Sensitivity Analysis and Parameter Optimization of Inductive Power Transfer

Da Li¹, Xusheng Wu¹, Jianxin Gao², Jianghua Lu³, Member, IEEE, and Wei Gao¹

¹ School of Electrical Engineering, Naval University of Engineering, Wuhan 430033, China
² National Key Laboratory of Science and Technology on Vessel Integrated Power System, Naval University of Engineering, Wuhan 430033, China
³ College of Information Automation, Wuhan University of Technology, Wuhan 430070, China

Corresponding author: Wei Gao (e-mail: depkin@163.com).

This work was supported in part by the National Natural Science Foundation of China 51807197; Innovation Group Talents Project of Hubei Natural Science Foundation(2018CFA008).

ABSTRACT There are several resonance frequencies points in the high-order resonant network to realize constant current/constant voltage output, but the disturbance of the resonant network parameters will affect the output characteristics of the system. Therefore, selecting the appropriate resonant frequency is necessary to achieve stable output characteristics of wireless power transmission. This paper analyzes the influence of sensitivity of the double-sided LCC compensation network parameters on resonance point and output characteristics. Moreover, this paper proposes a design method to realize load-independent constant current and constant voltage output under two ZPA frequencies, and the resonance parameters are optimized for the realization of ZVS. Under constant current and constant voltage output resonant points, the transmission efficiency of the double-sided LCC IPT system reaches 88.9% and 88.5%, respectively.

INDEX TERMS Inductive Power Transfer (IPT); Sensitivity Analysis; Constant Current/Constant Voltage; ZVS/ZPA

I. INTRODUCTION

Lithium-ion batteries are considered the most competitive battery for electric vehicles because of their high-power density, long cycle life, safety, and environmental protection. [1-3]. Lithium-ion batteries can be safely, efficiently, and quickly charged with inductive power transfer (IPT) or capacitive power transfer (CPT). Wireless power transfer is widely used in battery charging applications ranging from low-power battery charging for mobile phones to high-power charging for electric vehicles [4-6]. Therefore, magnetic field or electric field coupling is the development trend to realize the safe and efficient charging of lithium-ion batteries for electric vehicles.

Constant current/constant voltage (CC/CV) charging prolongs lithium-ion batteries cycle life and service time. During lithium-ion battery charging, the equivalent load of the battery changes from a few ohms to a few hundred ohms as the charging state changes [7]. Therefore, it is necessary to realize load independent constant current and constant voltage output in an extensive load range [8-9]. In IPT systems, DC/DC converters are usually added at the front or back end to realize CC/CV output. Furthermore, it is necessary to track the zero-phase angle between the input voltage and current of the resonant network to realize load-independent CC/CV output [10-11]. Due to frequency bifurcation, frequency conversion control may be unstable, resulting in electromagnetic compatibility problems [12-13]. Constant frequency duty cycle control can effectively avoid frequency bifurcation, but it is not easy to achieve zero voltage switching (ZVS) under light load. Therefore, it is an effective solution to realize the CC/CV output under zero phase switch (ZPA) in an IPT system with specific resonance parameters. The four basic compensation topologies in wireless power transmission can achieve different load-independent output characteristics: P-S topology can achieve CV output, P-P topology can achieve CC output, S-S topology can achieve CC output, and S-P topology can achieve both CC and CV output. However, S-S topology loses ZPA conditions in CV mode, and S-P topology loses ZPA conditions in CC mode [14-17]. In order to realize ZPA, Wang proposed a hybrid topology of S-S and P-S. The hybrid topology requires additional switches and driver circuits to realize topology conversion, increasing the number and loss of components and reducing transmission efficiency [18-20]. Therefore, for an ideal IPT charger, there are at least two load independent ZPA operating frequencies. The resonant
network can realize the load-independent CC output and the load-independent CV output to meet the battery charging characteristics. Esteban B proposes a double-sided LCC compensation network, achieving system output characteristics independent of load and coupling coefficient. The load-independent CC and CV outputs are achieved at two different operating frequencies, but the ZPA at two different frequencies is not achieved [21]. V.-B. Vu and X. Qu have realized load-independent constant current and constant voltage outputs of double-sided LCC compensation networks under ZPA conditions [22-23]. Furthermore, J. Lu has found that load-independent CC and CV outputs can be achieved with multiple resonant frequency points in a double-sided LCC compensation network under ZPA conditions. [24-26]. However, selecting the appropriate operating frequency in multiple resonant points of a high-order resonant network has attracted little attention. J. C derived the input impedance angle model of double-sided LCC compensation network using mutual inductance model and analyzed the influence of series compensation capacitor on the system input impedance angle [27]. Nonetheless, the problem of how to select the appropriate resonant frequency has not been solved. The sensitivity analysis of high-order resonant network parameters to constant current/constant voltage output is not enough and selecting the appropriate resonant frequency operating point still lacks theoretical analysis.

In this paper, the double-sided LCC topology is modeled by T-type circuits and π-type circuits, and the resonance conditions of load-independent CC/CV output under ZPA conditions are obtained. The sensitivity of topology parameters to the output of the resonant network is analyzed. The simulation model reveals the relationship between the output characteristics of the IPT system and topology parameters. Finally, the paper selects the appropriate working frequency from the multi-resonant frequency and establishes the experimental prototype to verify the accuracy of the theoretical analysis.

