Design and Optimization of Magnetic Coupled Resonant Wireless Power Transfer System at Weak - coupling Region

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Abstract. Frequency splitting is one of the hot topics in the research of magnetic coupling wireless power transfer technology. Its purpose is to improve the transmission efficiency by eliminating the frequency splitting at the over-coupled region of the system. Frequency splitting does not occur at the weak coupling region. The transmission characteristics of the system in weak-coupled region are also of research significance. The mathematical model of the system's transmission characteristic was established by equivalent circuit theory. Several key factors that affect the transmission characteristics of the system, self-inductance of the coil, mutual inductance between the coils, load resistance and so on, were obtained. A magnetically coupled resonant wireless power transfer system is designed and A method of coil design is proposed. The transmission efficiency of the system at the weak-coupling region was improved by optimized the design of the coil. Simulation and experimental results had good consistency. The results show that the transmission performance of the system at the weak-coupling area was improved.

1. Introduction

Wireless power transfer (WPT) technology has been widely used in electric vehicles, portable electronic devices, industrial manufacturing and implantable medical devices since the inspiring work of Nikola Tesla. As first proposed by MIT in 2007 [1], magnetic coupling resonant (MCR) WPT technology was much more convenient than traditional inductive coupling technology. MCR WPT has a high transmission efficiency in a long effective transmission distance, so it has triggered a great deal of research interest [2,3].

For the design of MCR WPT systems, power transfer efficiency was one of the most important factors to evaluate the transfer performance of the system. In order to enhance power transfer efficiency, previous work usually focused on impedance matching [4], frequency splitting [5,6], relay resonators [7] and so on. In addition, different from traditional inductive WPT, optimization approaches could be used to achieve the maximum power transfer efficiency of MCR WPT system at a certain distance. In the case of fixed load, mutual inductance as a critical factor to optimize the efficiency of WPT system needed more in-depth analysis [8]. In order to eliminate the frequency splitting phenomenon, literature [10] proposed a method of adjusting the load resistance. Due to the fact that the maximum efficiency point of the MCR WPT system was not the work frequency point in the strong coupling region. Literature [11] proposed the impedance matching method to improve the transmission efficiency. This means the distance between the sending coil and receiving coil could not be zero. The system usually worked at weak-coupled region, where the frequency splitting phenomenon has not occurred. Therefore, the transmission characteristics of the system which worked

at the weak coupling region need further study. In addition, the size of the receiving coil was limited in the field of the implantable medical devices. It is an urgent problem to optimize the transmission characteristics of the system through the design of the coil. This paper presented a coil design method. The proposed method not only improves the transmission efficiency of a system which worked at weak-coupled region, but also meets the need of the coil miniaturization. The correctness of the optimization method was verified by simulation and experiment. And an MCR WPT system was designed. In order to improve the receiving performance of the system in the weak-coupling region, the receiver selected the voltage doubler rectifier. Finally, the rectification circuit was tested.

2. Analysis of the WPT system

For implantable medical devices, the MCR WPT system has higher transmission efficiency and greater transmission distance than the Inductive Power Transfer, making it easier to transfer power through deeper biological tissue to the receiving device. This paper analyzes the four-coil MCR WPT system, since it could reduce the influence of the transmitting circuit and the receiving circuit at the sending coil and the receiving coil.
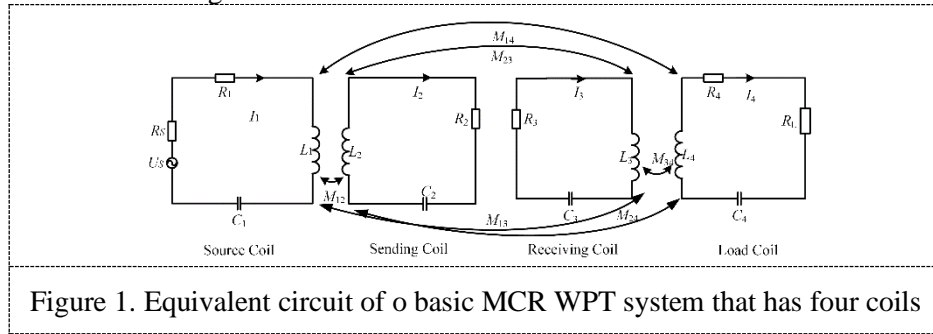

