Output characteristics of LCC-S compensation network and its optimal parameters design in IPT system

Bo Li, Guorong Zhu, Jianguang Wang, Wenjing Li, Gatla Ranjith Kumar, Jin Wang

School of Automation, Wuhan University of Technology, Wuhan, People’s Republic of China
E-mail: Leery@whut.edu.cn

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Abstract: A main circuit of inductive power transfer system based on LCC-S compensation network is built up. The resonant conditions for realising constant current (CC) output and constant voltage (CV) output with loads independent are revealed. By analysing the leakage inductance equivalent circuit of the LCC-S resonant network, the relation between efficiency with frequency, coupling coefficient and loads are revealed. An optimal parameter tuning for working at the maximal efficiency state in both CC mode and CV mode is designed through changing frequency and adjusting the coupling coefficient. The theoretical analyses are confirmed by simulation results.

1 Introduction
Owing to its advantages of without physical contact, safety and free from environmental impact, inductive power transfer (IPT) system is becoming widely applied, especially in electric vehicles (EVs) [1–3]. To minimise the power supply VA rating of power supply for high efficiency and improving power transfer capability, compensation networks must be adopted.

Although the structure of unilateral compensation is simple, it cannot guarantee the both original and secondary sides to achieve the unit power factor and have no constant current of primary coil, which resulting in low-power transmission capacity [4]. For this reason, bilateral compensation networks are more widely adopted. Combine SS compensation topology [5] with double-sided LCC compensation topology [6, 7], that is LCC-S compensation topology [8, 9]. For EV lithium-ion battery cell charging, the charging process starts with the CC mode, and during this period the switching frequency is equal to \( f_{cc} \) (resonance frequency in CC mode). When the charging voltage reaches a specified level, the charging process goes into CV mode with \( f_{cv} \) (resonance frequency in CV mode) [10].

Based on LCC-S compensation network, this paper investigates the resonance conditions to achieve CC output or CV output for EV charging. Meanwhile, the efficiency of LCC-S compensation network is analysed, an optimal parameter tuning for working at the maximal efficiency state in both CC mode and CV mode is designed through changing frequency and adjusting the coupling coefficient. Finally, the simulation models are established, which verified the correctness and feasibility of the theory.

2 Analysis of the compensation network structure
The whole structure of the compensation network with IPT system is demonstrated in Fig. 1. It contains of H-bridge inverter with high frequency, compensation network, LCT and uncontrolled rectifier.

In Fig. 1, \( Q_1–Q_4 \) are the silicon carbide power MOSFETs in the primary side. \( D_1–D_4 \) are the rectifier diodes in the secondary side. \( L_{g1}, C_{g1}, C_1 \) and \( C_2 \) are the primary and secondary side compensation components, respectively. \( L_p, L_s \) and \( M \) are the self-inductances in the primary side, the self-inductances in the secondary side and the mutual inductance, respectively. \( U_{AB} \) and \( U_{ab} \) are the input voltage and output voltage of the compensation network severally. \( R_L \) is the load and \( U_0 \) and \( i_0 \) are the output voltage and output current of the load, respectively. \( i_p \) is the current of the primary coil and the secondary coil, respectively.

The leakage inductance equivalent circuit of the IPT system in Fig. 1 referred to the primary side is derived as shown in Fig. 2. Two variables can be defined as

\[
k = \frac{M}{\sqrt{L_pL_s}} \quad (1)
\]

\[
n = \sqrt{\frac{L_s}{L_p}} \quad (2)
\]

where \( k \) is the coupling coefficient of loosely coupled transformer, and \( n \) is the turns-ratio of secondary to primary side.