II. LOAD-INDEPENDENT CC AND CV MODES WITH ZPA CONDITIONS OF DOUBLE-SIDED LCC COMPENSATION TOPOLOGIES

A. T- and π-network

T or π circuit is formed by adding reactance into L-circuit. Figure 1(a) is a voltage-fed T-circuit, \( U_w \) is the constant voltage source with angular frequency \( \omega \), \( U_o \) is the output voltage, \( X_{r1}, X_{r2} \) and \( X_{r3} \) are the impedance of the compensation network, \( R_i \) is the load impedance. The CC output characteristic of the T-circuit can be obtained when \( X_{r1} + X_{r2} = 0 \). Furthermore, the output current and the output impedance of the T-circuit are [28]:

\[
I_{R_i} = \frac{1}{jX_{r1}} U_w \tag{1}
\]

\[
Z_{in} = \frac{-X_{r1}X_{r2}}{R_i + jX_{r2} + jX_{r3}} \tag{2}
\]

From (2), \( Z_{in} \) is purely resistive when \( X_{r2} + X_{r3} = 0 \). It means that load independent ZPA conditions can be implemented, and the purely resistive input impedance \( R_{in} \) is given by

\[
R_{in} = \frac{-X_{r1}X_{r2}}{R_i} = \frac{1}{jX_{r2}} \left( \frac{U_w}{R_i} \right)^2 \tag{3}
\]

The T circuit is equivalent to two L-shaped circuits, as shown in Figure 1(b). \( X_{T2} \) is split into two reactance \( X_{T2V1} \) and \( X_{T2V2} \) in parallel.

\[
\begin{align*}
\{ X_{T2} & = (X_{T2V1} + X_{T2V2})/ (X_{T2V1} + X_{T2V2}) \\
X_{T2V1} + X_{T2V2} & \neq 0
\}
\end{align*} \tag{4}
\]

The CV output characteristics can be achieved when \( X_{r1} + X_{r2V1} + X_{r2V2} = 0 \). The output voltage and the output impedance of the T-circuit are

\[
U_0 = \frac{jX_{T2V2}U_w}{jX_{r1}} \tag{5}
\]

\[
Z_{in} = \frac{-R_iX_{T2V1}X_{T2V1}}{R_i(jX_{T2V1} + jX_{T2V2}) - X_{T2V2}X_{T3}} \tag{6}
\]

When \( X_{T2V1} + X_{T2V2} \neq 0 \), \( Z_{in} \) cannot be a pure resistance in CV output mode, the T-circuit cannot realize ZPA in the CV output mode. The T network can achieve both CC and CV output but load independent ZPA can only be implemented in CC mode. The π-circuit is equivalent to the connection of an L-circuit and reverses L-circuit, and the analysis process is similar to T-circuit, which is shown in Figure 2. The π-circuit can also realize CC and CV output, but the ZPA condition can only be realized in CV mode. For the T-circuit and π-circuit, CC and CV outputs can be realized. However, the ZPA operating condition is only achieved for the T-circuit in CC mode or the π-circuit in CV mode.

\[\text{Fig.1. (a) T-circuit (b) the equivalent circuit of the T-circuit in CV output}\]
A. Load-Independent CC Outputs with ZPA Conditions

The resonant compensation network works in the ZPA state, reducing the reactive power and making the inverter realize ZVS easily. The double-sided LCC compensation network in the IPT system is shown in Figure 3. \( L_s \) and \( L_3 \) are the self-inductances of primary and secondary coils. \( M \) is the mutual inductance between the transceiver coils. The LCC compensation network comprises a series compensation inductor \( L_{s1} \), series compensation capacitor \( C_1 \), and parallel compensation capacitor \( C_{s1} \). And compensation device \( L_{s2} \), \( C_{R2} \), \( C_2 \) constitute the LCC compensation network on the secondary side. \( U_{ab} \) is the input DC voltage of the system, \( U_{o} \), \( I_{a} \) are the input voltage and current of compensation network, \( U_{o} \), \( I_{o} \) are the output voltage and current of compensation network. \( U_{out} \), \( I_{out} \) are the output voltage and current of the wireless power transfer system, \( R_l \) is the load impedance. The coupling coefficient of the coil is:

\[
k = \frac{M}{\sqrt{L_p L_s}}
\]

expressed by Equation 8.

\[
\begin{align*}
L_{LP} &= (1-k)L_t \\
L'_{LS} &= \frac{(1-k)L_t}{n^2} \\
L_{ms} &= kL_t \\
L'_{R2} &= \frac{L_{R2}}{n^2} \\
C'_{R2} &= n^2 C_{R2} \\
C'_{2} &= n^2 C_2
\end{align*}
\]

Fig. 4. Leakage inductance equivalent circuit referred to the primary side of the double-sided LCC compensation network.

\[
U'_{o} = \frac{U_{o}}{n} \quad \Gamma'_{ab} = nI_{ab}
\]

The double-sided LCC compensation network is driven by the modulation voltage of the full-bridge inverter, and the driving voltage is approximately the first harmonic of the inverter's output voltage \( U_{ab} = (2\sqrt{2}U_{o})/\pi \) [29]. The double-sided LCC equivalent model in CC mode is obtained as shown in Figure 5, consisting of an LC-circuit and two \( \pi \)-circuits in series. The variables that can be expressed are:

\[
\begin{align*}
C_{s1VC} + C_{s2VC} &= C_{m} \\
L_{ms} &= \frac{L_{s1VC}L_{s2VC}}{L_{s1VC} + L_{s2VC}} \\
L_{1r} &= L_1 - \frac{1}{\omega^2_{1}C_1} \\
L_{2s} &= L_{s2} - \frac{1}{\omega^2_{2}C_2}
\end{align*}
\]

\[\omega_{ii} \quad (\omega_{ii} > 0)\] is the resonant angular frequency of the double-sided LCC resonant circuit to realize load-independent CC output and \( \omega_{ii} = 2\pi f_{ii} \).

