

A Multi-Relay Wireless Power Transfer System Without Cross Coupling

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Abstract: In a multi-relay wireless power transfer system, the cross-coupling phenomenon between non-adjacent coils will reduce the output power and efficiency of the system. To address the cross-coupling phenomenon in multi-relay wireless power transfer systems, a circular DD coil relay with relative rotation between relays is proposed. By designing the structure of a single coil and the relative rotation angle between coils, the cross-coupling phenomenon in the multi-relay wireless power transfer system is eliminated. Experimental results show that the multi-relay wireless power transfer system using circular DD coil relays can effectively solve the problem of cross-coupling and improve output power and transmission efficiency. In addition, the constant voltage output frequency of the system is studied, which can maintain a constant output voltage when the load changes.

Keywords: Relay coil, Circular DD coil, Wireless power transfer

1. Introduction

In recent years, multi-relay wireless power transfer systems have received increasing attention. Such wireless power transfer systems have significantly improved the coupling strength between coils and extended the transfer distance by introducing relay coils [1][2]. However, with the introduction of relay coils, the cross-coupling between coils has become a problem that cannot be ignored [3][4][5]. Reference [6] systematically analyzed the model mechanism of various multi-relay wireless power transfer systems with cross-coupling. To better solve the problem of power and efficiency reduction caused by cross-coupling, Reference [7] proposed a method to improve the output effect by changing the frequency. In addition to the frequency conversion method, optimization of compensation parameters is another important means to improve transmission performance. It has been reported that adjusting the compensation capacitance can make the multi-relay wireless power transfer system operate under better conditions [8]. Reference [9] proposed a non-resonant compensation method to optimize each capacitor. However, all these methods require precise calculations and real-time control, which are highly complex. Therefore, a method that can eliminate cross-coupling between relay coils without control is of great research value. Circular DD coils can flexibly change the mutual coupling through changes in rotation angle [10]. In this paper, cross-coupling is eliminated through the design of the coupling mechanism, improving the transmission effect of the multi-relay wireless power transfer system. Furthermore, constant voltage output of the system can be achieved by studying the constant voltage frequency of the system [11][12]. In this paper, the constant voltage output frequency of the system is obtained by studying the output characteristics of the system at different frequencies, realizing the constant voltage output of the system.

2. System Design

2.1 System Circuit Topology Design

The circuit topology of the multi-relay wireless power transfer system is shown in Figure 1, where L_1-L_5 is the wireless power transfer relay, and its arrangement is shown in Figure 2. The five coils from left to right are L_1-L_5 . The input DC voltage of the system is V_{DC} . L_f , C_f , C_1 are the compensation inductors and capacitors on the primary side. C_2-C_5 is the compensation capacitor corresponding to L_2-L_5 . C_6 and R_L are the filter capacitor and load resistor respectively. The primary and secondary sides each use an H-bridge inverter and a full-bridge rectifier.

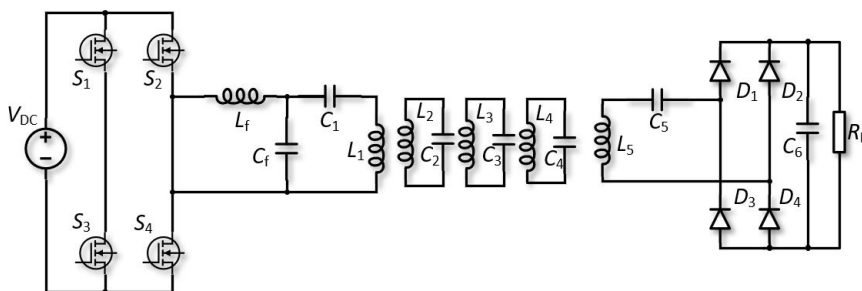


Figure 1 Circuit Topology of a Multi-Relay Wireless Power Transfer System

2.2 System Coupling Mechanism Design

The relay coils are designed as circular DD coils. DD coils have the characteristic of a coupling coefficient of 0 when placed vertically, while circular DD coils can adjust the coupling degree between the two coils according to their relative rotation angle. When they are facing each other directly, the coupling coefficient of the two circular DD coils is the maximum, and when the relative rotation angle is 90 degrees, the coupling coefficient of the two coils is 0. By adjusting the relative rotation angle between the relay coils, the coupling coefficient between two relay coils separated by one relay coil can be made 0: each subsequent relay coil rotates 45 degrees relative to the previous one in sequence. This method can achieve: 1) The coupling coefficients between adjacent relay coils are the same. 2) The coupling coefficient between two relay coils separated by one relay coil is 0. The coupling coefficient between two relay coils separated by two or more relay coils is small and can be ignored. Therefore, by designing the relay coils according to the above principles, a multi-relay wireless power transfer system without cross-coupling can be designed, which has the outstanding advantages of no resonant frequency offset, simple design, and stable operation. A schematic diagram of the coupling mechanism is shown in Figure 2.



