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A Passive Current Sharing Method with Common Inductor Multi-Phase LLC Resonant Converter

Hongliang Wang, *Senior member*, Yang Chen, *Student Member*, and Yan-Fei Liu, *Fellow, IEEE*
Department of Electrical and Computer Engineering
Queen's University, Kingston, Canada
hongliang.wang@queensu.ca, yang.chen@queensu.ca, yanfei.liu@queensu.ca

Jahangir Afsharian and Zhihua (Alex) Yang
Murata Power Solutions
Toronto, Canada
jafsharian@murata.com, ZYang@murata.com

***Abstract*— In this paper, a new common inductor current sharing method is proposed for multi-phase LLC resonant converter for high power applications. Automatic current sharing is achieved by using a common resonant inductor - connecting the resonant inductors in each LLC phase in parallel. The current sharing performance of the proposed method is evaluated under First Harmonic Approximation (FHA) assumption. The proposed method can automatically share the primary resonant current and the load current for all phases without any additional circuit and control strategy. A 600W two-phase LLC converter prototype based on the proposed method is built to verify the feasibility. Excellent current sharing performance (less than 0.5% current sharing error at full load) has been achieved.**

***Keywords*— Resonant Converter; Multi-phase LLC; Current sharing error.**

I. INTRODUCTION

RESONANT converter is attractive for isolated DC/DC applications, such as flat-panel TVs, laptop adapters, servers and so on, because of its attractive features: smooth waveforms, high efficiency and high power density. LLC resonant converter has been widely used due to the high efficiency as a result of the zero voltage switching (ZVS) for the primary-side MOSFET and zero current switching (ZCS) for the secondary-side diodes [1-6]. Other resonant converters, such as LCC [7-10], LCLC [11-15] are also used for industry applications. For resonant converter used in high power applications, high current stress on the power devices may reduce both efficiency and reliability. Multi-phase parallel technique can solve this problem by reducing the current stress in each phase [16-19]. However, due to the tolerance of resonant components, the resonant frequency of each individual LLC phase will be different, thus the output currents will be uneven [20-22]. It is observed that a small component tolerance (e.g. 5%) can cause significant current imbalance among phases, such as more than 50% current sharing error and thus degradation of the benefits achieved by parallel technique. Therefore, current sharing strategy is mandatory in multi-phase LLC converter.

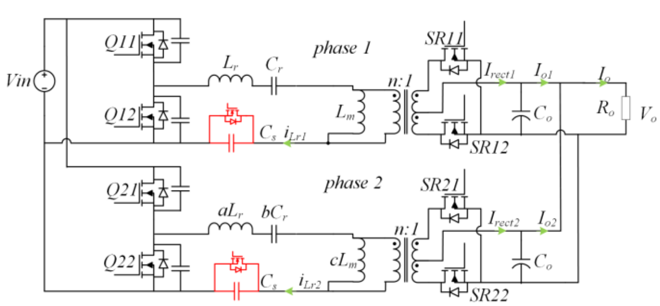

Fig. 1. Switch controlled capacitor multi-phase LLC converter

Three types of methods have been used to achieve current sharing for multi-phase LLC converters [23-31]. The first method is the active method, which adjusts the equivalent resonant capacitor [23-25] or resonant inductor [26] to compensate the components' tolerances using additional MOSFETs. The circuit diagram with switch controlled capacitor is shown in Fig. 1. The circuit diagram with linearly controlled inductor is shown in Fig. 2, where the value of the resonant inductor is controlled by an additional DC winding. Parameters *a*, *b* and *c* are used to indicate the tolerances between every two phases. Good load sharing performance can be achieved. However, these methods suffer from high cost, complex control and non-excellent dynamic performance caused by the sensing circuit and control loop.

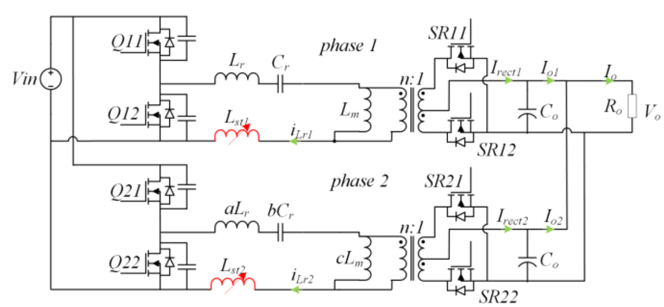

Fig. 2. Linearly controlled inductor multi-phase LLC converter

The second method is DC voltage self-balanced method based on series input capacitors [27, 28, 32], which is shown in Fig. 3. Ideally, for two-phase, the two input DC capacitor voltages are the same, and equal to half of the input bus voltage. If the load power is not shared, the mid-point voltage will be changed according to each phase's power. With this method, the system has low cost and good load current sharing performance. However, it is not suitable for modularization design in system level, as the input voltage for each phase is reduced with module number increasing. Furthermore the gate drive circuit for the top phase is complicated. In addition, the relative analysis [32] shows that 29% current sharing error can

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be achieved under +10% tolerance of resonant inductor, which is not very good.

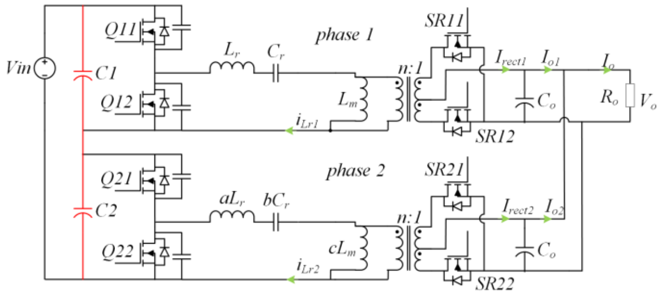

Fig. 3. Series DC capacitor multi-phase LLC converter

The third method is using three-phase three-wire structure for three-phase LLC resonant converter based on 120° phase-shift as shown in Fig. 4, which has good load current sharing near resonant frequency [30, 31]. But, it is only suitable for converters with three LLC modules in parallel. The load current will not share very well when the number of parallel modules is more than three.

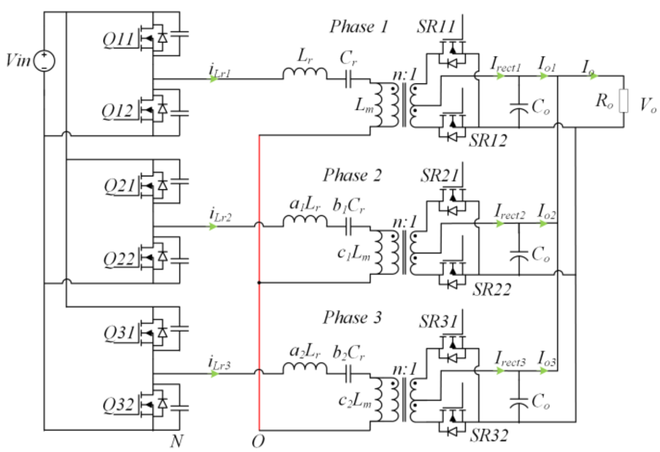

Fig. 4. Three-wire three-phase LLC converter

Therefore, from the above review, it is noted that the existing technologies cannot provide cost effective, flexible current sharing performance for multi-phase LLC resonant converters.

In this paper, a common inductor multi-phase LLC resonant converter is proposed. The resonant inductor in each LLC phase is connected in parallel to achieve current sharing. First Harmonic Analysis (FHA) shows that the load current of each phase can be automatically shared. This technology is simple that no additional cost or complex control is needed. It can be expanded to any number of phases.

This paper is organized as follows. Current sharing performance of conventional multi-phase LLC resonant converter is given in Section II. Section III discusses current sharing analysis of the proposed common inductor LLC resonant converter. The simulation results are provided in Section IV. Section V provides the experimental results of a two-phase 600W LLC resonant converter prototype with both the conventional method and the proposed method. The paper is concluded in Section VI.

II. CURRENT SHARING PERFORMANCE OF CONVENTIONAL MULTI-PHASE LLC

In this section, the current sharing performance of conventional multi-phase LLC converter will be demonstrated. The FHA-based method introduced in [34, 35] is used in this paper for analyzing the current sharing performance. This method utilizes the fact that the reflected AC voltages in FHA method have the same magnitude for different phases [22, 32, 33] for equation solving. The highlight of the method is that, it reveals that there exists a small phase difference between the reflected AC voltages. This method could be applied to both decoupled resonant tank (conventional structure) analysis and coupled resonant tank (common inductor structure) analysis.

