Design of a Double-Sided LCLC-Compensated Capacitive Power Transfer System With Predesigned Coupler Plate Voltage Stresses

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Abstract—A high-performance capacitive power transfer (CPT) system is expected to achieve the load-independent constant output, near-zero reactive power, and soft switching of power switches simultaneously, resulting in a reduced power stage, simple control circuitry, and minimum component ratings. However, a well-compensated CPT system still suffers very-high-voltage stresses among not only the main coupled plates but also the leakage coupled plates due to the small coupling and edge emission, which increases the risk of air breakdown and deteriorate the electromagnetic interference (EMI) issue. To solve this problem, the voltage stresses among such coupler plates should be predesigned at an acceptable level. This article systematically analyzes the characteristics of a double-sided LCLC-compensated CPT converter that is proven to have enough design freedom providing predesigned voltage stresses for two kinds of coupled plates. Also, three operating frequencies with load-independent current (CC) output and input zero-phase angle (ZPA) are found. Without reactive power in the circuit, a parameter design method is proposed for the double-sided LCLC-compensated CPT converter at each frequency to satisfy the desired CC output and the predesigned voltage limitations. In this way, the breakdown and EMI issues can be well mitigated by the intended design, and this method can also be extended to other CPT circuits. Finally, a CPT prototype is built to verify the theoretical analysis with the predesigned voltage stresses among the coupler plates.

Index Terms—Capacitive power transfer (CPT), design freedom, LCLC compensation, parameter design, voltage stresses.

I. INTRODUCTION

NOWADAYS, the wireless power transfer technology, including inductive power transfer (IPT) and capacitive power transfer (CPT) techniques, has found many applications due to advantages of convenience, safety, and isolation [1]–[6]. The CPT systems use metal plates as couplers, rather than expensive Litz wires and heavy magnetic cores in IPT converters, which could reduce the cost and weight of the whole system. Also, the power transfer medium of CPT systems, i.e., electric fields, can effectively avoid eddy currents and corresponding losses in the nearby metals [7], [8]. Thus, CPT systems are superior to IPT systems in some applications [9].

The coupled metal plates actually behave as capacitors in the CPT system [10], which generates significant reactive power in the circuit. The large reactive power will increase component ratings and degrade the power transfer capability. Therefore, compensation networks are necessary to improve these performances. Similar to a compensated IPT system [11], a well-compensated CPT system should desirably achieve the following characteristics.

1) Zero Phase Angle (ZPA) Between the Input Voltage and Input Current: The realization of input ZPA can eliminate the reactive power in the circuit and then minimize the component volt–ampere (VA) ratings. Thus, the power transfer capability can be improved effectively.

2) Soft Switching of the Driver Circuit: When the input ZPA is permitted, the input impedance can be easily modulated to be from purely resistive to slightly inductive for zero-voltage switching (ZVS) of MOS-FETs or slightly capacitive for zero-current switching (ZCS) of IGBTs. Soft switching can further reduce power losses and switching noises.

3) Load-Independent Constant Output: Constant current (CC) or constant voltage (CV) output is required in many practical applications, such as battery or supercapacitor charging and LED lighting. A single-stage CPT converter is expected to provide the desired load-independent output so that the front-end or back-end dc/dc regulator can be saved.

To satisfy the abovementioned requirements, some compensation circuits in CPT systems have been proposed and analyzed, such as a double-sided LC circuit [12], [13], a double-sided LCLC circuit [14], [15], and a four-coil...
compensation circuit [16]. Some circuit design methods are given to improve transfer efficiency [17]–[19]. Unlike the loosely coupled transformer in IPT systems, coupler plates in CPT systems behave like very small coupling capacitances due to the low dielectric coefficient in the air. Therefore, a large amount of electric field emission is released around the plates, especially on the edge of plates, as shown in Fig. 1 [21]. Usually, the plates on the same primary or secondary side are placed closely. From Fig. 1, the edge emission is more serious in the region close to $P_1$ and $P_2$ or close to $P_3$ and $P_4$. In this way, there are high-voltage stresses on the main coupling capacitors formed by $P_1$ and $P_3$ or $P_2$ and $P_4$ and the leakage capacitors formed by $P_1$ and $P_2$ or $P_3$ and $P_4$, which can readily exceed the breakdown voltage limitation of 3 kV/mm in the coupler plates [22] and cause a large leakage electric field radiation [23]. To solve the abovementioned issues, prior work [24] tries to maximize the coupling capacitance and then decrease the voltages on the main capacitors. Li et al. [16] use resonant networks and an isolated transformer to regulate input and output voltages of coupler plates, and then, the voltages on the main coupled capacitors are decreased. Mai et al. [25] reallocate voltage stresses of all compensation components and capacitive couplers by a mathematic calculation based on a double-sided $CL$ compensation circuit. However, the aforementioned works usually optimize the voltage stresses only on the main coupled plates. From Fig. 1, the voltage stresses on the leakage coupled plates are also critical to be optimized [26]. Lian and Qu [27] identify the relationship of voltage stresses between the main coupler plates and the leakage coupler plates based on a simple double-sided $LC$-compensated CPT system. With the desired load-independent CC output and input ZPA, the double-sided $LC$-compensated CPT system has no freedom to optimize such two kinds of voltage stresses. Therefore, a higher order compensation circuit is needed here for the voltage optimization of two kinds of coupled plates.

