Study on efficiency of different topologies of magnetic coupled resonant wireless charging system

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Abstract. This paper analyses the relationship between the output power, the transmission efficiency and the frequency, load and coupling coefficient of the four kinds of magnetic coupled resonant wireless charging system topologies. Based on mutual inductance principle, four kinds of circuit models are established, and the expressions of output power and transmission efficiency of different structures are calculated. The difference between the two power characteristics and efficiency characteristics is compared by simulating the SS (series-series) and SP (series-parallel) type wireless charging systems. With the same parameters of circuit components, the SS structure is usually suitable for small load resistance, while the SP structure can be applied to large load resistors, when the transmission efficiency of the system is required to keep high. If the operating frequency deviates from the system resonance frequency, the SS type system has higher transmission efficiency than the SP type system.

1. Introduction

As early as 1914, Tesla put forward the idea of using wireless mode for power transmission [1]. In 2007, the MIT research team, using two identical copper coils, successfully lightened a 60W bulb two meters outside, which provided ideas and new methods to study the wireless power transmission technology [2,3].

Magnetic coupled resonant wireless power transmission technology uses the principle of resonance. By setting the parameters of the device reasonably, the coil has the same resonant frequency as the whole system. Under the power supply of the resonant frequency, the system can achieve an "electric resonance" state. In this condition, energy can be transmitted efficiently between the transmitter and the receiver [4]. The magnetic coupled resonant wireless charging system consists of three parts: power supply, energy transmission device (coil resonator) and energy receiver. At present, the research about wireless charging technology focuses on topology and transmission coil innovation [5].

There are two basic structures of magnetic coupled resonant wireless charging system: two coil structure and multi coil structure [6]. The two coil structures of magnetic coupled resonant wireless charging system is divided into four different topologies [7]. On the basis of different topologies, different capacitors or inductors can be incorporated into the system circuit loop to form a new topology [8,9]. The four common topology structures are: transmitting coil series resonant, receiving coil series resonant (SS); transmitting coil series resonant, receiving coil parallel resonant (SP); transmitting coil parallel resonant, receiving coil series resonant (PS); transmitting coil parallel parallel
resonant, receiving coil parallel resonance (PP).

2. **Analysis of system theory**

2.1. *The basic principle of a wireless charging system*

The basic principle of a wireless charging system: The control part of the transmitting end completes the rectification and inversion of the electric energy supplied by the power section and converts it into a high-frequency alternating current. Then, the converted high-frequency alternating current is transmitted to the controller by electromagnetic conversion between the transmitting coil and the receiving coil. Finally, through the adjustment and rectification of the receiving end controller, the high-frequency alternating current is converted into direct current.

2.2. **Topology model of wireless charging system**

The analytical model of magnetic coupled resonant wireless power transmission can be established by equivalent circuit theory [10,11]. The circuit theory model of a wireless charging system can be divided into four kinds, as shown in figure 1.

![Four kinds of topology model of wireless charging system](image)

**Figure 1.** Four kinds of topology model of wireless charging system.

As shown in figure 1 above, $U_1$ is the voltage source, $C_1$ and $C_2$ are the compensation capacitors of the transmitter and receiver of the system. $L_1$ and $L_2$ are transmitter coils and receiver coils. $R_1$ and $R_2$ are the equivalent internal resistances of the transmitting coils and receiving coils, while $R_L$ is the equivalent load at the receiving end. Because the internal resistance of the power supply is much smaller than the coil’s internal resistance and the load resistance, it is negligible.

![Simplified circuit](image)

**Figure 2.** Simplified circuit: (a) mutual inductance coupling model and (b) equivalent circuit.
These four kinds of topology structure circuits can be simplified as the mutual inductance coupling model circuit and equivalent circuit according to the mutual inductance principle, as shown in figure 2. As shown above, figure 2(a) is a simplified mutual inductance coupling model. \( jX_1 \) and \( jX_2 \) are the equivalent reactance of the loop at the transmitter and receiver respectively, and \( j\omega M \) is the mutual inductance of both ends of the coil (\( \omega \) is frequency and \( M \) is mutual inductance). Figure 2(b) is a simplified equivalent circuit. Among them, \( Z_1 \) and \( Z_2 \) are self-impedance of the transmitter and receiver coil circuit, \( Z_{12} \) is impedance reflected from receiver circuit to transmitter circuit, \( Z_{21} \) is impedance reflected from the transmitter circuit to receiver circuit. While \( U_2 \) is the equivalent voltage source reflected from transmitter circuit to receiver circuit.