A conventional two-phase LLC converter is shown in Fig. 5. Switches Q11, Q12, Q21 and Q22 are the primary HB switches of two phases. SR11, SR12, SR21 and SR22 are synchronous rectifiers on the secondary side of two phases.

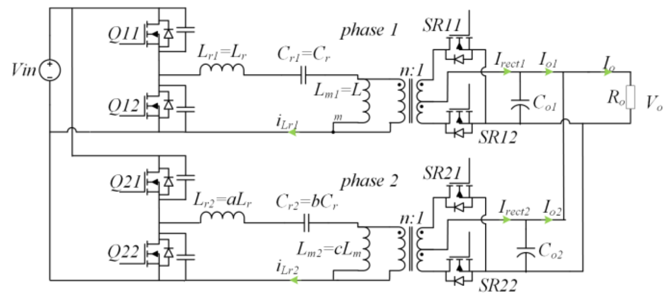

Fig. 5. Conventional two-phase LLC resonant converter

L_{r1}, C_{r1} and L_{m1} are the series inductor, series capacitor, magnetizing inductor of phase 1. L_{r2}, C_{r2} and L_{m2} are the series inductor, series capacitor, magnetizing inductor of phase 2. i_{Lr1}, i_{Lr2}, I_{rect1}, I_{rect2}, I_{o1}, I_{o2}, C_{o1} and C_{o2} are the resonant current, rectifier current, load current, output capacitor of two phases, respectively. n is transformer turn ratio. Parameters a, b and c are used to indicate that the resonant parameters for these two phases are different. The parameter relationship between the two resonant tank are shown in (1).

$$\begin{cases} L_{r2} = aL_{r1} \\ C_{r2} = bC_{r1} \\ L_{m2} = cL_{m1} \end{cases} \tag{1}$$

To evaluate the current sharing performance, the load current sharing error σ_{load} is defined in (2), where I_{o1} and I_{o2} are the DC value of output current for the two phases. For space consideration, the detailed derivation process will not be presented in this paper. The load sharing error can be calculated using the method in [34, 35] with given tolerance combination a, b and c.

$$\sigma_{load} = abs\left(\frac{I_{o1} - I_{o2}}{I_{o1} + I_{o2}}\right) \tag{2}$$

To analyze current sharing performance, a set of LLC parameters, based on load power 300W of each phase, is designed as shown in Table I using existing design method [36].

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TABLE I. NOMINAL PARAMETER VALUE

Input voltage	340V – 400V
Resonant inductor L_r	29 μH
Resonant capacitor C_r	12 nF
Magnetizing inductor L_m	95 μH
Transformer ratio n	20
Resonant frequency f_r	270 kHz
Output voltage V_o	12V (rated voltage)
Total Output load P_o	full power 600W
	half power 300W

Fig. 6 shows load current sharing error σ_{load} of the conventional two-phase LLC converter at 400V input with different component tolerances. The current sharing performance is evaluated at ±5% component tolerances. In the case $L_{r2} = L_{r1}$, $C_{r2} = C_{r1}$ and $L_{m2} = L_{m1}$, the two phases have the same parameters, which will result in the load current be perfectly shared, *i.e.* σ_{load} =0. If L_{r2} = 1.05 L_{r1}, C_{r2} = 1.05 C_{r1} and L_{m2} = 1.05 L_{m1}, it means that the resonant component values of resonant inductance, resonant capacitance and magnetizing inductance in phase #2 are all 5% more than the values in phase #1 respectively.

Theoretically there are total eight (2^3) possible combinations for L_r C_r and L_m at ±5% tolerance. In terms of performance, four of the total eight combinations are just equivalent to the other four types – current sharing error is same while current distribution is opposite. For example, the case L_{r2} = 1.05 L_{r1}, C_{r2} = 1.05 C_{r1} and L_{m2} = 1.05 L_{m1} is equivalent to the case L_{r2} = 0.95 L_{r1}, C_{r2} = 0.95 C_{r1} and L_{m2} = 0.95 L_{m1}. If under the case L_{r2} = 1.05 L_{r1}, C_{r2} = 1.05 C_{r1} and L_{m2} = 1.05 L_{m1}, phase #1 provides 40A of total 50A, while phase #2 provides the rest 10A, then the difference is 30A and the current sharing error is 60%. Then approximately for the case L_{r2} = 0.95 L_{r1}, C_{r2} = 0.95 C_{r1} and L_{m2} = 0.95 L_{m1}, phase #1 will provide 10A of total 50A, and phase #2 provides the rest 40A, then the current sharing error will still be 60%. Thus from the point of view of current sharing error, the four cases studied in Fig. 6 have covered all possible cases at 5% tolerance level.

Fig. 6 (a) shows the load currents of two phases and load current sharing error, where $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$ and $L_{m2} = 1.05\ L_{m1}$. The tolerances of resonant inductor and resonant capacitor is in the same direction (both > 1), then the

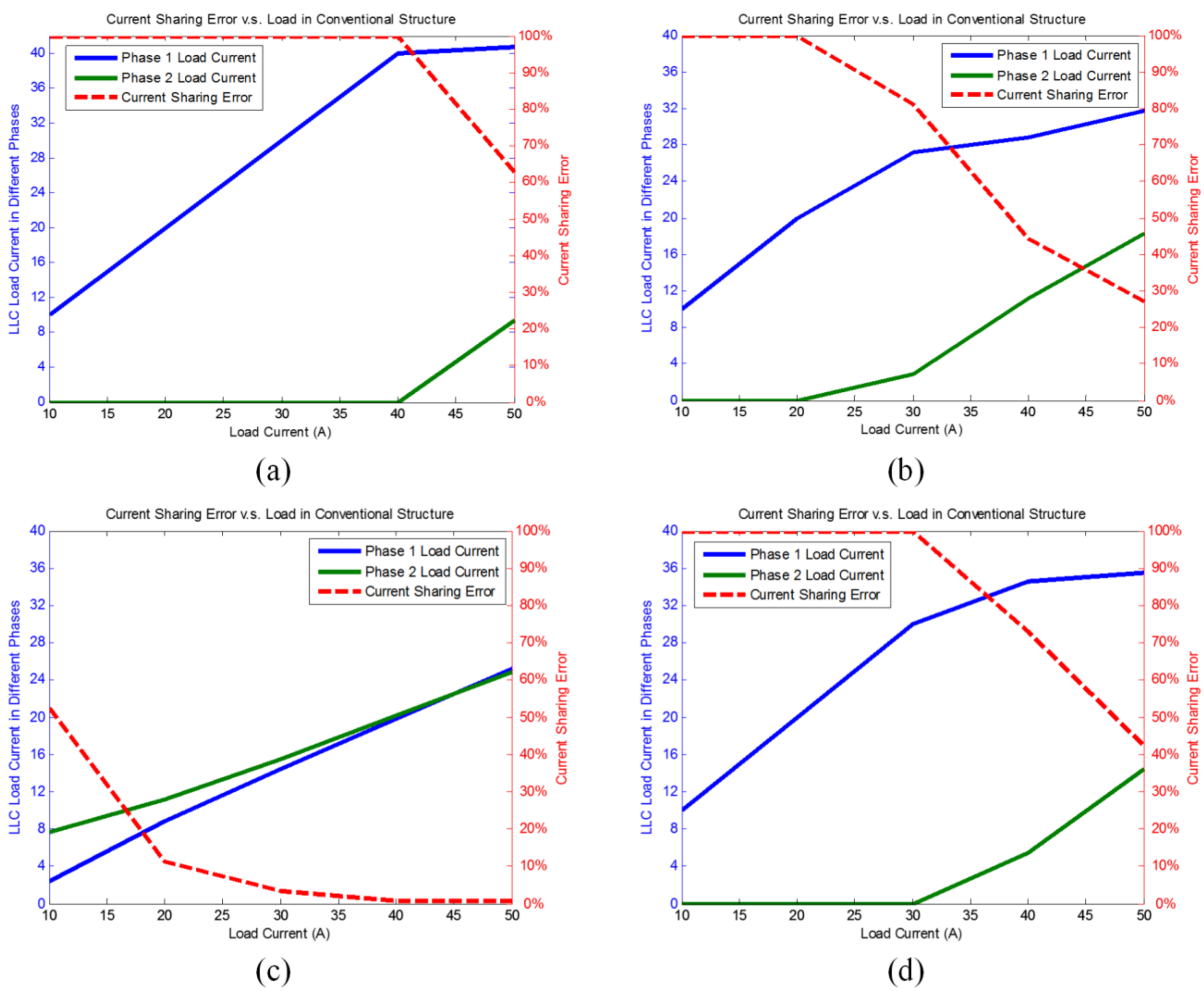

Fig. 6. Load current sharing error of conventional LLC converter at 400V input and different component tolerance
(a) $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$ (b) $L_{r2} = 0.95\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$
(c) $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 0.95\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$ (d) $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 0.95\ L_{m1}$

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resonant frequency of phase 2 deviates from that of phase 1, thus, the current sharing error is large. When the total load current is smaller than 40A, only phase 1 provides the total load power, and the load current sharing error is 100%. When total load current is 50A, phase 1 will provide 41A, and phase 2 will provide only 9A.