Figure 2 Schematic Diagram of Coupling Mechanism in Multi-Relay Wireless Power Transfer System

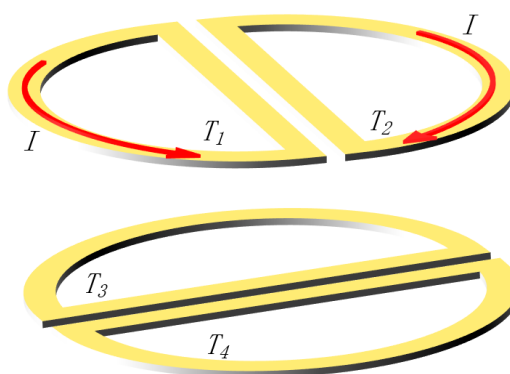


Figure 3 Schematic diagram of the coupling principle of two relay coils

In a multi-relay wireless power transfer system, the working principle of multiple energy transfer relays can be analyzed based on the coupling principle of two relays: Figure 3 shows a schematic diagram of the coupling between two circular DD coils. When the two coils are placed face to face, the generated magnetic fields are in the same direction, and the coupling coefficient is the largest. When the two coils are placed vertically, if there is an excitation current in the first coil, the magnetic induction lines in area T_3 of the second coil are divided into two parts, half from area T_1 of the first coil and half from area T_2

of the first coil. Since the directions of the magnetic induction lines generated by area T_1 and area T_2 are opposite, the magnetic flux in area T_3 of the second coil is 0. Similarly, the magnetic flux in area T_4 of the second coil is also 0. Therefore, when the two circular DD coils are placed vertically, the coupling coefficient between them is 0.

3. System Analysis

The following is the mathematical modeling based on the above model. By equating the inverter part in the circuit shown in Figure 1 to a voltage source U_s , the following circuit can be obtained:

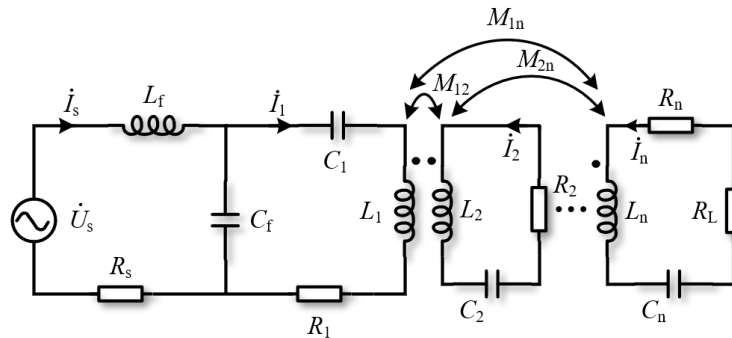


Figure 4 Equivalent Circuit Diagram of Multi-Relay Wireless Power Transfer System

By performing Kirchoff's Voltage Law analysis on the circuit shown in Figure 4, the KVL equation for the multi-relay wireless power transfer system is obtained:

$$\begin{bmatrix} Z_s & -1/(j\omega C_f) & 0 & 0 & \dots & 0 & 0 \\ -1/(j\omega C_f) & Z_1 & j\omega M_{1,2} & j\omega M_{1,3} & \dots & j\omega M_{1,n-1} & j\omega M_{1,n} \\ 0 & j\omega M_{1,2} & Z_2 & j\omega M_{2,3} & \dots & j\omega M_{2,n-1} & j\omega M_{2,n} \\ 0 & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & j\omega M_{n-1,1} & j\omega M_{n-1,2} & j\omega M_{n-1,3} & \dots & Z_{n-1} & j\omega M_{n-1,n} \\ 0 & j\omega M_{1,n} & j\omega M_{2,n} & j\omega M_{3,n} & \dots & j\omega M_{n-1,n} & Z_n \end{bmatrix} \cdot \begin{bmatrix} \dot{I}_s \\ \dot{I}_1 \\ \vdots \\ \dot{I}_n \end{bmatrix} = \begin{bmatrix} \dot{U}_s \\ 0 \\ \vdots \\ 0 \end{bmatrix} \quad (1)$$

