Study on Wireless Power Transfer Technology with Series-Series Type of Magnetic Coupling Resonance Model

JIANLIANG LI, JING KANG, CHENGLIN TIAN, DI TIAN and TINGCHUAN XIE

ABSTRACT

In order to further study the resonant wireless power transfer (RWPT) technology, according to the transmission principle of RWPT technology, a wireless charging mode based on the series to series (SS) structure is proposed. By calculating the related parameters of series resonance and parallel resonant equivalent circuit, it is found that the series resonant circuit has the maximum induction electromotive force. Then, combining the four topologies of SS, SP, PS, PP and the calculation formula of compensation capacitor, it is determined that the series resonant circuit is most suitable for the transmitter of the system. In order to facilitate the analysis and calculation, this study finally selected the series to series (SS) structure for research. Furthermore, according to the Kirchhoff Law and the requirement of vibration coupling, the expressions of the system load power and the system energy utilization are derived. Finally, the current technical difficulties are analyzed.

KEYWORDS
Resonant Wireless Power Transfer (RWPT), Series-Series model, the Kirchhoff Law

INTRODUCTION

Wireless power transfer (WPT) technology refers to the energy transmission between the power supply and the electrical equipment in a contactless wireless way. Proposed by Nicola Tesla in 1890, WPT technology makes up for the disadvantages of traditional charging cable, such as aging and wear. In recent years, WPT technology has been successfully applied in many fields, such as Samsung Galaxy S6, S7, S8, iPhone8, Audi A8L, Model S, BMW and so on. In 2007, MIT's team succeeded in using RWPT technology to light bulbs far away from the power supply 2m\(^{[1]}\). So far, RWPT has been recognized by people. Subsequently, Qualcomm, Witricity, KAIST, Tesla, The University of Tokyo and other companies or universities have carried out a series of studies. Chinese enterprises and universities have also carried out relevant research, such as BYD, HUAWEI, Chongqing University, Nanjing Aerospace University, Southeast University, Chang'an University and so on. For example, the first commercial wireless

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charging bus demonstration line runs in Hubei, Xiangyang in September 2016, and the technical support comes from Nanjing aerospace university.

WPT technology mainly has Inductive WPT, Resonant WPT and Electromagnetic Radiation WPT, etc\textsuperscript{[2]}. Table 1 briefly describes the relevant information of the three wireless power transfer.

In this paper, RWPT is selected as the main research object. Based on the principle of transmission, the corresponding resonant circuit and the analysis of four topologies are analyzed. It is concluded that the series resonant circuit is most suitable for the transmitter and the receiver has no limitation. In order to facilitate the analysis and research, the system model based on the S-S structure, and the parameter factors which affect the system efficiency and load power are analyzed.

**TRANSMISSION PRINCIPLE OF RWPT**

RWPT technology originates from the principle of electromagnetic induction. The basic idea is to achieve the same resonant frequency principle according to the transmitter and receiver circuit. In order to transmit the low frequency AC current from the power source to the load successfully, the circuit contains at least the components shown in Fig. 1. From the left, it is AC power supply, rectifier circuit, HF resonant inverter, tuning capacitor, primary side coil, auxiliary side coil, tuning capacitor, rectifier circuit and filter circuit and load.

<table>
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<tr>
<th>WPT</th>
<th>Principle</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Distance</th>
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<tr>
<td>Inductive WPT</td>
<td>inductive coupling</td>
<td>Mature technology</td>
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<td>Resonant WPT</td>
<td>Magnetic resonance coupling</td>
<td>Long distance transmission</td>
<td>Less transmission power</td>
<td>cm~m</td>
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</tr>
<tr>
<td>Electromagnetic Radiation WPT</td>
<td>Microwave</td>
<td>Great transmission power</td>
<td>Inefficiency</td>
<td>km</td>
<td>fundamental research</td>
</tr>
</tbody>
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**TABLE 1. THREE WIRELESS POWER TRANSFER.**

![Figure 1. Electrical schematic for wireless power transfer.](image)
Low frequency alternating current is rectified to obtain half wave or full wave direct current. At this time, the frequency of current and voltage is still low, in order to better realize the wireless transmission of electricity, we need to get high frequency AC. The high frequency inverter circuit can convert the direct current into high-frequency alternating current, and then transmit it to the coil at the transmitter. The two coils must have the same resonant frequency to realize the power transmission. Finally, the receiver can supply power to the load after tuning, rectifying and filtering circuits.