Fig. 6 (b) shows the load currents of two phases and the load current sharing error, where $L_{r2} = 0.95\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$ and $L_{m2} = 1.05\ L_{m1}$. The tolerance of resonant inductor is smaller than 1, and the tolerance of resonant capacitance is larger than 1. Thus, the resonant frequency of phase 2 is almost same with phase 1. If the total load current is smaller than 20A, only phase 1 provides the total load power. Load current of phase 1 is 32A when total load current is 50A.

Fig. 6 (c) shows the load currents of two phases and the load current sharing error, where $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 0.95\ C_{r1}$ and $L_{m2} = 1.05\ L_{m1}$. The resonant frequency of phase 2 is almost same with phase 1 because the tolerance of resonant inductance is larger than 1 and the tolerance of resonant capacitance is smaller than 1. Good current sharing performance can be achieved - the current sharing error is smaller than 3% when the total load current is larger than 30A. The maximum load current of phase 2 is about 25.3A at 50A total load current.

In Fig. 6 (d), $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$ and $L_{m2} = 0.95\ L_{m1}$. The tolerances of resonant inductor and resonant capacitor is in the same direction (both > 1), then the resonant frequency of phase 2 deviates from that of phase 1, thus, the current sharing error is large. When the total load current is smaller than 30A, only phase 1 provides the total load power, and the load current sharing error is 100%. Load current of phase 1 is 36A when total load current is 50A.

Thus, the worst case is working under $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$ and $L_{m2} = 1.05\ L_{m1}$ as shown in Fig. 6 (a). The conventional two-phase converter cannot share the load current for most load cases. In practice, if the two phases cannot achieve current sharing, then each phase has to be designed for 50A (600W) rather than 25A (300W) from the safety point of view, which goes against the initial desire to use two-phase converter to reduce current stresses.

Fig. 7 shows the current sharing performance at 340V input condition for conventional two-phase LLC converter with difference tolerance combinations.

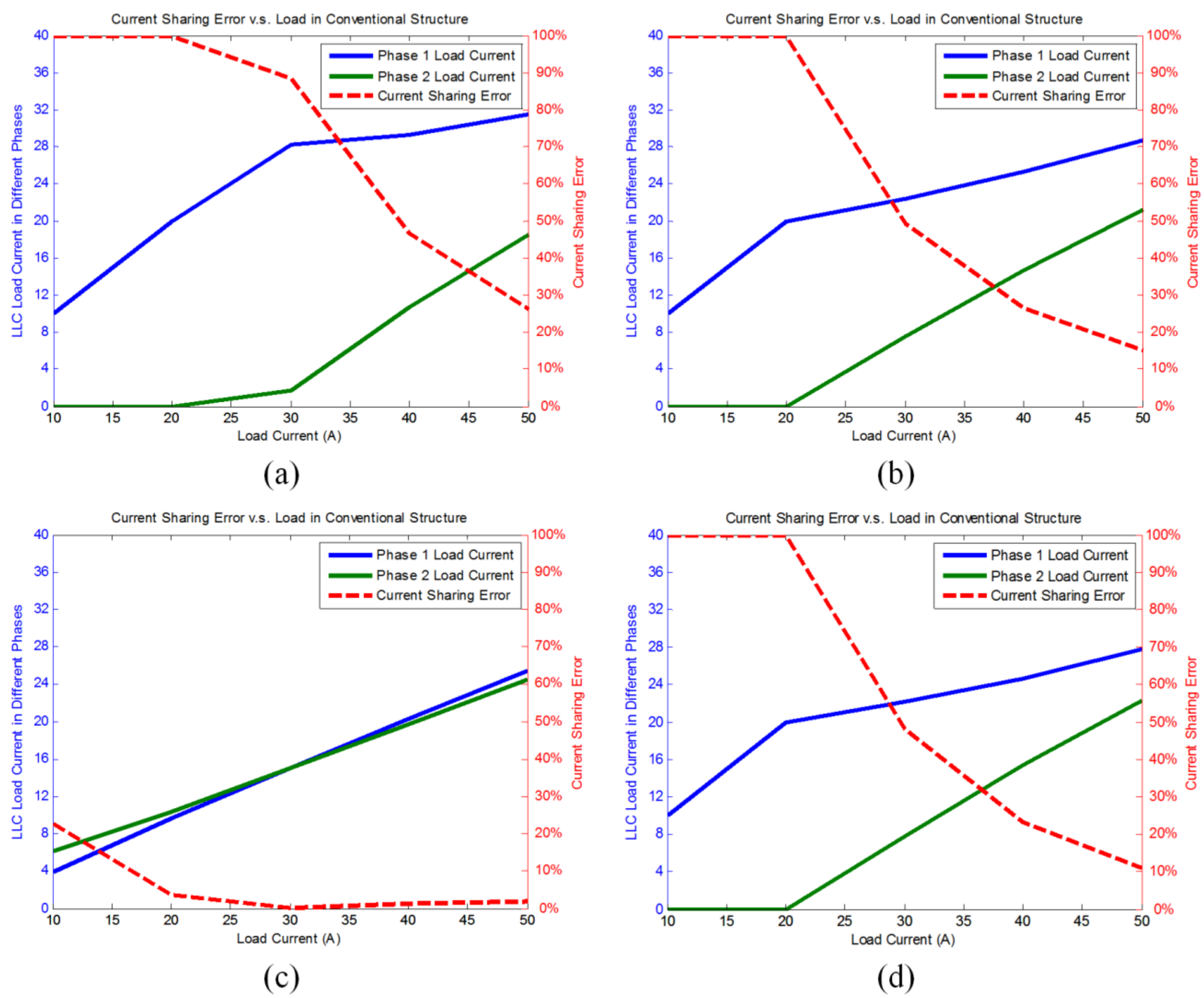

Fig. 7. Load current sharing error of conventional LLC converter at 340V input and different component tolerance
(a) $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$ (b) $L_{r2} = 0.95\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$
(c) $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 0.95\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$ (d) $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 0.95\ L_{m1}$

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In Fig. 7, it could be observed that generally better current sharing performance could be achieved at 340V input condition as compared to 400V case. For different tolerance combinations, the results for 340V input condition is similar as compared to 400V input results. The worst case happens when the three component tolerance is in the same direction, *i.e.* $L_{r2} = 1.05\,L_{r1}$, $C_{r2} = 1.05\,C_{r1}$, and $L_{m2} = 1.05\,L_{m1}$.

For the input voltage between 340V and 400V, the current sharing performance is also in between, i.e., better than 400V performance while worse than 340V performance.

III. Current Sharing Characteristic of Common Indctor Multi-phase LLC Converter

As shown in Fig. 7, the two LLC phases in conventional structure are connected in parallel at both the input side and the output side. Thus, the resonant tank of each phase is completely independent of the other phase. No current information can be exchanged between the phases, and no current sharing can be achieved.

From the voltage gain point of view, if the two phases provide the same load current, then the output voltage V_o will have certain discrepancy due to the components tolerances. In real case, the output of the two phases are connected together at the load side. This is equal to say, the V_o of the two phases are equal. In order to eliminate the discrepancy on the gain-to-control diagram, the phase with higher voltage gain will provide more load power, so that the voltage gain will reduce; while the phase with lower voltage gain will provide less power, and the voltage gain will increase. This explains the unbalanced load current at steady state of conventional two-phase LLC converter.

In this paper, a new multi-phase LLC resonant converter is proposed. The resonant inductors of different phases are connected in parallel to form a common inductor branch, which will take in the current of each phase and then re-distribute evenly. In the proposed common inductor LLC converter, the resonant inductor of the two phases are connected together, thus the tolerance on the resonant inductor is automatically removed. Besides, the common inductor could be equivalent to one virtual inductor plus one virtual resistor for each phase [34, 35]. The virtual resistor will always be positive for the phase with higher load current, and negative for the phase lower current. In this way, the positive virtual resistor will increase the input impedance and thus reduce the current for that phase; while the negative virtual resistor will increase the current for the other phase. As a result, the two phases will have same load current.

For easy understanding, two-phase common inductor LLC resonant converter will be discussed in this section. Current sharing performance will be evaluated through FHA analysis.

