Research on constant current Soft-switching Inductively Coupled Power Transfer system

Guo Ruifeng Liu Shulin Zhang Yuxi Zhang Zhen You Mengran
(School of Electrical and Control Engineering Xi’an University of Science & Technology Xi’an 710054 China)
e-mail: 614036240@qq.com

Abstract. To reduce the impact of load changes on the output current, a double LCC compensation network is designed to realize the wide load constant current output. First of all, by studying the basic characteristics of LCC compensation, the condition of realizing soft switch by inverter is deduced. Secondly, considering the parasitic resistance under the condition of loosely coupled transformer, the mutual inductance model of the system were analysed. And in keeping the coupling coefficient $k$ and frequency the same situation of LCC-P and double LCC constant current compensation system, comparing the maximum output power draw with double LCC compensation when the conclusion of the output power is larger. Finally, the correctness and validity of theoretical analysis and design results are verified by simulation and experiments.

1. Introduction
Inductively Coupled Power Transfer (ICPT) mainly uses the magnetic field as the medium to realize energy transmission without electrical connection by loosely coupled transformer [1]. ICPT system has high transmission power which can reach kW level [2], while the transmission distance is short, which belongs to the close-range radio energy transmission technology. This technology can effectively solve the leakage, spark, corrosion and other problems caused by traditional wired power supply, and is widely used in biomedical and transportation power supply, especially in combustible and explosive environments such as coal mine and petrochemical [3].

In this paper, a double LCC compensated constant-current radio energy transmission system is designed to achieve a wide load range constant current output of the radio energy transmission system. By analysing the system mutual inductance model, the parameter conditions that can make the system have constant current output characteristics are derived. The influence of the parasitic resistance of the loosely coupled transformer on the constant current characteristics of the system is studied. By comparing the output power of the double LCC and LCC/P compensation structure, it is concluded that the output power of the double LCC compensation structure is relatively strong. Finally, the theoretical correctness is verified through MATLAB simulation and experimental results.

2. A double LCC circuit analysis and soft switch implementation method
According to the circuit topology analysis shown in Figure 1, ignoring the influence of parasitic parameters, the mutual inductance equivalent circuit of the double LCC compensation topology loose coupling transformer shown in Figure 1. $U_{AB}$ is High frequency inverter output voltage, $I_p$ and $I_s$ are the primary and secondary loop currents respectively, $M$ is the mutual inductance, and $R_e$ is the equivalent resistance of the rectifier circuit and the back circuit.
Assume that the resonant angular frequency of the primary and secondary resonant networks of the double LCC compensation network is $\omega_0$. In order to make the total impedance of the input of the system purely resistive, the resonant network must meet the following conditions.

$$\omega_0 = \frac{1}{\sqrt{L_f C_f}} = \frac{1}{\sqrt{(L_p - L_f)C_p}} = \frac{1}{\sqrt{(L_s - L_f^2)C_s}}$$  \hspace{1cm} (1)

The double LCC can be equivalent to the LCL-T structure circuit. Figure 2 shows that the double LCC compensation is equivalent to a double LCL circuit, in which the circuit satisfies:

$$L_{sc} = \omega_0^2 L_p - \frac{1}{\omega_0^2 C_p}, \quad L_{se} = \omega_0^2 L_s - \frac{1}{\omega_0^2 C_s}$$  \hspace{1cm} (2)

Since the original side and the secondary side of the double LCC compensation network have the same structure, the double LCC structure circuit is analyzed. Figure 3 shows the equivalent circuit of LCC:

According to Figure 5, the input impedance $Z_1$ of the LCC circuit is:

$$Z_1 = j\omega L_4 + \left( R + j\omega L_2 \right) / \left( j\omega C_4 \right) = \omega_n L_2 \frac{1 - \omega_n^2 \lambda + j\omega_n Q_S \left( 1 - \omega_n^2 \right) + j\omega_n}{Q_S \left( 1 - \omega_n^2 \right) + j\omega_n}$$  \hspace{1cm} (3)

In the middle, $\omega_0$ is resonant angle frequency. $\lambda$ is inductance $L_4$ to inductance $L_2$ ratio $\omega_n$ is normalized angular frequency, $\omega_n = \omega / \omega_0$, $Q_S$ is quality factor, $Q_S = Q_S \omega_n L_2 / R$.

