An Analysis and Optimization on Circuit Characteristics of Non-Contact Wireless Charging System for Electric Vehicles with the TS Resonant Network

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Abstract: The load characteristics of non-contact wireless charging system to electric vehicle are exploited in this paper to improve the output power and transmission efficiency of the system. Firstly, this paper makes a mathematical modeling for the TS-S wireless charging system based on Two-Port Network theory. Then, the features of constant voltage output, output power, and transmission efficiency are discussed later. The results show that TS resonant compensation network could improve the system’s output power, and transmission efficiency. After that, the system’s frequency and load resistance in the optimal working state are calculated. Finally, simulations and experimental results are presented to verify the correctness from theoretical derivations.

1. Introduction

Electromagnetic field is the medium of non-contact charging, which can transmit wireless electric energy and without leakage interface. It has the advantages of consumable saving, safety operating and flexibility, while the disadvantage is the large loss of transmission power [1-3]. References [4, 5] mentioned that there are three main principles of non-contact wireless charging, among which the non-radiation magnetically-coupled resonant mode can be transmitted when obstacles rise, and it has the functions of medium transmission distance, large transmission power, high transmission efficiency and relatively small peripheral radiation. This mode is more suitable for wireless charging transmission of electric vehicles. References [6, 7] proposed that there are various ways of wireless charging of accumulator in electric vehicles such as constant current or voltage charge, and each has its advantages and disadvantages.

The magnetically-coupled resonant wireless charging system is loosely coupled, and there is an air gap between coils, which will result in large reactive power loss thus affect transmission efficiency. In order to improve the transmission efficiency of wireless charging, references [8, 9, 10] raised that the resonant network circuit should be inverted to the original edge circuit and then resonant with the transmission coil’s self-inductance to compensate system’s power loss. The main compensations are series (SS, SP) compensation, parallel (PS, PP) compensation and common hybrid reactive power compensation topology, which can realize charging for constant current and constant voltage output in the system under different load conditions. Reference [11] analyses the characteristics of voltage load, current load, output power and the efficiency of transmission system and then make an optimal design based on it. However, it is necessary to consider circuit stability and high power charging in practical application. Reference [12-14] model the WPT system of LCL resonant compensation network by...
introducing two-port circuit theory and proved that this mode can output more voltage and power than traditional resonant network, whereas the transmission efficiency of the system will not be affected.

The above four kinds of traditional resonance compensation network and LCL resonance compensation network have the disadvantages of low output voltage gain and transmission power. In order to overcome the above shortcomings, this paper introduces a two-port circuit theory to model TS wireless charging system, to make the circuit analysis more simple and clear. On this basis it is found that the compensation circuit can amplify the input voltage characteristics, so the system has the characteristics of constant voltage output load. Based on the above results, the formula of output power and transmission efficiency of TS-type wireless transmission system is then deduced, meanwhile, the best load values of transmission power and efficiency are obtained. Besides, this paper presents a method for parameter configuration in the system. To sum up, the simulations and experimental results show that the TS-type wireless transmission system can output more voltage and power, and the overall system efficiency has increased.

2. Background

2.1 Overall structure of WPT system

Figure 1 is the structure of WPT (Wireless Power Transmission) system. The energy transmitter coil is placed above the ground and the energy pickup coil is positioned below the chassis of electric vehicle. Firstly, the high frequency converter generates DC voltage through circuit transformation of circuit electronics. Then, the resonant compensation network outputs high frequency voltage thus the resonant voltage is provided to the primary coil. After electromagnetic coupling, the pickup coil is generated by electromagnetic induction, and the current is connected to the resonant circuit later, which is supplied to the battery after high frequency rectifying.

Figure 1 the structure diagram of fixed-point wireless charging system for electric vehicles

2.2 The TS resonance network in WPT system

The resonant compensation of primary or secondary circuit of wireless transmission system could improve the system’s transmission efficiency, hence the basic resonant compensation method is widely used in wireless transmission field [6]. The primary circuit discussed in this paper is TS type resonance compensation, while the secondary circuit is compensated by series resonance, which is the WPT system of TS topology. The basic circuit structure is shown in Figure 2. In which the TS resonant compensation circuit resonates with the transmitting coil’s self-inductance, then it generates alternating electromagnetic fields around transmitting coil. After that, the secondary coil resonates to produce induced voltage with the same frequency, which then generates DC current to charge the battery after
LC connection in series of resonance circuit, rectification filter circuit and voltage stabilization with bulk capacitor [12].

