A Common Capacitor Multi-Phase LLC Resonant Converter

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***Abstract*— In this paper, a new common capacitor current sharing method is proposed for multi-phase LLC resonant converter. Automatic current sharing is achieved by using a common resonant capacitor for all the LLC resonant stages, by connecting the resonant capacitors in each phase in parallel. The proposed method can automatically share the load current without any additional circuits and control strategy. The current sharing performance of the proposed common capacitor current sharing method is analyzed under Fundamental Harmonic Analysis (FHA) assumption. A 600W two-phase LLC converter prototype based on the proposed method is built to verify the feasibility. Excellent current sharing performance (6.5% current sharing error at a wide load range) has been achieved.**

I. INTRODUCTION

Resonant converter is attractive for isolated DC/DC application, such as flat-panel TVs, laptop adapters, server power supplies and so on, due to its high efficiency and high power density. LLC resonant converter can naturally achieve zero voltage switching (ZVS) for the primary-side MOSFET and zero current switching (ZCS) for the secondary-side diodes [1], [2]. For high power applications, the current stress of power devices increases with the power rating increasing. Multiphase parallel technique is a good choice to solve this problem [3][4][5]. However, due to the tolerance of resonant components, the resonant frequency of each individual LLC stage will be different, thus the output currents will be different [6][7][8]. It is observed that small component tolerance (such as 5%) can cause significant current imbalance. Therefore, current sharing is essential in order to achieve multiphase operation for LLC converter.

Some technologies have been developed to achieve current sharing for multiphase LLC converters. A category of active methods adjust the equivalent resonant capacitor [9], [10] or inductor [11] to compensate the resonant tank components' tolerances using additional MOSFETs. The circuit diagram for switched capacitor is shown in Fig. 1. The circuit diagram for variable inductor is shown in Fig. 2. Excellent load sharing performance can be achieved using these active methods. However, these methods suffer from high cost, complex control and non-excellent dynamic performance because sensing and control circuits have delays. DC voltage self-balanced method based on series input capacitors is one of the passive methods used to achieve current sharing [12][13]. Fig. 3 shows the circuit diagram of a two-phase LLCs as an example. The mid-point voltage is changed according to two phase's power. The system is of low cost and good load current sharing performance. However, it is hard to achieve modularization design and hot swap, because once the parameter design is finished, the module counts cannot be changed. There is another current sharing method based on three-phase three-wire structure. The three-phase LLCs have a 120° phase-shift between each phase. The load current sharing performance is good near resonant frequency, as all of three-phase resonant current is zero [14][15]. However, it can only be applied to three LLC modules in parallel. The load current will not share when the numbers of parallel modules is more than three.

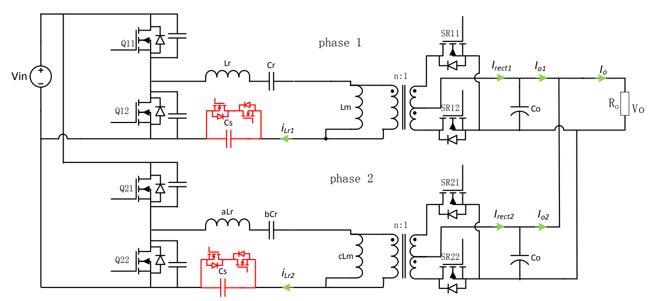

Fig. 1. Switched capacitor multi-phase LLC converter

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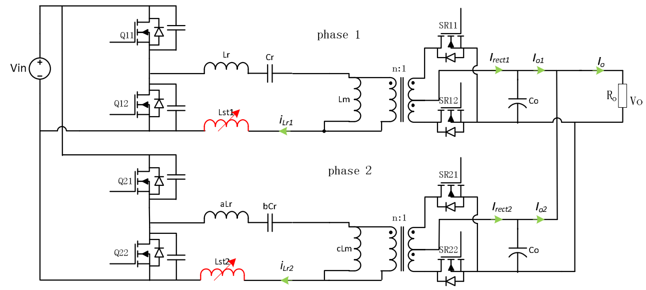