From the leakage inductance equivalent model, we can obtain the following formula:

\[
\begin{align*}
L_{in} &= kL_p \\
L_{s1} &= (1 - k)L_p \\
L_{s2} &= (1 - k)L_s/n^2 \\
C_1' &= C_2n^2 \\
U_{ab} &= U_{ab}/n \\
U_{AB} &= \frac{2\sqrt{2}}{\pi} U_{dc} \\
R_{ac} &= \frac{8}{\pi^2} R_L/n^2
\end{align*}
\]

Alternating current voltage gain from input voltage to output voltage of compensation network can be derived as

\[
G = \frac{U_{ab}}{U_{AB}} = nG_0 = nG' = n\left|\frac{R_{ac}Z_0Z_{f_1}}{Z_2Z_1Z_{f_2}}\right|
\]

\( G' \) is the equivalent AC voltage gain referred to primary side.
3. Output characteristics and efficiency analysis

3.1 CC mode

To achieve CC mode, the equivalent circuit in CC mode is shown in Fig. 3. From Fig. 3, the resonance conditions can be expressed

\[ L_{f1}C_{cc1} = \frac{1}{\omega_{cc}^2} \]  

(5)

\[ (L_m + L_{cc})C_{cc2} = \frac{1}{\omega_{cc}^2} \]  

(6)

\[ j\omega_{cc}L_{cc} = j\omega_{cc}L_{s1} + \frac{1}{j\omega_{cc}C_1} \]  

(7)

\[ C_{f1} = C_{cc1} + C_{cc2} \]  

(8)

is the equivalent inductance of \( L_{cc1} \) and \( C_1 \). \( \omega_{cc} \) is the resonance angular frequency of CC output.

The output current can be got as

\[ I_{\text{out}} = \frac{U_{\text{AB}}}{k\sqrt{L_pL_m\omega_{cc}(1 - \omega_{cc}^2L_{f1}C_{f1})}} \]  

(9)

\( I_{\text{out}} \) is the root-mean square of the output current. From (9), the conclusion can be made that when the system works stably, the input voltage, inductance and capacitor for compensation is fixed, the output current is constant and independent with loads.

3.2 CV mode

The equivalent circuit to achieve CV mode at the resonance frequency of CV output is shown in Fig. 4.

From Fig. 4, the relation can be expressed as

\[ \frac{L_{f1}L_{cc1}}{L_{f1} + L_{cc1}}C_{f1} = \frac{1}{\omega_{cc}^2} \]  

(10)

\[ L_m(C_{cc1} + C_{cc2}) = \frac{1}{\omega_{cc}^2} \]  

(11)

\[ j\omega_{cc}L_{s1} + \frac{1}{j\omega_{cc}C_1} = j\omega_{cc}L_{cc1} + \frac{1}{j\omega_{cc}C_{cc1}} \]  

(12)

\[ j\omega_{cc}L_{s2} + \frac{1}{j\omega_{cc}C_2} = \frac{1}{j\omega_{cc}C_{cc2}} \]  

(13)

\( L_{cc1} \) and \( C_{cc1} \) are equivalent inductance and capacitor of \( L_{cc1} \) and \( C_1 \). \( C_{cc2} \) is equivalent capacitor of \( L_{cc2} \) and \( C_2 \). \( \omega_{cc} \) is the resonance angular frequency of CV output, respectively.

According to (10), (12) and (13), the output voltage can be calculated as

\[ U_{\text{AB}} = \frac{\omega_{cc}k\sqrt{L_pL_m}}{(1 - \omega_{cc}^2L_{f1})} U_{\text{AB}} \]  

(14)

It can be seen from (14) that when the system works normally, the input voltage, coils of both sides and inductance for compensation are fixed, the output voltage can be constant independent with loads.

3.3 Efficiency analysis

Efficiency is an important indicator of the viability of a system. The efficiency \( \eta \) of the resonant network in this paper can be calculated from (14), and is shown as

\[ \eta = \frac{U_{\text{AB}}^2/R_p}{U_{\text{AB}}^2/\text{Real}[Z_m]} = G^2 \frac{\text{Real}[Z_m]}{R_{dc}} \]  

(15)