Fig. 5. Equivalent circuit of the voltage-fed double-sided LCC compensation network to achieve load-independent CC output.

It can be obtained by analyzing T-circuit and \( \pi \)-circuit that the resonance conditions and output current of the double-sided LCC resonant network to achieve CC output can be calculated as:
\[ \alpha_{2v}^3 = \frac{1}{L_{1v}C_{1vC}} = \frac{1}{(L_{2v} + L_{n2vC})C_{2vC}} \]  
\[ I_0 = \frac{L_{n2vC}I'}{L_{n2vC} + L_{2v}} = \frac{L_{n2vC}I'}{L_{n2vC} + L_{2v}} \]  
\[ L_{mlv} + L_{mlv} = \frac{1}{j\omega_L} \]  
\[ G_{th} = \frac{I_0}{L_{2v}} = \frac{1}{L_{mlv} + L_{mlv} + L_{n2vC} + L_{2v}} \]  
\[ I_0 + I_{cf} \] are the output current of equivalent \( \pi \)-circuit and LC-circuit in Fig. 5. The output current of IPT system as
\[ I_{out} = \frac{2\sqrt{2}}{\sqrt{n\pi} I'} = \frac{2\sqrt{2}}{\sqrt{n\pi}} \frac{L_{mlv} + L_{1v}}{L_{mlv} + L_{1v}} \]  
The resonant network’s input impedance and input current in CC output mode are equation (14) and equation (15), respectively.
\[ Z_{inc} = \frac{(n\pi)^2}{8R_L} \left[ \frac{L_{mlv}}{L_{mlv} - L_{1v}} \right] \]  
\[ I_{ABC} = \frac{8Z_L}{(n\pi)^2} \left[ \frac{L_{mlv}}{L_{mlv} - L_{1v}} \right] \]  
\[ U_{inc}, I_{out} \] are the output voltage and current of the IPT system in CC output mode. It can be seen from formula (14) that ZPA can be realized when the double-sided LCC IPT system is in the CC mode.

C. Load-Independent CV Outputs with ZPA Conditions

In order to achieve load-independent CV output of double-sided LCC compensation network, the leakage inductance model in Fig. 4 is equivalent to the series connection of three T-circuit in Fig. 6. The conversion of the equivalent variable in Figure 6 is shown in Formula 16.

\[ L_{2v} = \frac{1}{\omega_{2v}^2 C_{2vC}} = L_{2v} - \frac{1}{\omega_{2v}^2 C_{1vC}} \]  
\[ L_{1v} = \frac{1}{\omega_{1v}^2 C_{1vC}} = L_{1v} - \frac{1}{\omega_{1v}^2 C_{2vC}} \]  
\[ \omega_{1v} (\omega_{2v} > 0) \] is the resonant angular frequency of double-sided LCC resonator under constant voltage output mode and \( \omega_{1v} = 2\pi f_{1v} \).

Based on the above analysis of CV output characteristic of T-circuits, the resonance condition of the load-independent constant voltage output of double-sided LCC resonant compensation network can be obtained:
\[ j\omega_L L_{s1} \frac{1}{j\omega_C C_{4}} + j\omega_L L_{s1} Z_1 = 0 \]  
\[ j\omega_L L_{s2} \frac{1}{j\omega_C C_{2}} + j\omega_L L_{s2} Z_2 = 0 \]
\[ Z_1 = \frac{j\omega_L L_{s1} + 1}{j\omega_C C_{4}} \]  
\[ Z_2 = \frac{j\omega_L L_{s2} + 1}{j\omega_C C_{2}} \]

The impedance and output voltage of the double-sided LCC compensation network in the CV output mode can be obtained:
\[ U_{out} = \frac{n\pi L_{2v}}{2\sqrt{2} L_{2v} C_{2vC} L_{s1}} \]  
\[ Z_m = \frac{j\omega_L M_{s1} Z_{s1} C_{s1}}{Z_{s1} L_{s1} C_{s1}} \]

ZPA in the CV output mode of the double-sided LCC compensation network can be realized when the equation (21) is satisfied.
\[ j\omega_L M_{s2} + \frac{Z m Z_s}{\omega L Z_{s2}} + \frac{j\omega_L M_{s1} L_{s1} C_{s1}}{L_{s1} C_{s1}} = 0 \]