In this article, a higher order double-sided $LCLC$-compensated CPT converter with enough design freedom is systematically analyzed to fulfill the predesigned voltage stresses among the coupled plates. Meanwhile, three operating frequencies with load-independent CC output and input ZPA are found in Section II. Without reactive power in the circuit, a parameter design method is proposed to satisfy the required CC output and predesigned voltage stresses for both main coupled plates and leakage coupled plates, as detailed in Section III. This method can be readily extended to the other CPT systems. Finally, a 40-W double-sided $LCLC$ CPT system is built, and the experimental results agree well with the theoretical analysis in Section IV. Section V concludes this article.

II. CHARACTERISTIC ANALYSIS FOR INPUT ZPA AND LOAD-INDEPENDENT CONSTANT OUTPUT

Fig. 2 shows the schematic of a double-sided $LCLC$-compensated CPT system where the full-bridge inverter generates the high-frequency ac voltage $u_{AB}$ to power the resonant circuit and two pairs of coupler plates $P_1$, $P_2$, $P_3$, and $P_4$. $L_{f1}$, $C_{f1}$, $L_1$, and $C_{ex1}$ construct the primary $LCLC$ network, while $L_{f2}$, $C_{f2}$, $L_2$, and $C_{ex2}$ construct the secondary $LCLC$ network. The structure and dimensions of the coupler are shown in Fig. 3(a) where $l$ is the plate length, $d$ is the air distance, and $d_1$ is the distance between two plates on the same side. A $Π$-type model with the equivalent primary capacitor $C_P$, secondary capacitor $C_S$, and mutual capacitor $C_M$ can be used in the metal plates, as shown in Fig. 3(b) [28]. The native coupling coefficient $k_C$ is defined as $(C_M/(C_PC_S)^{1/2})$. With $C_{ex1}$ and $C_{ex2}$ parallel to equivalent capacitors $C_P-C_M$ and $C_S-C_M$, respectively, it defines that

$$C_1 = C_{ex1} + C_P \text{ and } C_2 = C_{ex2} + C_S.$$  \hspace{1cm} (1)

Then, the equivalent coupling coefficient $k$ becomes

$$k = \frac{C_M}{\sqrt{C_1C_2}}.$$  \hspace{1cm} (2)

And $k < k_C$.

To facilitate the analysis, the double-sided $LCLC$-compensated CPT converter in Fig. 2 can be driven by a purely sinusoidal ac voltage source $u_{im}$, i.e., the vector of the fundamental component of $u_{AB}$ and delivers power to an equivalent load $R_E$, as shown in Fig. 4. With the $C$ filter, $R_L = ((\pi^2 R_E)/8)$. Based on the reciprocity principle, Fig. 4 can be further derived as an equivalent $T$-type network with $C_A$, $C_B$, and $C_C$, as shown in Fig. 5. Here, $C_A$, $C_B$, and $C_C$ satisfy

$$\begin{align} C_A &= \frac{C_1C_2 - C_M^2}{C_2 - C_M} = \frac{C_1(1-k^2)}{1-k\sqrt{C_1/C_2}} \\
C_B &= \frac{C_M}{C_1C_2 - C_M^2} = \frac{1-k^2}{k^2}\frac{C_M}{C_2} \\
C_C &= \frac{C_1C_2 - C_M^2}{C_1 - C_M} = \frac{C_1(1-k^2)}{1-k\sqrt{C_1/C_2}} \end{align}$$  \hspace{1cm} (3)

A. One Frequency for Input ZPA and Load-Independent Output

From Fig. 5, the primary compensation inductor $L_1$ can be divided into three parts in series, i.e., $L_{11}$, $L_{12}$, and $L_{13}$, while the secondary $L_2$ can be divided as $L_{21}$, $L_{22}$, and $L_{13}$.
Fig. 2. Schematic of a double-sided LCLC-compensated CPT converter.

Fig. 3. Coupler structure and equivalent circuit model in the shadow area of Fig. 2. (a) Structure of the coupler. (b) Equivalent Π-type model.

Fig. 4. Equivalent circuit of double-sided LCLC-compensated CPT circuit using the Π-type model.

Fig. 5. Equivalent circuit of double-sided LCLC-compensated CPT circuit using the T-type model. Each shadow denotes a T network.

Fig. 6. Typical T network.

Fig. 7. Equivalent circuit of Fig. 5 operating at ω1, not ω0.

Fig. 8. (a)–(d) Derivation circuits of Fig. 7.

in series. Then, three T networks are given in different color shadows. To find a working angular frequency ω0 for the CPT converter having properties of input ZPA and load-independent output, every T network should satisfy $Z_1 = -Z_2 = Z_3$ at ω0 in Fig. 6 where

$$\omega_0 = \frac{1}{\sqrt{L_{f1}C_{f1}}} = \frac{1}{\sqrt{L_{f2}C_{f2}}}$$

and

$$Z_{IN1} = \frac{1}{R_E} \left[ \frac{C_M}{\omega_0 C_{f1} C_{f2}} \left( \frac{1}{k^2} - 1 \right) \right]^2. \quad (6)$$

A load-independent CC output and input ZPA are realized at ω0 that is consistent with the result in [14].