A. Common Inductor Two-phase LLC Resonant Converter

Fig. 8 shows the proposed two-phase common inductor LLC resonant converter. The series resonant inductors of the two LLC converters are connected in parallel.

It can also be implemented with one inductor whose value equals to the total inductance of L_{r1} and L_{r2} in parallel. *a*, *b*, *c* are the component tolerances of phase 2 as compared to phase 1. For simplicity, Q11 and Q21 have same drive signal. Q12 and Q22 have same drive signal.

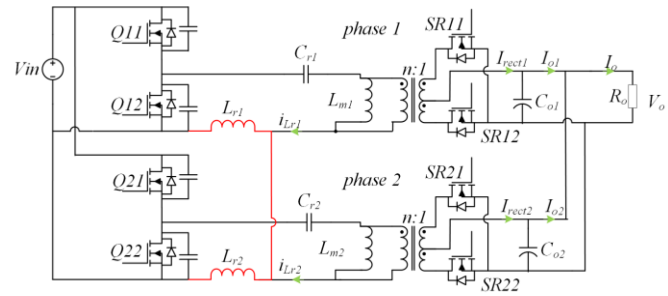

Fig. 8. Common inductor two-phase LLC resonant converter

In Fig. 8, V_o, P_o, R_o are the output voltage, total output power and total load resistor of the two phases. The load resistor can be expressed as follows.

$$R_o = \frac{V_o^{\,2}}{P_o} \tag{3}$$

In steady-state, the total load power P_o is separated into P_{o1} for phase 1 and P_{o2} for phase 2.

$$P_o = P_{o1} + P_{o2} \tag{4}$$

The equivalent load resistors of each phase are R_{o1} and R_{o2}.

$$\begin{cases} R_{o1} = \dfrac{V_o^{\,2}}{P_{o1}} \\ R_{o2} = \dfrac{V_o^{\,2}}{P_{o2}} \end{cases} \tag{5}$$

The coefficient *k* is defined as the phase 1 load power proportion of total load power. Then the load power P_{o1} of phase 1 and P_{o2} of phase 2 can be expressed as

$$P_{o1} = kP_o \tag{6}$$

$$P_{o2} = (1-k)P_o \tag{7}$$

Combining (3), (4), (5), (6) and (7) gives (8).

$$\begin{bmatrix} R_{o1} & R_{o2} \end{bmatrix} = \begin{cases} \begin{bmatrix} \infty & R_o \end{bmatrix} & k = 0 \\ \begin{bmatrix} R_o/k & R_o/(1-k) \end{bmatrix} & k \in (0,1) \\ \begin{bmatrix} R_o & \infty \end{bmatrix} & k = 1 \end{cases} \tag{8}$$

B. Current Sharing Analysis of Proposed Two-phase LLC Resonant Converter

Mathematical model of LLC converter is needed for analyzing the current sharing performance of two-phase LLC converter. FHA circuit is used to analyze the two-phase LLC resonant converter [34, 35], in which the resonant tanks of each phase are coupled. The equivalent circuit is shown in Fig. 9. According to (1), the total resonant inductance L_{r_total} is shown in (9).

$$L_{r\_total} = \frac{a}{1+a} L_r \tag{9}$$

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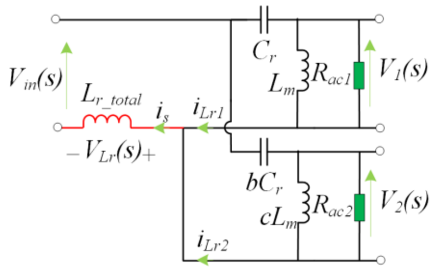

Fig. 9. FHA equivalent circuit of common inductor LLC resonant converter

The primary-side equivalent ac resistors R_{ac1} and R_{ac2} are shown in (10).

$$\begin{cases} R_{ac1} = \dfrac{8n^2}{\pi^2} \mathrm{R}_{o1} \\ R_{ac2} = \dfrac{8n^2}{\pi^2} \mathrm{R}_{o2} \end{cases} \tag{10}$$

Combing (8) and (10) gives (11).

$$\begin{bmatrix} R_{ac1} & R_{ac2} \end{bmatrix} = \begin{cases} \begin{bmatrix} \infty & \dfrac{8n^2}{\pi^2} R_o \end{bmatrix} & k = 0 \\ \begin{bmatrix} \dfrac{8n^2 R_o}{\pi^2 k} & \dfrac{8n^2 R_o}{\pi^2 (1-k)} \end{bmatrix} & k \in (0,1) \\ \begin{bmatrix} \dfrac{8n^2}{\pi^2} R_o & \infty \end{bmatrix} & k = 1 \end{cases} \tag{11}$$

In steady-state operation, the voltage gains of each phase are same as they are connected to the same input voltage and output voltage. Thus, the magnitude of ac voltage $V_1(s)$ and $V_2(s)$ are the same, while the phase angles are always different due to parameter tolerance. The relationship is shown in (12).

$$\left|V_1(s)\right| = \left|V_2(s)\right| \tag{12}$$

From Fig. 9, the transfer function of ac voltage $V_1(s)$, $V_2(s)$ are shown in (13).

$$\begin{cases} V_1(\mathrm{s}) = \dfrac{R_{ac1} // sL_m}{R_{ac1} // sL_m + 1/sC_r} (V_{in}(s) + V_{Lr}(s)) \\ V_2(\mathrm{s}) = \dfrac{R_{ac2} // scL_m}{R_{ac2} // scL_m + 1/sbC_r} (V_{in}(s) + V_{Lr}(s)) \end{cases} \tag{13}$$

Manipulating (10), (12) and (13), the load factor k can be calculated from (14).

$$Ak^2 + Bk + C = 0 \tag{14}$$

For common inductor LLC converter, the coefficient A, B, C are expressed in (15).

$$\begin{cases} A = \omega^2 (1-b^2) c^2 L_m{}^2 \\ B = -2\omega^2 c^2 L_m{}^2 \\ C = \omega^2 c^2 L_m{}^2 + (1-b^2c^2) R_{ac}{}^2 - 2\omega^2 (bc - b^2c^2) L_m C_r R_{ac}{}^2 \end{cases} \tag{15}$$

Combing (14) and (15), the load factor k can be solved for given input voltage and different load conditions. The load factor k is valid when k is between 0 and 1. Conditions $k = 0$ and $k = 1$ mean only one phase provides all the power and the other phase does not provide power. $k < 0$ and $k > 1$ are invalid answers.

To evaluate the current sharing performance, the load current sharing error σ_{load} is defined in (16), where I_{o1} and I_{o2} are the DC value of output current for the two phases.

$$\sigma_{load} = abs(\frac{I_{o1} - I_{o2}}{I_{o1} + I_{o2}}) = abs(1-2k), k \in [0,1] \tag{16}$$

Similarly, the resonant current sharing error $\sigma_{Resonant}$ is defined in (17), where $rms(i_{Lr1})$, $rms(i_{Lr2})$ are the root mean square (RMS) value of resonant current i_{Lr1} and i_{Lr2}.

$$\sigma_{Resonant} = abs(\frac{rms(i_{Lr1}) - rms(i_{Lr2})}{rms(i_{Lr1}) + rms(i_{Lr2})}) \tag{17}$$

When N (N > 2) phases are connected in parallel, the load current sharing error and resonant current sharing error are defined in (18), where, N is phase number, $rms(i_{Lrj})$ *and* I_{oj} are resonant current RMS value, output current of the j^{th} phase.

$$\begin{cases} \sigma_{load-\mathrm{j}} = abs\left[\dfrac{I_{0j} - \sum_{j=1}^{N} I_{0j}/N}{\sum_{j=1}^{N} I_{0j}/N}\right] \\ \sigma_{Resonant-j} = abs\left[\dfrac{rms(i_{Lrj}) - \sum_{j=1}^{N} rms(i_{Lrj})/N}{\sum_{j=1}^{N} rms(i_{Lrj})/N}\right] \end{cases} \tag{18}$$

C. Current sharing performance with specific parameters

In this section, current sharing performance will be demonstrated with specific LLC parameters. The parameters of phase 1 has been given in Table I.

Fig. 10 shows load current sharing error σ_{load} of the proposed two-phase LLC converter at 400V input condition under different component tolerances. The ±5% component tolerance is assumed to evaluate the current sharing performance.

Fig. 10 (a) shows the load currents of two phases and load current sharing error, where $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$ and $L_{m2} = 1.05\ L_{m1}$. The load current sharing error is 6% at 50A total load. The maximum current of phase 1 is 26.5 A and the maximum current of phase 2 is 23.5A when total load current is 50A. The good current sharing performance can be achieved with total load current increasing.