Here, ω is the resonant angular frequency, and the impedance of each circuit can be expressed as:

$$\begin{cases} Z_s = j\omega L_f + 1/(j\omega C_f) + R_s \\ Z_1 = R_1 + j\omega L_1 + 1/(j\omega C_1) + 1/(j\omega C_f) \\ Z_1 = R_2 + j\omega L_2 + 1/(j\omega C_2) \\ \vdots \\ Z_{n-1} = R_{n-1} + j\omega L_{n-1} + 1/(j\omega C_{n-1}) \\ Z_n = R_n + j\omega L_n + 1/(j\omega C_n) + R_L \end{cases} \quad (2)$$

When the system is in complete resonance, the resonant angular frequency ω of each circuit equals the operating angular frequency ω_0 of the system. At this time, we have:

$$\omega = \omega_0 = \frac{1}{\sqrt{L_f C_f}} = \frac{1}{\sqrt{(L_1 - L_f) C_1}} = \frac{1}{\sqrt{L_2 C_2}} = \dots = \frac{1}{\sqrt{L_n C_n}} \quad (3)$$

Substituting condition (3) into (1), we get:

$$\begin{bmatrix} R_s & j\omega L_f & 0 & 0 & \dots & 0 & 0 \\ j\omega L_f & R_1 & j\omega M_{1,2} & j\omega M_{1,3} & \dots & j\omega M_{1,n-1} & j\omega M_{1,n} \\ 0 & j\omega M_{1,2} & R_2 & j\omega M_{2,3} & \dots & j\omega M_{2,n-1} & j\omega M_{2,n} \\ 0 & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & j\omega M_{n-1,1} & j\omega M_{n-1,2} & j\omega M_{n-1,3} & \dots & R_{n-1} & j\omega M_{n-1,n} \\ 0 & j\omega M_{1,n} & j\omega M_{2,n} & j\omega M_{3,n} & \dots & j\omega M_{n-1,n} & R_n + R_L \end{bmatrix} \cdot \begin{bmatrix} \dot{I}_s \\ \dot{I}_1 \\ \vdots \\ \dot{I}_n \end{bmatrix} = \begin{bmatrix} \dot{U}_s \\ 0 \\ \vdots \\ 0 \end{bmatrix} \quad (4)$$

The system's output power is:

$$P_{out} = I_n^2 R_L \tag{5}$$

4. System Simulation

4.1 Cross-Coupling Simulation

To obtain the mutual inductance between the five coils, a finite element simulation software was used for modeling and simulation. The outer radius of the coils was set to 100mm, the inner radius to 76mm, the number of turns to 12, the distance between adjacent coils to 50mm, and the adjacent coils were rotated by 45 degrees. The simulation diagram is shown in Figure 5 below.

