in electric vehicle charging applications are presented. The different winding designs for wireless transformer are described and compared [6].

However, it is not enough to optimize the parameters of resonant coil, especially in some specific applications. To increase the transmission distance for a two-coil magnetic coupling wireless power transmission system, a relay coil is placed near the transmitting coil or receiving coil [7–9]. The relay

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* Corresponding author: Jianpo Li (jianpoli@163.com).
[1] School of Computer Science, Northeast Electric Power University, Jilin 132012, China. [2] Global Energy Interconnection Group Co., Ltd, Beijing 100031, China. [3] Beijing China-Power Information Technology CO., Ltd, Beijing 110000, China. [4] State Grid Information & Telecommunication Branch, Beijing 100142, China.

coil can even be combined with the transmitting coil or receiving coil into a whole. An auxiliary coil is added between the transmitting coil and receiving coil. The relationship between the transmission efficiency and coupling coefficient and the self-resonant frequency of auxiliary coil is discussed in [10].

In view of the influence of azimuth change between the coils on the system transmission performance, the mutual inductance coupling model is built to obtain the relationship between mutual inductance coefficient and transmission power. At the same time, the influence of axial distance, radial distance, and deflection angle on the transmission performance is analysed in [11–13].

In the ICPT system, there are three different situations for power transfer, under-coupling, critical coupling, and over-coupling. When the transmission distance is reduced, the transmission power at the original resonant frequency decreases with the decrease of distance. The transmission power has multiple extreme points, but the transmission power at the resonant frequency is not the system's maximum value. If the corresponding frequency of each extreme point of the system transmission power is called resonant frequency, a number of resonant frequencies will inevitably exist with the splitting of the transmission power, which is called frequency splitting phenomenon. In [14–16], the equivalent circuit model is used to analyse the frequency splitting phenomenon of two-coil system and three-coil system, and the odd frequency and even frequency are obtained. The critical coupling coefficient that determines the over-coupling region is obtained. Reference [17] proposes a method of asymmetric resonant coils to suppress the frequency splitting of a two-coil system. A transmitting structure for multiple receiving coils is proposed in [18, 19]. Each receiving coil is connected with a different compensation capacitance, and the resonant conditions can be satisfied by dynamically adjusting the distance between receiving coils and transmitting coils.

In this paper, in view of the dynamic wireless energy charging of electric vehicles, because of the different types or the dynamic changes of carrying capacity, the distance between receiving coil at the chassis of electric vehicles and transmitting coil under the road will change dynamically. The unsuitable distance may make the system keep an under-coupling state and reduce the output power of energy transmission system. It is proposed that the system output power can be improved by adding a relay coil between transmitting coil and receiving coil according to the distance between transmitting coil and receiving coil. That is, in a traditional two-coil ICPT system, the positions of transmitting coil and receiving coil are fixed. The introduction of relay coil will improve the output power greatly, but the system charging state may change from under-coupling state to over-coupling state directly, at the same time frequency splitting phenomenon may appear in the system. In addition, considering the different measures to suppress frequency splitting, it is difficult to find the best solution.

In this paper, the frequency splitting phenomenon in an ICPT system is inhibited by rotating the relay coil, adjusting its space position, and changing the load resistance of receiving coil. The system output power is improved accordingly. In order to obtain the above optimal parameters, a genetic algorithm is introduced. At last, using the optimal system parameters, we design a magnetic coupling resonant wireless power transmission (MCRWPT) system.

2. SYSTEM PRINCIPLE AND STRUCTURE ANALYSIS

2.1. Coil Resistance, Self-Inductance and Mutual Inductance Calculation

The coil's equivalent resistance is composed of an ohmic resistance and a radiation resistance. The radiation resistance is negligible relative to ohmic resistance and load resistance. The coil's equivalent resistance can be calculated according to formula (1) [20, 21].

$$R = \sqrt{\frac{\omega\mu_0}{2\sigma}}\frac{l}{4\pi r} \tag{1}$$

The self-inductance of spiral coil is calculated by formula (2).

$$L = N^2 r\mu_0 \left[\ln\left(8r/g\right) - 2\right] \tag{2}$$

where ω is the angular frequency; μ_0 is a vacuum permeability; σ is the copper conductivity; l is the length of copper wire; N is the number of coil turns; r is the radius of copper wire; $g = k(2a + 2a \times N)$, $k = 0.2236$; a is the radius of wire cross section.

The mutual inductance between coils is closely related to the turn number, coil radius, and the distance between turns. If the resonant coil is a coaxial spiral coil, the mutual inductance between coils is as follows.

$$M = \begin{cases} \dfrac{\mu_0 \pi N_{\mathrm{i}} N_{\mathrm{j}} r_{\mathrm{i}}^2 r_{\mathrm{j}}^2}{2\left(d_{\mathrm{ij}}^2 + r_{\mathrm{i}}^2\right)^{\frac{3}{2}}} & r_{\mathrm{j}} < r_{\mathrm{i}} \\ \dfrac{\mu_0 \pi N_{\mathrm{i}} N_{\mathrm{j}} r_{\mathrm{i}}^2 r_{\mathrm{j}}^2}{2\left(d_{\mathrm{ij}}^2 + r_{\mathrm{j}}^2\right)^{\frac{3}{2}}} & r_{\mathrm{j}} \geq r_{\mathrm{i}} \end{cases} \tag{3}$$

where the transmission distance between coil i and coil j is d_{ij}.

2.2. MCRWPT System with Relay Coil

Figure 1 is a structure schematic diagram of MCRWPT system with relay coil. The system includes a driving power, a transmitting coil, a receiving coil, a relay coil, and a load. The transmitting coil is connected with the power supply. The receiving coil is connected with the load. The transmitting coil and relay coil, and also the relay coil and receiving coil are all weakly coupled by magnetic field. The rotation angle θ is the angle between the plane of relay coil and the vertical direction to the ground.