Figure 2 The WPT systems with TS-S resonant compensation network

For the primary system, the T structure composed of $L_{p_1}$, $L_{p_2}$ and $C_{p_1}$ has the function of voltage output and current harmonics of filtering inverters, which enlarges the adaptive range of the equivalent resistance in primary side and improves the efficiency of the system. For the resonance network, the reactive power compensation network of $L_{p_1}$, $L_{p_2}$, $C_{p_1}$, $C_p$ and $L_p$ series and parallel with parameter optimization makes the system a good frequency stability. Based on the above advantages, the TS reactive power compensation network has been widely used in high power WPT system [13].

2.3 The load characteristics of the TS resonance network

According to Figure 2, the reflection impedance of TS-type hybrid reactive power compensation topology in WPT system is calculated [7], getting the total impedance of the pickup is $Z_t$, the transmitting impedance from pickup to primary side is $Z_p$, the impedance of TS-type reactive power compensation network is $Z_y$. The impedance of each part of the system under the condition of complete resonance in this system is:

$$
\begin{align}
Z_t &= R_L \\
Z_p &= \omega^2 M^2 \\
Z_y &= \frac{V_dM}{L_{p_1}}
\end{align}
$$

According to equation (1), the primary current, load output voltage and load output current in system are:

$$
\begin{align}
I_p &= \frac{V_{in}}{L_{p_1} \omega} = \frac{2\sqrt{2}V_d}{\pi L_{p_1} \omega} \\
V_{RL} &= \frac{V_{inM}}{L_{p_1}} = \frac{2\sqrt{2}V_dM}{\pi L_{p_1}} \\
I_{RL} &= \frac{V_{inM}}{L_{p_1} R_L} = \frac{2\sqrt{2}V_dM}{\pi L_{p_1} R_L}
\end{align}
$$

From equation (2), the TS reactive power compensation network realizes constant pressure input and constant current output under the condition of system resonance; For the overall system, the circuit network realizes the load constant voltage output without any control, the output current varies with load, and the load characteristic is expressed as constant voltage source.

3. Modeling of the TS in WPT system

3.1 An analysis on output characteristics of primary TS reactive power compensation circuit

As shown in figure 2, the full bridge converter with high frequency of voltage source type outputs pulse to TS reactive power compensation network. Meanwhile, the primary circuit can be equivalent as shown in figure 3.
Figure 3: The equivalent circuit with TS network.

As the TS WPT system is inputted by voltage source, the two-port network in figure 3 can be expressed as [12]:

\[
\begin{bmatrix}
Z_{11} & Z_{12} \\
Z_{21} & Z_{22}
\end{bmatrix}
\begin{bmatrix}
\hat{U}_{\text{in}} \\
\hat{U}_{\text{out}}
\end{bmatrix}
= \begin{bmatrix}
\hat{I}_{\text{in}} \\
\hat{I}_{\text{out}}
\end{bmatrix}
\quad (3)
\]

\[
Z_{11} = \frac{\hat{U}_{\text{in}}}{\hat{I}_{\text{in}}} = j\omega L_{p1} + \frac{1}{j\omega C_{p1}}
\quad (4)
\]

\[
Z_{12} = \frac{\hat{U}_{\text{out}}}{\hat{I}_{\text{in}}} = \frac{\hat{U}_{\text{in}}}{\hat{I}_{\text{out}}} = \frac{1}{j\omega C_{p1}}
\quad (5)
\]

\[
Z_{22} = \frac{\hat{U}_{\text{out}}}{\hat{I}_{\text{out}}} = j\omega L_{p1} + j\omega L_{p2} \frac{1}{j\omega C_{p1}} + \frac{1}{j\omega C_{p2}}
\quad (6)
\]

Ignoring the mutual inductance between circuit coils of primary resonance, the relationship between input and output voltage of TS compensation network can be expressed as:

\[
\frac{U_{\text{out}}}{U_{\text{in}}} = \frac{j\omega C_{p1}}{1 - \omega^2 L_{p1} C_{p1}}
\quad (7)
\]