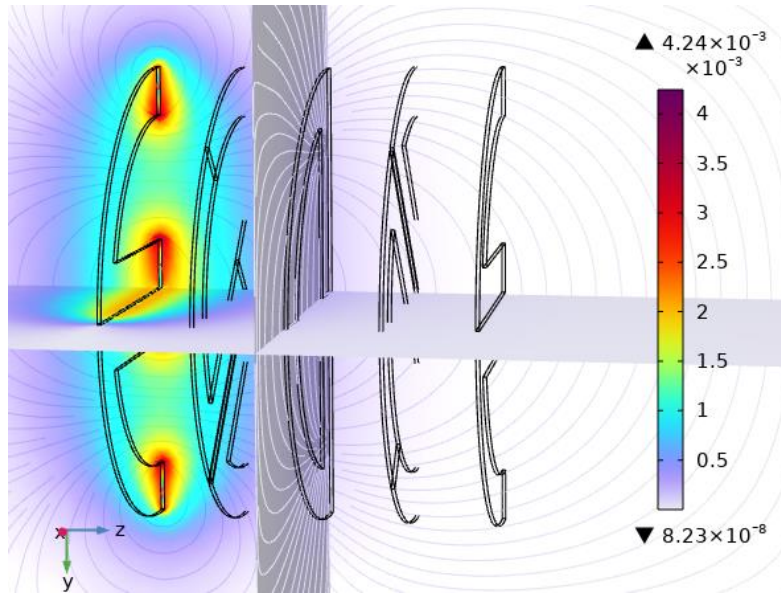


Figure 5 Finite Element Simulation Diagram

The following results obtained through finite element simulation are shown in Table 1. It can be seen from the table that the coupling coefficients of adjacent relay coils are equal, the coupling coefficient between two relay coils separated by one relay coil is close to 0, and the coupling coefficients between two coils separated by two or three relay coils are very small and can be ignored.

Table 1 Coil Coupling Coefficient Table

Parameters	Value
$k_{12}, k_{23}, k_{34}, k_{45}$	0.12
k_{13}, k_{24}, k_{35}	0.000007
k_{14}, k_{25}	0.006
k_{15}	0.002

4.2 Simulation of Output Voltage Variation with Load Resistance

When electrical equipment (such as some monitoring devices) is working, the value of its load resistance may change. When the value of the load resistance changes, it is necessary to maintain a constant output voltage to ensure the normal operation of the electrical equipment. Therefore, it is necessary to study at which frequencies the multi-relay wireless power transmission system operates such that its output voltage does not change with the change of the load resistance. Through simulation software, the curve of the system's output voltage changing with frequency when the load resistance changes is obtained, so as to study the constant voltage frequency. The simulation results are shown in Figure 6 below:

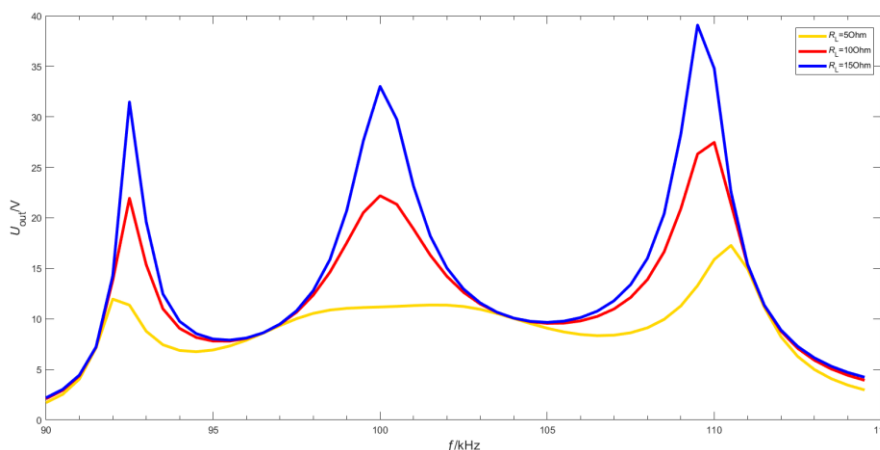


Figure 6 Frequency Response of Output Voltage with Varying Load Resistance

As shown in the figure, there is more than one constant voltage transmission frequency in the multi-relay wireless power transmission system. The figure shows three constant voltage frequencies: 96.8kHz is the first constant voltage frequency, 104.1kHz is the second constant voltage frequency, and 111.3kHz is the third constant voltage frequency. Among them, the voltage change rate at the second constant voltage frequency of 104.1kHz is the smallest, with the smallest slope. Therefore, 104.1kHz is the optimal constant voltage transmission frequency.

5. Experimental Verification

5.1 Experimental Results at Resonant Frequency

Conduct experimental verification of the circuit based on the above simulation results. The circuit data for the experimental verification are shown in Table 2 below:

Table 2 Circuit Parameter Values

Parameters	Value
f (kHz)	100
U_{in} (V)	24
L_1-L_5 (uH)	55
L_f (uH)	12
C_f (nF)	211
C_1 (nF)	59
C_2-C_5 (nF)	46
R_L (Ω)	20

Based on the parameters shown in Table 2, experimental verification was conducted, and the resulting output voltage on the load resistor is shown in Figure 7.