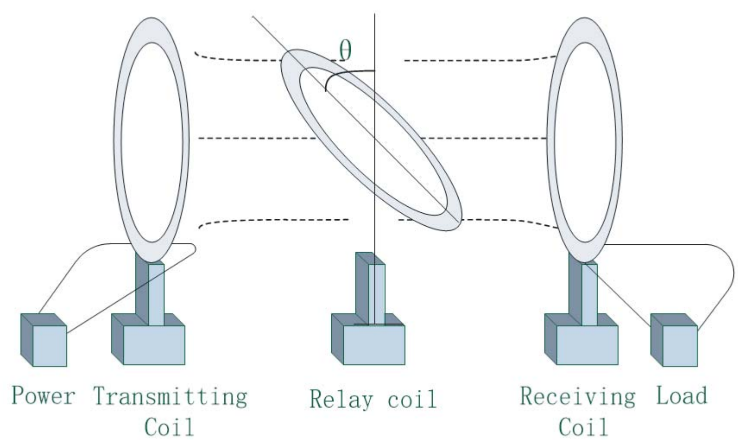

Figure 1. Structure schematic diagram of MCRWPT system with relay coil.

The equivalent circuit of MCRWPT system with relay coil is shown in Figure 2.

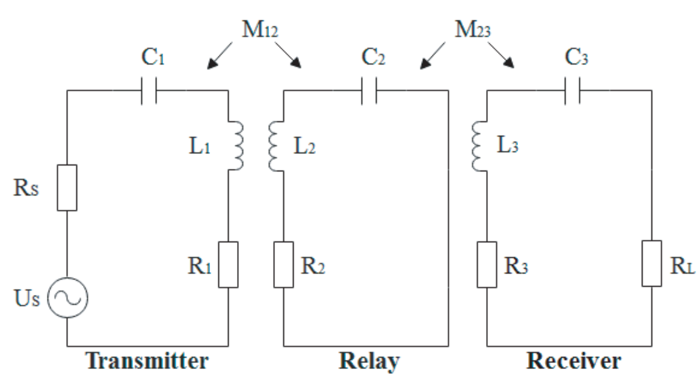

Figure 2. Equivalent circuit of MCRWPT system with relay coil.

In Figure 2, U_{s} is the system equivalent voltage. The resistances R_{s} and R_{L} represent the internal resistance of power supply and load resistance, respectively. The resistances R_1, R_2, and R_3 are the equivalent resistances of transmitting coil, relay coil, and receiving coil at high frequency, respectively, and $R_1 = R_2 = R_3$. Their self-inductances are L_1, L_2, and L_3, and $L_1 = L_2 = L_3$. Their equivalent capacitances are C_1, C_2, and C_3, and $C_1 = C_2 = C_3$. The mutual inductance between transmitting coil and relay coil is M_{12}. The mutual inductance between relay coil and receiving coil is M_{23}. The mutual inductance M_{13} between transmitting coil and receiving coil is much smaller than M_{12} and M_{23}, so it can be neglected. The current of receiving coil is i_3. The system output power is P_{out}. The angular frequency is ω. Their coil radii are r_1, r_2, and r_3, respectively, and $r_1 = r_2 = r_3$. Their turns are N_1, N_2, and N_3, respectively, and $N_1 = N_2 = N_3$. The distance between transmitting coil and relay coil is d_{12}. The distance between relay coil and receiving coil is d_{23}. The position of the relay coil is represented as $\zeta = d_{12}/(d_{12} + d_{23})$.

Under resonant frequency, the input impedance based on mutual inductance is:

$$Z_{\mathrm{in}} = R_{\mathrm{S}} + R_1 + \frac{(\omega_0 M_{12})^2}{R_2 + \dfrac{(\omega_0 M_{23})^2}{R_3 + R_{\mathrm{L}}}} \tag{4}$$

The equivalent impedances of transmitting coil, relay coil, and receiving coil are:

$$\begin{aligned} Z_{11} &= R_{\mathrm{S}} + R_1 + j\omega L_1 + \frac{1}{j\omega C_1} \\ Z_{22} &= R_2 + j\omega L_2 + \frac{1}{j\omega C_2} \\ Z_{33} &= R_3 + j\omega L_3 + \frac{1}{j\omega C_3} + R_{\mathrm{L}} \end{aligned} \tag{5}$$

According to the equivalent circuit, the following KVL equation can be obtained.

$$\begin{aligned} Z_{11} i_1 + j\omega M_{12} i_2 &= U_{\mathrm{S}} \\ Z_{22} i_2 + j\omega M_{12} i_1 + j\omega M_{23} i_3 &= 0 \\ Z_{33} i_3 + j\omega M_{23} i_3 &= 0 \end{aligned} \tag{6}$$

In the formula, i_1, i_2, and i_3 are the currents of transmitting coil, relay coil, and receiving coil, respectively.

The system works in resonance state and satisfies formula (7).

$$\begin{aligned} \omega L_1 &= \frac{1}{\omega C_1} \\ \omega L_2 &= \frac{1}{\omega C_2} \\ \omega L_3 &= \frac{1}{\omega C_3} \end{aligned} \tag{7}$$

The matrix equation of the resonant state:

$$\begin{bmatrix} U_{\mathrm{s}} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_{\mathrm{s}} + R_1 & -j\omega M_{12} & 0 \\ -j\omega M_{12} & R_2 & -j\omega M_{23} \\ 0 & -j\omega M_{23} & R_{\mathrm{L}} + R_3 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \tag{8}$$

The currents of transmitting coil, relay coil, and receiving coil can be obtained respectively.