Fig. 2. Variable inductor multi-phase LLC converter

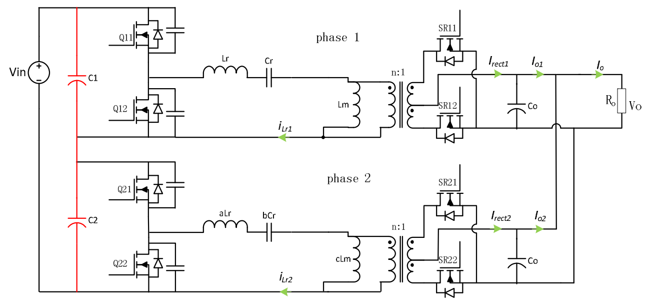


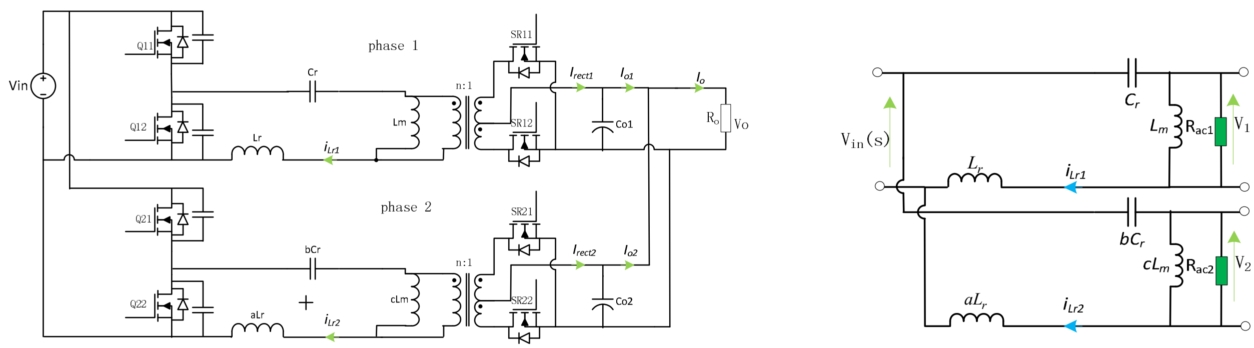
Fig. 3. Series DC-capacitor multi-phase LLC converter

Therefore, the existing technologies cannot provide cost effective and flexible current sharing technologies for multi-phase LLC resonant converters.

In this paper, a new common capacitor multi-phase LLC resonant converter is proposed to achieve load sharing without any addition components or control. In this method, the resonant capacitor in each LLC phase is connected in parallel. As a result, the load current is automatically shared. This technology is simple to implement with no additional cost. It can be expanded to arbitrary module counts without redesign the resonant parameters. This paper is organized as following: Section II describes the load sharing characteristic with/without the proposed common capacitor method; Section III provides simulation and experimental results of a two-phase 600W prototype with common capacitor; and Section IV concludes the whole paper.

II. LOAD SHARING CHARACTERISTIC OF COMMON INDCTOR MULTI-PHASE LLC RESONANT CONVERTER

Mathematic model of LLC converter is needed for analyzing the current sharing characteristics. For simple understanding, two-phase LLC converter will be used as example in this paper. Fig. 4 shows the circuit diagram and its FHA equivalent circuit for two-phase LLC converter in conventional structure without current sharing [16]. L_r, C_r, L_m are the series resonant inductor, series resonant capacitor, magnetizing inductor of phase #1 respectively. aL_r, bC_r, cL_m are the resonant inductor, resonant capacitor, magnetizing inductor of phase #2. The values, a, b, c indicate the



(a) Circuit structure

(b) FHA equivalent circuit

Fig. 4. Conventional two-phase LLC resonant converter

components' tolerances between the two LLC phases. n is transformer turn ratio. i_{Lr1}, i_{Lr2} , I_{rect1}, I_{rect2}, I_{o1}, and I_{o2} are the resonant currents, rectifier currents and load currents of two phases. Fig. 4 (b) is the equivalent circuit based on Fundamental Harmonic Analysis (FHA). In steady-state, the load resistor R_o is virtually divided into R_{o1} and R_{o2} according to the actual load current of each phase. The primary-side equivalent ac resistors R_{ac1} and R_{ac2} are determined accordingly and shown in (1).

$$\begin{cases} R_{o1} = \dfrac{1}{k} R_o, R_{o2} = \dfrac{1}{(1-k)} R_o, k \in [0,1] \\ R_{ac} = \dfrac{8n^2}{\pi^2} \mathrm{R}_o, R_{ac1} = \dfrac{8n^2}{\pi^2} \mathrm{R}_{o1}, R_{ac2} = \dfrac{8n^2}{\pi^2} \mathrm{R}_{o2} \end{cases} \quad (1)$$

In (1), k is the impedance sharing error. The value of k should be between 0 and 1. k=0.5 means the load power can be equally shared by two phases. k=0 or 1 means the load power can only be provided by one phase.