Figure 1. Equivalent circuit of o basic MCR WPT system that has four coils

Figure.1 shows the equivalent circuit model of the MCR WPT system. It consists of a source coil, a sending coil, a receiving and load coil. L_i is the inductance of the ith coil; C_i is the corresponding resonant capacitor; R_i is the parasitic resistance of coil (where i=1, 2, 3, 4). R_L is the load resistance. The coefficients M_{12}, M_{23} and M_{34} are the dominant coupling coefficient, while M_{13}, M_{14} and M_{24} are negligible here. By applying circuit theory to this system, according Figure. 2 we can obtain:

$$
\begin{cases}
I_1(R_S + R_1 + j\omega L_1 + \dfrac{1}{j\omega C_1}) + j\omega I_2 M_{12} = U_s \\[2mm]
I_2(R_2 + j\omega L_2 + \dfrac{1}{j\omega C_2}) + j\omega(I_1 M_{12} - I_3 M_{23}) = 0 \\[2mm]
I_3(R_3 + j\omega L_3 + \dfrac{1}{j\omega C_3}) + j\omega(I_4 M_{34} - I_2 M_{23}) = 0 \\[2mm]
I_4(R_L + R_4 + j\omega L_4 + \dfrac{1}{j\omega C_4}) + j\omega I_3 M_{34} = 0
\end{cases}
\tag{1}
$$

And then:

$$
k_{ij} = M_{ij} / \sqrt{L_i L_j}
\tag{2}
$$

Where $0 < k_{ij} < 1$; i=1,2,3,4; j=1,2,3,4; $i \neq j$.

In MCR WPT systems, the scattering(S) parameters are used to analyzed the forward gain [14]. S_{21} was defined as the ratio of output voltage to input voltage. The transmission efficiency of the system can also be expressed as:

$$
S_{21} = 2 \frac{U_L}{U_S} (\frac{R_S}{R_L})^{1/2}
\tag{3}
$$

Using (1), one can obtain the voltage across the load resistor:

$$
\frac{U_L}{U_S} = \frac{i\omega^3 k_{12} k_{23} k_{34} L_2 L_3 \sqrt{L_1 L_4} R_L}{(k_{12}^2 k_{34}^2 L_1 L_2 L_3 L_4 \omega^4 + Z_1 Z_2 Z_3 Z_4 + \omega^2 (k_{12}^2 L_1 L_2 Z_3 Z_4 + k_{23}^2 L_2 L_3 Z_1 Z_4 + k_{34}^2 L_3 L_4 Z_1 Z_2))}
\tag{4}
$$

Where

$$\begin{cases} Z_1 = R_S + R_1 + j\omega L_1 + \dfrac{1}{j\omega C_1} \\[2mm] Z_2 = R_2 + j\omega L_2 + \dfrac{1}{j\omega C_2} \\[2mm] Z_3 = R_3 + j\omega L_3 + \dfrac{1}{j\omega C_3} \\[2mm] Z_4 = R_L + R_4 + j\omega L_4 + \dfrac{1}{j\omega C_4} \end{cases} \tag{5}$$

3. System design

Transdermal wireless power transfer system can be divided into external transmission circuit and internal receiving circuit, as showed in Figure 2. The external transmitting part includes a DC power supply, an inverter circuit and a transmitting coil. The receiving part includes a receiving coil, a rectifier circuit and a load.