$$I_1 = \frac{U_{\mathrm{S}}[\omega^2 {M_{23}}^2 + R_2(R_3 + R_{\mathrm{L}})]}{\omega^2 {M_{23}}^2 (R_1 + R_{\mathrm{S}}) + \omega^2 {M_{12}}^2 (R_3 + R_{\mathrm{L}}) + (R_1 + R_{\mathrm{S}}) R_2 (R_3 + R_{\mathrm{L}})} \tag{9}$$

$$I_2 = \frac{\omega M_{12} R_{\mathrm{S}} (R_3 + R_{\mathrm{L}})}{\omega^2 {M_{23}}^2 (R_1 + R_{\mathrm{S}}) + \omega^2 {M_{12}}^2 (R_3 + R_{\mathrm{L}}) + (R_1 + R_{\mathrm{S}}) R_2 (R_3 + R_{\mathrm{L}})} \tag{10}$$

$$I_3 = \frac{\omega^2 M_{12} M_{23} U_{\mathrm{S}}}{\omega^2 {M_{23}}^2 (R_1 + R_{\mathrm{S}}) + \omega^2 {M_{12}}^2 (R_3 + R_{\mathrm{L}}) + (R_1 + R_{\mathrm{S}}) R_2 (R_3 + R_{\mathrm{L}})} \tag{11}$$

The input power of transmitting coil and the output power of receiving coil are:

$$P_{\text{in}} = \frac{{U_{\text{S}}}^2[\omega^2 {M_{23}}^2 + R_2(R_3 + R_{\text{L}})]}{\omega^2 {M_{23}}^2(R_1 + R_{\text{S}}) + \omega^2 {M_{12}}^2(R_3 + R_{\text{L}}) + (R_1 + R_{\text{S}})R_2(R_3 + R_{\text{L}})} \tag{12}$$

$$P_{\text{out}} = \frac{\omega^4 {M_{12}}^2 {M_{23}}^2 {U_S}^2 R_{\text{L}}}{\left[\omega^2 {M_{23}}^2(R_1 + R_{\text{S}}) + \omega^2 {M_{12}}^2(R_3 + R_{\text{L}}) + (R_1 + R_{\text{S}})R_2(R_3 + R_{\text{L}})\right]^2} \tag{13}$$

According to $\eta = P_{\text{out}}/P_{\text{in}}$, the system transmission efficiency can be further obtained:

$$\eta = \frac{\omega^4 {M_{12}}^2 {M_{23}}^2 R_{\text{L}}}{[\omega^2 {M_{23}}^2(R_1 + R_{\text{S}}) + \omega^2 {M_{12}}^2(R_3 + R_{\text{L}}) + (R_1 + R_{\text{S}})R_2(R_3 + R_{\text{L}})][\omega^2 {M_{23}}^2 + R_2(R_3 + R_{\text{L}})]} \tag{14}$$

3. THEORETICAL ANALYSIS AND DESIGN OF POWER OPTIMIZATION METHOD FOR WPT SYSTEM

3.1. Construction of MCRWPT System in Critical Coupling State

As the mechanical parameters of various resonant coils are known, in order to obtain the maximum output power of MCRWPT system, the optimal position parameters of relay coil, including ζ, d_{12}, and d_{23} should be known. Under normal circumstances, the internal resistance of power supply R_3 is not equal to that of load R_L. The whole system structure is not completely symmetrical, so $d_{12} \neq d_{23}$. That is, the relay coil is not in the middle of transmitting coil and receiving coil. The output power is a function of mutual inductance M_{12} and mutual inductance M_{23}, while M_{12} and M_{23} are the functions of distances d_{12} and d_{23}, respectively. When the load resistance is known, the optimal mutual inductances M_{12} and M_{23} can be obtained with the output power as the target function. So the distances d_{12} and d_{23} can be obtained respectively in the critical coupling state.

The resonant frequency can be obtained according to formula (7), and formula (11) can be simplified.

$$I_3 = \frac{U_{\text{S}}}{\dfrac{M_{23}}{M_{12}}(R_1 + R_{\text{S}}) + \dfrac{M_{12}}{M_{23}}(R_3 + R_{\text{L}}) + \dfrac{(R_1 + R_{\text{S}})R_2(R_3 + R_{\text{L}})}{\omega^2 M_{12} M_{23}}} \tag{15}$$

Formula (15) shows that, in order to obtain the maximum output current and the maximum output power, the denominator part should be minimized. So the following two conditions need to be met at the same time.

$$\begin{aligned} &\min\left[\frac{M_{23}}{M_{12}}(R_1 + R_{\text{S}}) + \frac{M_{12}}{M_{23}}(R_3 + R_{\text{L}})\right] \\ &\min\left[\frac{(R_1 + R_{\text{S}})R_2(R_3 + R_{\text{L}})}{\omega^2 M_{12} M_{23}}\right] \end{aligned} \tag{16}$$

According to the mean inequality, it can be obtained:

$$\frac{M_{23}}{M_{12}}(R_1 + R_{\text{S}}) + \frac{M_{12}}{M_{23}}(R_3 + R_{\text{L}}) \geq 2\sqrt{(R_1 + R_{\text{S}})(R_3 + R_{\text{L}})} \tag{17}$$

If and only if $\frac{M_{23}}{M_{12}}(R_1 + R_{\text{S}}) = \frac{M_{12}}{M_{23}}(R_3 + R_{\text{L}})$, it is known that when M_{12} and M_{23} satisfy formula (18), the inequality of Eq. (17) is established.

$$M_{12} = \sqrt{\frac{R_1 + R_{\text{S}}}{R_3 + R_{\text{L}}}} M_{23} \tag{18}$$

In addition, in order to minimize $\frac{(R_1 + R_{\text{S}})R_2(R_3 + R_{\text{L}})}{\omega^2 M_{12} M_{23}}$ at the same time, $M_{12}M_{23}$ should be maximum. It is shown that M_{12} is affected by the inductance of transmitting coil and relay coil, and M_{23} is affected by the inductance of relay coil and receiving coil. That is, according to the principle that coupling coefficient $k_{12} \leq 1$, $k_{23} \leq 1$, we can get the following conclusions.

