Design of High Distance Diameter Ratio Wireless Transmission System Based On LCC-S Compensation Network

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Abstract. A wireless power transmission system based on LCC-S compensation network is designed. The transmission system is composed of power frequency power supply, LCC-S compensation resonant converter and DC / DC converter, and the output power supply for the battery system. Through the design of transmission coil and compensation network parameters, zero current input is realized. A wireless transmission coil with outer diameter of 47cm and spacing of 30cm is designed. A 2kW wireless transmission system prototype is built. Under 311V input, the actual transmission efficiency of high frequency inverter / wireless transmission / high frequency rectifier reaches 88.5%, and the wireless energy transmission with high distance to diameter ratio is realized.

1. Introduction
Inductive wireless power transmission system is widely used in electric vehicle charging, mobile phone charging and commercial UAV charging because of its electrical isolation, convenience and reliability.

In order to improve the efficiency of wireless energy transmission, the transmitter and receiver of wireless power transmission system will use compensation circuit to achieve higher power and maximum efficiency of energy transmission. The four basic compensation networks of wireless power transmission system are S-S, S-P, P-P, P-S topology. In order to improve the transmission efficiency and input-output characteristics of the system, LCC and LCL compensation networks are proposed. Through the analysis of wireless power transmission system. Wireless charging coil has been a lot of research\textsuperscript{[1]}\textsuperscript{[2]}. Through a lot of research on coil configuration, core shape and number, there are various coil designs to choose from in different application scenarios\textsuperscript{[3]}. In this paper, in order to meet the demand of non-contact charging, a wireless power transmission system based on LCC-S compensation network is designed. This system is used for non-contact wireless charging at a long distance, using smaller volume and lighter weight coils to achieve high efficiency charging of high voltage lithium batteries. The parameters of LCC-S compensation network and a wireless charging coil with high distance to diameter ratio are designed and analyzed. A 2kW prototype is made, from 311V DC input to 280V DC output. The full load wireless transmission efficiency is 87.5%.

2. Design of wireless power transmission system
This system uses 220 V / 50 Hz AC power supply to 100 V Li-ion battery pack. The full bridge inverter with constant frequency and duty cycle is used in the primary side, and the uncontrolled rectifier circuit is used in the secondary side. In order to achieve faster and more stable voltage and current regulation,
DC / DC converter is connected in the back stage to realize constant voltage and current charging of battery.

For different compensation networks, the output of wireless power transmission system can be divided into constant voltage output and constant current output. Considering the demand, LCC-S compensation network with constant voltage output is adopted. The designed wireless power transmission system is shown in Figure 1. Among them, the AC rectification circuit is omitted, and Vin is the DC voltage after rectification.

![Figure 1 wireless power transmission system](image)

2.1. Parameter design of LCC-S compensation network

The structure of LCC-S compensation network is shown in Figure 1. In order to achieve the highest efficiency of wireless energy transmission, the three resonant loops of this topology are Lr and C1; C1, C2 and L1, L2 and C3. The resonant frequencies of the three resonant circuits are the same[4]. Therefore, there are:

\[
\begin{align*}
    j\omega L_r - j\frac{1}{\omega C_1} &= 0 \\
    j\omega L_r - j\frac{1}{\omega C_1} - j\frac{1}{\omega C_2} &= 0 \\
    j\omega L_r - j\frac{1}{\omega C_3} &= 0
\end{align*}
\]

(1)

The circuit topology is analyzed without considering the parasitic parameters of inductance and capacitance. The topological loop equation matrix is obtained as follows:

\[
\begin{pmatrix}
    U_z \\
    0 \\
    0
\end{pmatrix} =
\begin{pmatrix}
    j\omega L_r + \frac{1}{j\omega C_1} & -\frac{1}{j\omega C_1} & 0 \\
    -\frac{1}{j\omega C_1} & j\omega L_r + \frac{1}{j\omega C_1} + \frac{1}{j\omega C_2} & -j\omega M \\
    0 & -j\omega M & j\omega L_r + \frac{1}{j\omega C_3} + R_i
\end{pmatrix}
\begin{pmatrix}
    I_s \\
    I_1 \\
    I_2
\end{pmatrix}
\]

(2)

The output voltage can be obtained as follows:

\[
U_{\text{out}} = \frac{M}{L_r} U_z
\]

(3)

Obviously, the LCC-S compensation network is a constant voltage output topology, and the output voltage is related to the input voltage, inductance Lr and coil mutual inductance M. Similarly, the efficiency and output power of LCC-S topology system can be deduced as follows[5]:

\[
\begin{align*}
    P &= \left(\frac{R_i}{Z_{s}Z_{r}^2(R_s + Z_{r})}\right)^2 \frac{U_z^2 R_t}{Z_r Z_s (R_s + Z_s)} \\
    &\left(\frac{R_i}{Z_{s}Z_{r}^2(R_s + Z_{r})}\right)^2 \frac{R_t}{Z_r Z_s (R_s + Z_s)}
\end{align*}
\]

(4)
Here, we choose the parameters of compensation network as follows: resonant frequency $f_c = 120\text{kHz}$, secondary side capacitance $C_2 = 10\text{nF}$, secondary side inductance $L_2 = 178.9\mu\text{H}$, primary side capacitance $C_1 = 10\text{nF}$, $C_1 = 100\text{nF}$, we can get primary side inductance $L_1 = 196.8\mu\text{H}$, resonant inductance $L_r = 17.89\mu\text{H}$. At this time, the three resonant circuits of the compensation network work at the resonant frequency, and the transmission efficiency can reach the maximum. According to equation (4), the curve of the output power and transmission efficiency of wireless transmission network can be obtained with the load.