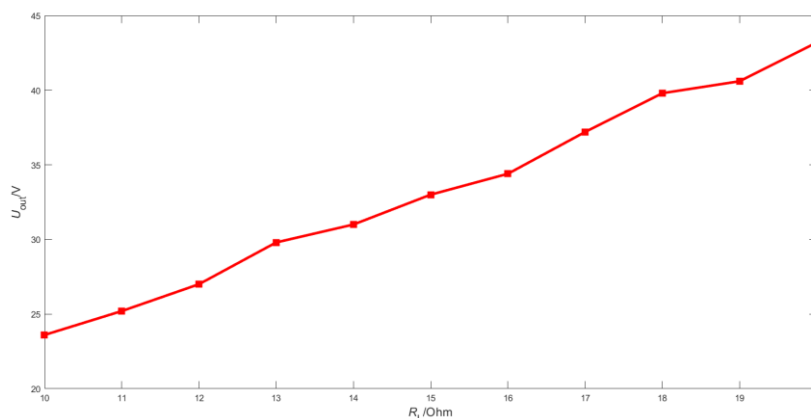


Figure 7 Output Voltage of Load Resistor at Resonant Frequency

The voltage across the load resistor R_L is shown in the figure above. According to the above simulation results, it can be seen that after using the DD circular coil, a larger power can be achieved at the designed resonant frequency, realizing the design goal of wireless power transfer at the resonant frequency.

5.2 Experimental Results at the Frequency of Constant Voltage

According to the simulation results, the multi-relay wireless power transfer system can achieve a constant voltage output at the constant voltage frequency of 104.1 kHz. After changing the operating frequency of the system to 104.1 kHz, the following results can be obtained through experimental verification of the system.

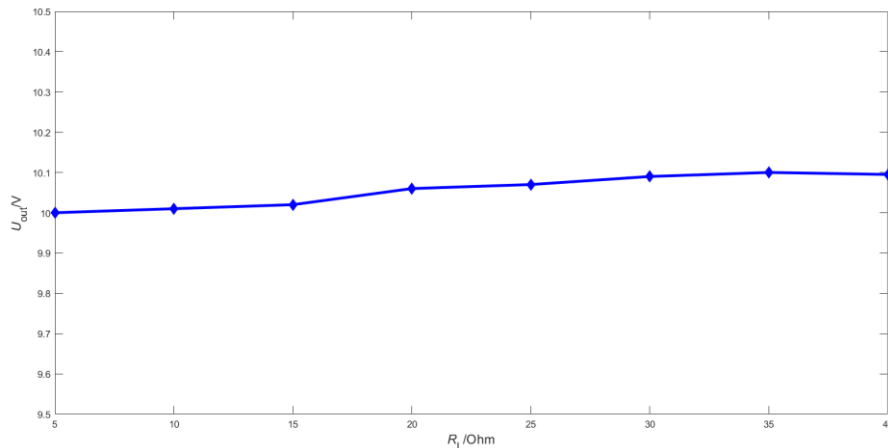


Figure 8 Voltage Variation with Load Resistance

As shown in Figure 8 above, it is the experimental result of the output voltage varying with the load. It can be seen from the result that when the load resistance changes within the range of 5-40 Ω , the voltage basically remains constant at 10V. Its voltage variation rate is less than 1%, which achieves the design goal of constant voltage output for the multi-relay wireless power transmission system.

6. Conclusion

In summary, the coupler of the cross-coupling-free multi-relay wireless power transfer system based on circular DD coils studied in this paper consists of five circular DD coils. The relative rotation angle between adjacent circular DD coils is 45°, the radius of each coil is 100mm, the distance between adjacent coils is 50mm, and the total transmission distance of the five coils is 200mm. The circuit model of the system was established and analyzed. Under the guidance of this analysis, a finite element simulation software was carried out to obtain the coupling coefficients between the five coils, and based on this, the constant voltage output frequency was calculated. After obtaining the constant voltage output frequency, the wireless power transfer experiment with five coils was conducted. The experiment was divided into two parts: one was the experiment at the resonant frequency, where the output voltage of the coefficient was 43V, and a relatively large voltage and power output could be achieved at the designed resonant frequency of 100kHz; the other was the experiment at the constant voltage output frequency, where a constant voltage output of 5-40 Ω could be achieved at the constant voltage output frequency, with an output voltage of 10V, and the voltage fluctuation was less than 1% in the range of 5-40 Ω .

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