Modeling and Efficiency Analysis of LCC-S Inductive Power Transmission (IPT) system

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Abstract: This paper analyzed the factors affecting the transmission efficiency of IPT system based on LCC-S compensation topology. By modeling LCC-S compensation networks, the condition of input impedance as resistive load is derived and the frequency characteristics of input impedance have been analyzed. And the frequency working range to improve the efficiency of the system have been also derived. The input and output characteristics of LCC-S compensation are further studied, and the effect of parameters on regulating the transmission power of IPT system have been verified, which provide an idea for the parameter design of IPT system compensation network.

1. Introduction
The problems of traditional contact power transmission system are more and more obvious in industrial automation, such as the line aging, the existence of leakage, wear, electric spark and other safety problems. Therefore, inductive power transmission (IPT) system has been widely used in recent years. [1-4].

The compensation network topology in IPT system has a very important effect on the system. There are four traditional compensation networks: string - string (SS), string - parallel (SP), parallel - string (PS) and parallel - parallel (PP). On the basis of traditional compensation methods, second-order compensation methods such as LCL and LCC are derived. In [5], the characteristics of LCC topology are analyzed, and then, LCC-S and LCC-P compensation has been present from multiple aspects of load characteristics and power characteristics. In [6], the article optimizes the configuration of compensation network parameters based on multi-objective genetic algorithm, and optimizes the transmission performance of LCC-S WPT system in various working modes. In [7], the article analyzes the parasitic resistance of S-LCC compensation topological loosely coupled transformer, deduces the working conditions of the system under constant current mode, obtains the expressions of system output power and transmission efficiency, and studies the influence of parasitic resistance of loosely coupled transformer on the constant current output characteristics of the system.

By modeling the IPT system of LCC-S compensation topology, this paper studies the impedance characteristics of the system, discusses the influence of different parameters on the input impedance Angle, and analyzes the input and output transmission characteristics of the system. It is verified that LCC-S compensation mode has the advantages of string-string (SS) and parallel-string (PS) compensation, that is, the system resonance has the characteristics of obvious resistance of input
impedance, high transmission efficiency, and independent of output voltage and load.

2. Modeling of LCC-S compensation network

The mutual inductance equivalent circuit of the LCC-S compensation IPT system studied in this paper is shown in Fig1. Among them, the original edge adopts LCC resonance compensation, and the secondary edge adopts traditional LC series compensation. In Fig1, the $U_{in}$ is a category system before the inverter output voltage, $L_{p1}$, $C_p$, $L_p$ of the original edge LCC compensation network, mutual inductance $M$ for the former vice edge, $L_s$ for receiving side coil inductance, $C_s$ for vice edge compensation capacitance, and $L_s$ together form the edge series compensation, $R_L$ as the equivalent load resistance, $r_p1$, $r_p$, $r_s$ is compensated inductance $L_{p1}$ respectively, the transmitter coil $L_p$, deputy while receiving coil $L_s$ of parasitic resistance, $U_c$ for original convert to deputy while induced voltage, $Z_{12}$ as equivalent to the original while reflecting impedance.

The parasitic resistance of the compensation capacitors $C_p$, $C_{p1}$ and $C_s$ is ignored to achieve the function of simplified analysis. Meanwhile, the rectifier part and load resistance in the subsequent circuit are replaced by equivalent resistance $R_L$.