3.1. The design of the transmitting circuit.

As the theoretical energy conversion rate of the Class-E power amplifier was 100%, and it has a simple structure. Therefore, the transmitter inverter circuit selection Class-E power amplifier. The circuit structure of the Class-E power amplifier was shown in Figure 2.
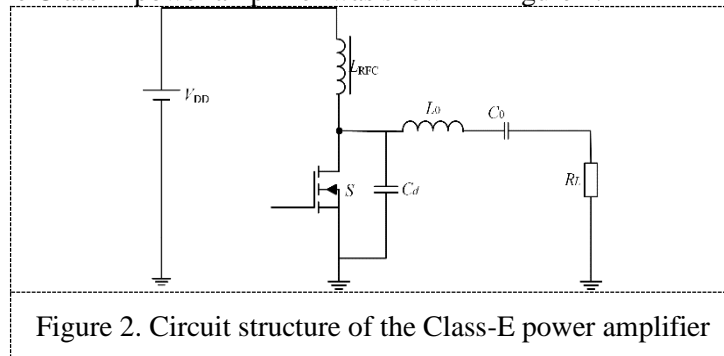

Figure 2. Circuit structure of the Class-E power amplifier

As showed in Figure 2. The topology of the Class-E power amplifier includes DC input power V_{DD}, choke inductor L_{RFC}, shunt capacitor C_d, switch S, L_0-C_0 series resonant filter circuit and load R_L. The choke inductor act as a current stabilizer, it have a high AC impedance and only allow the DC component in V_{DD} pass through. The switch S is periodically turned on and off in the RF input range. The series resonant filter circuit operates at the resonant frequency, so that the basic frequency signal is transmitted to the load, whose role is to keep the output signal sinusoidal.

3.2. The design of the resonant coil.

Due to the particularity application in the field of implantable medical devices, resonant coils of wireless power transfer system require special consideration. For receiving coils, the size was limited due to the size of the device. In the wireless energy transmission system, there were three main types of winding methods as mentioned in section III. They were shown in Figure 3.
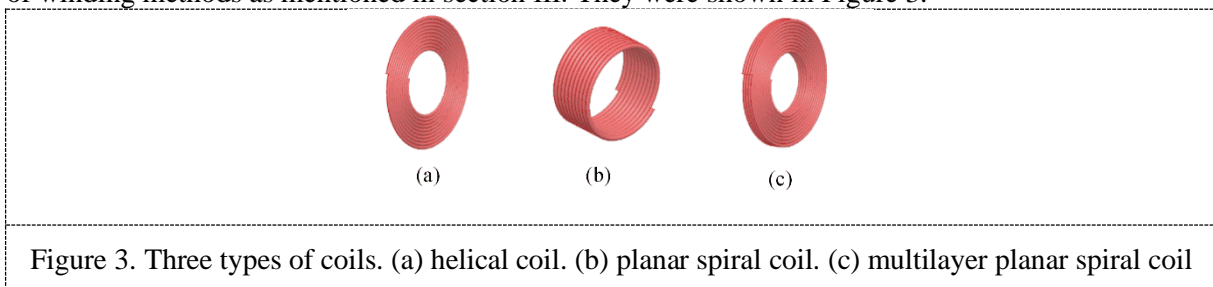

(a)   (b)   (c)

Figure 3. Three types of coils. (a) helical coil. (b) planar spiral coil. (c) multilayer planar spiral coil

Firstly, assumed that these three types of coils have a number of turns of 20, an inner diameter of 21.22 mm and a wire diameter of 1.10 mm. The volumes of these three types of coils were 3538.02