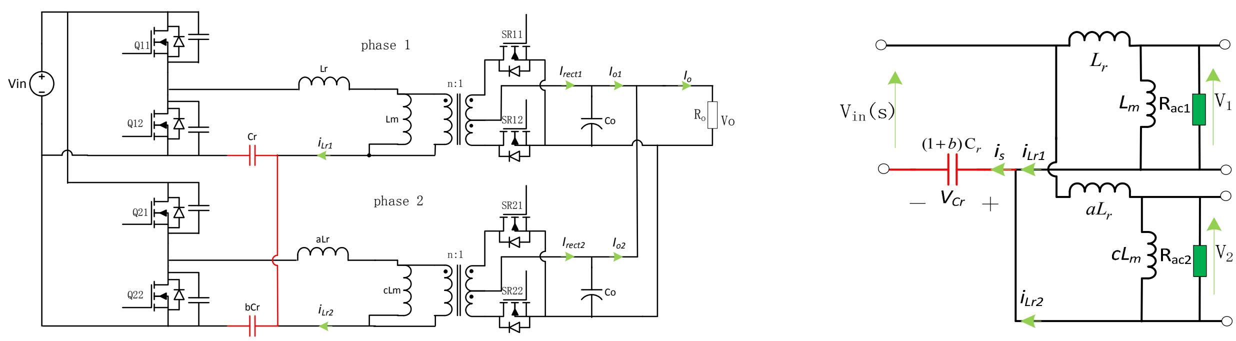
The output side of the two phases are connected together, thus the ac voltage magnitude should always be the same, while the angles should be different because of the parameter tolerance. The relationship is described in (2).

$$\left|V_1(\mathrm{s})\right| = \left|V_2(\mathrm{s})\right| \tag{2}$$

The transfer function of $V_1(s)$ and $V_2(s)$ can be derived from the components impedance in (3):

$$\begin{cases} V_1(\mathrm{s}) = \dfrac{R_{ac1} // sL_m}{R_{ac1} // sL_m + sL_r + 1/sC_r} V_{in}(s) \\ V_2(\mathrm{s}) = \dfrac{R_{ac2} // scL_m}{R_{ac2} // scL_m + saL_r + 1/sbC_r} V_{in}(s) \end{cases} \tag{3}$$

Fig. 5 (a) shows two-phase LLC resonant converter with proposed current sharing technology. The only difference from the conventional structure is that the series resonant capacitors of the two LLC converters are connected together. Fig.5 (b) shows the FHA equivalent circuit.



(a) circuit structure

(b) FHA equivalent circuit

Fig.5 Proposed two-phase LLC resonant converter

Similarly, the transfer function of $V_1(s)$ and $V_2(s)$ can be derived in (4):

$$\begin{cases} V_1(\mathrm{s}) = \dfrac{R_{ac1} // sL_m}{R_{ac1} // sL_m + sL_r}\left(V_{in}(s) + V_{Cr}(s)\right) \\ V_2(\mathrm{s}) = \dfrac{R_{ac2} // s\left(cL_m\right)}{R_{ac2} // s\left(cL_m\right) + s\left(aL_r\right)}\left(V_{in}(s) + V_{Cr}(s)\right) \end{cases} \tag{4}$$

According to (1), (2) and (3) or (4), a quadratic equation (5) can be found for the impedance sharing error k for both the conventional and the proposed parallel LLC converters:

$$Ak^2 + Bk + C = 0 \tag{5}$$

For two-phase proposed LLC converter, the parameter A, B, C can be expressed in (6):

$$\begin{cases} A = \omega^4(a^2-1)c^2 L_r^{\,2} L_m^{\,2} \\ B = -2\omega^4 a^2 c^2 L_r^{\,2} L_m^{\,2} \\ C = \omega^4 a^2 c^2 L_r^{\,2} L_m^{\,2} + \omega^2[(a^2-c^2)L_r^{\,2} + 2(ac-c^2)L_r L_m]R_{ac}^{\,2} \end{cases} \tag{6}$$

For two-phase conventional LLC converter, the parameter A, B, C can be expressed in (7):

$$\begin{cases} A = \omega^2(1-b^2)c^2 L_m^{\,2} - \omega^4(2ab-2b^2)c^2 L_r L_m^{\,2} C_r \\ \quad + \omega^6(a^2-1)b^2 c^2 L_r^{\,2} L_m^{\,2} C_r^{\,2} \\ B = -2\omega^2 c^2 L_m^{\,2} + 4\omega^4 abc^2 L_r L_m^{\,2} C_r - 2\omega^6 a^2 b^2 c^2 L_r^{\,2} L_m^{\,2} C_r^{\,2} \\ C = \omega^2 c^2 L_m^{\,2} - 2\omega^4 abc^2 L_r L_m^{\,2} C_r + \omega^6 a^2 b^2 c^2 L_r^{\,2} L_m^{\,2} C_r^{\,2} \\ \quad + (1-b^2c^2)R_{ac}^{\,2} - \omega^2[(2ab-2b^2c^2)L_r + (2bc-2b^2c^2)L_m]C_r R_{ac}^2 \\ \quad + \omega^4(ab-bc)[(ab+bc)L_r^{\,2} + 2bcL_r L_m]C_r^{\,2} R_{ac}^{\,2} \end{cases} \tag{7}$$