Fig. 10 (b) shows the load currents of two phases and the load current sharing error where $L_{r2} = 0.95\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$. Almost same current sharing performance can be achieved both Fig. 10 (a) and Fig. 10 (b) as the tolerance of resonant inductance doesn't impact the current sharing error because of in parallel of each resonant inductors based on proposed multi-phase LLC resonant converter. The maximum load currents of each phase are 26.5A and 23.5A under total 50A load. The current sharing error is about 6%.

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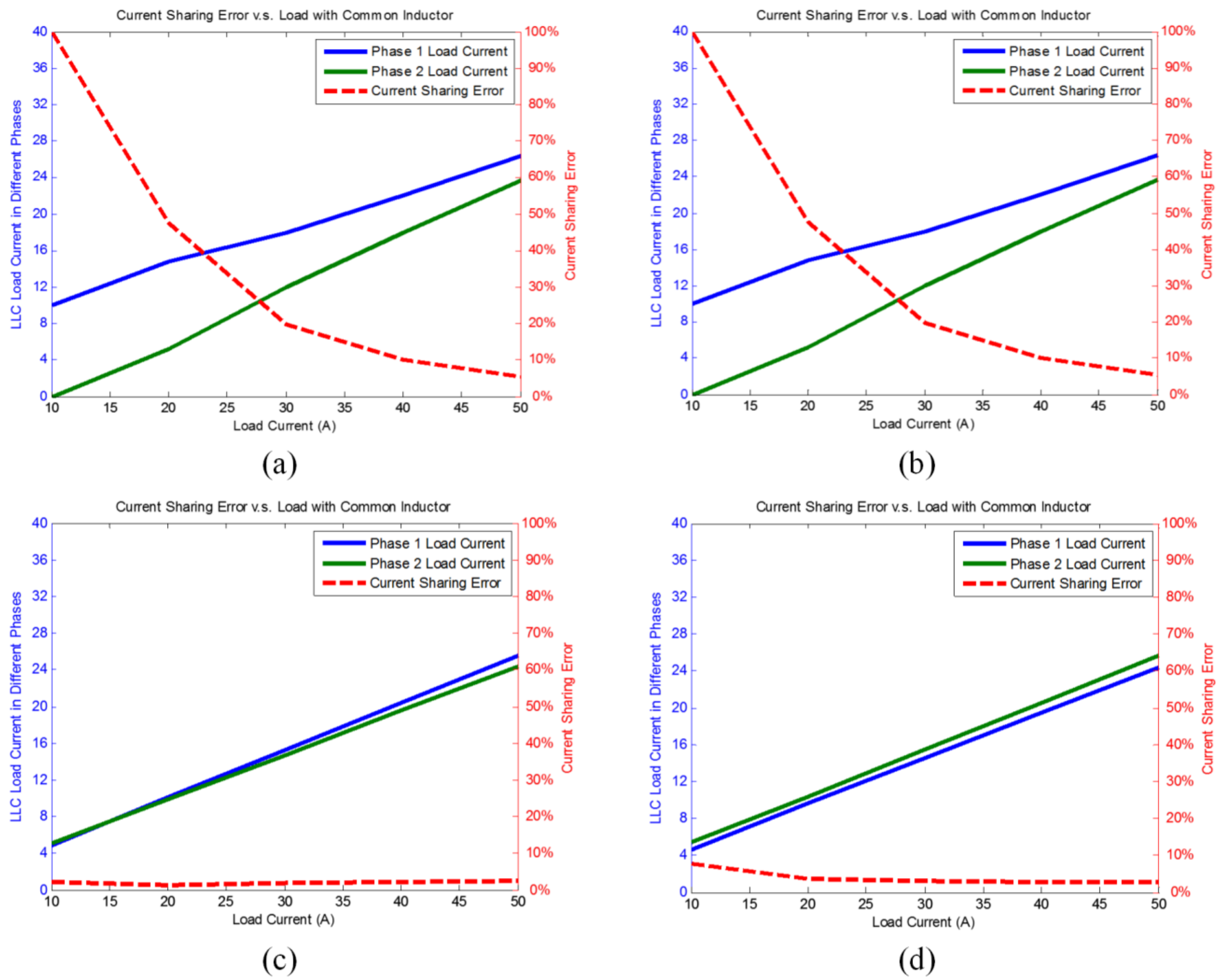

Fig. 10. Load current sharing error of common inductor LLC converter at 400V input and different component tolerance
(a) $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$ (b) $L_{r2} = 0.95\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$
(c) $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 0.95\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$ (d) $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 0.95\ L_{m1}$

Fig. 10 (c) shows the load currents of two phases and the load current sharing error where $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 0.95\ C_{r1}$ and $L_{m2} = 1.05\ L_{m1}$. the current sharing performance can be achieved from light load to heavy load. The maximum load current of two phases are 25.5A and 24.5A under total 50A load. The current sharing error is about 2%. The load currents are almost same for each phase.

Fig. 10 (d) shows the load currents of two phases and the load current sharing error where $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$ and $L_{m2} = 0.95\ L_{m1}$. The current sharing performance can be achieved from light load to heavy load. The maximum load currents of each phase are 25.7A and 24.3A under total 50A load. The current sharing error is about 2.8%.The load current is almost same for each phase.

Compared the four tolerance combinations, it could be concluded that the worst case is under $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 0.95\ C_{r1}$ and $L_{m2} = 1.05\ L_{m1}$ as shown in Fig. 10 (a). Still, good current sharing performance (6% current sharing error) can also be achieved.

Fig. 11 shows the current sharing performance at 340V input voltage condition for common inductor LLC converter with difference tolerance combinations.

From Fig. 11 it could be observed that the current sharing performance at 340V input condition is very similar with that at 400V input. As the tolerance on the resonant inductor L_r has been eliminated, the results for case (a) is basically the same with case (b). Same result can be found on case (c) and case (d). The worst case happens when the resonant capacitor C_r deviates to the same direction with the magnetizing inductor L_m.

For input voltage between 340V and 400V, the current sharing performance is in between and very similar.

IV. Simulation Results

In order to verify and compare the current sharing performance further, in this section, PSIM simulation results of both conventional two-phase LLC converter and the proposed common inductor LLC converter will be provided.

In section A and B, for respective 400V and 340V input voltage condition, PSIM simulation results will be compared to FHA calculation for both conventional structure and proposed common inductor structure at ±5% tolerances level.

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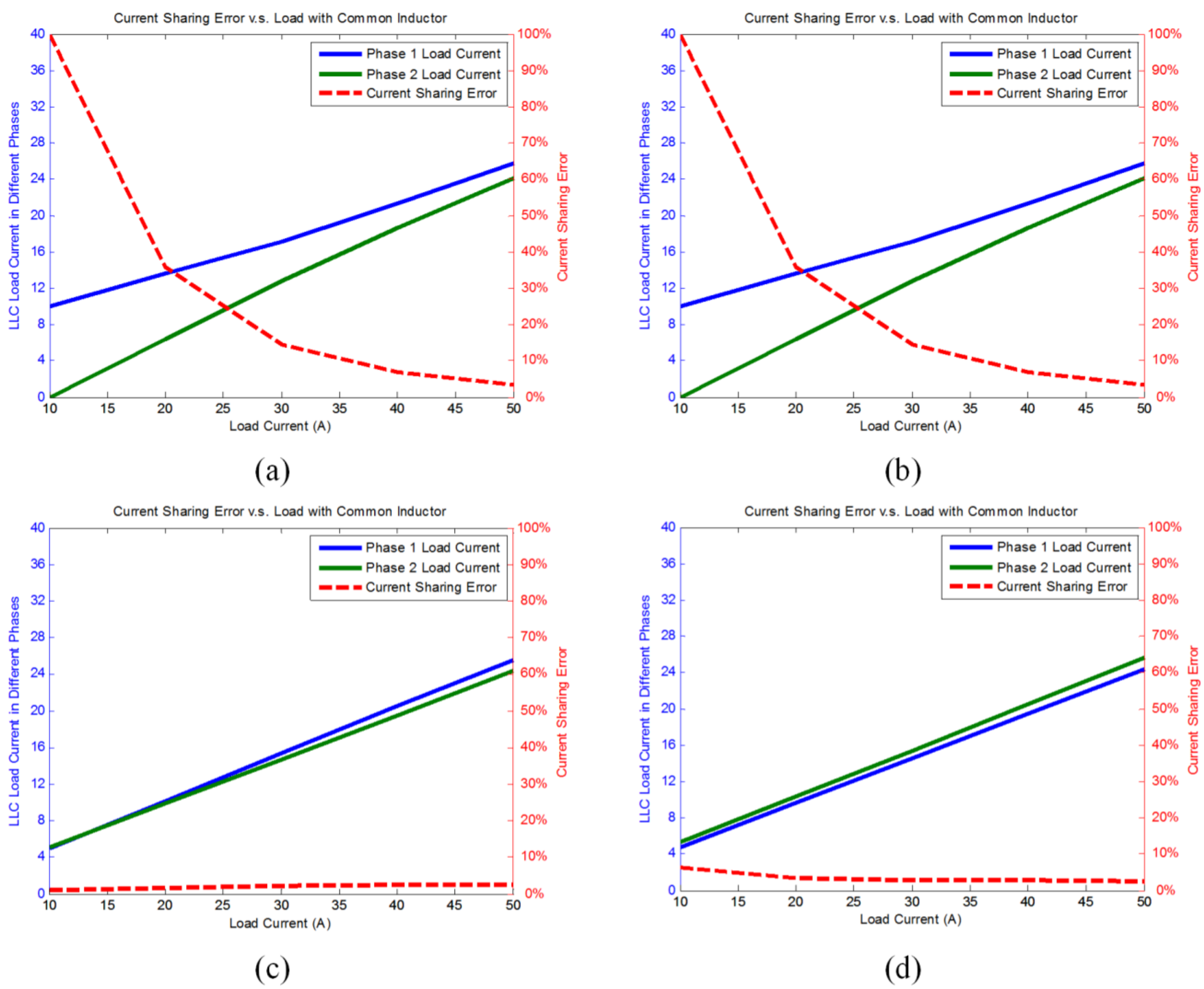