![Fig. 1 Equivalent circuit of LCC-S IPT system](image)

Based on the equivalent diagram of the mutual inductance model, the impedance is:

$$Z_2 = r_s + R_L + j\omega L_s + \frac{1}{j\omega C_s}$$

(1)

The reflection impedance of the secondary side converted to the original side is:

$$Z_{12} = \frac{j\omega M I_s - \omega^2 M^2}{Z_2}$$

(2)

Thus, the input impedance of LCC-S compensation network is:

$$Z_{in} = r_p + j\omega L_{p1} + \frac{1}{j\omega C_{p1}} + Z_{12}$$

(3)

The working frequency of the system is defined as, so when the resonance is satisfied:

$$j\omega L_s + \frac{1}{j\omega C_s} = 0$$

(4)

Substituting (4) into (1) and combining (1) - (3), the system impedance model can be obtained as follows:

$$Z_2 = r_s + R_L$$

$$Z_{12} = \frac{\omega^2 M^2}{r_s + R_L}$$

$$Z_{in} = r_p + \frac{L_{p1}}{C_p} + \frac{1}{j\omega C_{p1}} + \frac{r_p + Z_{12}}{j\omega C_p}$$

(5)

Where, $Z_2$, $Z_{12}$ and $Z_{in}$ are the equivalent impedance of the side of the system, the reflection impedance converted from the side to the original side and the input impedance of the system respectively.

In order to improve the transmission efficiency of the system and reduce the reactive power loss as much as possible, the phase difference between the input voltage $U_{in}$ and the input current $I_{in}$ of the
system should be guaranteed to be zero, that is, the input impedance of the system should be the resistance. Therefore, it can be obtained from (5) as:

$$\omega = \frac{R_L}{M^2}$$  \hspace{1cm} (6)

The input impedance of the system is simplified as:

$$Z_{in} = \frac{L_p C_p - L_p C_{p1} - L_p C_p - L_p C_{p1}}{C_p C_{p1}}$$  \hspace{1cm} (7)

At this point, the input impedance angle of the system is zero, that is, the phase difference between the input voltage and current of the system is zero. And the reactive component of the system is zero, so that the system works in a resonant state.

3. Analysis of input impedance characteristics

According to $Z_{in}$ in (5), its amplitude and phase angle can be influenced by several factors such as $L_p$, $C_p$, $L_{p1}$, $C_{p1}$, etc. The difference of input impedance of the whole IPT system will affect the transmission efficiency, operation stability and the full bridge switch converter characteristics, the soft switch and the bridge arm port input current harmonic characteristics.

For the convenience of analysis, the ratio of $L_p$ to $C_p$ (let $L_p/C_p = P$) is analyzed as a whole, and the relationship between the input impedance amplitude, phase angle and resonance frequency is shown as Fig.2.

![Graph showing input impedance characteristics](image)
As shown in Fig. 2, with different $P$ values, the input impedance amplitude and phase angle have the same overall trend as the frequency changes: that is, in Fig. 2(a), with the increase of frequency, the input impedance amplitude tends to the stable value related to $P$. As shown in Fig. 2(b) at the same time, the system input impedance at low frequency impedance, with the increase of frequency, presents a relatively symmetrical resistance capacity and resistance to the perceptual, this frequency range is small, then arriving at high frequency range, the input impedance has stable in perceptual range, and the input impedance is the impedance of the frequency range is associated with the value of $P$. This indicates that the lower $P$ value is conducive to the realization of system high-frequency, and has a positive effect on the system to reduce the line loss.

After the above analysis, the value of $P$ should be as small as possible in order to make the frequency range of IPT system input impedance pure resistance larger. As shown in the solid red line in Fig. 2(b), when $P = 1000$, the input impedance has the widest range of resistance. However, it can be seen from the image that the frequency is in the range of 20K–35K, the input impedance is resistance and capacitance, and the change speed is relatively slow, which leads to the reduction of the frequency range when the input impedance is resistive.
Fig. 3 Relation diagram between input impedance Angle and frequency at different $L_{p1}$

Fig. 3 shows the influence of different $L_{p1}$ values on the relationship between input impedance angle and frequency. In the case of constant $P = 1000$, it can be seen from the comparison with the solid red line in Fig. 2(b) that the value of $L_{p1}$ not only affects the size of the input impedance angle at high frequencies, but also affects the frequency range of input impedance. As can be seen from the figure, when $L_{p1}$ value is 100uH, the input impedance angle at high frequency is approximately 0, which is conducive to the realization of high-frequency.