For quadratic equations, the roots, which are the current sharing error in this case, can be found in (8),

$$k = \begin{cases} -\dfrac{C}{B} & A = 0, B \neq 0 \\ \dfrac{-B \pm \sqrt{B^2-4AC}}{2A} & A \neq 0, \sqrt{B^2-4AC} \geq 0 \end{cases} \quad and\ k \in [0,1] \tag{8}$$

The current sharing error k is valid when k is between 0 and 1. Conditions $k = 0$ and $k = 1$ mean one phase provides all the power and the other phase does not provide power. Conditions $k < 0$ and $k > 1$ does not exist because this means one phase absorbs the power. Accordingly, the load current sharing error σ_{load} is defined in (9); and the resonant current sharing error $\sigma_{Resonant}$ is defined in (10).

$$\sigma_{load} = \frac{|I_{01} - I_{02}|}{|I_{01} + I_{02}|} = abs(1-2k), k \in [0,1] \tag{9}$$

$$\sigma_{Resonant} = \frac{|rms(i_{Lr1}) - rms(i_{Lr2})|}{|rms(i_{Lr1}) + rms(i_{Lr2})|} \tag{10}$$

Table.1 shows the resonant parameters of the phase #1, serving as the reference, to which the component tolerances of phase #2 will be compared.

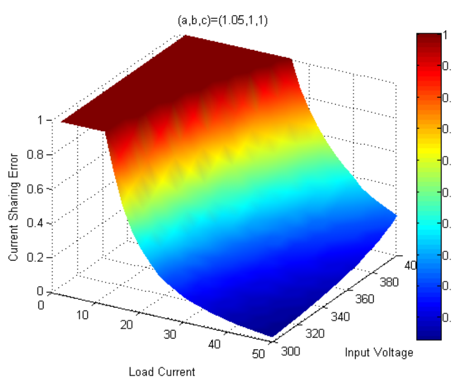
TABLE I. NOMINAL PARAMETER

L_r	C_r	L_m	n	f_r	V_o	P_o(total)
29μH	12nF	95μH	20	270kHz	12V	600W

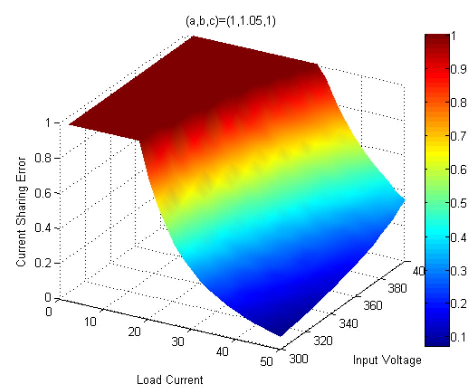
If a>1 or b>1, it means phase #2 has lower resonant frequency compared with phase #1. Assuming same load, at given switching frequency, phase #2 will have lower voltage gain. If the two phases achieve same output voltage, phase #1 will output more power. If c>1, phase #2 will have higher inductor ratio which results in lower voltage gain. Phase #1 will output more power to keep the output voltage same. And vice versa, if a<1, b<1, or c<1, phase #2 will output more power. Thus, the worst situation is that parameters *a, b, c* deviates in the same direction.

Fig. 6 shows load current sharing error with different parameter tolerances in conventional two-phase LLC converter. Fig. 6 (a), (b), (c) shows the current sharing error at +5% L_r, +5% C_r, +5% L_m tolerance respectively. The current sharing error reduces with total load current increasing and input voltage decreasing. The worst case is shown in Fig.6 (d), in which three resonant parameters have +5% deviation simultaneously. The current sharing error is 60% at 50A load current for nominal 400V input voltage.

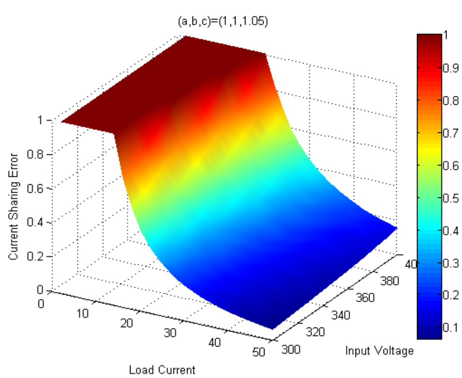
Fig. 7 shows the load current sharing error with different parameter tolerances in proposed two-phase common capacitor LLC converter. Fig.7 (a), (b), (c) shows the current sharing error at +5% L_r, +5% C_r, +5% L_m, respectively. Specifically, for +5% C_r case, L_r and L_m have no tolerance, thus there is no current difference as the two capacitors are paralleled. For simultaneous +5% tolerance on L_r, C_r, L_m case shown in Fig.7 (d), the current sharing error is about 2% at 50A load current, 400V input voltage.