mm^3, 8856.57 mm^3, 3112.17 mm^3, respectively (the number of layers of the multilayer planar spiral coil was two). Therefore, under the condition of certain coil parameters, the volume of the multi-layer planar spiral coil was the smallest, and the double-layer spiral coil was selected as the receiving coil in this paper.
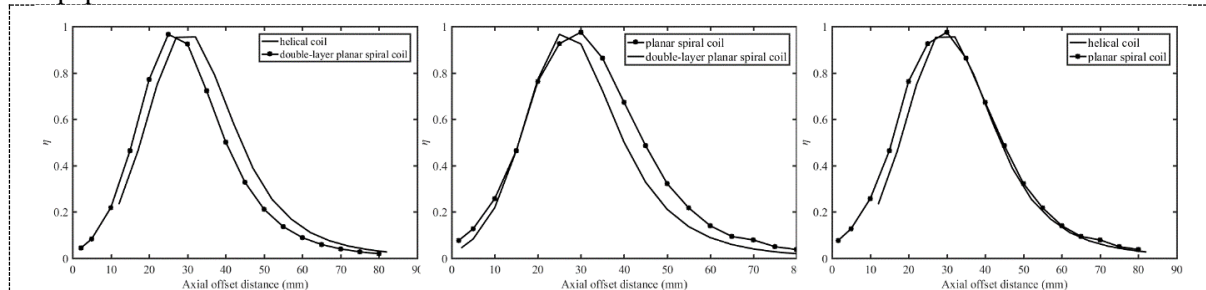

Figure 4. Changes in transmission efficiency of different types of transmission coil. (a) Helical coil and double-layer planar spiral coil. (b) Planar spiral coil and double-layer planar spiral coil. (c) Helical coil and planar spiral

Secondly, assumed that the outer diameter of these three types of coils was 21.22 mm and the diameter of the wire was 1.10 mm. So the number of turns of the helical coil was two, the number of turns of the planar spiral coil was ten, and the multilayer planar spiral coil was ten turns of two layers each. These three types of coils were used as the transmitting coil and the receiving coil was the double-layer planar spiral coil. Compared with these three cases, the change of the system transmission efficiency was shown in Figure. 4. As shown in Figure. 4, comparing these three types of transmitting coils, the system had better transmission characteristics when the transmitting coil was a single-layer planar spiral coil. Therefore, a single-layer planar spiral coil was selected as the transmitting coil in this paper.

4.Simulation and experiment

4.1 Finite Element Simulation and Experimental Measurement of the coupling coefficients

Their parameters were two layers of ten turns per layer, the inner radius of the coil is 10.22 mm, the material of the wire was copper and the wire diameter was 1.10 mm. Thus, the mutual inductance between them can be obtained by formula (12), finite element simulation and experiment. Therefore, the coupling coefficient can be obtained indirectly. The Mutual inductance measurement experiment platform was shown in Figure. 5.
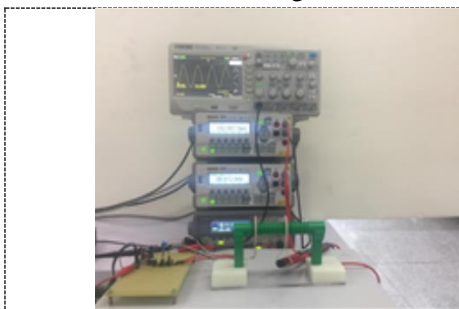

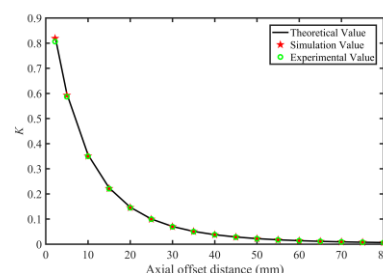Figure 5. Mutual inductance measurement experiment platform

Figure 6. Theory, simulation and experimental results of the coupling coefficient

From Figure. 6 we could see that the theoretical value, the simulation value and the experimental value were in good agreement. The maximum relative error between theoretical and simulated values was 1.5%. The maximum relative error between theoretical and experimental values was 2.6%. The maximum relative error between simulated and experimental values was 1.7%. In the simulation of

ANSYS software, different mesh subdivisions bring discrete error, which was the main source of the relative error. this paper reduces the random error existing in the experiment by multiple measurements. It can be seen from Figure 6 that the relative error is less than 5%. within the allowable error range of the project. The coupling coefficient decreases with the increase of the axial offset.