**RESONANT CIRCUIT AND FOUR TOPOLOGIES**

**Analysis of Resonant Circuit**

As is shown in Fig. 2, it is a series resonant equivalent circuit. As is shown in Fig. 3, it is a parallel resonant equivalent circuit.

Analysis Fig. 2, the total impedance can be expressed as follows:

$$Z = R + j\omega L - j\frac{1}{\omega C} = R + jX \quad (1)$$

Loop current can be expressed as follows:

$$I = \frac{\ddot{U}_s}{Z} = \frac{\ddot{U}_s}{R + jX} \quad (2)$$

In order to guarantee the circuit showing a purely resistive, that is $X = 0$.

$$\omega L - \frac{1}{\omega C} = 0 \quad (3)$$

Get:

$$\omega = \frac{1}{\sqrt{LC}} \quad (4)$$

$$I_{ls} = \frac{U_s}{R} \quad (5)$$
Where, \( U_s \) is AC power, \( R \) is equivalent resistance, \( L \) is inductance, \( C \) is compensation capacitor, \( i \) is electric current, \( i_c \) is capacitive current, \( i_L \) is inductive current, \( I_{ls} \) the circuit flows through the inductor current, \( \omega \) is angular frequency.

In summary, in order to ensure that the circuit appears purely resistive, increase the capacitance to offset the adverse effects caused by coil energization. At the same time, when the imaginary part is zero, the circuit has the maximum current \( I = U_s / R \). This not only eliminates the adverse effects of the coil, but also ensures that the LC oscillator circuit has the maximum current value.

According to the above analysis principle, analysis Fig. 3.

\[
I_{lp} = \frac{U_s}{j\omega L + R} \tag{6}
\]

Comparison formula (5) and formula (6):

\[
\frac{I_{ls}}{I_{lp}} = \frac{U_s / R}{U_s / (j\omega L + R)} = \frac{j\omega L + R}{R} \tag{7}
\]

Analytical formula (7), we can learned \((j\omega L + R)/R > 1\), so \( I_{ls} > I_{lp} \). Therefore, the series resonant circuit is larger than the induction electromotive force in the parallel resonant circuit. Therefore, the series resonant circuit is an ideal topology for the design of the RWPT transmitter.

**Four Topological Types of RWPT**

![SS topology](image1)

![SP topology](image2)

![PS topology](image3)

![PP topology](image4)
TABLE 2. Calculation Formula of C1 at Transmitting End.

<table>
<thead>
<tr>
<th>Topological Structure</th>
<th>$C_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS</td>
<td>$\frac{1}{\omega^2 L_1}$</td>
</tr>
<tr>
<td>SP</td>
<td>$\frac{L_4}{\omega^2 (L_1 L_2 - M^2)}$</td>
</tr>
</tbody>
</table>

Where, $L_1$ and $L_2$ are inductors of primary and secondary side, $C_1$ and $C_2$ are capacitances of primary and secondary side, $R_L$ is load resistor, $M$ is mutual inductance coefficient.

The different forms of LC series and parallel connection between the transmitter and receiver will have a great impact on the transmission efficiency of the circuit. This section introduces four basic topological types. Analysis Fig. 4, it is a SS type topology, and both the transmitter and receiver are LC in series. Analysis Fig 5, it is a SP type topology. The transmitter is connected in series with LC and the receiver is LC in parallel. Analysis Fig. 6, it is a PS type topology, the transmitter is LC parallel, and the receiving end is LC series. Analysis Fig. 7, it is a PP type topology, and its transmitter and receiver are LC parallel form.

According to the analysis of the upper section, it is known that the high frequency induction electromotive force can be easily obtained in the form of series resonant circuit at the transmitting end, and the receiving end can be in series or parallel resonance circuit form. According to the references [3], the topology of the circuit directly affects the selection of transmitter compensation capacitor $C_1$.

As shown in Table 2, we can learn that the value of $C_1$ is only related to $L$ and $C$ about SS topological. However, $C_1$ is also affected by $M$ about SP topological. $M = \kappa \sqrt{L_1 L_2}$, $k$ is the coupling coefficient. It is impossible to ensure that the coupling coefficient is a definite value due to the frequent offset between the transmitter and the receiver when the load is charged.

Therefore, it can not be guaranteed that the transmission efficiency and energy utilization rate of the system. Therefore, this paper designs RWPT system based on SS topology.