Fig. 11. Load current sharing error of common inductor LLC converter at 340V input and different component tolerance
(a) L_{r2} = 1.05 L_{r1}, C_{r2} = 1.05 C_{r1}, and L_{m2} = 1.05 L_{m1} (b) L_{r2} = 0.95 L_{r1}, C_{r2} = 1.05 C_{r1}, and L_{m2} = 1.05 L_{m1}
(c) L_{r2} = 1.05 L_{r1}, C_{r2} = 0.95 C_{r1}, and L_{m2} = 1.05 L_{m1} (d) L_{r2} = 1.05 L_{r1}, C_{r2} = 1.05 C_{r1}, and L_{m2} = 0.95 L_{m1}

Four types of tolerance combination will be included: (a) L_{r2} =1.05 L_{r1}, C_{r2} = 1.05 C_{r1}, and L_{m2} = 1.05 L_{m1} tolerance, (b) L_{r2} = 0.95 L_{r1}, C_{r2} = 1.05 C_{r1}, and L_{m2} = 1.05 L_{m1} tolerance, (c) L_{r2} = 1.05 L_{r1}, C_{r2} = 0.95 C_{r1}, and L_{m2} = 1.05 L_{m1} tolerance, and (d) L_{r2} = 1.05 L_{r1}, C_{r2} = 1.05 C_{r1}, and L_{m2} = 0.95 L_{m1} tolerance.

In section C, the deviation between FHA and PSIM results will be explained.

In section D, simulation waveforms based on the measured prototype parameters will be shown at different load current. The leakage inductor of transformers will also be considered in the simulation.

A. Two-phase LLC Simulation Results under 400V with Different Tolerance Combinations

The simulation is conducted under 400V input and total 50A load condition. The rated output voltage is 12V. The parameters of two phases are shown in Table II.

Fig. 12 shows the PSIM simulation waveforms of the resonant current, rectifier current of conventional two-phase LLC converter at 400V input voltage condition.

TABLE II. PARAMETERS OF TWO-PHASE LLC CONVERTER IN PSIM

	Resonant Inductor L_r	Resonant capacitor C_r	Magnetizing inductor L_m
Phase 1 (reference)	29 μH	12 nF	95 μH
Phase 2 (a)	30.5 μH (+5%)	12.6 nF (+5%)	100 μH (+5%)
Phase 2 (b)	28.5 μH (-5%)	12.6 nF (+5%)	100 μH (+5%)
Phase 2 (c)	30.5 μH (+5%)	11.4 nF (-5%)	100 μH (+5%)
Phase 2 (d)	30.5 μH (+5%)	12.6 nF (+5%)	90 μH (-5%)

Table III shows the load current (I_{rect1_ave} and I_{rect2_ave}) of FHA calculation and PSIM simulation. It can be observed that load current sharing error σ_{load} from simulation matchs with the calculation results in general trends (the value is different). The difference is generally caused by the absence of high order harmonics in FHA. In PSIM simulation, the worst case L_{r2} = 1.05 L_{r1}, C_{r2} = 1.05 C_{r1}, and L_{m2} = 1.05 L_{m1} of load current sharing error σ_{load} reaches 98%, and almost only phase #1 provides the total 50A load current.

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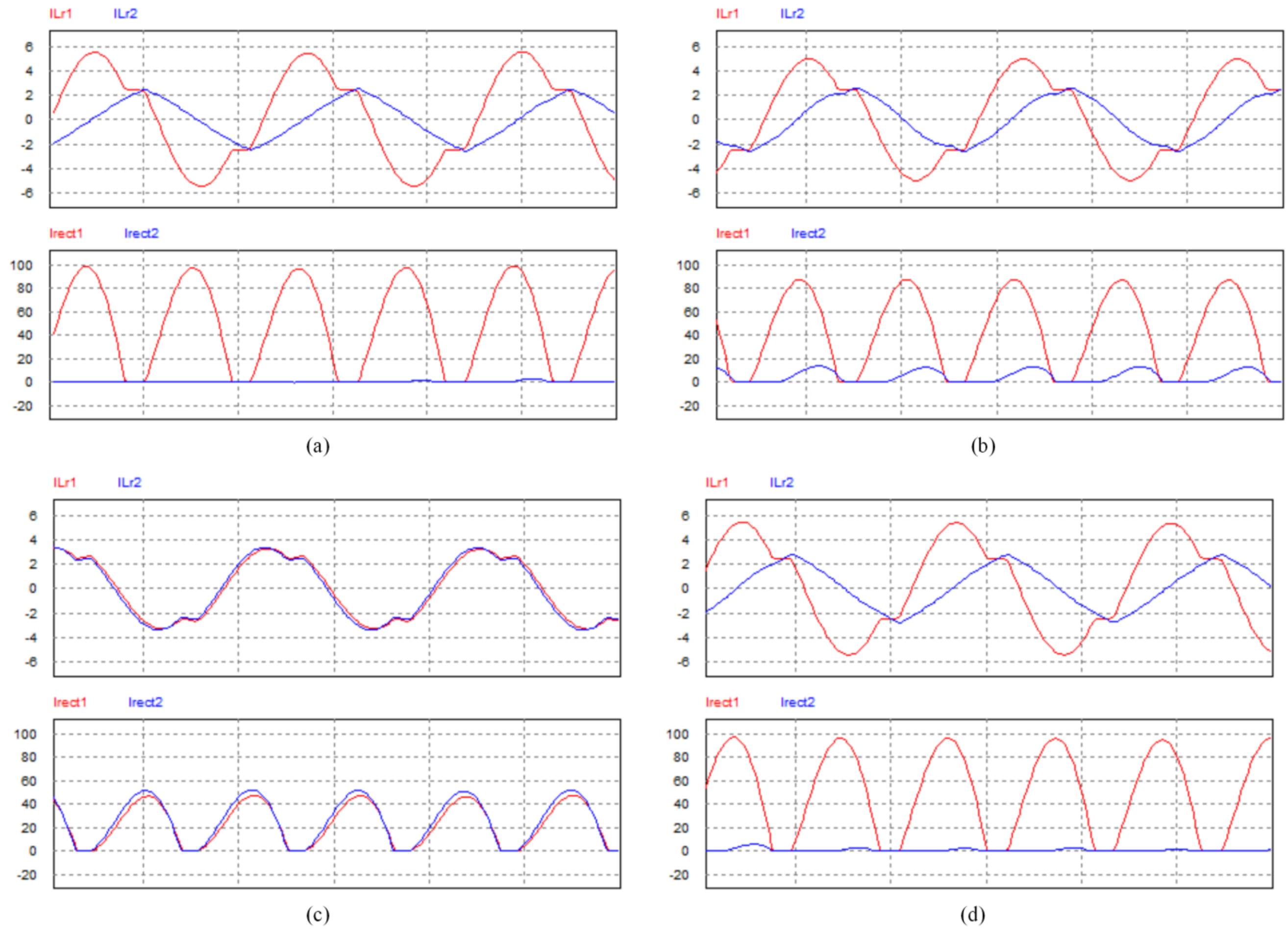