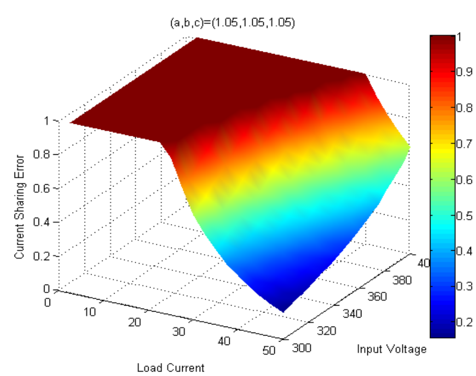
(a) +5% L_r parameter tolerance



(b) +5% C_r parameter tolerance

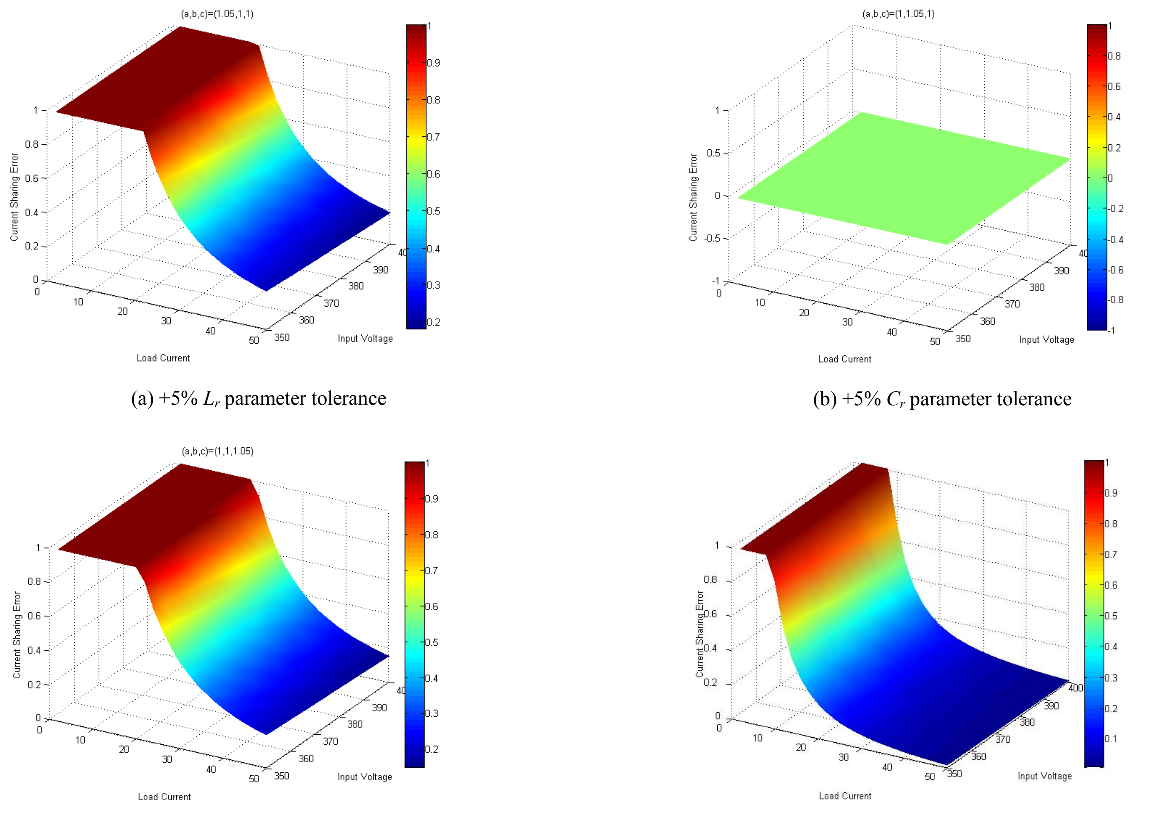


(c) +5% L_m parameter tolerance



(d) +5% L_r, +5% C_r, and +5% L_m parameter tolerance

Fig. 6. Current sharing error under two-phase independent LLC converter.



(a) +5% L_r parameter tolerance

(b) +5% C_r parameter tolerance

(c) +5% L_m parameter tolerance

(d) +5% L_r, +5% C_r, and +5% L_m parameter tolerance

Fig. 7. Current sharing error under two-phase common capacitor LLC converter

III. SIMULATION AND EXPERIMENT RESULTS

A 600W two-phase LLC converter prototype using common capacitor current sharing technology is built to verify the feasibility and to demonstrate the advantages of the proposed method. The circuit diagram is shown in Fig.5 (a). The parameters are shown in Table 2.