According to the circuit theory, it can be concluded that:

\[
\begin{align*}
  Z_1 &= jX_1 + R_1 \\
  Z_2 &= jX_2 + R_2 + R_L
\end{align*}
\]

(1)

\[
\begin{align*}
  Z_{12} &= \frac{\omega^2 M^2}{Z_2} \\
  Z_{21} &= \frac{\omega^2 M^2}{Z_1}
\end{align*}
\]

(2)

\[ U_2 = \frac{j\omega MU_1}{Z_1} \]

(3)

For type SS, the \( jX_1 \) and \( jX_2 \) can be computed as follows:

\[
\begin{align*}
  jX_1 &= j\omega L_1 + \frac{1}{j\omega C_1} \\
  jX_2 &= j\omega L_2 + \frac{1}{j\omega C_2}
\end{align*}
\]

(4)

Due to the characteristics of series resonance, \( \omega^2 C = 1 \), in the SS type structure, the resistance values of each impedance element can be computed by expression (5).

\[
\begin{align*}
  Z_1 &= R_1 \\
  Z_{12} &= \frac{\omega^2 M^2}{R_2 + R_L} \\
  Z_2 &= R_2 + R_L \\
  Z_{21} &= \frac{\omega^2 M^2}{R_1}
\end{align*}
\]

(5)

The \( I_1 \) and \( I_2 \) are currents flowing through the transmitting coil loop and the receiving coil circuit, respectively. The expression is as follows:

\[
\begin{align*}
  I_1 &= \frac{U_1}{Z_1 + Z_{12}} \\
  I_2 &= \frac{U_2}{Z_2 + Z_{21}}
\end{align*}
\]

(6)

The transmission power and efficiency analysis of SS structure can be obtained:

\[
\begin{align*}
  P_{in} &= U_1 I_1 = \frac{U_1^2 (R_2 + R_L)}{R_1 (R_2 + R_L) + \omega^2 M^2} \\
  P_{out} &= I_2^2 R_L = \frac{\omega^2 M^2 U_1^2 R_L}{(R_1 (R_2 + R_L) + \omega^2 M^2)^2}
\end{align*}
\]

(7)
\[ \eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{\omega^2 M^2 R_L}{(R_2 + R_L) \left[ R_1 (R_2 + R_L) + \omega^2 M^2 \right]} \] (8)

Similarly, the other three topologies can be computed using the above methods. There is something different: For the wireless charging system with type SS and PS, the current flowing through the load is consistent with the current flowing through the coil. But for the wireless charging system which is parallel to the receiving end, like type SP and PP, the current flowing through the load is different from the current flowing through the coil.

The following expression (9) uses \( I_L \) to represent the current flowing through the load, in the SP and PP type wireless charging systems. The expression of output power is expressed as equation (10).

\[ I_L = \frac{I_2}{\gamma / \omega C_2 + R_L} \cdot \frac{1}{\gamma / \omega C_2} = \frac{I_2}{1 + \gamma / \omega C_2 R_L} \] (9)

\[ P_{\text{out}} = I_L^2 R_L \] (10)

The output power, input power and efficiency of the remaining three topologies can be calculated as follows:

\[ P_{\text{in-SP}} = \frac{U_1^2 \left( R_2 + \gamma / \omega C_2 \right)}{(R_1 + \gamma / \omega C_1) \left[ R_2 + \gamma / \omega C_2 \right] + \omega^2 M^2} \cdot \frac{1}{(R_1 + \gamma / \omega C_1) \left[ R_2 + \gamma / \omega C_2 \right] + \omega^2 M^2} \] (11)

\[ P_{\text{out-PS}} = \frac{U_1^2 \left( R_1 + R_L \right)}{(R_1 + \gamma / \omega C_1) \left[ R_1 + R_L \right] + \omega^2 M^2} \cdot \frac{1}{(R_1 + \gamma / \omega C_1) \left[ R_1 + R_L \right] + \omega^2 M^2} \] (12)
The system has more advantage and the inductance of the coil at the transmitter is set to 248 \( \mu \text{H} \), and the inductance of the coil at the receiving end is set to 149 \( \mu \text{H} \). The resonance frequency of the system is set to 85 kHz, and the coupling coefficient is set to 0.182. The 60-ohm-resistance is selected as the load resistance. The voltage source is selected as a three-phase alternating current of 220 V.

### 3. Simulation

The following six graphs show the frequency characteristics of the SS and SP wireless charging systems after simulation by using MATLAB.

#### 3.1. Simulation parameter setting

The internal resistances of the transmitter coil and the receiving coil are set to 0.5 ohms and 0.2 ohms respectively. The inductance of the coil at the transmitter is set to 248 \( \mu \text{H} \), and the inductance of the coil at the receiving end is set to 149 \( \mu \text{H} \). The resonance frequency of the system is set to 85 kHz, and the coupling coefficient is set to 0.182. The 60-ohm-resistance is selected as the load resistance. The voltage source is selected as a three-phase alternating current of 220 V.