**Modeling and Analysis of SS Topology System**

System modeling is shown in Fig. 8. Where, $U_s$ is AC power, $L_1$ and $L_2$ are inductance, $C_1$ and $C_2$ are capacitors, $R_1$ and $R_2$ are equivalent resistance, $R_L$ is load resistance, and $M$ is mutual inductance coefficient.
Analysis Figure 8, based on Kirchhoff’s Law (KVL) analysis, we can see that:

The voltage equation of the circuit is:

\[
\begin{align*}
U_s &= \left( R_1 + j\omega L_1 - j\frac{1}{\omega C_1} \right) i_1 + j\omega M i_2 \\
0 &= \left( R_2 + R_L + j\omega L_2 - j\frac{1}{\omega C_2} \right) i_2 + j\omega M i_1
\end{align*}
\]

(8)

The principle of electric energy transmission is that the circuit produces the same self-resonance frequency, therefore:

\[
\omega_1 = \omega_2 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}}
\]

(9)

So, when \( L_1 = L_2, C_1 = C_2 \), can meet the requirements.

Self-inductance of primary and secondary coils:

\[
M = k\sqrt{L_1 L_2}
\]

(10)

According to the formula (8) and (9), the current of the equivalent circuit is:

\[
\begin{align*}
i_1 &= \frac{U_s (R_2 + R_L)}{\omega^2 M^2 + R_1 (R_2 + R_L) - j\omega M U_s} \\
i_2 &= \frac{U_s (R_2 + R_L)}{\omega^2 M^2 + R_1 (R_2 + R_L)}
\end{align*}
\]

(11)

According to formula (10) and (11), the working power of the load can be obtained:

\[
P_L = i_2^2 R_L = U_s^2 \frac{R_L}{R_2 + R_L} \frac{k^2 Q_1 Q_2}{(1 + k^2 Q_1 Q_2)^2}
\]

(12)

System efficiency is:

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Figure 8. SS charging system.
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\[ \eta = \frac{P_L}{P_S} = \frac{i_s^2 R_L}{U_s i_1} = \frac{R_L}{R_2 + R_L} \frac{k^2 Q_1 Q_2}{1 + k^2 Q_1 Q_2} \]  

(13)

Where, Q1, Q2 are quality factors.

\[
\begin{align*}
Q_1 &= \frac{\omega L_1}{R_1} \\
Q_2 &= \frac{\omega L_2}{(R_2 + R_i)}
\end{align*}
\]  

(14)

The purpose of the system design is to achieve high power transmission efficiency and maximum load efficiency. Analytical formula (12), when \( k = \frac{1}{\sqrt{Q_1 Q_2}} \), maximum work efficiency is:

\[ P_{L_{\text{max}}} = \frac{1}{4} \frac{U_s^2 R_L}{R_1} \frac{R_L}{R_2 + R_L} \]  

(15)

It is also known that with the increase of coupling coefficient K, the load power increases first and then decreases. The analysis formula (13) shows that the transmission efficiency of the system will increase with the increase of coupling coefficient K. However, considering the transmission efficiency, it is necessary to ensure that the load can achieve as much work efficiency as possible. Therefore, in the present analysis, when the load reaches the maximum power:

\[ \eta = \frac{1}{2} \frac{R_L}{R_2 + R_L} \]  

(16)

The analysis formula (15) shows that the measures to improve the load power are as follows: ① Increase the \( U_s \). ② Reduce the equivalent resistance \( R_1 \) and \( R_2 \) of the former circuit. ③ Increasing load resistance \( R_L \). Because \( R_1 \) & \( R_2 \ll R_L \), the effect of measure 3 on load power is not obvious.

The coupling coefficient K is directly related to the quality factor Q. With the Q value increasing, the selectivity of the circuit of this component will be better. Analytical formula (14), the quality factor is closely related to the resonant frequency of the system. That is to say, the selection of coil inductance is also very critical. In this design, the inductance is the determined value after selection.

CONCLUSION

Wireless charging technology, as one of the current hot technologies, has attracted much attention since it was put forward. In view of the current achievements, there are still some obstacles in the technology. For example, the energy conversion rate is low, the waste of resources is serious; the charging standards are not unified; there are technical barriers to mobile charging technology; the contradiction between the wireless charging cost and the market; human safety and so on.

Based on the principle of WPT technology, this paper focuses on analyzing the influence factors of system efficiency and load power of SS type structure, and puts
forward some technical difficulties. The next step will focus on the above analysis, set
the specific parameters, using PSpice, MATLAB and other software simulation
analysis and verification.

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