B. Other ZPA Frequencies for Load-Independent Output

With the parameter constraints in (4), the CPT converter may not work at ω0 but at another frequency ω1. Then, the equivalent circuit in Fig. 5 can be transformed as that in Fig. 7 by Thevenin’s theorem. The primary $L_1$ can still be divided into three parts, i.e., $L'_{11}$, $L'_{12}$, and $L'_{13}$, and the secondary $L_2$ is divided as $L'_{21}$, $L'_{22}$, and $L'_{13}$. If $L'_{11}$ is designed to resonate with $L_{f1}$ paralleled by $C_{f1}$ at $\omega_1$, a load-independent voltage source $U_{in1}$ drives the following circuit, as shown in Fig. 8(a). Designing that $L'_{13}$ resonates with
While $L'_{21}$ resonates with $C_C$, Fig. 8(a) has two typical T networks. There are two cases for further derivation, which are as follows.

1) If $L'_{12}$ resonates with $C_B$ at $\omega_1$, $U_{in1}$ can be transformed to a load-independent current source $I_1$, as shown in Fig. 8(b). By (4), $L_{f2}$ cannot resonate with $C_f2$ at $\omega_1$. Thus, it is impossible to realize CC or CV output for $R_E$ in Fig. 8(b).

2) If $L'_{12}$ cannot resonate with $C_B$ at $\omega_1$, Fig. 8(a) can be converted to Fig. 8(c) by Thevenin’s theorem with a new load-independent voltage source $U_{in2}$ in series with the parallel connection of $L'_{12}$ and $(1/(j\omega C_B))$. Design that $L'_{22}$ resonates with $L'_{12}$ paralleled by $C_B$ while $L'_{23}$ resonates with $C_f2$. Then, a load-independent current $I_2$ can drive the load $R_E$ directly, as shown in Fig. 8(d).

Following the abovementioned analysis, we have:

$\omega_1 = \sqrt{\frac{L_{f1} + L'_{12}}{L'_{12} + L'_{22}C_f1}} = \sqrt{\frac{L_{f1} + L'_{12}}{L'_{12} + L'_{22}C_f1}} \sqrt{L'_{13}C_A} = \sqrt{L'_{23}C_{f2}}$.

Under the constraint of the same set of compensation parameters

$L_1 = L_{11} + L_{12} + L_{13} = L'_{11} + L'_{12} + L'_{13}$

and

$L_2 = L_{21} + L_{22} + L_{23} = L'_{21} + L'_{22} + L'_{23}$.  

(8)

Substituting (4) and (7) into (8), we have (9), as shown at the bottom of the page.

Although a new load-independent CC output can be found at $\omega_1$ in Fig. 8(d), the input impedance cannot be guaranteed to be resistive. To ensure the input ZPA, a transmission matrix $A_T$ of the CPT system is introduced here, which satisfies

$$
\begin{bmatrix}
U_{in} \\
I_{in}
\end{bmatrix} = A_T
\begin{bmatrix}
U_1 \\
I_1
\end{bmatrix} \begin{bmatrix}
A_{11} & jA_{12} \\
\bar{A}_{12} & \bar{A}_{12}
\end{bmatrix}
\begin{bmatrix}
U_f \\
I_f
\end{bmatrix}.
$$

(10)

The CPT converter can still be divided into three T networks with matrices $A_1$, $A_2$, and $A_3$, as shown in Fig. 5, where $L_{11,12,13,21,22,23}$ should be $L'_{11,12,13,21,22,23}$. By the basic

$$
A_T = A_1A_2A_3 = \begin{bmatrix}
\alpha'_{11} & \alpha'_{12} & \alpha'_{21} & \alpha'_{22} & \alpha'_{31} & \alpha'_{32} \\
\alpha_{13} & \alpha_{14} & \alpha_{23} & \alpha_{24} & \alpha_{33} & \alpha_{34}
\end{bmatrix}.
$$

(11)

Matrices $A_1$, $A_2$, and $A_3$ are given by

$$
A_1 = \begin{bmatrix}
1 - \omega^2C_f1L_{f1} & 0 \\
-j\omega C_f1 & 1 - \omega^2C_f1L_{f1}
\end{bmatrix}
$$

and

$$
A_3 = \begin{bmatrix}
0 & j\omega_1L'_{23} \\
1 - a_0^2L_{f2}C_f2 & 1
\end{bmatrix}.
$$

(12)

By solving (11) and (12), $a_{11} = a_{11}'(a_{11}'a_{21}' + a_{12}'a_{22}') + a_{13}' = 0$. Then, the input impedance of the CPT circuit can be expressed as

$$
Z_{in} = \frac{U_{in}}{I_{in}} = A_{12} + ja_{12}R_E + ja_{22}R_E.
$$

(13)

If $Z_{in}$ is purely resistive, $a_{12}R_E = 0$ from (13). If $a_{12} = 0$, the input impedance is always zero, which is not practical. Therefore, $a_{22} = 0$. By (11)

$$
a_{22} = a_{22}'(a_{12}'a_{22}' + a_{14}'a_{24}') + a_{14}'a_{24}'a_{34}'
$$

(14)