In the case where the double LCC compensation system satisfies the resonance condition, the input impedance is purely resistive, but in order to realize the ZVS of the full-bridge inverter circuit, the input impedance must exhibit a certain inductiveness, for the LCC compensation network system, by adjusting the ratio of $L_1$ to $L_2$, since the inductance $L_2$ is the sum of the inductance $L_p$ and the capacitance $C_p$, for the sake of simple adjustment, the input impedance can be slightly inductive by changing the size of the capacitance $C_p$, so that there is a certain phase angle $\phi$ between the input voltage and the input current.

For the system input current phase can expressed as:
When $\omega_n = 1$, the current $I_1$ express as:

$$I_1 = \frac{U_1}{Z_1} = U_1 \frac{Q^2}{\omega_n L_p \left(1 - \omega_n^2\right) + j \omega_n} \left[1 + \lambda \left(1 - \omega_n^2\right)\right]$$  \hfill (4)

At this point, the phase angle of the system voltage and current can convert to:

$$\phi = \arctan \left[\frac{Q^2}{\omega_n L_p \left(1 - \omega_n^2\right)}\right] \left[\lambda - 1\right]$$  \hfill (5)

$$\begin{cases} \lambda = 1, \phi = 0 \\ \lambda < 1, \phi < 0 \\ \lambda > 1, \phi > 0 \end{cases}$$  \hfill (7)

In the full bridge circuit a dead zone, a MOS tube shut off, the input current of the capacitance of the system at the ends of the complete charge and discharge, then the same bridge arms of another parallel conduction of MOS tube, achieve the zero voltage opening, as can be seen from the type (15), when the $\lambda < 1$, inverter can work under lagging power factor model, the parallel diode to lead in the switch, to ensure that the zero voltage switching (ZVS).

3. Analysis of output power and transmission efficiency characteristics

3.1A double LCC compensation transmission efficiency

Figure 4 shows the equivalent circuit diagram of the inductor parasitic resistance in the double LCC compensation transmission system. Figure 4b shows the equivalent circuit diagram of Figure 4a. $R_p$ is the parasitic resistance of the transmitting coil, $R_S$ is the parasitic resistance of the secondary coil, and $R_{f1}$ is the parasitic resistance of $L_{f1}$. $R_2$ is the parasitic resistance of the inductor $L_2$. $Z_r$ is the equivalent impedance of the secondary side reflected the primary side, $I_i$ is the system input current, $I_O$ is the output current, and $U_1$ is the secondary side induced voltage.

![Double LCC circuits](image1)

![Double LCC circuit equivalent circuit](image2)

Considering the parasitic resistance of the inductor, at this time:

$$\begin{bmatrix} Z_i \\ Z_2 \\ Z_3 \\ Z_4 \end{bmatrix} = \begin{bmatrix} R_{f1} + j\omega L_{f1} \\ R_p + j\omega L_p + \frac{1}{j\omega C_p} + Z_i \\ R_S + j\omega L_S + \frac{1}{j\omega C_S} \\ R_{f2} + j\omega L_{f2} + R_L \end{bmatrix}$$  \hfill (8)

According to Kirchhoff’s voltage law:
When the system is in $\omega_o$, the system output current $I_o$ can express as:

$$I_o = \frac{U_o}{j\omega_o\left[C_f R_{f1} A + L_{f1}\right] \left[C_f R_f A + L_f + L_{f2}\right]}$$

(10)

The system transmission efficiency $\eta$ is:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{\omega^2 M^2 R_L \left[C_f R_{f1} A + L_{f1}\right]^2 \left[C_f R_f A + L_f + L_{f2}\right]^2}{\omega^2 C_f A \left[C_f R_{f1} A + L_{f1}\right]^2 \left[C_f R_f A + L_f + L_{f2}\right]^2}$$