![Fig. 6. Equivalent circuit of the voltage-fed double-sided LCC compensation network to achieve load-independent CV output.](image)
The fundamental wave component of the output current \( I_{f1-1w} \) can be calculated:

\[
Z_{in} = \frac{\omega^2 L_1^2 L_2}{k^2 L_p R_e + j(\omega_0 L_p - \frac{1}{\omega_0 C_0}) L_2^2} \quad (24)
\]

\[
G_v = \frac{8 k^2 L_p L_2}{\pi^2 \omega_0 L_1^2 R_e} \quad (25)
\]

\[
I_{f1-1w} = \frac{U_{AB}}{Z_{in}} \left( \frac{kU_{AB} \sqrt{L_p L_2}}{\omega_0 L_1 L_2} - \frac{U_{AB}^2}{\omega_0 L_1^2} \left( \frac{C_{f1}}{C_1} + 1 - \omega_0^2 L_p C_{f1} \right) \right) \quad (26)
\]

The time-domain expression of the fundamental wave component of the input current \( I_{f1-1w} \) is:

\[
I_{f1-1w}(t) = \sqrt{2} I_{f1-1w} \sin(\omega_0 t - \alpha) \quad (27)
\]

\[
t = \frac{b}{b}
\]

\[
\tan \alpha = \frac{b}{a}
\]

\[
a = \frac{kU_{AB} \sqrt{L_p L_2}}{\omega_0 L_1 L_2}
\]

\[
b = \frac{U_{AB}^2}{\omega_0 L_1^2} \left( \frac{C_{f1}}{C_1} + 1 - \omega_0^2 L_p C_{f1} \right)
\]

The fundamental component of the cut-off current when the full-bridge inverter cuts off the upper tube of the front bridge arm and the lower tube of the lagging bridge arm.

\[
I_c = I_{f1-1w}
\]

\[
= \sqrt{2} I_{f1-1w} \sin(\omega_0 t - \alpha)
\]

\[
= \sqrt{2} \sqrt{a^2 + b^2} \sin \alpha
\]

\[
= \sqrt{2} b
\]

The fundamental wave component of the turn-off current is \( \sqrt{2} \) of the imaginary component of the fundamental wave component of the input current \( I_{f1-1w} \). So, the fundamental component of the turn-off current \( I_{off} \) can be obtained when \( C_1 \) changes.

\[
I_{off-c1-1w} = \sqrt{2} \frac{U_{AB}}{\omega_0 L_1} \left( \frac{C_{f1}}{C_1} + 1 - \omega_0^2 L_p C_{f1} \right)
\]

2. Change the secondary side compensation capacitor \( C_2 \).

The resonance conditions of the double-sided LCC compensation network are:

\[
\begin{align*}
L_{s1} \times C_{s1} &= \frac{1}{\omega_0^2} \\
L_{s2} \times C_{s2} &= \frac{1}{\omega_0^2} \\
(L_s - L_{s2}) \times C_2 &= \frac{1}{\omega_0^2}
\end{align*}
\]

\[
L_{s1} \times C_{s1} = \frac{1}{\omega_0^2}
\]

\[
L_{s2} \times C_{s2} = \frac{1}{\omega_0^2}
\]

\[
(L_s - L_{s2}) \times C_1 = \frac{1}{\omega_0^2}
\]

According to the resonance conditions (23), the input impedance of the system \( Z_{in} \), the output voltage gain \( G_v \), and the fundamental wave component of the output current \( I_{f1-1w} \) can be calculated:

\[
Z_{in} = \frac{\omega^2 L_1^2 L_2}{k^2 L_p R_e + j(\omega_0 L_p - \frac{1}{\omega_0 C_0}) L_2^2} \quad (24)
\]

\[
G_v = \frac{8 k^2 L_p L_2}{\pi^2 \omega_0 L_1^2 R_e} \quad (25)
\]

\[
I_{f1-1w} = \frac{U_{AB}}{Z_{in}} \left( \frac{kU_{AB} \sqrt{L_p L_2}}{\omega_0 L_1 L_2} - \frac{U_{AB}^2}{\omega_0 L_1^2} \left( \frac{C_{f1}}{C_1} + 1 - \omega_0^2 L_p C_{f1} \right) \right) \quad (26)
\]

The time-domain expression of the fundamental wave component of the input current \( I_{f1-1w} \) is:

\[
I_{f1-1w}(t) = \sqrt{2} I_{f1-1w} \sin(\omega_0 t - \alpha) \quad (27)
\]

\[
\tan \alpha = \frac{b}{a}
\]

\[
a = \frac{kU_{AB} \sqrt{L_p L_2}}{\omega_0 L_1 L_2}
\]

\[
b = \frac{U_{AB}^2}{\omega_0 L_1^2} \left( \frac{C_{f1}}{C_1} + 1 - \omega_0^2 L_p C_{f1} \right)
\]

The fundamental component of the cut-off current when the full-bridge inverter cuts off the upper tube of the front bridge arm and the lower tube of the lagging bridge arm.

\[
I_c = I_{f1-1w}
\]

\[
= \sqrt{2} I_{f1-1w} \sin(\omega_0 t - \alpha)
\]

\[
= \sqrt{2} \sqrt{a^2 + b^2} \sin \alpha
\]

\[
= \sqrt{2} b
\]

The fundamental wave component of the turn-off current is \( \sqrt{2} \) of the imaginary component of the fundamental wave component of the input current \( I_{f1-1w} \). So, the fundamental component of the turn-off current \( I_{off} \) can be obtained when \( C_1 \) changes.

\[
I_{off-c1-1w} = \sqrt{2} \frac{U_{AB}}{\omega_0 L_1} \left( \frac{C_{f1}}{C_1} + 1 - \omega_0^2 L_p C_{f1} \right)
\]