TABLE II. PROTOTYPE PARAMETERS

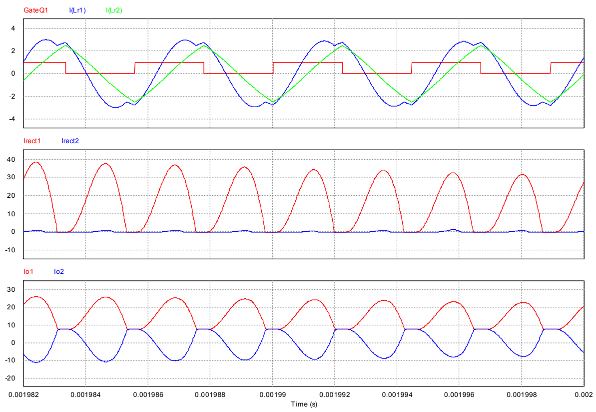
Input Voltage range	350V-400V
Output Voltage	12V
Output Power	300W × 2
Transformer Ratio *n*	20:1
Output Capacitance	1790µF
Series Capacitance(C_r)	13nF(Phase1) 12nF(Phase2)
Resonant Inductance(L_r)	24.5µH(Phase1) 22.5µH(Phase2)
Leakage Inductance(L_e)	6.5µH(Phase1) 6µH(Phase2)
Magnetizing Inductance(L_m)	95µH(Phase1) 92µH(Phase2)

Fig.8 show simulation waveforms of conventional two-phase LLC converter without current sharing at 15A, 25A total load under 400V input voltage. The designed rated load current is 25A for each phase, thus, in conventional parallel structure, only 25A total load current experiment is provide to avoid the overcurrent of each phase.

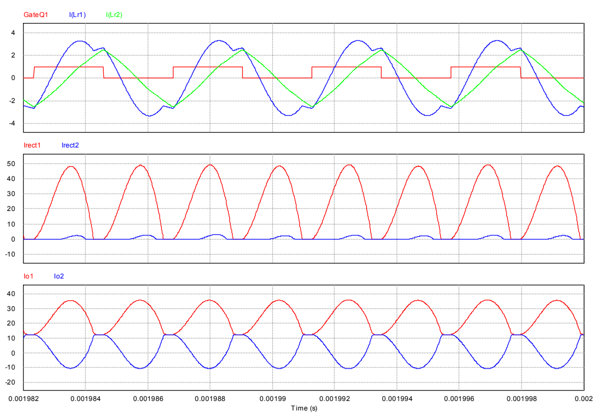
In Fig. 8, the load current I_{o1} and I_{o2} are measured after the output capacitor. I_{o2} may have negative current at switching frequency level. This is because the output voltage has switching frequency ripple, the load current I_{o2} also has a switching frequency ripple to charge or discharge the output capacitor C_{o2}. On the other side, the average value of I_{o2} is zero. Thus, only phase #1 provides the load power.

Fig.9 shows simulation waveforms of two-phase LLC converter using the proposed common capacitor current sharing method at 15A, 25A, 50A total load under 400V input voltage. The load current difference is reduced from 15A to 0.6A between Fig. 8 (a) and Fig. 9 (a). The load current difference is reduced from 25A to 1A between Fig.8 (b) and Fig. 9 (b). Fig.9 (c) shows that at 50A total load, the load difference between the two phases is around 1A.

The resonant current, rectifier current are almost same for two phases. Thus, the load current is shared by two phases. It is believed that good resonant inductor current sharing guarantees good load current sharing as indicated according to Fig. 8 and Fig. 9.