(11)

Among them:

$$A = \frac{\omega^2 M^2 (R_f + R_{f2}) C_f^2}{R_s (R_f + R_{f2}) C_f^2 + L_{f2}} + R_p$$

(12)

### 3.2 Simulation Results and Analysis

In MATLAB, the variation rules of output power and efficiency of LCC circuit with equivalent load size, frequency and coupling coefficient of the original side coil of the coupling coil were analyzed. The simulation circuit parameters are: inductance $L_P = 66.75 \mu H$, $L_S = 67.69 \mu H$, $L_{f1} = L_{f2} = 45.75 \mu H$, capacitance $C_P = 33.22 \text{nF}$, $C_S = 28.86 \text{nF}$, $C_{f1} = C_{f2} = 18.34 \text{nF}$, $C_P = 67.69 \mu H$.

It can see from Fig. 5 that when the load resistance $R_L$ changes from 0 to 100Ω, $I_o$ decreases with the increase of the load $R_L$ due to the internal parasitic resistance of the coil, so the load is within a certain range, and the parasitic resistance of the coil the effect of the system's current gain is small.

![Double LCC load characteristics](image)

Fig. 5 Double LCC load characteristics

In order to further highlight the LCC compensation advantage of the secondary side, when the input voltage is 48V, the resonant frequency is 200kHz, and the coupling coefficient is 0.44, the primary side uses LCC compensation, and the secondary side uses LCC and parallel compensation modes to transmit the power $P_{out}$ (Figure 6, Figure 7).

![LCC/P compensation output power curve](image) ![Double LCC compensation output power curve](image)

Fig. 6 LCC/P compensation output power curve Fig. 7 Double LCC compensation output power curve

By comparing the curves of Fig. 8 and Fig. 9, we can see that the double LCC compensation output power is stronger than the LCC/P compensation output power capability under the same resonance frequency and coupling coefficient.
4. System Simulation and Experiment

In order to make the system better reflect the constant current characteristics, the parameters optimization design carried out to further verify the effectiveness of the circuit analysis and parameter design given in the paper.

By constructing the LCC-type ICPT transmission system platform, a constant current system with an output current of 0.5A design. Under different load conditions, as shown in Figure 8, $U_i$ is the full bridge inverter output voltage, and $I_i$ is the full bridge inverter output current. In the constant current mode, in order to reduce the system switching loss, ZVS is realized by adjusting the size of the resonant capacitor $C_p$. It can see from the waveform diagram that the voltage and current have a certain phase difference, and the phase of the output voltage leads the current phase, which indicates that the system implements ZVS.

![Waveform Diagram](image1)

**Fig. 8** Full-bridge inverter output voltage and current waveforms under different loads

Figure 9 shows the waveform of the system input voltage $U_{in}$ and the primary coil current $I_p$. The current flowing through the primary coil changes in a sinusoidal manner, and the current phase lags the voltage phase by 90°.

![Waveform Diagram](image2)

**Fig. 9** System input voltage $U_{in}$ and primary output current $I_p$ waveform

The output voltage and current waveforms of the system load shown in Figure 10. As can see from the figure, when the load resistance is arbitrarily 40Ω and 60Ω, the system output current is 0.5A. Further, increasing the resistance value, and measure the load to in the range of 0~100Ω to achieve constant current output.

![Waveform Diagram](image3)

**Fig. 10** System output voltage $V_o$ and current $I_o$ waveform

5. Conclusion

This paper designs a double LCC compensated constant current radio energy transmission system. According to the basic characteristics of the double LCC compensation, combined with the full-bridge inverter to achieve the conditions of the soft switch, the double LCC system used to realize the constant
current working conditions, and the experimental circuit built. The theoretical research is verified. The experiment proves that the circuit structure of the double LCC compensation can effectively realize the wide load constant current output of the wireless energy transmission system, and can be applied to the occasions where the constant current characteristics is required.

References
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