#### 3.2. Simulation of SS type topology

Firstly, the influence of the load, the coupling coefficient and the operating frequency on the resonant network of the wireless charging system with SS topology is analysed.

The following figure 3 shows the influence of the coupling coefficient on the transmission efficiency.
Figure 3. The relationship between the efficiency and coupling coefficient (SS).

As shown in the figure above, the transmission efficiency rises with the increase of the coupling coefficient.

The influence of load resistance on the transmission efficiency of the system is shown in figure 4.

Figure 4. The influence of load on the transmission efficiency of the SS system.

The curve in the graph shows that the system transmission efficiency decreases as the load increases when the load resistance exceeds a certain value.

The simulation diagram of the relationship between the system transmission efficiency and the operating frequency is as follows. Turn the system operating frequency to a variable parameter that changes the range between 80 kHz-95 kHz as shown in figure 5.

The maximum efficiency point of the system deviates from the resonant frequency. But there is still a high efficiency at the resonant frequency.

3.3. Simulation of SP type topology

The following picture shows the frequency characteristics of the SP wireless charging system. Figure
Figure 5. The relationship between the efficiency and the frequency (SS).

Figure 6. The relationship between efficiency and coupling coefficient (SP).

Figure 7. The influence of load on the transmission efficiency of the SP system.
From the above figure, we can see that the efficiency of coupling coefficients is very similar between the SP resonant network and the SS resonant network, and the transmission efficiency increases as the coupling coefficient increases.

As shown in Figure 7, the transmission efficiency of the system keeps increasing with the increase of the load resistance. When the resistance is over 100 ohms, the efficiency is slowly increased and is stabilized at around ninety percent. At this point, there are great differences between the SP type system and the SS system.

The last graph is concerned with the relationship between the efficiency of the SP structure system and the operating frequency. The other parameters remain the same, allowing the operating frequency to vary between 80 kHz-95 kHz.

![Graph](image.png)

**Figure 8.** The relationship between the efficiency and the frequency (SP).

Figure 8 is a frequency efficiency characteristic diagram of an SP system. As shown in figure 8, the maximum efficiency point is close to the resonant frequency 85 kHz. But with the decrease of the operating frequency, the efficiency will drop rapidly.

4. Conclusion

For the four topologies of a wireless charging systems, series of systems are much simpler than parallel systems. The PP and PS type systems require the use of current sources which are infrequently used. Therefore, type SS and SP are more suitable for practical applications than the other two structures.

By comparing the previous SS and SP topologies, the simulation of a wireless charging system can be obtained: There is no great difference between the SS system and the SP type system. Compared with type SS, the SP topology is better suited for systems with a relatively large load resistance because it can maintain high efficiency under heavy load conditions. However, the SS type system is able to withstand large frequency fluctuations while maintaining high efficiency.

References

[1] Huang X L, Tan L L, et al 2013 Overview of research and application of wireless charging technology *Transactions of China Electrotechnical Society* **28** 101-11

[2] Zhao Z M, Zhang Y M, et al 2013 Recent advances in magnetically coupled resonant charging technology *Proceedings of The Chinese Society for Electrical Engineering* **33** 31-13

[3] Jang Y and Jovanović M M 2003 A contactless electrical energy transmission system
for portable-telephone battery chargers *IEEE Transactions on Industrial Electronics* **50** 3520-7

[4] Qu X D 2016 Research on wireless charging system of electric vehicle based on magnetic resonance 1-18

[5] Zeng H, Liu Z Z, et al 2017 Optimization of magnetic core structure for wireless charging coupler *IEEE Transactions on Magnetics* **53** 61-2

[6] Sun Z F, Ding E J, et al 2015 Magnet coupled resonant automotive wireless power transmission system research and design 9-41

[7] Wang G D, Qiao Z P, et al 2015 Research on topology of magnetically-coupled resonant wireless power transmission *Ind and Mine Autom* **41** 558-63

[8] Li J F, Liao C L, et al 2015 Decoupling method of maximum efficiency and transferring power for electric vehicle wireless charging system via LCCL circuit *Transactions of China Electrotechnical Society* **30(S)** 1199-203

[9] Liu C, Guo Y, et al 2015 Characteristics analysis and experimental verification of the double LCL resonant compensation network for electrical vehicles wireless power transfer *Transactions of China Electrotechnical Society* **30** 15127-35

[10] Liu Z F, Liu R, et al 2015 Study on wireless electric energy transmission with series type of magnetic coupling resonance mode *Modern Electron Technique* **38** 17127-32

[11] Huang X L, Ji Q J, et al 2013 Study on series-parallel model of wireless power transfer via magnetic resonance coupling *Transactions of China Electrotechnical Society* **28** 3171-6