From the above analysis, it can be seen that, among the above parameters, when $P = 1000$ and $L_{p1} = 100$uH, the frequency range of input impedance resistance is the widest.

Fig. 4 Relation between input impedance with angle and frequency at different $C_{p1}$

Fig. 4 shows the influence of different $C_{p1}$ values on the relationship between input impedance angle and frequency. Combined with the above analysis, it can be seen that the input impedance angle can be 0 within a certain frequency range through the parameter selection of $P$, $L_{p1}$ and $C_{p1}$, which is conducive to the improvement of system power, the characteristics of full-bridge converter, the input current harmonic characteristics of soft switch and bridge arm port.
4. Analysis of transmission characteristics

When the system operates in resonant state, that is, when (8) is satisfied, the transmission efficiency of the system is the highest.

$$\omega = 1/\sqrt{L_\text{i}C_\text{s}} = 1/\sqrt{L_{p1}C_p}$$

(8)

To simplify the analysis, the internal resistance of each coil is ignored. The input current of the system is:

$$
\begin{align*}
I_{in} &= \frac{U_{in}C_pC_{p1}}{L_pC_{p1} - L_{p1}C_p} \\
I_{p} &= \frac{U_{in}}{j\omega L_{p1}} \\
I_{o} &= \frac{j\omega L_{p1}}{Z_2} - \frac{MU_{in}}{L_{p1}R_L}
\end{align*}
$$

(9)

It can be concluded from (9) that, when the parameters are determined, the original coil current of LCC-S IPT system is independent of the load.

Table (1) shows the input and output characteristics of LCC-S IPT system. Tab.1 shows that the output voltage of the system is independent of load $R_L$ and proportional to the input voltage $U_{in}$. The output power $P_o$ is directly proportional to the square of the input voltage $U_{in}$ and the mutual inductance $M$ of loosely coupled transformer, and inversely proportional to the square of the compensation inductance $L_{p1}$ and the load resistance $R_L$. Similarly, the transmission efficiency is proportional to the square of $M$ and the difference of resonant network parameters, and inversely proportional to the square of compensating inductor $L_{p1}$, compensating capacitor $C_{p1}$, resonant capacitor $C_p$, and load resistance $R_L$. The voltage gain $G_v$ is only related to mutual inductance $M$ and compensating inductance $L_{p1}$, which is proportional to $M$ and inversely proportional to $L_{p1}$. The current gain $G_i$ is directly proportional to the compensated inductance $L_{p1}$ and the resonant capacitor $C_p$, and inversely proportional to the mutual inductance value $M$ and the compensated capacitor.

| PHYSICAL QUANTITIES | LCC - S compensation | Physical quantities | LCC - S compensation |
|---------------------|----------------------|--------------------|----------------------|
| INPUT CURRENT $I_{in}$ | $U_{in}C_pC_{p1}/L_pC_{p1} - L_{p1}C_p$ | Output power $P_o$ | $M^2U_{in}^2/L_{p1}^2$ |
| INPUT POWER $P_{in}$ | $U_{in}^2C_pC_{p1}/L_pC_{p1} - L_{p1}C_p$ | Transmission efficiency $\eta$ | $M^2(L_pC_{p1} - L_{p1}C_p)/L_{p1}^2R_LC_pC_{p1}$ |
| OUTPUT VOLTAGE $U_o$ | $MU_{in}/L_{p1}$ | Voltage gain $G_v$ | $M/L_{p1}$ |
| OUTPUT CURRENT $I_o$ | $MU_{in}/L_{p1}R_L$ | Current gain $G_i$ | $M(L_pC_{p1} - L_{p1}C_p)/L_{p1}R_LC_pC_{p1}$ |