2. Change the secondary side compensation capacitor \( C_2 \).

The resonance conditions of the double-sided LCC compensation network are:

\[
\begin{align*}
L_{s1} \times C_{s1} &= \frac{1}{\omega_0^2} \\
L_{s2} \times C_{s2} &= \frac{1}{\omega_0^2} \\
(L_s - L_{s2}) \times C_2 &= \frac{1}{\omega_0^2}
\end{align*}
\]
and the fundamental component of the input current $I_{1-Af}$ can be calculated:

$$Z_m = \frac{\phi_1^2 L_1 L_2}{k^2 L_I L_R} + j \frac{\phi_1^2 L_1 L_2}{k^2 L_I L_R}$$

$$G = \frac{V_m}{V_i} = \frac{k L_I L_R}{\alpha L_1 L_2} - \frac{\phi_1^2 L_1 L_2}{\alpha L_1 L_2}$$

$$I_{off} = \frac{k U_{ab} L_I}{\alpha L_1} - j \frac{U_{ab} L_{ab}}{\alpha L_2}$$

The fundamental wave component of the turn-off current can be obtained when the secondary side series capacitor $C_2$ changes.

$$I_{off} = \sqrt{2} \frac{U_{ab}}{U_{ab}} (\phi^2 L_1 C_{R2} - C_{R2} - 1) / (\phi L_{R2})$$

The optimized value of the primary-side compensation capacitor is $C_1$, and $\Delta C = C_1 / C_1$, the primary-side current $I_{ab}$ can be obtained as:

$$I_{ab} = \frac{U_{ab}}{\phi^2 L_{ab}} - j \frac{U_{ab} C_1}{\phi L_{ab}} (\Delta C - 1)$$

The magnitude of the off current $I_{off}$ is related to the current on the primary side. The fundamental wave $I_{off}$ is obtained by $\sqrt{2}$ the imaginary part in equation (36). Moreover, the high-frequency component $I_{off}$ can be expressed by equation (37).

$$\max \{ \sum I_{off} \} = \sqrt{2} \sum_{k=1}^{\infty} I_{off-k} = \frac{\sqrt{2} U_{ab}}{4 \phi L_{S1}}$$

According to formulas (30), (35), (37), changing the turn-off current of the primary side compensation capacitor $C_1$ and the secondary side compensation capacitor $C_2$ can be expressed as:

$$I_{off,c1} = \frac{\sqrt{2} U_{ab}}{4 \phi L_{S1}} + \frac{\sqrt{2} U_{ab} (C_{S1} + C_{C1} - C_{R2} - 1)}{\phi L_{S1}}$$

$$I_{off,c2} = \frac{\sqrt{2} U_{ab}}{4 \phi L_{S2}} + \frac{\sqrt{2} U_{ab} (C_{R2} - C_{S2} - 1)}{\phi L_{S2}}$$

The input impedance is inductive, the full double-sided LCC compensation network is shown in Figure 8. The design parameters of the IPT system based on a double-sided LCC compensation network are shown in Table 1.

### III. SIMULATION AND experimental evaluation WITH Double-sided LCC compensation network

#### A. Parameter Design

In order to verify the above analysis, MATLAB simulation and experimental prototype of IPT system for double-sided LCC compensation network are established. The design method for the parameters of the double-sided LCC compensation network is shown in Figure 8. The design parameters of the IPT system based on a double-sided LCC compensation network are shown in Table 1.

#### Table I Specifications of IPT system

| Parameter | Value |
|-----------|-------|
| Primary/secondary coil self-inductance $L_1 / L_2$ | 120.82μH |
| Coupling coefficient $k$ | 0.15-0.30 |
| DC input voltage $U_{dc}$ | 350V |
| Rated output power $P_o$ | 3.3KW |
| Primary/secondary side compensation inductance $L_{S1} / L_{S2}$ | 45.18μH |
| Primary/secondary side parallel compensation capacitor $C_{S1} / C_{S2}$ | 116.32nF |
| Primary/secondary side series compensation capacitor $C_1 / C_2$ | 42.37nF |
B. Sensitivity analysis of the double-sided resonant network

According to the parameters in Table 1, the relationship between the current gain, voltage gain, and frequency of the double-sided LCC compensation network under different loads can be calculated. There are three resonant frequency points (51.715, 81.198, 97.786 kHz) in the double-sided LCC compensation network for CC output and four resonant frequency points (50.534, 53.427, 90.315, 100.644 kHz) in the double-sided LCC compensation network for CV output.

The constant current resonance frequency of \( f_2 \) decreases with the increase of the series compensation capacitance of the secondary side, but the change of the series compensation capacitance of the primary side has little effect on the constant current frequency of \( f_2 \). The constant output frequency is affected equally by the series compensation capacitance of the primary and secondary sides. The variation of the secondary series compensation capacitance will not affect the constant output frequency of \( f_2 \).

It can be seen from figure 10 that the resonant frequency of constant voltage output is changed when the original side series compensation capacitance is less than 32.3 nF. The constant-voltage output resonant frequency has high stability in the process of compensation capacitance change when the original side series compensation capacitance is more than 32.3 nF. Due to the symmetrical structure of the double-sided LCC compensation network, the series compensation capacitor has the same effect on the constant voltage frequency point.