Thus, a ZPA design constraint is obtained as

$$
C_f1C_2 - C_f1C_f2 = 0.
$$

(15)

Substituting (15) into (9), the other two frequencies $\omega_{1H,1L}$ with input ZPA and load-independent CC output can be given as

$$
\omega_{1H} = \omega_0\sqrt{1 + a} \quad \text{and} \quad \omega_{1L} = \omega_0\sqrt{1 - a}
$$

(16)

where $a = \frac{((1 - k^2)^2(b/C_f2)^2 + (2\alpha_1/C_f2)(1 - k^2) + k^2)/(1 + (1 - k^2)(b/C_f2)))}$. The load-independent CC current $I_2$ and the input impedance $Z_{in2}$ at $\omega_{1H}$ and $\omega_{1L}$ are identical and given by

$$
I_2 = -j\frac{\omega_1C_M}{k^2} \left(1 - k^2 + \frac{1}{\beta}\right) U_{in}
$$

(17)

and

$$
Z_{in2} = \frac{k^2\beta^2}{[(1 - k^2)^2(1 + \beta) + 2\alpha_1C_M^2]}.
$$

(18)

where $\beta = (C_f1/C_f2) = (C_f1/C_f2)$. In summary, with so many compensation components, i.e., $C_{11,12}$, $L_{11,12}, C_{21,22}$, and $L_{12,2}$, the double-sided LCLC-compensated CPT converter has three ZPA frequencies with load-independent CC output and may have enough design freedom to optimize the voltage stresses among coupler plates, which will be analyzed in Section III.

III. Design and Implementation of CPT Converter

With Voltage Stress Optimization

A. Design Freedom and Optimization Theory

As analyzed in Section II, the double-sided LCLC-compensated CPT converter can be designed at $\omega_0$ or $\omega_1$ to realize input ZPA and output load-independent

$$
\omega_1 = \omega_0 \left[1 \pm \sqrt{\left[1 + \left(\frac{1}{k^2} - 1\right) \frac{C_f1}{C_f2} + \left(\frac{1}{k^2} - 1\right)^2 \frac{C_f2}{C_f1} \frac{C_f2}{C_f1}\right]} \right]^{1/2}.
$$

(9)
As shown in Fig. 2, the input dc voltage $U_{dc}$ can be modulated by $Q_{1,2,3,4}$ with $D$ being the duty cycle of $\mu_{AB}$ in one half cycle. The fundamental component of $\mu_{AB}$, denoted as $\mu_{IN}$, is given as

$$\mu_{IN}(t) = \frac{4U_{dc}}{\pi} \sin \frac{\pi D}{2} \sin \omega t. \quad (19)$$

By (5) and (17), the output current $I_{O1}$ at $\omega_0$ and $I_{O2}$ at $\omega_1$ under $C$ filter should be given as

$$\begin{align*}
I_{O1} &= \frac{8}{\pi^2} \frac{\omega_0 L^2 C_f f_1 C_f^2 U_{dc} \sin \frac{\pi D}{2}}{C_M (1 - k^2)} U_{dc} \sin \frac{\pi D}{2}, \\
I_{O2} &= \frac{8}{\pi^2} \frac{\omega_1 C_f}{k^2} \left(1 - k^2 + \frac{C_f^2}{C_2}\right) U_{dc} \sin \frac{\pi D}{2}.
\end{align*} \quad (20)$$

From (20), with the given $U_{dc}$, coupler parameter $C_M$, and operating frequency, both $I_{O1}$ and $I_{O2}$ are functions of $C_f$1, $C_f$2, $C_1$, and $C_2$. Meanwhile, it should be noticed that $L_{f1}$, $L_{f2}$, $L_1$, and $L_2$ are also the functions of $C_f$1, $C_f$2, $C_1$, and $C_2$ by (4) and (7). Therefore, with one constraint of (20), the double-sided LCCLC-compensated CPT converter has the design freedom to optimize $U_{CM}$, $\mu_1$, and $\mu_2$ with four independent control variables: $C_f$1, $C_f$2, $C_1$, and $C_2$. It is the reason why the low-order compensation circuit cannot optimize all voltages among the coupler plates. For example, the double-sided LC-compensated CPT converter only has two independent variables $C_1$ and $C_2$ so that voltage stresses of $\mu_1$ and $\mu_2$ cannot be designed below the given values in [27].

For any CPT system, the key coupler plates can be modeled as a $\Pi$-type network, as shown in Fig. 4. Assuming that all reactive components are lossless, the transferred real power $P$ of the CPT converter is actually the power transferred via the $\Pi$-type network. Therefore, we have

$$\begin{align*}
P &= \frac{1}{2} \omega C_M U_1 U_2 \sin \phi, \\
U_{CM}^2 &= U_1^2 + U_2^2 - 2U_1 U_2 \cos \phi \geq 2U^2(1 - \cos \phi)
\end{align*} \quad (21)$$

where $P = I_0^2 R_L$, $U_{1,2}$ is the magnitude of $\mu_{1,2}$, and $\phi$ is the phase angle between $\mu_1$ and $\mu_2$. The minimum $U_{CM}$ occurs when $U_1 = U_2 = U$. By solving (21), it can be written as