$$\begin{aligned} M_{12} &\leq \sqrt{L_1 L_2} \\ M_{23} &\leq \sqrt{L_2 L_3} \end{aligned} \tag{19}$$

According to the system mechanical parameter $R_L > R_S$, so $\sqrt{\frac{R_1+R_S}{R_3+R_L}} < 1$, $M_{23} > M_{12}$. Therefore, to maximize $M_{12}M_{23}$, we can simplify it and bring it into formula (18) and get the new formula (20).

$$\begin{aligned} M_{23} &= \sqrt{L_2 L_3} \\ M_{12} &= \sqrt{\frac{R_1 + R_S}{R_3 + R_L}} M_{23} = \sqrt{\frac{R_1 + R_S}{R_3 + R_L}} \sqrt{L_2 L_3} \end{aligned} \tag{20}$$

When the best mutual inductance M_{12} and mutual inductance M_{23} are obtained, accordingly, the optimal distances d_{12} and d_{23} can be obtained. So, in the critical coupling state, the distance between transmitting coil and receiving coil is $D_0 = d_{12} + d_{23}$.

3.2. Construction of MCRWPT System in Over-Coupling State

In the MCRWPT system with relay coil mode, the research of suppressing frequency splitting method plays a key role in improving the output power. In order to construct an MCRWPT system in over-coupling state, the method of suppressing frequency splitting is studied. Under the premise of constant mechanical parameters, the distance between transmitting coil and receiving coil $D = d_{12} + d_{23}$ and $D < D_0$. At this time, the introduction of relay coil will cause the frequency splitting.

3.3. Study on the Method of Suppressing Frequency Splitting

Figure 3 is the equivalent circuit of the traditional two-coil MCRWPT system. According to the method in [21], in order to make the system exit the frequency splitting region, it should satisfy formula (21).

$$(\omega M_{ab})^2 \leq (R_b + R_L)^2 \tag{21}$$

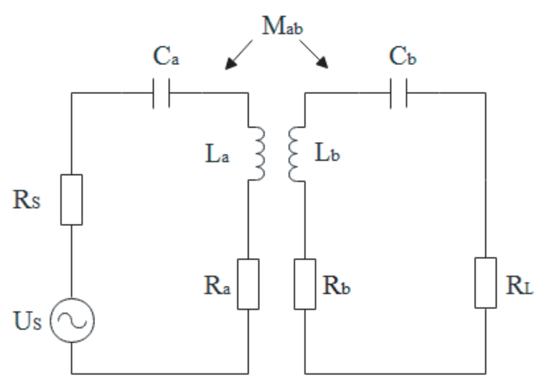

Figure 3. Equivalent circuit of the traditional two-coil MCRWPT system.

In order to obtain the condition for the MCRWPT system with relay coil to exit frequency split region, the equivalent circuit is simplified to the two-coil structure listed in Figure 4, and formula (22) is obtained.

$$(\omega M_{12})^2 \leq \left[R_2 + \frac{\omega M_{23}(R_3 + R_L)}{\omega M_{23} + R_3 + R_L} \right]^2 \tag{22}$$

When the frequency of power supply is stable, and the system mechanical parameters are constant, the frequency splitting can be suppressed by changing M_{12} and M_{23}, and adjusting the load value R_L.

3.3.1. Rotate the Relay Coil

When the frequency splitting phenomenon occurs in the MCRWPT system, the mutual inductance between the coils can be changed by rotating the relay coil, and the rotation angle is θ.

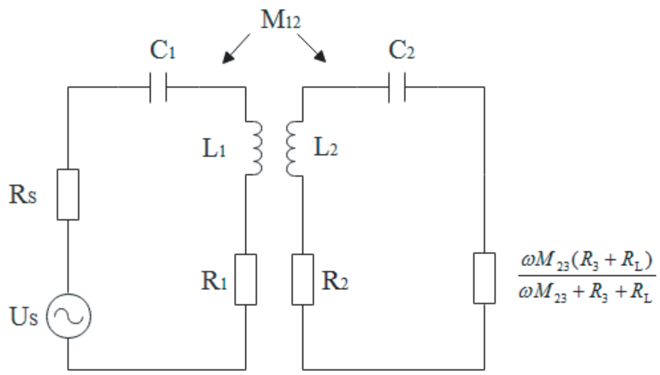

Figure 4. Equivalent circuit of MCRWPT system with relay coil converting to two-coil MCRWPT system.

The mutual inductance between transmitting coil and relay coil is as follows [22].

$$M_{12} = \mu_0\sqrt{r_1 r_2}\int_0^{\frac{\pi}{2}-\theta} \frac{(2\sin^2\theta - 1)\mathrm{d}\theta}{\sqrt{1-\dfrac{4r_1r_2\sin^2\theta}{{d_{12}}^2+(r_1+r_2)^2}}} \tag{23}$$

The mutual inductance between relay coil and receiving coil is as follows.

$$M_{23} = \mu_0\sqrt{r_2 r_3}\int_0^{\frac{\pi}{2}-\theta} \frac{(2\sin^2\theta - 1)\mathrm{d}\theta}{\sqrt{1-\dfrac{4r_2r_3\sin^2\theta}{{d_{23}}^2+(r_2+r_3)^2}}} \tag{24}$$

So the mutual inductances M_{12} and M_{23} are the functions of angle θ, $\theta \in [0, 90°]$.