Take the resonant network parameters in Table 1 as an example. The resonance frequency offset of the IPT system under constant current and voltage output is analyzed by perturbation of capacitor parameters in series with a double-sided LCC compensation network. Figures 10(a) and (b) show the effect of changing the primary/secondary side series compensation capacitor on the constant current resonance frequency. The constant current resonance frequency of \( f_2 \) decreases with the increase of the series compensation capacitance of the secondary side, but the change of the series compensation capacitance of the primary side has little effect on the constant current frequency of \( f_2 \). The constant output frequency is affected equally by the series compensation capacitance of the primary and secondary sides. The variation of the secondary series compensation capacitance will not affect the constant output frequency of \( f_2 \).

The change of the primary and secondary side series compensation capacitor has a greater impact on the current gain of \( f_2 \) under constant current output. At the constant current output, the output current gains of \( f_2 \) and \( f_3 \) are less sensitive to the primary side series compensation capacitance. The voltage gain of \( f_2 \) varies greatly when the primary compensation capacitance is larger than 47 nF, and the voltage gains of \( f_2 \), \( f_3 \), and \( f_4 \) have higher stability. The voltage gain of each resonance point varies greatly under constant voltage output when the secondary series compensation capacitance is less than 47 nF. \( f_2 \), \( f_3 \), \( f_4 \) are less sensitive to the secondary side compensation capacitance when the secondary series compensation capacitance is larger than 47 nF.
As can be seen from Fig. 12, the variation trend of the voltage gain is similar to that of the frequency according to the analysis of the compensation capacitance parameters determined in Table 1. The sensitivity of the constant voltage point to the frequency does not change obviously when the primary/secondary side compensation capacitance parameters change.

After switching the load, the load is switched at \( t = 50\,\text{ms} \), the output characteristics of the system at different frequencies as shown in figure 13. \( \Delta I_o \) is the current difference before and after switching the load. \( SI = \Delta I_o / I_o \) is used to indicate the sensitivity of the output current in CC mode. The smaller the \( SI = \Delta I_o / I_o \), the more stable the output current in CC mode. After switching the load, as shown in figure 13, the output current remains constant, so the three frequency points are constant current frequency points.

As can be seen from Table 2, \( SI_{f_1} > SI_{f_3} > SI_{f_2} \). The simulation result is in good agreement with the theoretical curve. We choose the wireless power transfer system to achieve constant current operating frequency of \( f_2 = 81.198kHz \).

The output characteristics of four constant voltage operating frequencies are analyzed, and the operating frequencies are respectively set to \( f_1 = 50.534kHz \), \( f_2 = 53.427kHz \), \( f_3 = 90.315kHz \), \( f_4 = 100.644kHz \) and the load is switched at \( t = 50\,\text{ms} \), the output characteristics of the system at different frequencies as shown in figure 14. \( \Delta V_o \) is the voltage difference before and after switching the load. \( SV = \Delta V_o / V_o \) is used to indicate the sensitivity of the output current in CV mode. The smaller the \( SV = \Delta V_o / V_o \), the more stable the output voltage in CV mode. After

---

**Table 2 Sensitivity of resonance point in CC mode**

| Frequency point | \( SI \) |
|-----------------|--------|
| \( f_1 = 51.715kHz \) | 38.5% |
| \( f_2 = 81.198kHz \) | 1.6% |
| \( f_3 = 97.786kHz \) | 33.4% |
switching the load as shown in figure 14, the output voltage remains constant, so the four frequency points are constant voltage frequency points.

Table 3 Sensitivity of resonance point in CV mode

| Frequency point | SI   |
|-----------------|------|
| $f_1 = 50.534kHz$ | 3.28% |
| $f_2 = 53.427kHz$ | 1.6%  |
| $f_3 = 90.315kHz$ | 1.1%  |
| $f_4 = 100.644kHz$ | 70.7% |

As can be seen from Table 3, $SV_{f_2} > SV_{f_4} > SV_{f_2} > SI_{f_3}$. The simulation result is in good agreement with the theoretical curve. We choose the wireless power transfer system to achieve a constant current operating frequency of $f_3 = 90.315kHz$.

C. Experimental evaluation with Double-sided LCC compensation network

Experiments were conducted on a 3.3 kw wireless charging system with double-sided LCC compensation to validate the above analysis, as shown in figure 15. The primary side switch is Cree SiC power MOSFET C3M0065090D, the primary/secondary side compensation capacitance is EPCOS-TDK B32921C3103M289, and the secondary side rectifier is SIC diode IDW30G65C. The compensation capacitor is made up of several standard capacitors in series and parallel. The difference between the experimental value and the theoretical value is less than 0.2nF. The IPT system is driven by chroma 62100h programmable DC power supply. In addition, chroma DC electronic load 63210 is used to simulate the resistance value change during battery charging.