$$U_{CM} = \sqrt{\frac{P}{\frac{1}{2} \omega C_M}} \left[1 \pm \sqrt{1 - \left(\frac{2P}{\omega C_M U^2}\right)^2}\right] \quad (22)$$

where $\pm$ is decided by $\phi$ with $-$ for $[-(\pi/2), (\pi/2)]$ and $+$ for $[-\pi, -(\pi/2)]$ or $[(\pi/2), \pi]$ in one period. If (22) makes sense

$$\omega \geq \frac{2P}{C_M U^2} \geq \frac{2P}{C_M U_{CM}^2} \quad (23)$$

where $U_{max}$ is the maximum input voltage of $\mu_1$ or $\mu_2$. Besides, the maximum output $U_{CM}_{max}$ of $U_{CM}$ is usually given to avoid the air breakdown and electromagnetic interference (EMI) issue. From (22), with the given output power $P$, coupler parameter $C_M$, $U_{max}$, and $U_{CM}_{max}$, the operating frequency $\omega$ should be considered carefully besides the constraint of (23).

With the abovementioned consideration, (22) can be rewritten as

$$\omega = \frac{4P}{C_M U_{CM} \sqrt{4U^2 - U_{CM}^2}} \quad (24)$$

The relationship of $\omega$ to $U$ and $U_{CM}$ can be judged by

$$\frac{\partial \omega}{\partial U} = -\frac{16PU}{C_M U_{CM} \sqrt{4U^2 - U_{CM}^2}^3} \quad (25)$$

and

$$\frac{\partial \omega}{\partial U_{CM}} = \frac{8P(U_{CM}^2 - 2U^2)}{C_M U_{CM}^3 \sqrt{4U^2 - U_{CM}^2}^3}. \quad (26)$$

According to (25) and (26), $(\partial \omega/\partial U) < 0$, while $(\partial \omega/\partial U_{CM})$ depends on the relationship between $U_{CM}$ and $\sqrt{2U}$.

1. If $\phi \in [-\pi/2, \pi/2)$, $U_{CM} < \sqrt{2U}$ in (22). From (26), $(\partial \omega/\partial U_{CM}) < 0$. Therefore, with the given $U_{max}$ and $U_{CM_{max}}$, the minimum $\omega$ can be readily determined by

$$\omega \geq \frac{4P}{C_M U_{CM_{max}} \sqrt{4U_{CM_{max}}^2 - U_{CM_{max}}^2}} \quad (27)$$

2. If $\phi \in [-\pi, -(\pi/2)]$ or $(\pi/2, \pi]$, $U_{CM} > \sqrt{2U}$.

From (26), $(\partial \omega/\partial U_{CM}) > 0$. It is hard to determine a minimum $\omega$ by (24). Thus, we should check the relationship between $U_{CM}$ and $U$. From (22) with $+$, it is evident that $(\partial U_{CM}/\partial U) < 0$, and then, we have $U_{CM} \geq \sqrt{2U}$. Substitute $U \geq (2P/\omega C_M)^{1/2}$ by (23) into $U_{CM} \geq \sqrt{2U}$, and we have

$$\omega \geq \frac{4P}{C_M U_{CM} \sqrt{4U_{CM}^2 - U_{CM}^2}} \geq \frac{4P}{C_M U_{CM_{max}}^2} \quad (28)$$

Summarily, for any CPT converter with enough independent variables, the operating angular frequency $\omega$ can be designed by (23) and (27) for $\phi \in [-\pi/2, (\pi/2)]$ or by (23) and (28) for $\phi \in [-\pi, -(\pi/2)]$ or $[(\pi/2), \pi]$, satisfying the requirement of output power, given coupler plate and given coupler plate voltage stresses. The range of $\phi$ should be analyzed for the detailed CPT topology.

**B. Phase Angle for Different Angular Frequencies**

The phase angle $\phi$ between $\mu_1$ and $\mu_2$ for a double-sided LCCLC-compensated CPT converter, as shown in Fig. 2, can be determined by the expressions of vectors $U_1$ and $U_2$, as given in (29), at $\omega_0$ and (30) at $\omega_1$, i.e., $\omega_{HI,IL}$.

$$\begin{align*}
U_{1,2} &= \left(\begin{array}{c}
1 - \frac{L_1}{L_{f1}} \\
\frac{1}{j\omega_0 C_{f1} Z_{IN1} L_{f1}}
\end{array}\right) U_{in} \\
U_{2,2} &= \left(\begin{array}{c}
R_{E}
L_2 \\
\frac{1}{j\omega_0 C_{f2} L_{f2}}
\end{array}\right) I_{R}.
\end{align*} \quad (29)$$

From (4), $L_1 > L_{f1}$ and $L_2 > L_{f2}$. From (6), $Z_{IN1} > 0$. Substituting (5) into (29), we have $\Re(U_1) < 0$, $\Im(U_1) < 0$, $\Re(U_2) < 0$, and $\Im(U_2) < 0$. Thus, both $U_1$ and $U_2$ are located at the third quadrant at $\omega_0$, as shown in Fig. 9(a) and (b), where $\phi \in [-\pi/2, (\pi/2)]$. 