Fig. 12. Simulation results of common inductor two-phase LLC converter with +5% tolerance at 400V input condition
(a) $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$ (b) $L_{r2} = 0.95\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$
(c) $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 0.95\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$ (d) $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 0.95\ L_{m1}$

TABLE III. DATA COMPARISON OF SIMULATION AND FHA CALCULATION OF CONVENTIONAL TWO-PHASE LLC CONVERTER AT 400V INPUT CONDITION

Tolerances	FHA calculation			PSIM simulation		
	I_{rect1_ave}	I_{rect2_ave}	σ_{load_FHA}	I_{rect1_ave}	I_{rect2_ave}	σ_{load_PSIM}
Type a: $(a, b, c) = (1.05, 1.05, 1.05)$	41	9	64%	49.5	0.5	98%
Type b: $(a, b, c) = (0.95, 1.05, 1.05)$	32	18	28%	45	5	80%
Type c: $(a, b, c) = (1.05, 0.95, 1.05)$	24.5	25.5	2%	23.5	26.5	6%
Type d: $(a, b, c) = (1.05, 1.05, 0.95)$	36	14	44%	48	2	92%

TABLE IV. DATA COMPARISON OF SIMULATION AND FHA CALCULATION OF COMMON INDUCTOR LLC CONVERTER AT 400V INPUT CONDITION

Tolerances	FHA calculation			PSIM simulation		
	I_{rect1_ave}	I_{rect2_ave}	σ_{load_FHA}	I_{rect1_ave}	I_{rect2_ave}	σ_{load_PSIM}
Type a: $(a, b, c) = (1.05, 1.05, 1.05)$	26.5	23.5	6%	24.5	25.5	2%
Type b: $(a, b, c) = (0.95, 1.05, 1.05)$	26.5	23.5	6%	24.5	25.5	2%
Type c: $(a, b, c) = (1.05, 0.95, 1.05)$	25.5	24.5	2%	25.5	24.5	2%
Type d: $(a, b, c) = (1.05, 1.05, 0.95)$	25.7	24.3	2.8%	24.2	25.8	1.6%

Fig. 13 shows the PSIM simulation waveforms of resonant current and rectifier current of common inductor two-phase LLC converter at 400V input condition.

In Fig. 13 (a) and Fig. 13 (b) when the tolerance on C_r (b) and the tolerance on L_m (c) deviates in the same direction, good current sharing performance could be achieved. In Fig. 13 (c) and Fig. 13 (d), the two-phase current is almost the identical, which verifies the FHA calculation results in Fig. 10 (c) and (d).

Table IV shows the load current data comparison of FHA calculation and PSIM simulation for common inductor two-phase LLC converter at 400V input condition.

The simulation results match well with the FHA prediction. At worst case $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$, the load current error between the two phases (σ_{load}) is only 2%, while the worst case for conventional two-phase LLC is 98% (almost no sharing).

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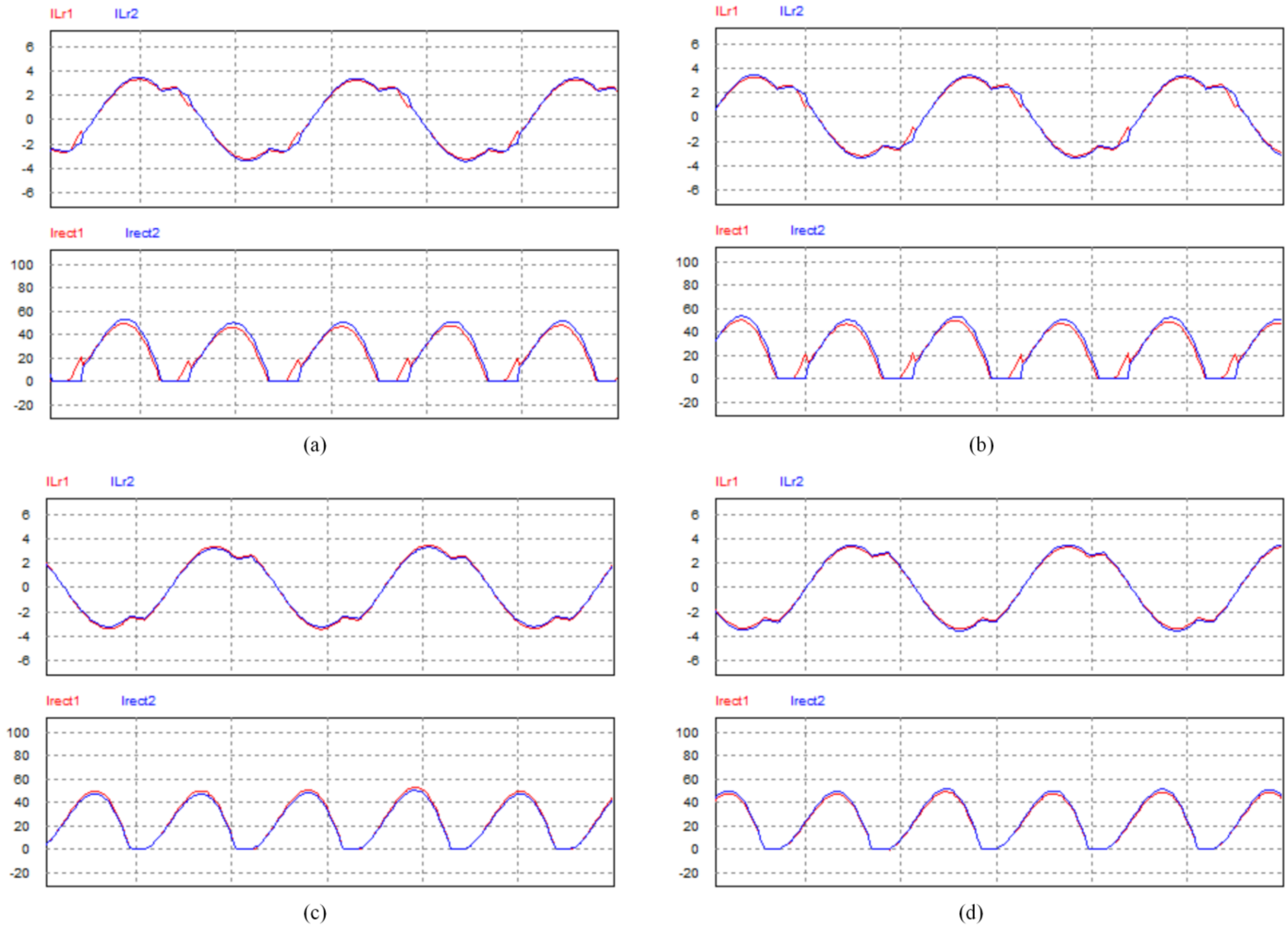


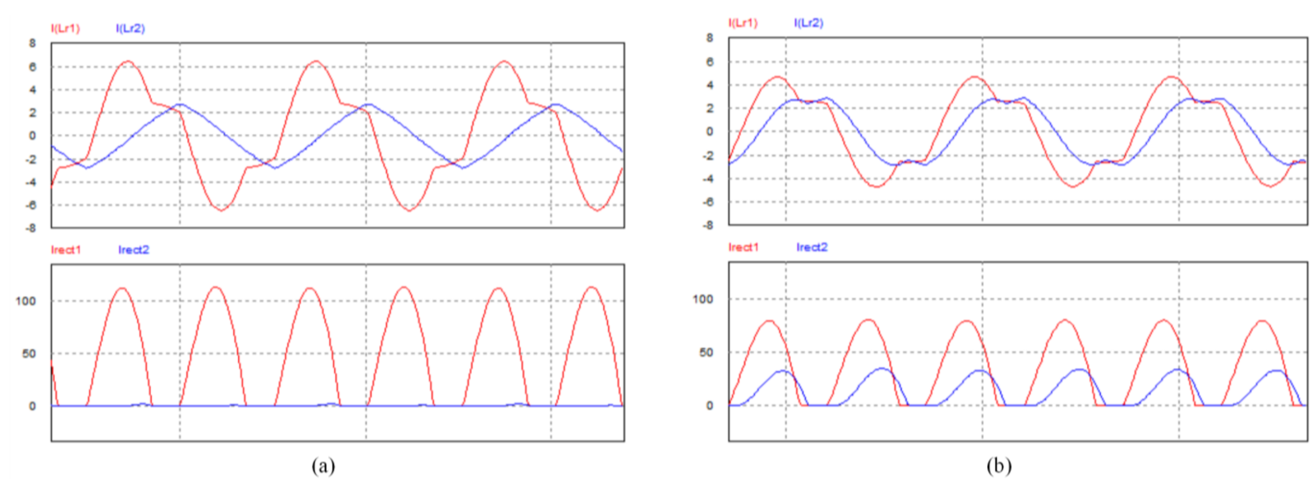
Fig. 13. Simulation results of conventional two-phase LLC converter with +5% tolerance at 400V input condition
(a) $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$ (b) $L_{r2} = 0.95\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$
(c) $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 0.95\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$ (d) $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 0.95\ L_m$

B. Two-phase LLC Simulation Results under 340V with Different Tolerance Combinations

In real world, the converter will need to operate not only at 400V (resonant frequency) but also somewhere lower. As comparison, the 340V 50A load operation results are also simulated. The parameters are shown in Table II.