According to the equivalent impedance of the system in Fig. 3. The input impedance representation of the system \( Z_m \) is shown in (16). According to the efficiency expression of the resonant work above, it is closed to frequency, coupling coefficient and loads. Thus, an assumed strategy is that the efficiency of LCC-S can be always working at the maximal state in CC mode or CV mode by appropriate parameters design.
Table 1 IPT system specifications

| Parameters                        | Value   |
|-----------------------------------|---------|
| input DC voltage (Udc)            | 400 V   |
| primary and secondary coil inductance (L_p = L_s) | 120 μH  |
| coupling coefficient (k)          | 0.15–0.3|
| resonance frequency for CC mode (f_cv) | 79 kHz |
| resonance frequency for CV mode (f_ac) | 94.36 kHz |

4 Parameters design and simulation results

4.1 Parameters design

To be simplified, the turns-ratio n of the secondary to primary side is equal to 1, and circular pads are selected for (see (16)) primary and secondary coils. Other basic parameters of IPT EV charging system are listed in Table 1.

Primary compensation inductor \( L_{p1} \) is designed to be equal to 58 μH and the value of coupling coefficient \( k \) is designed to be 0.25.

According to the formula (10)–(13)

\[
C_{cc1} = \frac{1}{L_{f1} \omega_{cc1}^2} = 33.82 \text{ nF} 
\]

\[
C_{f1} = \frac{1}{L_{f1} \omega_{cc1}^2} = 70 \text{ nF} 
\]

From (5)–(8)

\[
C_{cc1} = \frac{1}{L_{f1} \omega_{cc1}^2} = 69.97 \text{ nF} 
\]

\[
C_{cc2} = C_{f1} - C_{cc1} = 0.03 \text{ nF} 
\]

\[
L_{cc} = \frac{1}{C_{cc2} \omega_{cc2}^2} - L_m = 135.29 \text{ μH} 
\]

According to the formula (7)

\[
C_1 = \frac{1}{(L_{cc} - L_{f1}) \omega_{cc}} = 18.05 \text{ nF} 
\]

4.2 Simulation results

Based on the designed parameters in Table 1, simulation is undertaken as follows.

Fig. 5 presents the relationship of the AC voltage gain (G) from (5) with frequency of different loads. It can be seen that at the resonance frequency point of 79 kHz, constant voltage output can be achieved.

Fig. 6 shows the output current curves versus frequency with different loads. It can be seen the output current curves intersect at one point, at which the resonance frequency is 94.36 kHz. Thus CC mode can be achieved.

Fig. 7 shows the 3D curve between the efficiency and coupling coefficient and frequency. It can be seen the efficiency of LCC-S reduce along with the decrease of the coupling coefficient, and the maximal efficiency can be acquired at the resonance frequency point of 79 and 94.36 kHz. That is, through appropriate control and adjustments the efficiency of LCC-S can be always working at the maximal state both in CC mode and CV mode CC.

Fig. 8 shows the 3D curve between the efficiency with coupling coefficient and loads. In this curve, frequency point is fixed equal to 79 kHz, the efficiency increases first and then decreases along with the loads, the maximal efficiency is got at the rated load percentage point. It is the same trend of change between the efficiency with coupling coefficient, while the coupling coefficient \( k \) is almost equal to 0.25, the maximal efficiency is obtained.

\[
Z_{in} = \frac{\omega L_p^2 - \omega^2 L_p C_1 [(1 - k^2) - L_s C_2] + j \omega L_p R_{ac} (\omega^2 L_p C_1 - 1)}{[L_p R_{ac}^2 + j \omega (L_p^2 + L_s C_2)] (C_1 + C_2) - \omega L_p^2 C_1 R_{ac} - j \omega L_p C_1 C_2 [L_p^2 (1 - k^2) - L_s C_2]}
\]
5 Conclusion

This paper investigates the leakage inductance equivalent model of loosely coupled transformer (LCT) based on LCC-S compensation network, and the resonant conditions for realising CC and CV modes are revealed. Meanwhile, the relationship between the efficiency of the resonant network with the coupling coefficient, frequency and loads are analysed, based on which an optimal parameters design for working at the maximal efficiency state in both CC mode and CV mode is designed through changing frequency and adjusting the coupling coefficient. Simulation results validated the theoretical analyses and proposed optimisation scheme.

6 References

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