3.3.2. Adjust the Position of Relay Coil

Immobilize the rotation angle of relay coil and adjust its position to change the mutual inductance M_{12} and M_{23} so as to suppress the frequency splitting phenomenon. As $\zeta = d_{12}/D$, formulas (23) and (24) can be converted as:

$$M_{12} = \mu_0\sqrt{r_1 r_2}\int_0^{\frac{\pi}{2}-\theta_0} \frac{(2\sin^2\theta - 1)\mathrm{d}\theta}{\sqrt{1-\dfrac{4r_1r_2\sin^2\theta}{\zeta^2D^2+(r_1+r_2)^2}}} \tag{25}$$

$$M_{23} = \mu_0\sqrt{r_2 r_3}\int_0^{\frac{\pi}{2}-\theta_0} \frac{(2\sin^2\theta - 1)\mathrm{d}\theta}{\sqrt{1-\dfrac{4r_2r_3\sin^2\theta}{(1-\zeta)^2D^2+(r_2+r_3)^2}}} \tag{26}$$

So mutual inductances M_{12} and M_{23} become the functions of ζ, $\zeta \in [0, 1]$.

3.3.3. Adjust the Load Resistance

If the rotation angle of relay coil and its position are fixed, the frequency splitting phenomenon can also be suppressed by adjusting the load resistance. According to formula (13), the relationship between load R_L and output power P_{out} can be obtained by taking P_{out} as objective function and controlling other variables. For the resonant frequency ω_0, there is a critical resistance R_{Lcr}. When the external load value is larger than R_{Lcr}, the system will exit the frequency splitting region. By transforming formula (22), we can get R_{Lcr}. The condition to withdraw from the frequency splitting region is:

$$R_{\mathrm{L}} \geq R_{\mathrm{Lcr}} = \frac{\omega^2 M_{12} M_{23} - \omega M_{23} R_2}{\omega(M_{23} - M_{12}) + R_2} - R_3 \tag{27}$$

3.4. Parameters Optimization Method Based on Genetic Algorithm

The system optimization variables are the location of relay coil ζ, rotation angle θ, and load resistance R_{L}. So the variable number in genetic algorithm is 3. According to the model of WPT system, the solution range of optimization variables is set as follows: $\zeta \in [0, 1]$; $\theta \in [0, 90°]$; $R_{\mathrm{L}} \in [0, 1500]$, unit is ohm.

In simulation experiments, the accuracy of variable location ζ is 0.1 mm, and its binary number is 7. The accuracy of variable rotation angle is 0.1°, and the binary number is 10. The accuracy of variable load resistance R_{L} is 0.1 Ω, and its binary number is 9. The population size is 50, and the maximum genetic iteration number is 200.

The initial population is randomly generated. The binary variables are encoded for optimized variables. Their chromosomes are expressed as:

$$X = [x_1\ x_2\ x_3] = [\zeta R_{\mathrm{L}} \theta] \tag{28}$$

Selection, crossover, and mutation are three genetic factors in basic genetic algorithm. The selection operator makes the chromosomes have higher fitness and more likely to be chosen. Here the selection probability is set to 0.9, so that excellent individuals can be selected from the old population. The new individuals can be obtained by cross operation. Here multipoint cross method is used. The cross probability is set to 0.65. To avoid local premature optimization, the mutation operation is used to ensure genetic diversity. The mutation probability is set to 0.002. The fitness function is formula (13). By genetic iteration, the individuals in new species are decoded, and the best individuals are saved. If it satisfies the requirement, it will output the optimization result. Finally, a set of optimization parameters and maximum output power can be obtained through genetic algorithm.

4. EXPERIMENT AND SIMULATION ANALYSIS

The main system parameters are set as follows. Power supply $U_{\mathrm{S}} = 50$ V, internal resistance of power supply $R_{\mathrm{S}} = 50\,\Omega$, and load value $R_{\mathrm{L}} = 100\,\Omega$. The winding way and parameters for transmitting coil, relay coil, and receiving coil are all the same. The radius of copper wire $a = 0.0445$ cm. The coil radius $r_1 = r_2 = r_3 = 12$ cm. The coil turns $N_1 = N_2 = N_3 = 15$. The equivalent resistance $R_1 = R_2 = R_3 = 3.2794\,\Omega$. The equivalent capacitance $C_1 = C_2 = C_3 = 2 \times 10^{-10}$ F. The coil self-inductance $L_1 = L_2 = L_3 = 1.2577 \times 10^{-4}$ H. The resonant frequency is about 10 MHz.

According to the established mechanical parameters, in order to obtain the maximum output power, the specific value of mutual inductances M_{12} and M_{23} can be obtained according to formula (20), $M_{12} = 3.824 \times 10^{-5}$ H, $M_{23} = 5.3242 \times 10^{-5}$ H. According to formulas (25) and (26), the best distance $d_{12} = 0.134$ m, $d_{23} = 0.12$ m. Therefore, $D_0 = d_{12} + d_{23} = 0.254$ m.

In the traditional two-coil MCRWPT system, the locations of transmitting coil and receiving coil are fixed, and the distance between them $D = 0.21$ m, $D < D_0$, load $R_{\mathrm{L}} = 100\,\Omega$. Then the load current is 0.136 A, and output power $P_{\mathrm{out}} = 1.8496$ W. It is obvious that the output power is insufficient. Therefore, the relay coil is added between transmitting coil and receiving coil. All of the following system simulation analyses are based on the MCRWPT system with relay coil.

Figure 5 shows the relationship between output power P_{out} of receiving coil and rotation angle θ of relay coil when the load of receiving coil is set to 100 Ω, and the position of relay coil is set to $\zeta = 0.45$, $\zeta = 0.50$, $\zeta = 0.55$, and $\zeta = 0.60$, respectively.