The two-port-theory analysis on TS network is intuitive and simple, which can easily get the voltage and current relationship of the whole network. When the transmission system is in a resonant state, \(\omega^2 C_{p1} L_{p1} = 1\), and the input and output voltage relationship of TS compensation network can be expressed as:

\[
\frac{U_{\text{out}}}{U_{\text{in}}} = \frac{j\omega C_{p1}}{1 - \omega^2 L_{p1}}
\quad (8)
\]

From equation (8), the output voltage of TS compensation network is \(R_{\text{eq}}\omega C_{p1}\) times of input voltage, and the output voltage is less than input voltage of \(\pi/2\) in phase. Under resonant state, the amplification of input and output voltage of transmission system is related to resonant frequency, the compensation circuit capacitance of primary resonance, and the secondary reflection impedance.

3.2 The output voltage in WPT system

In regard to the coupling loops, secondary compensation network and equivalent to two-port network, the circuit equivalent model is shown in figure 4.

Figure 4: The equivalent circuit of coupling loops and secondary compensation.

In figure 4, \(r_p\) is internal resistance of primary coil, \(U_p\) is input voltage of primary equivalent circuit, that is, the output voltage of TS network is \(U_{\text{out}}\). \(L_s\) is the secondary resonance network inductance, \(C_s\) is secondary resonance network inductance, \(r_{\text{eq}}\) is load resistor, and \(U_{\text{eq}}\) is output voltage of the system. Therefore, the circuit and reactance parameters of compensation equivalent in figure 4 can be expressed as equation (9), (10), (11).

\[
Z_{11} = r_p
\quad (9)
\]

\[
Z_{12} = Z_{21} = j\omega M
\quad (10)
\]
The relationship between $U_p$ and $U_{eq}$ can be expressed as equation (12):

$$u_{eq} = \frac{\omega^2 M C_p r_{eq}}{\omega^2 M^2 + r_{eq} r_p}$$

When the system is under the condition of resonant angular frequency, the relationship between output and input voltage of the whole transmission system can be obtained, as shown in (13).

$$u_{eq} = \frac{\omega^2 M C_p r_{eq}}{\omega^2 M^2 + r_{eq} r_p}$$

3.3 An analysis on the characteristics of output power in WPT system

According to equation (13), the output power is:

$$P_{TS-S} = \frac{U_{eq}^2}{r_{eq}} = \frac{R_{eq}^2 \omega^4 M^2 C_p^2 U_{eq}^2}{\left(\omega^2 M^2 + r_{eq} r_p\right)^2} = \frac{n^2 U_{in}^2 \omega^2 M^2 r_{eq}}{\left(\omega^2 M^2 + r_{eq} r_p\right)^2}$$

The change curve of output power with load resistance of which is shown in Figure 5. In which the dotted line shows the output power of LCL-S WPT system, while the solid line represents the output power of TS-S WPT system. And the figure shows that the system’s output power reaches the maximum if the load resistance reaches a certain value.

3.4 An analysis on efficiency in TS-S WPT transmission system

Assuming other circuit devices are ideal options, the main loss of the system mainly comes from internal resistance of primary and secondary coils. Besides, the internal resistance of secondary coils is much less than the load resistance, and the loss can be ignored. Because the resistance of inductance can reduce the resistance by changing magnetic core, which can be ignored either [15]. Moreover, the output power of system $P_{out}$ is the power consumed by secondary reflection impedance, which can be expressed as equation (15), and the system loss mainly comes from internal resistance loss $P_{loss}$ inside primary coils, that can be expressed as equation (17). Therefore, the overall efficiency $\eta$ of TS-S WPT system can be expressed as equation (18).

$$P_{out} = \frac{U_{out}^2}{R_{eq}} = \frac{U_{in}^2 R_{eq} \omega^2 C_p^2}{r_{eq}} = \frac{U_{in}^2 \omega^4 M^2 C_p^2}{r_{eq}}$$

$$P_{loss} = \frac{U_{out}^2}{r_p} = \frac{U_{in}^2 R_{eq} \omega^2 C_p^2}{r_p} = \frac{U_{in}^2 \omega^4 M^2 C_p^2}{r_{eq} r_p}$$

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} = \frac{R_{eq} r_p}{r_{eq} r_p + \omega^2 M^2 C_p^2}$$
According to equation (18), the transmission efficiency can be improved by changing the primary capacitor $C_{p1}$. Compared with LCL-S compensation circuit, this compensation circuit further improves the efficiency of transmission system, as shown in figure 6, and the transmission efficiency of TS-S WPT system increases with load. When the load resistance $r_{eq} = \omega^2 M^2 / r_p$, the output power and transmission efficiency of the system reach the maximum simultaneously.