Figure 16 (a) is the experimental waveforms of the output voltage and current of the double-sided LCC resonator in the constant current mode (81.198 kHz). The load is switched from 15ohms to 35ohms, and the output current of the wireless power transfer system remains constant. The system achieves load-independent CC output. Fig.16(b) is the experimental waveform of the output voltage and current of wireless power transfer system at a constant voltage (90.315 kHz). The load is switched from 35ohms to 55ohms, and the output voltage of the system remains constant. The system realizes the load-independent CV output characteristic.
In figures 17 and 18, Oscilloscope Channel 1 is the output voltage of the inverter, channel 2 is the output current of the inverter, and channel 3 is the output voltage of the compensation network at the receiving end, channel 4 is the output current of the receiving loop compensation network. Figure 18(a) shows the waveforms of gate-source voltage $V_{gs}$ and drain-source voltage $V_{ds}$ for mosfet in CC mode. $V_{gs} = 0$, the on-state voltage drop of the mosfet can realize ZVS. As can be seen from figure 18(a), in CC mode, the mosfet in the inverter circuit of the system realizes ZVS. Similar to the analysis of CC mode, figure 18(b) shows that the IPT system with double-sided LCC compensation network can realize ZVS in CV mode.

**Fig.16** Output DC voltage and current of the IPT system in CC and CV modes

IV. Conclusion

In this paper, $T/\pi$ circuit is used to model double-sided LCC compensation network, and the load-independent CC and CV outputs of double-sided LCC compensation network in ZPA mode with two different frequencies are analyzed. The series compensation capacitor of a double-sided LCC resonant network is optimized, which is helpful to realize ZVS. The sensitivity of the series compensation capacitor parameter disturbance to the output of the IPT system is
analyzed. On this basis, an optimization method of series compensation capacitor for double-sided LCC compensation network is proposed. A 3.3 kW prototype was built, and it was proved that the IPT system could realize CC and CV outputs in ZPA mode. The relevant design and analysis method in this paper is helpful to select the appropriate working frequency among the multiple resonant frequencies of the high-frequency resonant network, thus achieving stable output, reducing power consumption, and improving efficiency.

REFERENCES

[1] A. El Mejdoubi, H. Chaoui, H. Gualous, P. Van Den Bossche, N. Omar and J. Van Mierlo, "Lithium-Ion Batteries Health Prognosis Considering Aging Conditions," in IEEE Transactions on Power Electronics, vol. 34, no. 7, pp. 6834-6844, July 2019.

[2] R. Xiong, J. Tian, W. Shen and F. Sun, "A Novel Fractional Order Model for State of Charge Estimation in Lithium Ion Batteries," in IEEE Transactions on Vehicular Technology, vol. 68, no. 5, pp. 4130-4139, May 2019.

[3] R. Xiong, Y. Zhang, J. Wang, H. He, S. Peng and M. Pecht, "Lithium-Ion Battery Health Prognosis Based on a Real Battery Management System Used in Electric Vehicles," in IEEE Transactions on Vehicular Technology, vol. 68, no. 5, pp. 4110-4121, May 2019.

[4] L. Zhao, D. J. Thrimawithana, U. K. Madawala, A. P. Hu and C. C. Mi, "A Misalignment-Tolerant Series-Hybrid Wireless EV Charging System With Integrated Magnetics," in IEEE Transactions on Power Electronics, vol. 34, no. 2, pp. 1276-1285, Feb. 2019.

[5] Y. Huang, C. Liu, Y. Xiao and S. Liu, "Separate Power Allocation and Control Method Based on Multiple Power Channels for Wireless Power Transfer," in IEEE Transactions on Power Electronics, vol. 35, no. 9, pp. 9046-9056, Sept. 2020.

[6] W. Tang, Q. Zhu, J. Yang, D. Song, M. Su and R. Zou, "Simultaneous 3-D Wireless Power Transfer to Multiple Moving Devices With Different Power Demands," in IEEE Transactions on Power Electronics, vol. 35, no. 5, pp. 4533-4546, May 2020.

[7] G. Buja, M. Bertoluzko and K. N. Mude, "Design and Experimentation of WPT Charger for Electric City Car," in IEEE Transactions on Industrial Electronics, vol. 62, no. 12, pp. 7436-7447, Dec. 2015.

[8] D. H. Tran, V. B. Vu and W. Choi, "Design of a High-Efficiency Wireless Power Transfer System With Intermediate Coils for the On-Board Chargers of Electric Vehicles," in IEEE Transactions on Power Electronics, vol. 33, no. 1, pp. 175-187, Jan. 2018.

[9] X. Qu, H. Chu, S. Wong and C. K. Tse, "An IPT Battery Charger With Near Unity Power Factor and Load-Independent Constant Output Combating Design Constraints of Input Voltage and Transformer Parameters," in IEEE Transactions on Power Electronics, vol. 34, no. 8, pp. 7719-7727, Aug. 2019.

[10] H. Li, J. Li, K. Wang, W. Chen and X. Yang, "A Maximum Efficiency Point Tracking Control Scheme for Wireless Power Transfer Systems Using Magnetic Resonant Coupling," in IEEE Transactions on Power Electronics, vol. 30, no. 7, pp. 3998-4008, July 2015.

[11] H. Li, J. Li, K. Wang, W. Chen and X. Yang, "A Maximum Efficiency Point Tracking Control Scheme for Wireless Power Transfer Systems Using Magnetic Resonant Coupling," in IEEE Transactions on Power Electronics, vol. 30, no. 7, pp. 3998-4008, July 2015.

[12] Chwei-Sen Wang, G. A. Covic and O. H. Stielau, "Power transfer capability and bifurcation phenomena of loosely coupled inductive power transfer systems," in IEEE Transactions on Industrial Electronics, vol. 51, no. 1, pp. 148-157, Feb. 2004.