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Similarly, if the CPT converter operates at \( \omega_1 \)

\[
\begin{align*}
\mathbf{U}_{1|\omega_1} &= \left[ \gamma - \frac{j \omega_1 L f_1}{Z_{in2}} \left( \gamma + \frac{\omega_0^2}{\omega_1^2}(1 - \gamma) \right) \right] \mathbf{U}_{in} \\
\mathbf{U}_{2|\omega_1} &= \left[ \gamma R E + j \omega_1 L f_2 \left( \gamma + \frac{\omega_0^2}{\omega_1^2}(1 - \gamma) \right) \right] \mathbf{I}_2
\end{align*}
\]  

(30)

where \( \gamma = 1 - (\omega_0^2/\omega_1^2)(1 + 1/(1 - k^2_2)\beta)) \). If the CPT converter works at \( \omega_{1H}, \omega_{1L}^2/\omega_0^2 = 1 + \alpha \) by (16) and \( \alpha > 0 \). Thus, \( \gamma < 0 \). The expression of \( \gamma + (\omega_0^2/\omega_1^2)(1 - \gamma) \) can be derived to be always negative. From (18), \( Z_{in2} > 0 \). Substituting (17) into (30), we have \( \Re(\mathbf{U}_1) < 0 \), \( \Im(\mathbf{U}_1) > 0 \), \( \Re(\mathbf{U}_2) < 0 \), and \( \Im(\mathbf{U}_2) > 0 \). Then, both \( \mathbf{U}_1 \) and \( \mathbf{U}_2 \) at \( \omega_{1H} \) are located at the second quadrant with \( \varphi \in [-(\pi/2), (\pi/2)] \), as shown in Fig. 9(c) and (d). If the CPT converter works at \( \omega_{1L}, \omega_{1L}^2/\omega_0^2 = 1 - \alpha \). The expression of \( \gamma + (\omega_0^2/\omega_1^2)(1 - \gamma) \) can be derived to be always positive. Thus, \( \Im(\mathbf{U}_1) < 0 \) and \( \Re(\mathbf{U}_2) > 0 \). However, the polarity of \( \gamma \) cannot be uniquely determined by

\[
\gamma |_{\omega_{1L}} = \sqrt{(1 - k^2_2)\beta^2 + (1 + k^2_2)\beta + k^2_2 - 1}. \tag{31}
\]

There are two cases for \( \gamma \), which are as follows.

1) If \( \beta < ((5 - 4k^2_2)^{1/2} - 1)/(2(1 - k^2_2)) \), \( \gamma < 0 \). Then, \( \Re(\mathbf{U}_1) < 0 \) and \( \Im(\mathbf{U}_2) > 0 \). Thus, \( \mathbf{U}_1 \) is located at the third quadrant, and \( \mathbf{U}_2 \) is located at the first quadrant at \( \omega_{1L} \), as shown in Fig. 9(e) and (f). Thus, \( \varphi \in [-\pi, -\pi/2) \) or \( [\pi/2, \pi] \).

2) If \( \beta > ((5 - 4k^2_2)^{1/2} - 1)/(2(1 - k^2_2)) \), \( \gamma > 0 \). Then, \( \Re(\mathbf{U}_1) > 0 \) and \( \Im(\mathbf{U}_2) < 0 \). Thus, \( \mathbf{U}_1 \) and \( \mathbf{U}_2 \) are both located at the fourth quadrant with \( \varphi \in [-\pi/2, (\pi/2)] \), as shown in Fig. 9(g) and (h).

From Section III-A, in the double-sided \( LCLC \)-compensated CPT converter, the operating angular frequencies \( \omega_0 \) and \( \omega_{1H} \) should be designed by (23) and (27) due to \( \varphi \in [-\pi/2, (\pi/2)] \). The operating angular frequency \( \omega_{1L} \) can be designed by (23) and (27) for \( \varphi \in [-\pi, -\pi/2) \) or by (23) and (28) for \( \varphi \in [-\pi, -\pi/2) \) or \( [\pi/2, \pi] \). However, it should be noticed that the operation range of \( \varphi \) is determined by the relationship between \( \beta \) and \((5 - 4k^2_2)^{1/2} - 1)/(2(1 - k^2_2)) \). Therefore, if the CPT converter is designed at \( \omega_{1L} \), \( \beta \) and \( k \) can be solved by Section III-C, and \( \varphi \) must be rechecked to satisfy the predesigned range.

### C. Parameter Design Process

From Section III-B, the phase angle \( \varphi \) of the double-sided \( LCLC \)-compensated CPT converter has two cases. With the predesigned \( U_{Cmax}, U_{max}, I_O, C_M, U_{dc} \), and full output power \( P \), the operating angular frequencies \( \omega_0, \omega_{1H}, \) and \( \omega_{1L} \) can be calculated in a range by (23) and (27) or by (23) and (28). Select \( \omega \) as the operating angular frequency, and (23) can be rewritten as

\[
\sqrt{\frac{2P}{\omega C_M}} \leq U \leq U_{max}. \tag{32}
\]

Meanwhile, \( U_{CM} \leq U_{Cmax} \). With (22), two cases of \( \varphi \) should be considered, which are as follows.