From Figure 5, we can see that every curve has a wave peak. When the relay coil is rotated to some angle, the maximum output power P_{out} can be obtained. If we continue to rotate the relay coil, the output power will decrease, because the mutual between the coils will decrease. Besides, the location of relay coil ζ directly affects the output power P_{out}. When the rotation angle θ is set to about 20°, $\zeta \in [0.45, 0.55]$, with the increase of ζ, the output power is also increased. When $\zeta = 0.60$, the output

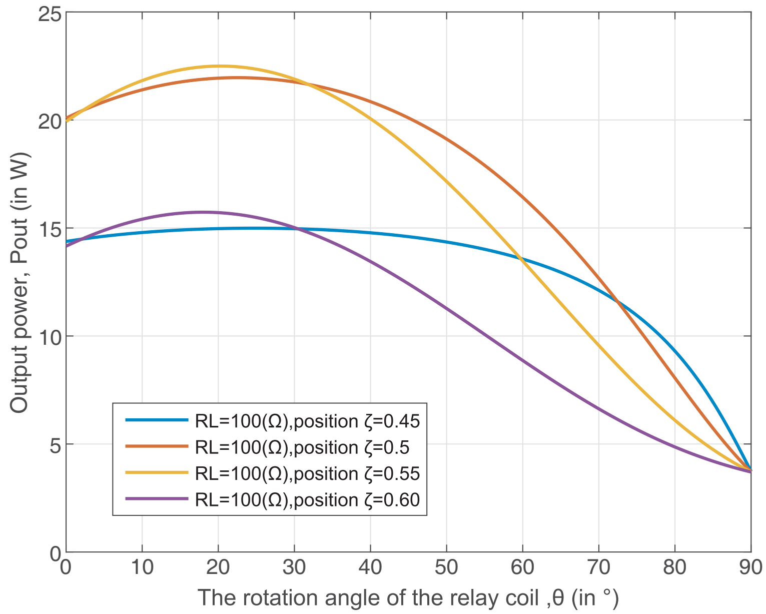

Figure 5. Relationship between output power P_{out} and rotation angle θ of relay coil, when load $R_{\text{L}} = 100\,\Omega$.

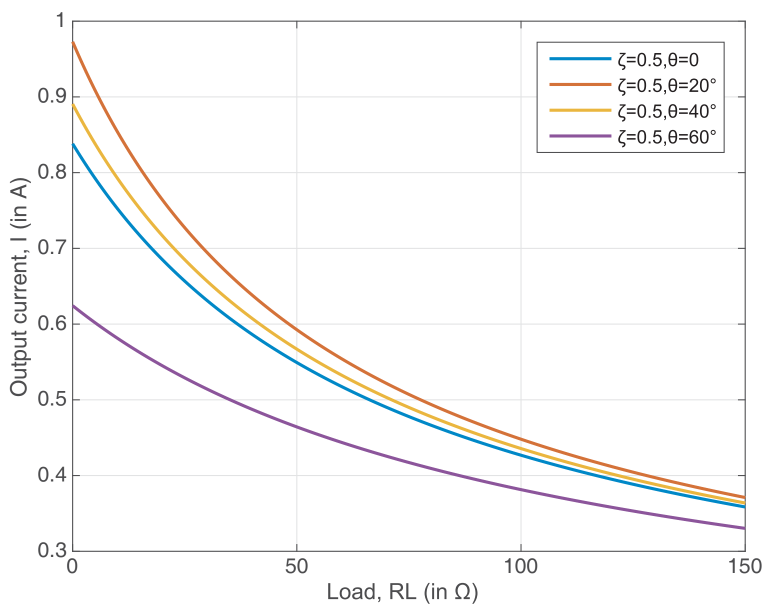

Figure 6. Relationship between output current I_3 and load R_{L}, when the coil position $\zeta = 0.5$.

power decreases evidently. So the maximum value of output power can be obtained when $\zeta \in [0.55,\ 0.60]$. In addition, the location of relay coil ζ has influence on rotation angles θ_{opt} for maximum output power.

Figure 6 shows the relationship between output current I_3 and load R_{L} when the relay coil is fixed in the middle of transmitting coil and receiving coil, and the rotation angle θ of relay coil is set to 0°, 20°, 40°, and 60°, respectively.

As can be seen from Figure 6, rotating relay coil is beneficial to increasing the output current I_3 through the load, but the excessive rotation angle will decrease I_3. It shows that for the same load, the output current I_3 increases with the increase of rotation angle θ when $\theta \in [0^\circ,\ 20^\circ]$. But the output current I_3 decreases with the increase of rotation angle θ when $\theta \in [40^\circ,\ 60^\circ]$. Besides, for a different

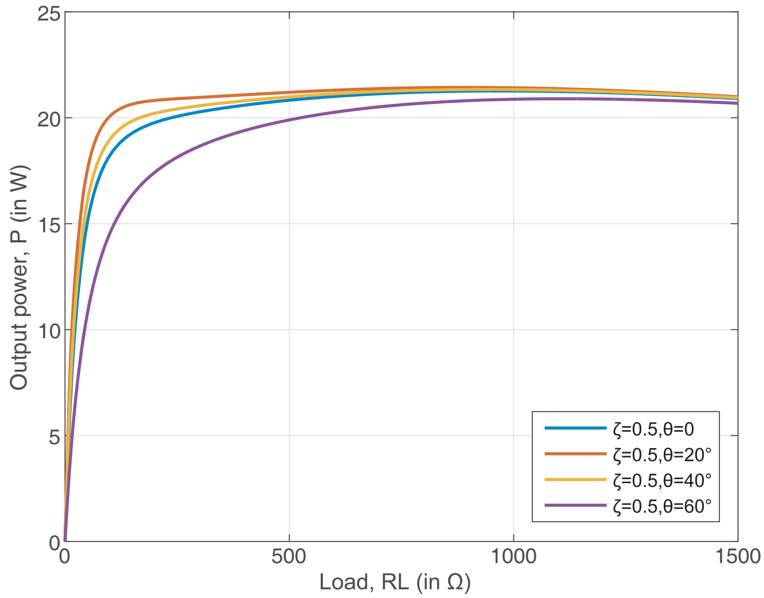

Figure 7. Relationship between output power P_{out} and load R_{L} when the location of relay coil $\zeta = 0.5$.

load, rotating relay coil can increase I_3 and P_{out} to some extent.