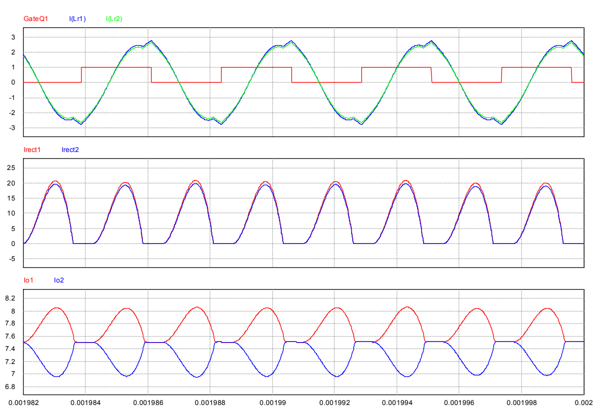


(a) Steady state at 15A load

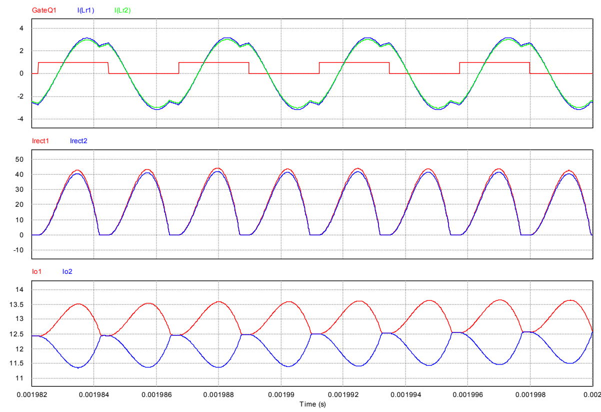


(b) Steady state at 25A load

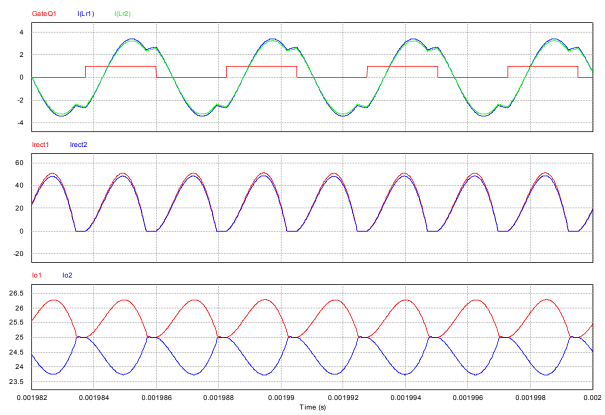
Fig. 8. Simulation waveform of conventional two-phase LLC converter



(a) Steady state at 15A load



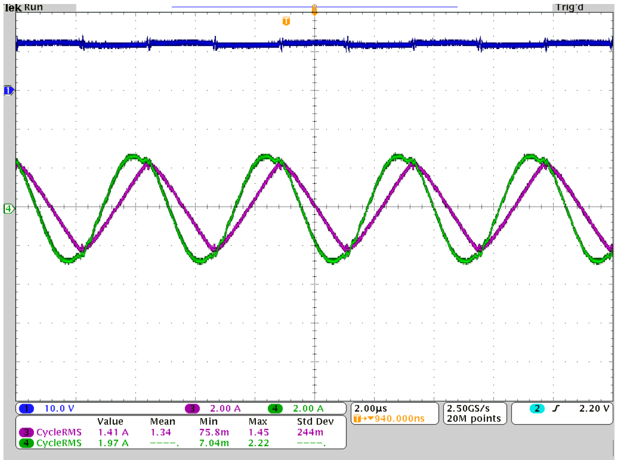
(b) Steady state at 25A load



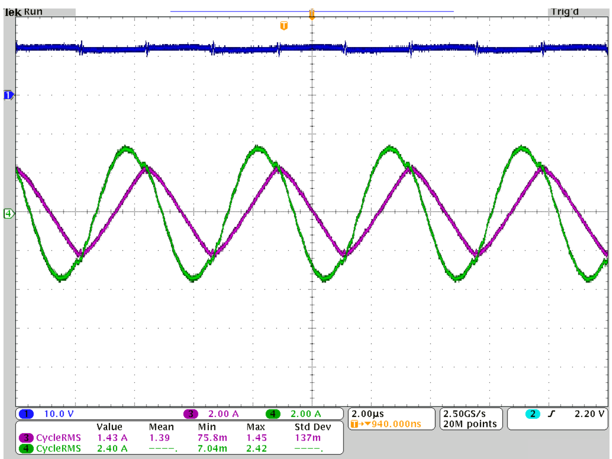
(c) Steady state at 50A load

Fig. 9. Simulation waveform of proposed two-phase LLC converter

Fig.10 shows the experiment waveform of conventional two-phase LLC converter for 15A and 25A load under 400V input voltage. Channel 1 is the output voltage. Channel 3, channel 4 are the resonant current of two phases. The resonant current i_{Lr_ch3} is almost triangular waveform, which means that phase almost does not provide the power for output load. Fig. 11 shows the experiment waveform of proposed two-phase LLC converter under 400V input voltage. The resonant current i_{Lr_ch3} and i_{Lr_ch4} is almost same. This indicates the two phases have shared loads.