4.2. Distance experiment

Under the condition that the receiving coil is fixed as a double-layer planar spiral coil, the transmitting coil used for the wireless energy transmission experiment is a single-layer planar spiral coil and a double-layer planar spiral coil, respectively. The wireless power transfer experiment platform was shown in Figure.7. In the experiment, the working frequency of the system was 1MHz. The parameters of the power coil, the load coil and the receiving coil were kept consistent, and they were all double-layer planar spiral coils. Load resistance was 50Ω. By selected the appropriate matching tunable capacitor to make the coil worked at the resonant frequency. In the experiment, the axial distance between the transmitting coil and the receiving coil changes every 5mm. And the peak-to-peak voltage across the load was measured. The experimental results were shown in Figure. 8.

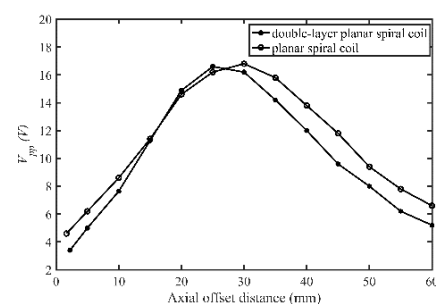Figure 7. Experiment platform of the wireless power transfer.

Figure 8. Experiment results of the distance experiment

As can be seen from Figure. 8, the peak-to-peak load voltage increases first and then decreases with increasing axial distance and reaches the maximum at 30mm. As the distance continues to increase, the voltage across the load begins to decrease, indicating that the system has experienced frequency splitting. When the sending coil was a single-layer planar spiral coil, the higher output voltage can be received in the weak-coupling region load. It can be seen from the above analysis, when the inner diameter and the turn of the single-layer planar spiral coil kept consistent with the double-layer planar spiral coil, sending coil choose a single-layer planar spiral coil enhances the wireless energy transmission of the system, improved the transmission performance in the weak-coupling region.

4.3. Receiving circuit experiment

In order to verify the operation of the voltage doubler rectifier circuit as a rectifier in the wireless power transfer system, the receiver circuit was measured experimentally. The voltage waveform on the load coil and the output voltage waveform of the voltage doubler rectifier circuit are measured.
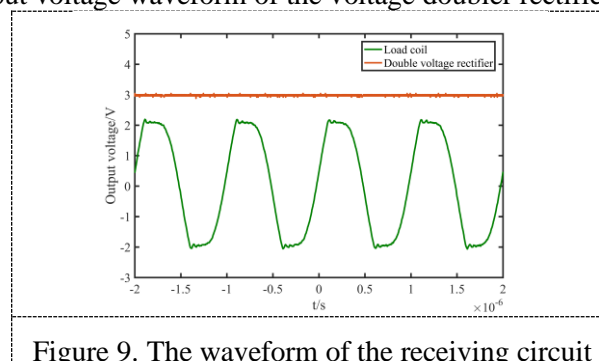

Figure 9. The waveform of the receiving circuit

The data obtained from the oscilloscope are exported and processed by Matlab software. The test waveform of the receiving circuit was shown in Figure. 9. The orange line was output voltage waveform of voltage doubler rectifier. The green curve was voltage waveform of the load coil. It can be seen from Figure. 9 that the output voltage of the voltage doubler rectifier circuit was close to twice the effective value of the AC voltage on the load coil. The output voltage was stable, which enhances the transmission performance of the system in the weak-coupling region.

5. Conclusion

In this paper, the theoretical model of the magnetic coupling resonant wireless power transfer system was established. The transmission characteristics of the system were analysed and the phenomenon of frequency splitting is explained. The key factors that affect the system are obtained. The transmission characteristics of the magnetic coupling resonant wireless power transfer system in the weak-coupling region were conducted a key research. Aimed at the special application field of implantable medical devices, a coil design method was proposed to improve the transmission characteristics of the system in the weak-coupling region. The percutaneous wireless power transfer system was designed. In order to solve the problem of low energy transmission and low output voltage amplitude under weak energy reception, the voltage doubler rectifier circuit was selected as the receiver rectification circuit. The results show that the system designed in this paper can improve the transmission characteristics of the system in the weak-coupling region.

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