2.2. Design of wireless energy transmission coil

In order to realize wireless power transmission with high aspect ratio, the coil needs to be optimized. In practical applications, the transmission distance is given, and the wireless energy transmission coil has weight and size requirements. Therefore, it is necessary to select the optimal coil design scheme under the condition of meeting the size and weight.

For a circular coil, the self inductance, mutual inductance and equivalent series resistance of the resonant coil can be expressed as:

$$
\begin{align*}
\begin{cases}
L_1 &= N_1^2 L_{10} \\
L_2 &= N_2^2 L_{20} \\
M &= N_1 N_2 M_0 \\
R_1 &= N_1 R_{10} \\
R_2 &= N_2 R_{20}
\end{cases}
\end{align*}
$$

Among them, $N_1$ and $N_2$ are the turns of transmitting coil and receiving coil, $L_{10}$, $L_{20}$ and $M_0$ are the equivalent self inductance and mutual inductance of single turn transmitting coil and single turn receiving coil respectively, $R_1$ and $R_2$ are the resistance of transmitting coil and receiving coil, $R_{10}$ and $R_{20}$ are the equivalent resistance of single turn transmitting coil and single turn receiving coil.

The equivalent mass of primary and secondary coils is as follows:

$$m = \rho \pi r^2 N l$$

Where $m$ is the mass of coil, $\rho$ is the equivalent density of coil conductor, $r$ is the equivalent radius of conductor, $N$ is the number of coil turns, and $l$ is the equivalent length of single coil turn. In the iterative design of the coil, it is necessary to consider the weight limitation of the coil.

By changing the coil turns and coil diameter, the magnetic field between the two coils can be enhanced as much as possible while keeping the self inductance of the coil unchanged. By increasing the mutual inductance of the coil appropriately by increasing the magnetic field, the output voltage can be increased, and the output current can be reduced under the same power, so as to improve the transmission efficiency.

Usually, the magnetic field strength of the coil is increased by adding ferrite core or making the coil configuration more complex. But adding ferrite core or changing coil configuration will greatly increase coil weight. Under the same conditions, the self inductance of square coil is larger than that of circular coil, but the coupling coefficient is the same. For the core design of the coil, in the same case, with the
increase of the coil distance, the coupling coefficient of the coil with magnetic core decreases rapidly, and is close to the coupling coefficient of the coil without magnetic core. When the coil distance is longer, the coil mass will be significantly increased. Meanwhile, the coupling coefficient will be slightly improved. Therefore, a square coil without magnetic core is designed.

Through several iterations, the coil as shown in Figure 3 can be obtained. The coil spacing is 30 cm, the outer diameter is 47 cm, the primary side is 14 turns, and the secondary side is 13 turns. The primary inductance of actual coil is $L_1 = 199\mu\text{H}$, the secondary inductance is $L_2 = 180\mu\text{H}$. And the coupling coefficient of primary and secondary sides is $k = 0.087$, the mutual inductance is $M = 16.32\mu\text{H}$.

3. Simulation and experiment

The simulation circuit of wireless power transmission system is built by PLECS to verify the design of LCC-S compensation network.

Figure 4 shows the input voltage and current waveforms of LCC-S compensation network. It can be seen that due to a small deviation of inductance and capacitance parameters during design, the input is weak inductive at $120\text{kHz}$, and the circuit realizes zero current turn-on, reducing the switching loss of the circuit.

According to equation 3, the theoretical output value of DC voltage is $283\text{V}$, which is consistent with the peak value of output voltage in Figure 5.

By building the actual circuit and winding the coil, the physical diagram of the system as shown in Figure 6 is obtained. By testing the circuit of the system, we can get the input voltage and current waveform shown in Figure 7, which is basically consistent with the simulation waveform in Figure 4.
Fig. 7 waveform of input voltage and current

When the system is full load output, the output power is 2003W, the input power is 2264W, and the wireless transmission efficiency is 88.5%.

4. Conclusion
In this paper, a coil with a diameter of 47 cm is used to achieve high efficiency wireless power transmission at a distance of 30 cm. By designing the coil reasonably, considering the coil size, weight and coupling coefficient, a coil with high aspect ratio can be obtained. The design of compensation network can make the high frequency circuit work at zero current and reduce the loss of the system. After the comprehensive optimization design of the system, high transmission efficiency can be obtained at the receiving end even if the uncontrolled rectifier is used.

In order to further improve the transmission efficiency, we can consider adding magnetic core on the coil, or using synchronous rectifier circuit to further improve the wireless transmission system from the circuit design and coil design. By increasing the magnetic core, the coupling strength of the transmitting coil and the receiving coil can be enhanced, so as to improve the energy transmission efficiency. Using synchronous rectifier circuit can reduce the energy loss of the receiving circuit, so as to improve the energy transfer efficiency of the system. Therefore, there is still a lot of room to improve the performance of this system.

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