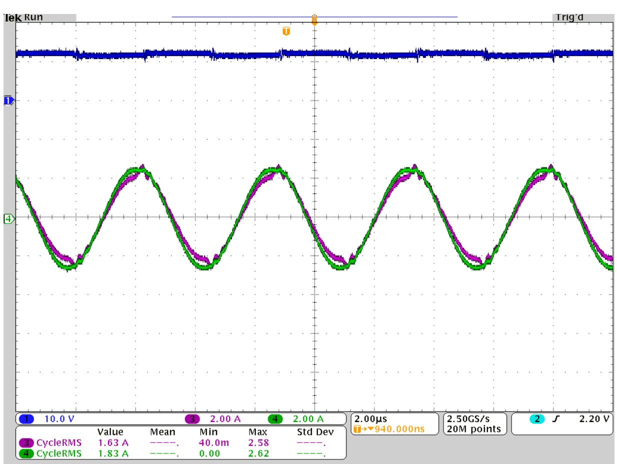


(a) Steady state at 15A load

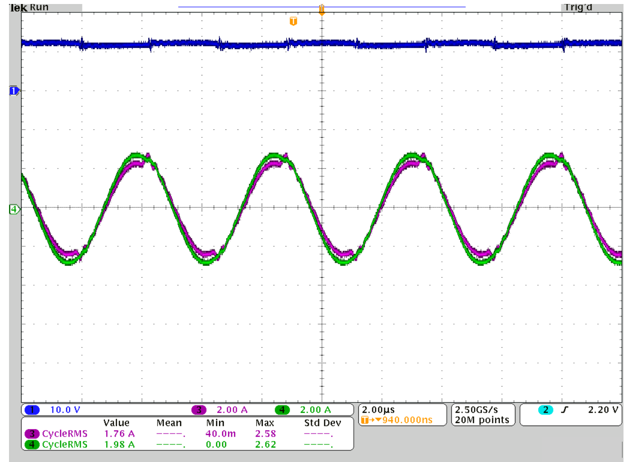


(b) Steady state at 25A load

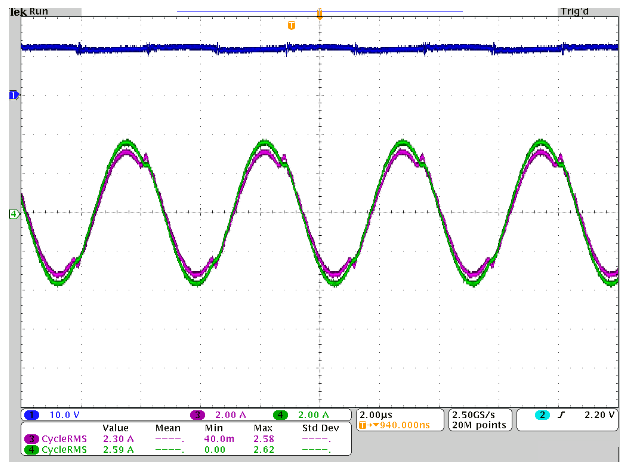
Fig. 10. Experiment waveform of conventional two-phase LLC converter



(a) Steady state at 15A load



(b) Steady state at 25A load



(c) Steady state at 50A load

Fig. 11. Experiment waveform of proposed two-phase LLC converter

To express circulating resonant current according to (5), the resonant current and relative resonant current error are shown in Fig. 12 and Fig.13.

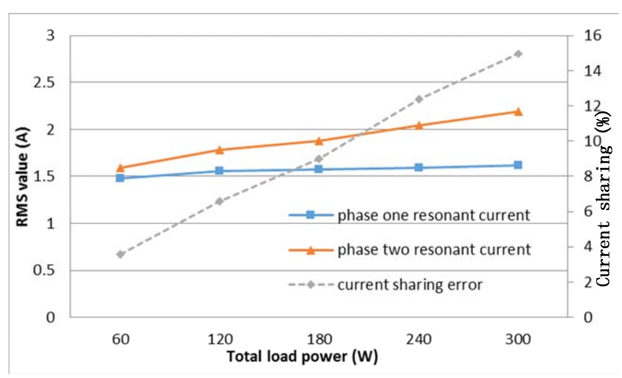


Fig. 12. Resonant current and relative error of conventional two-phase LLC converter

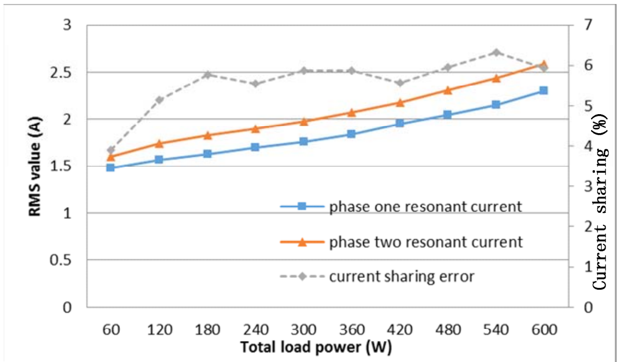


Fig. 13. Resonant current and relative error of common capacitor two-phase LLC converter

For conventional two-phase LLC converter, the resonant current error increases from 10% to 28% with load current increasing from 5A to 25A according to Fig. 12.

For the two-phase LLC converter with common capacitor technology, the resonant current error is at around 6.5% for the whole load range from Fig.13. Thus, the circulating current between phases is significantly reduced using the proposed method.

IV. Conclusion And Future Work

A new, common capacitor current sharing strategy for multi-phase LLC resonant converter is proposed. The series resonant capacitors in each LLC converter are connected in parallel. No additional components are needed to achieve current sharing. Mathematical model is built based on FHA to analyze the current sharing characteristics of a two-phase LLC converter. The analysis results shows that the circulating current is significantly reduce using the proposed method. A two-phase LLC converter prototype with 300W per phase is built using the common capacitor current sharing method. The simulation and experiment results show that the relative circulating resonant current can be maintained at 6.5% for all load conditions with proposed common capacitor method.

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