1) If \( \varphi \in [-\pi/2, (\pi/2)] \), substitute \( U_{Cmax} \) into (22) with \( - \) and solve \( U \) as \( U_{sol1} \). The relationship between \( U \) and \( U_{CM} \) can be determined by

\[
\frac{\partial U_{CM}}{\partial U} = \frac{\sqrt{2}}{1 - \sqrt{1 - \frac{4P^2}{\omega^2 C_M^2 U^2}} \left( 1 - \frac{1}{1 - \frac{4P^2}{\omega^2 C_M^2 U^2}} \right)} < 0. \tag{33}
\]

Thus

\[
U \geq U_{sol1}. \tag{34}
\]
Given $U_{SC}$, $C_p$, $C_S$, $C_f$, $I_{O1}$, $f$, $U_{CM_{\text{max}}}$ and $U_{\text{max}}$

Calculate range of $\omega_0$, $\omega_{1H}$, and $\omega_{1L}$ by (21) & (25)

Calculate range of $\omega_{1H}$ by (21) & (26)

Choose the operating frequency $\omega$

Choose $U$ by (30) & (32)

Choose $U$ by (30) & (33)

Solve $\{ U_1 = U \text{ by (27)} \}$
$\{ U_2 = U \text{ by (27)} \}$
$\{ I_{O1} = I_0 \text{ by (18)} \}$
Choose $C_1 = C_2$

Solve $\{ U_1 = U \text{ by (28)} \}$
$\{ U_2 = U \text{ by (28)} \}$
$\{ I_{O2} = I_0 \text{ by (18)} \}$
Choose $C_1C_2 - C_3C_4$ by (13)

Solve $\{ U_1 = U \text{ by (28)} \}$
$\{ I_{O2} = I_0 \text{ by (18)} \}$
Choose $C_1C_2 - C_3C_4$ by (13)

Calculate $C_1$, $C_2$, $C_p$, $C_S$

Calculate $C_1$, $C_2$, $C_p$, $C_S$

Calculate $C_1$, $C_2$, $C_p$, $C_S$

Calculate $L_1$, $L_2$, $I_{O1}$, $I_{O2}$, $C_{ex1}$ and $C_{ex2}$ by (1), (4), (7), (8) & (14)

Complete

2) If $\varphi \in [-\pi, -(\pi/2)]$ or $[(\pi/2), \pi]$, substitute $U_{CM_{\text{max}}}$ into (22) with $+$ and solve $U$ as $U_{\text{sol2}}$. Due to $(\partial U_{CM}/\partial U) > 0$ at this case

$$U \leq U_{\text{sol2}}.$$ (35)

From (32) and (34) or (35), $U$ can be selected to guarantee $U_{CM} \leq U_{CM_{\text{max}}}$. Then, we can combine four equations to solve four independent parameters $C_{f1}$, $C_{f2}$, $C_1$, and $C_2$, which includes $U_1 = U_2$ by (29) or (30), $I_{O1} = I_0$, or $I_{O2} = I_0$ by (20) and (15) for $\omega_1$. Here, it should be noted that there are only three equations for $\omega_0$ case. Therefore, one parameter among $C_{f1}$, $C_{f2}$, $C_1$, and $C_2$ can be predesigned, for example, $C_1 = C_2$. The detailed design process is given in Fig. 10. From Fig. 10, $\varphi$ must satisfy one case of $|\varphi| < (\pi/2)$ or $(\pi/2) < |\varphi| < \pi$ at least. Thus, if one case is not satisfied, there is no solution, and $\varphi$ can satisfy the other case to find the solution. The operating frequency could be selected according to the requirements of applications, product volume, cost, efficiency, and EMI issues.

D. Soft Switching Realization

Fig. 11 shows the normalized output current and phase angle versus normalized parameters at $\omega_0$, $\omega_{1H}$, and $\omega_{1L}$, respectively. From Fig. 11(a) and (b), it can be seen that the output current is not sensitive to $L_1$ and $L_{f2}$ variations at $\omega_0$. Then, the smaller $L_1$ and $L_{f2}$ will permit the ZVS of CPT converters, which is consistent with the results in [15]. Similarly, the output current is not sensitive to the variation of $L_{f2}$ at both $\omega_{1H}$ and $\omega_{1L}$ from Fig. 11(c) and (e). A small decrement of $L_{f2}$ can ensure ZVS from Fig. 11(d) and (f).

IV. EXPERIMENT VERIFICATION

To verify the abovementioned analysis, a 40-W double-sided LC-LC-compensated CPT prototype is built to provide a CC of 2 A, as shown in Fig. 12. The length $l$ of each coupler plate is 200 mm, and the air distance $d$ is 6 mm. The distance $d_1$ between two plates on the same primary or secondary side is 10 mm. The equivalent parameters can be measured as $C_M = 35$ pF and $C_P = C_S = 40$ pF. The input dc voltage is 24 V, and the duty cycle is set as 0.95. The predesigned maximum voltage stress $U_{CM_{\text{max}}}$ is 800 V, and $U_{\text{max}}$ is 1200 V.