Figure 7 shows the relationship between output power P_{out} and load R_{L} when the relay coil is fixed in the middle of transmitting coil and receiving coil, and the rotation angle θ of relay coils are 0°, 30°, 45°, and 60°, respectively.

As can be seen from Figure 7, for each curve, there is always a load R_{L} that makes the system get the maximum output power when relay coil position and rotation angle are fixed. For the same location and different rotation angles, the load R_{L} corresponding to the maximum output power P_{out} is also different. When the rotation angle exceeds the optimal rotation angle θ_{opt}, the greater the rotation angle θ is, the greater the resistance of corresponding load R_{L} will be.

Figure 8 shows the relationship between output current I_3 and position of relay coil ζ when load R_{L} is fixed to $100\,\Omega$, and the rotation angles of relay coil θ are 0, 30°, 45°, and 60°, respectively.

It can be seen from Figure 8 that the maximum output power P_{out} can be obtained when ζ is slightly larger than 0.5. According to the model of WPT system, R_{S} is usually not equal to R_{L}. If $R_{\text{L}} > R_{\text{S}}$, the output power P_{out} can reach maximum when ζ is slightly greater than 0.5. If $R_{\text{L}} < R_{\text{S}}$, the output power P_{out} can reach the maximum when ζ is slightly less than 0.5. In addition, for a certain R_{L} ($R_{\text{L}} > R_{\text{S}}$), if the rotation angle of relay coil θ satisfies $\theta \in [0°, \theta_{\text{opt}}]$, to get the maximum output power P_{out}, the position of relay coil ζ is increased with the increase of angle θ. If the rotation angle of relay coil θ satisfies $\theta \in [\theta_{\text{opt}}, 90°]$, to get the maximum output power P_{out}, the position of relay coil ζ is decreased with the increase of angle θ.

Figure 9 is the iteration result of output power P_{out} in genetic algorithm, considering the position of relay coil ζ, rotation angle of relay coil θ, and load R_{L} at the same time.

It can be seen from Figure 9, the maximum output power P_{out} can be obtained by genetic algorithm in very few iterations. The maximum output power is obtained when the iteration number is about 70. It shows the algorithm advantage of fast convergence to optimize the multi-objective function. After calculation, the rotation angle of relay coil $\theta = 18.57°$, load $R_{\text{L}} = 928.5\,\Omega$, and position of relay coil $\zeta = 0.619$. According to formulas (13) and (14), the maximum output power $P_{\text{out}} = 21.1045\,\text{W}$, and the efficiency $\eta = 58.62\%$.

5. EXPERIMENTAL VALIDATION

In order to test and verify the simulation result, a MCRWPT system with relay coil is designed, as shown in Figure 10. The experimental device is divided into three parts. The first part is a high

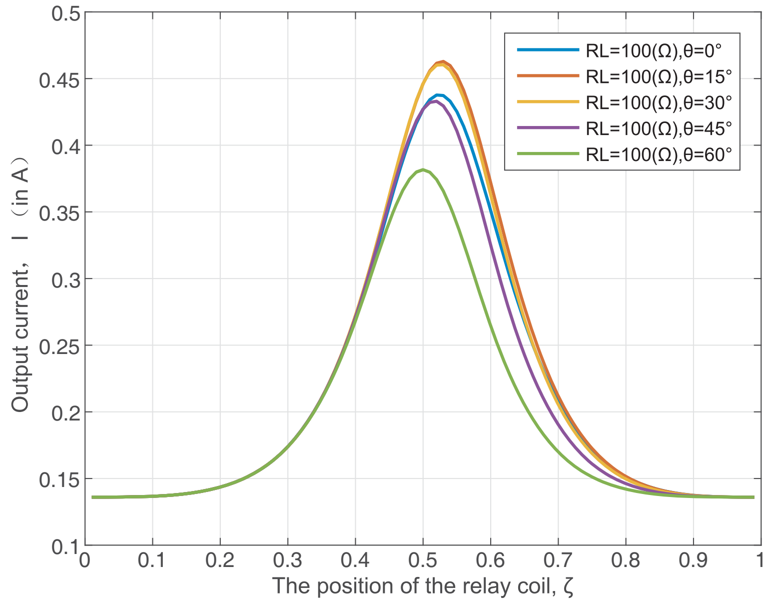

Figure 8. Relationship between the output current I_3 and the location of the relay coil ζ when the load $R_{\mathrm{L}} = 100\,\Omega$.

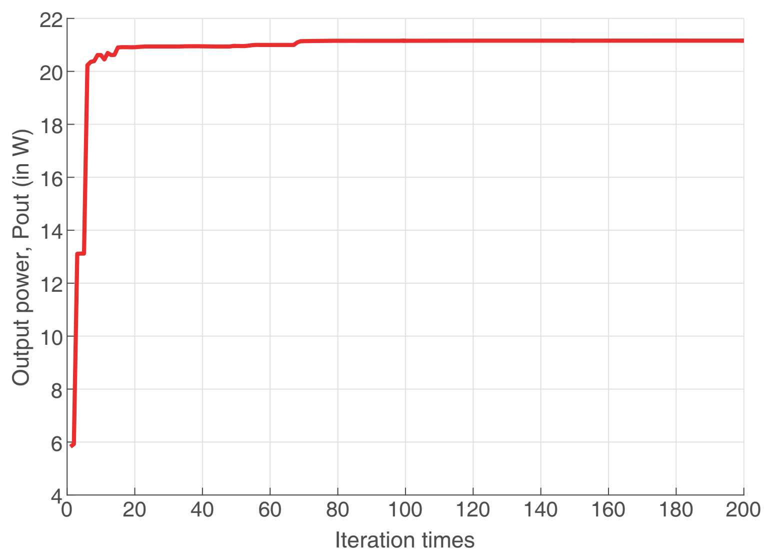

Figure 9. Relationship between the output power P_{out} and the iteration numbers.

frequency signal generating circuit, which provides high frequency AC signals to the high frequency power amplifying circuit. The second part is a high-frequency power amplifier. The DC power supply provides energy for power amplifier. The high-frequency AC signal flows through the amplifier circuit to provide high-frequency power to the transmitting coil. The third part is a coil coupling part, which transmits energy to the load through the conversion of electric field and magnetic field.