4. System parameter configuration and simulation experiment

In the resonance state, the input/output voltage gain ratio is as equation (8), makes $n = R_{eq} \omega C_{p1}$, which can be concluded that the multiple of voltage gain is related to the capacitance, system resonant frequency and secondary reflection impedance. For TS WPT system, the method of parameter configuration could be described as follows\[13\]: Selecting the system’s working frequency in line with its needs; Adopting LC series compensation in the secondary side; Presenting pure resistance under the state of system’s resonance, then it meets $\omega^2 C_{eq} L_{eq} = 1$. According to the multiple of voltage amplification in TS compensation network in equation (8), the capacitance $C_{p1}$ of compensation network is determined, and the compensation capacitor $C_{p1}$ is satisfied with:

$$C_{p1} = \frac{n}{R_{eq} \omega} \quad \text{(19)}$$

According to the above methods, the TS system parameters are designed as table (1):

| Voltage gain multiple, $n = R_{eq} \omega C_{p1}$ | $U_{out}$ (V) | $C_{p1}$ (μF) | $R_{eq}$ (Ω) | $\omega$ (Hz) | $U_{in}$ (V) | $L_{p1}$ (μH) | $L_{p2}$ (μH) | $L_p$ (μH) | $C_p$ (μF) | $L_s$ (μH) | $C_s$ (μF) |
|-----------------------------------------------|---------------|---------------|--------------|--------------|-------------|---------------|---------------|------------|------------|-----------|-----------|
| $n_1 = 2$                                      | 80            | 0.401 $\times 10^{-6}$ | 250          | $2 \times 10^4$ | 40          | 50.23 $\times 10^{-6}$ | 50.23 $\times 10^{-6}$ | 100.16 $\times 10^{-6}$ | 0.401 $\times 10^{-6}$ | 151 $\times 10^{-6}$ | 16.56 $\times 10^{-6}$ |
| $n_2 = 3$                                      | 120           | 0.601 $\times 10^{-6}$ |              |              |             |               |               |            |            |           |           |

According to equation (8) of equivalent circuit and voltage gain in section 2.1, the parameter setting of compensation network is set up and the system simulation model is built applying table 1. Figure 7 is the simulation output waveform of input and output voltage in compensation network, where the output waveform is sine wave, and the voltage amplitude is twice the square wave of input waveform. Meanwhile, the same simulation results in figure 8 show that the output voltage is three times the input voltage.
Figure 7 The voltage waveforms of input and output at n=2

Figure 8 The voltage waveforms of input and output at n=3

Figure 9 and figure 10 are input and output waveforms of network circuit experiment in TS.

Based on the above analysis, the experiment output is similar to theoretical results and simulation output, by changing input voltage frequency and capacitance in primary coil, the amplification of system’s output voltage is related to parameters of the system, which proves the correctness of theoretical analysis.

5. Conclusion

In this paper, electric vehicle’s wireless charging system chooses a proper compensation network can improve transmission efficiency and change load characteristics in system. Therefore, the mathematical model of TS-S type resonant network is modeled by the theory of two port circuit, which deduces the characteristics of the load output in system is constant voltage, likewise the characteristics of voltage gain with TS-S resonant compensation circuit is achieved. Meanwhile, the characteristics and transmission efficiency of output power in resonant circuit system is further derived. After that, those characteristics indicates that the WPT system for TS-S has better output power and transmission efficiency than WPT system for LCL-S under the same parameter configuration. Finally, the voltage amplification characteristics of TS-type resonant compensation network are verified. In summary, these findings are of great guidance to the design for charging system of electric vehicles with non-contact TS-type compensation network.

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