From Fig. 10, the operating frequency can be calculated as $f \geq 402$ kHz for $f_{0}$, $f_{1H1L}$, and $\varphi \in [-(\pi/2), (\pi/2)]$, while $f \geq 1.14$ MHz for $f_{1L}$ and $\varphi \in [-\pi, -(\pi/2)]$ or $[(\pi/2), \pi]$. If $f$ is designed at 500 kHz as $f_0$ and $f_{1H1L}$ for $\varphi \in [-(\pi/2), (\pi/2)]$, the calculated $U$ belongs to [994 V, 1200 V] and $U_{CM}$ belongs to [629 V, 800 V]. If $f$ is designed as 1.5 MHz as $f_{1L}$ for $\varphi \in [-\pi, -(\pi/2)]$ or $[(\pi/2), \pi]$, $U$ belongs to [493 V, 502 V] and $U_{CM}$ belongs to [697 V, 800 V]. We choose $U_{CM} = 750$ V with a design margin, and the calculated $U$, $C_{f1.2}$, $C_{ex1.2}$, $L_{1.2}$, and $L_{f1.2}$ are given in Table I. It should be noted there is no solution for $f_{1L}$ when $\varphi \in [-(\pi/2), (\pi/2)]$. The CPT converter can be designed to
work at $f_0$ or $f_{1H}$ of 500 kHz in the consideration of the implementation of the inventor, efficiency, and EMI issues [29]. Comparing the inductor sizes at two frequencies listed in Table I, $f_{1H}$ of 500 kHz is used here. A microcontroller TMS320F28335 and the gate driver 1EDI20N12AF are used to drive $Q_1$, $Q_2$, $Q_3$, $Q_4$. $Q_1$, $Q_2$, $Q_3$, $Q_4$ use IPA180N10N3, while the secondary rectifier diodes $D_1$, $D_2$, $D_3$, $D_4$ use VB30100S.

Fig. 13 shows the experimental waveforms of the indicated voltage $u_{GS1}$ for MOSFET $Q_1$, modulated voltage $u_{AB}$, input current $i_{IN}$, and output current $I_O$ for half load of $R_L = 5 \Omega$ and full load of $R_L = 10 \Omega$. It is found that the output current keeps at the required 2 A independent of the load. The small phase angle of $i_{IN}$ lagging $u_{AB}$ facilitates ZVS of the full-bridge switches.

To verify the voltage stress optimization, voltage waveforms of $u_{GS1}$, $u_{C13}$, $u_1$, and $u_2$ at full load are given in Fig. 14. From Fig. 14, the measured $U_1$ and $U_2$ are 1030 and 985 V, which are close to the theoretical values, and the small difference is caused by the capacitor tolerance. $U_{C13}$ is measured as 380 V, where $U_{CM} \approx 2U_{C13}$, which is also consistent with the value in Table I. The experimental results show good agreement with the calculated values. If the plate misalignment happens, the secondary plates of $P_3$ and $P_4$ may move in the $X$-axis or $Y$-axis direction, as shown in Fig. 3(a). Fig. 15 gives the maximum voltage variations of the calculated $U_{CM}$ (i.e., $2U_{C13}$), $U_1$, and $U_2$ under the $X$-axis and $Y$-axis misalignment percentages to the plate length.

It can be seen that a small misalignment for the $X$-axis or $Y$-axis is permitted with the predesigned voltage stresses. The efficiency of the CPT converter is measured around 83% at full load, and the losses mainly distribute in the coupler plates, magnetic inductors, and rectifier diodes, which is not the key and omitted in this article.

To further show the electric field emission reduction with the proposed design method, Fig. 16(a) gives the voltage waveforms of $u_{C13}$, $u_1$, and $u_2$ at the same output current and full load for the double-sided LCLC CPT circuit using conventional symmetric parameters, i.e., $C_{ex1} = C_{ex2} = 145 \mu F$, $C_{f1} = C_{f2} = 6 \mu F$, $L_1 = L_2 = 731 \mu H$, and $L_{f1} = L_{f2} = 21 \mu H$. Compared with Fig. 16(b) with the proposed parameter design, the voltage stresses of $U_1$ and $U_2$ are much larger although $U_{C13}$ decreases. Thus, the electric field emissions around the coupler plates are much larger than those in the proposed design, as shown in Fig. 17.
Fig. 16. Comparison of $\mu_{C_{13}}$, $\mu_1$, and $\mu_2$ at full load with (a) conventional symmetric parameters and (b) proposed parameters in a double-sided LC-\(C\)-compensated CPT converter.

Fig. 17. Electric field emissions around the coupler plates at two cases of parameter design. (a) With conventional symmetric parameters. (b) With proposed parameters.

V. CONCLUSION

To reduce the risk of air breakdown and mitigate the EMI issue in a CPT system, the voltage stresses among both the main coupled plates and the leakage coupled plates should be optimized to the acceptable levels. In this article, a double-sided LCLC-compensated CPT circuit is proven to have enough design freedom to optimize the voltage stresses among the coupler. Meanwhile, three frequencies are found in the double-sided LCLC-compensated CPT circuit to realize input ZPA and load-independent CC output simultaneously, which can facilitate a reduced power stage, simple control circuitry, and high transfer efficiency. Also, a parameter design method is proposed to realize the required load-independent CC output and the predesigned voltage stresses at each frequency. The method can be readily extended to the other CPT systems. Experimental results have validated the theoretical analysis well.

REFERENCES


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