[13] Wireless Power Transfer for Light-Duty Plug-In/Electric Vehicles and Alignment Methodology, Standard SAE J2954, 2016.

[14] W. Zhang, S. Wong, C. K. Tse and Q. Chen, "Design for Efficiency Optimization and Voltage Controllability of Series-Series Compensated Inductive Power Transfer Systems," in IEEE Transactions on Power Electronics, vol. 29, no. 1, pp. 191-200, Jan. 2014.

[15] W. Zhang, S. Wong, C. K. Tse and Q. Chen, "Design for Efficiency Optimization and Voltage Controllability of Series-Series Compensated Inductive Power Transfer Systems," in IEEE Transactions on Power Electronics, vol. 29, no. 1, pp. 191-200, Jan. 2014.

[16] R. Leveigne, P. Germaine, D. Ladas and Y. Perriard, "A dual-topology ICPT applied to an electric vehicle battery charger," 2012 XXth International Conference on Electrical Machines, 2012, pp. 2287-2292.

[17] X. Qu, H. Han, S. Wong, C. K. Tse and W. Chen, "Hybrid IPT Topologies With Constant Current or Constant Voltage Output for Battery Charging Applications," in IEEE Transactions on Power Electronics, vol. 30, no. 11, pp. 6329-6337, Nov. 2015.

[18] D. Wang, X. Qu, Y. Yao and F. Yang, "Hybrid Inductive-PowerTransfer Battery Chargers for Electric Vehicle Onboard Charging With Configurable Charging Profile," in IEEE Transactions on Intelligent Transportation Systems, vol. 22, no. 1, pp. 592-599, Jan. 2021.

[19] R. Mai, Y. Chen, Y. Li, Y. Zhang, G. Cao and Z. He, "Inductive Power Transfer for Massive Electric Bicycles Charging Based on Hybrid Topology Switching With a Single Inverter," in IEEE Transactions on Power Electronics, vol. 32, no. 8, pp. 5897-5906, Aug. 2017.

[20] Y. Chen, Z. Kou, Y. Zhang, Z. He, R. Mai and G. Cao, "Hybrid Topology With Configurable Charge Current and Charge Voltage Output-Based WPT Charger for Massive Electric Bicycles," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 6, no. 3, pp. 1581-1594, Sept. 2018.

[21] B. Esteban, M. Sid-Ahmed and N. C. Kar, "A Comparative Study of Power Supply Architectures in Wireless EV Charging Systems," in IEEE Transactions on Power Electronics, vol. 30, no. 11, pp. 6408-6422, Nov. 2015.

[22] V. Vu, D. Tran and W. Choi, "Implementation of the Constant Current and Constant Voltage Charge of Inductive Power Transfer Systems With the Double-Sided LCC Compensation Topology for Electric Vehicle Battery Charge Applications," in IEEE Transactions on Power Electronics, vol. 33, no. 9, pp. 7398-7410, Sept. 2018.

[23] X. Qu, H. Chu, S. Wong and C. K. Tse, "An IPT Battery Charger With Near Unity Power Factor and Load-Independent Constant Output Combating Design Constraints of Input Voltage and Transformer Parameters," in IEEE Transactions on Power Electronics, vol. 34, no. 8, pp. 7719-7727, Aug. 2019.

[24] J. Lu, G. Zhu, D. Lin, S. Wong and J. Jiang, "Load-Independent Voltage and Current Transfer Characteristics of High-Order Resonant Network in IPT System," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 7, no. 1, pp. 422-436, March 2019.

[25] J. Lu, G. Zhu, D. Lin, Y. Zhang and J. Jiang, "Unified Load-Independent ZPA Analysis and Design in CC and CV Modes of Higher Order Resonant Circuits for WPT Systems," in IEEE Transactions on Transportation Electrification, vol. 5, no. 4, pp. 977-987, Dec. 2019.

[26] J. Lu, G. Zhu, D. Lin, Y. Zhang, H. Wang and C. C. Mi, "Realizing Constant Current and Constant Voltage Outputs and Input Zero Phase Angle of Wireless Power Transfer Systems With Minimum Component Counts," in IEEE Transactions on Intelligent Transportation Systems, vol. 22, no. 1, pp. 600-610, Jan. 2021.

[27] Cai Jin, Wu Xusheng, "Stability analysis and efficiency optimization design of bilateral LCC inductive coupling radio energy transmission system," Journal of Electrotechnics, vol. 35, no. 2, 2020.

[28] W. Zhang and C. C. Mi, "Compensation Topologies of High-Power Wireless Power Transfer Systems," in IEEE Transactions on Vehicular Technology, vol. 65, no. 6, pp. 4778-4788, June 2016.

[29] Z. Guorong, L. Peng, J. Lu. "Research on dual LCC resonant compensation circuit for wireless energy transmission system", Journal of Huazhong University of Science and Technology (NATURAL SCIENCE EDITION) . vol.004, no.005, pp.104-109,2017.

[30] L. Peng, L. Xiao-kun, G. Zhu, M. Xie and A. X. Li, "Characteristics Research on Double LCC Compensation Converter in the Inductive Energy Transfer System," 2015 International Conference on Industrial Informatics - Computing Technology, Intelligent Technology, Industrial Information Integration, 2015, pp. 243-246.