Therefore, in order to improve the output power of the system, the mutual inductance $M$ and input voltage $U_{in}$ of loose-coupling transformer should be increased as much as possible or the compensating inductance $L_{p1}$ should be reduced under the condition of constant load. Similarly, when selecting resonant network parameters, the value of $L_pC_{p1} - L_{p1}C_p$ should be improved as much as possible, which can effectively improve the transmission efficiency of the system. Reducing the value of compensating inductance $L_{p1}$ can also improve the transmission characteristics of the system.
5. Influence of parameters on transmission characteristics

5.1 Load RL

[Graphs showing the relationship between load resistance and various system characteristics]

Fig. 5 Transmission characteristics and load RL variation diagram

It can be concluded from Fig. 5 that the voltage gain of the system shows load independence, while with the increase of the load resistance, the output power, transmission efficiency and current gain all have the same trend of reduction, and the characteristic of reduction has the greatest trend within the range of 100-200 ohms of the load RL.

5.2 Mutual inductance M

[Graphs showing the relationship between mutual inductance and various system characteristics]
As shown in Fig.6, when other parameters of the system remain unchanged and the mutual inductance value only increases, the output power, transmission efficiency, voltage gain and current gain of the system all show an upward trend. With the increase of mutual inductance, the output power and efficiency also increase. Therefore, in the system design, increasing the mutual inductance value of loose-coupling transformer has a very positive effect on improving the system efficiency and output power.

6. Simulation analysis
In order to verify the characteristics of LCC-S, this paper set up a LCC-S simulation model, parameters are shown in Tab.2.

| PARAMETER | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| UIN/V     | 200   | Lp/uH     | 180   |
| F/KHz     | 25    | Cp/uF     | 0.4508|
| LP1/UH    | 90    | Cp1/uF    | 0.4625|
| M/UH      | 90    | Ls/uH     | 180   |
| CS/UF     | 0.254 | RL/Ω      | 200   |

6.1 Load RL changing
Fig. 7 Waveform figure of output current and output voltage at the different load

Fig. 7(a) shows the overall waveform of the output current and output voltage when the load is switched, and Fig. 7(b) shows the enlarged waveform of the output current and voltage when the load is switched. With the load switching, the output voltage is always unchanged, that is, the output voltage is load independent. The simulation results show that the LCC-S compensated IPT system has the characteristics of constant voltage output. Fig. 7(c) is a relation curve fitted according to the data of the output current waveform in Fig. 7(a). It can be seen from the figure that the output current is inversely proportional to the load, which is consistent with the above analysis results.

Similarly, by fitting the data of the output power waveform figure in Fig. 8(a), the corresponding curve is obtained as shown in Fig. 8(b), which is consistent with the analysis results in Fig. 5 above. With the increase of the load resistance, the output power decreases continuously and is inversely proportional to the load, which verifies its correctness.
6.2 Mutual inductance $M$ changing

The curve of current, voltage gain, output voltage and output power fitted according to the simulation data as they change with mutual inductance is shown in Fig.9, which is consistent with the analysis results in Section 4.2. The voltage gain and output voltage are in direct proportion to the mutual inductance $M$, while the output power and current gain are in inverse proportion to $M$.

7. Conclusion

The LCC-S compensation network in an IPT system has been proposed in this paper. And when the input impedance is resistive, the system can achieve high efficiency. Then, the influence of parameters of input impedance is studied from the amplitude and phase angle respectively, and the parameter selection of frequency range is obtained. Finally, the transmission characteristics of LCC-S compensation network are studied, and the output power and transmission efficiency can be improved by increasing the mutual inductance of loosely-coupled transformer or reducing the load, which can provide information for designing LCC-S compensation network.

About the author:

Bo Chen was born in 1994. He received the B.S degree in electric and electrical engineering School from HuBei Polytechnic University. He was working towards Master degree in Hubei Normal University. His main research interests are energy transformation and control of inductive power transmission system.
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