Figure 11 shows a physical picture of experimental device. In order to make the transmitting coil self-resonant, it is necessary to adjust the driving signal and power frequency to produce high frequency alternating magnetic field. Firstly, the PXI-5422 arbitrary waveform generator in NI series instruments can send out sinusoidal wave with the frequency of 10 MHz and the voltage of 1 V. The output power of the signal generator is about 3.6 mW. The DC power supply of MS-1510D is used in the laboratory to provide power amplifier with rated voltage of 13.6 V and rated current of 6 A. Then, the sine wave

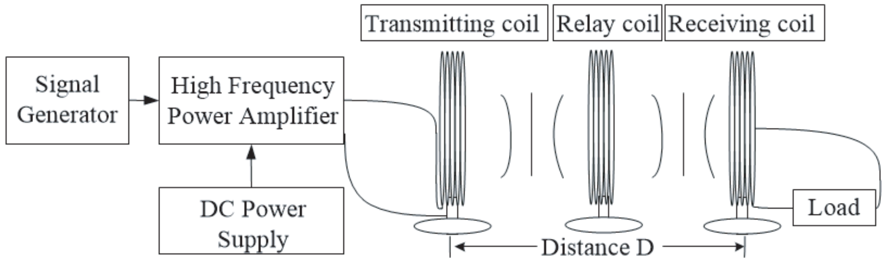

Figure 10. Schematic diagram of experimental device for MCRWPT system with relay coil.

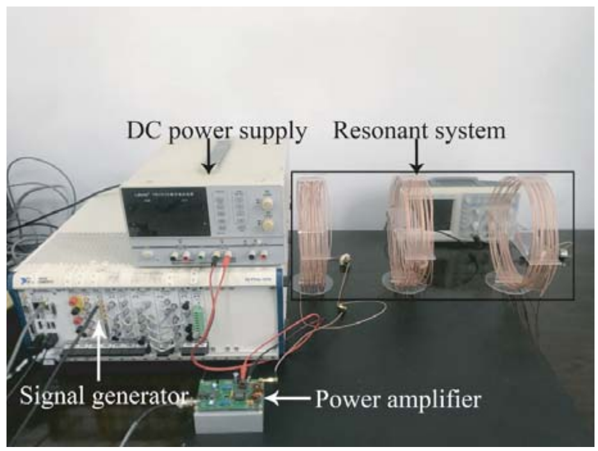

Figure 11. Physical picture of experimental device for MCRWPT system with relay coil.

signal is amplified by a power amplifier. Under the condition of impedance matching, the overall gain of the power amplifier is about 40 dB, and the amplification factor is about 10000 times. The output of the power amplifier is about 36 W measured by a standing wave meter, which provides energy for the transmitting coil. In order to make the system resonant, the transmitting coil, relay coil, and receiving coil are connected in series with a ceramic air adjustable capacitor. In the conversion between electric field energy and magnetic field energy, the energy is transmitted to the load of the receiving coil.

Table 1 shows the data obtained from the operation of experimental device. The distance between the transmitting coil and receiving coil is 0.21 m, and the load is 100 Ω. In the absence of relay coils, the output power is 1.5 W. The system output power is obviously insufficient, and the system is under-coupled. In order to improve the output power, the relay coil is introduced while keeping the position of transmitting coil and receiving coil unchanged. However, when the output power is increased, the frequency splitting occurs due to the excessive coupling between adjacent coils. The frequency splitting

Table 1. Experimental data of position ζ, rotation angle θ, load R_L, and output power P_{out}.

	Position ζ	Angle $\theta/°$	Load R_L/Ω	Output power P_{out}/W
Data 1			100	1.50
Data 2	0.50	0	100	18.24
Data 3	0.52	0	100	18.81
Data 4	0.50	15	100	19.91
Data 5	0.50	0	500	20.50
Data 6	0.61	18.5	930	21.00

phenomenon can be suppressed by taking corresponding measures to further improve the output power. The specific data are shown in Table 1 below.

As shown in data 1, in the traditional two-coil MCRWPT system, when the load is $100\,\Omega$, and the output power is only 1.5 W. When a relay coil is added in the middle of transmitting coil and receiving coil, as shown in data 2, the output power is increased from 1.5 W to 18.24 W. However, the system directly transits from the original under-coupled state to the over-coupled state. In order to suppress frequency splitting, the position of relay coil, rotation angle of relay coil, and load are adjusted, respectively. Compared with data 2, the system output power is further improved, as shown in data 3 to data 6. The experimental device tests and verifies the simulation result in some degree.

6. CONCLUSION

In the MCRWPT system with relay coil, because the positions of transmitting coil and receiving coil are fixed, the introduction of relay coil may make system charging state change from under-coupling state to over-coupling state, and at the same time frequency splitting phenomenon may appear in the system. By adjusting the rotation angle, position of relay coil, and load resistance, the frequency splitting is suppressed so as to further increase the output power. The simulation results show that when the rotation angle $\theta = 18.57^\circ$, the load resistance $R_\mathrm{L} = 928.5\,\Omega$, the position $\zeta = 0.619$, and the maximum output power $P_\mathrm{omax} = 21.1045\,\mathrm{W}$. Compared with the traditional structure that the relay coil is in the middle, the output power changes from 18.24 W to 21.1045 W, increasing by about 15.7%. The transmission efficiency changes from 50.67% to 58.62%, increasing by about 8%. Finally, an MCRWPT system with relay coil is designed and verifies the simulation result in some degree.

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