Fig. 14 shows the simulation waveforms of conventional LLC converter for 340V input.

The load current sharing error is summarized in Table V. It can be observed that load current sharing error σ_{load} from simulation agrees with the calculation results in general trends (the value is different). In PSIM simulation, the worst case $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$. The load current sharing error σ_{load} reaches 98%, and almost phase 1 provide the total load power.



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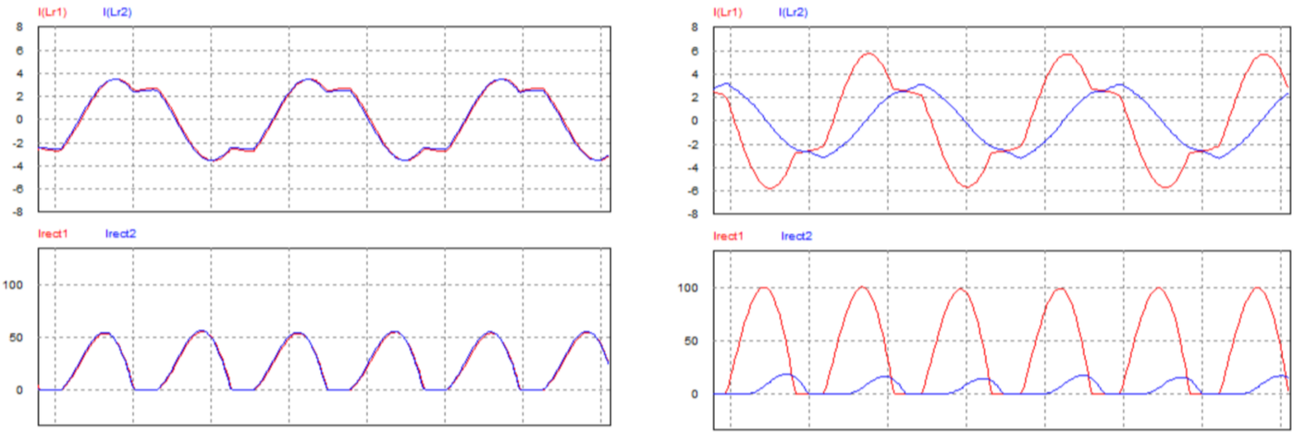
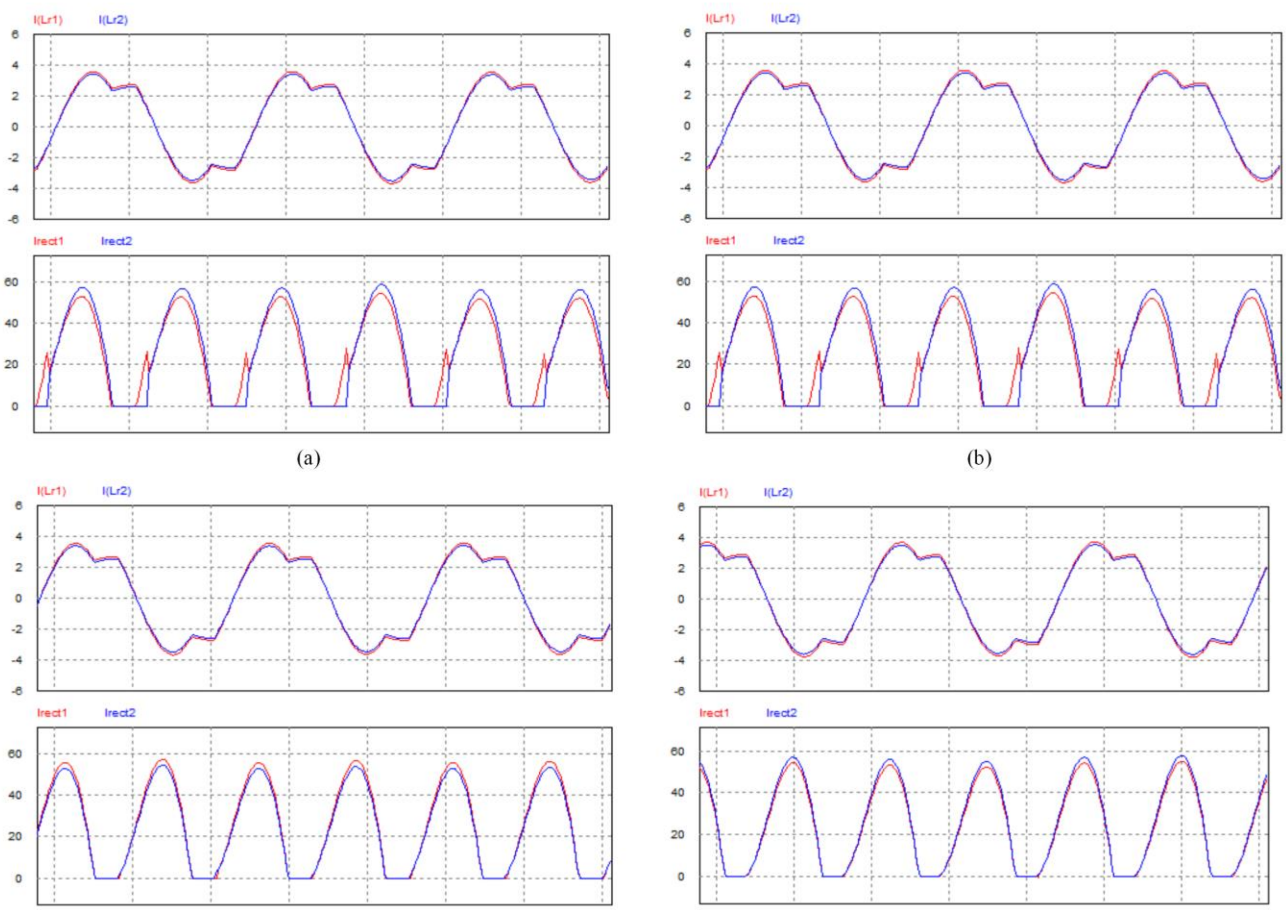


(c) (d)

Fig. 14. Simulation results of conventional two-phase LLC converter with +5% tolerance at 340V input condition
(a) $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$ (b) $L_{r2} = 0.95\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$
(c) $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 0.95\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$ (d) $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 0.95\ L_m$



(a) (b) (c) (d)

Fig. 15. Simulation results of common inductor two-phase LLC converter with +5% tolerance at 340V input condition
(a) $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$ (b) $L_{r2} = 0.95\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$
(c) $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 0.95\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$ (d) $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 0.95\ L_{m1}$

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TABLE V. DATA COMPARISON OF SIMULATION AND FHA CALCULATION OF CONVENTIONAL TWO-PHASE LLC CONVERTER AT 340V INPUT CONDITION

Tolerances	FHA calculation			PSIM simulation		
	I_{rect1_ave}	I_{rect2_ave}	σ_{load_FHA}	I_{rect1_ave}	I_{rect2_ave}	σ_{load_PSIM}
Type a: (a, b, c) = (1.05, 1.05, 1.05)	31.5	18.5	26%	49.5	0.5	98%
Type b: (a, b, c) = (0.95, 1.05, 1.05)	29	21	16%	36	14	44%
Type c: (a, b, c) = (1.05, 0.95, 1.05)	25.5	24.5	2%	24.7	25.2	1%
Type d: (a, b, c) = (1.05, 1.05, 0.95)	28	22	12%	45	5	80%

TABLE VI. DATA COMPARISON OF SIMULATION AND FHA CALCULATION OF COMMON INDUCTOR LLC CONVERTER AT 340V INPUT CONDITION

Tolerances	FHA calculation			PSIM simulation		
	I_{rect1_ave}	I_{rect2_ave}	σ_{load_FHA}	I_{rect1_ave}	I_{rect2_ave}	σ_{load_PSIM}
Type a: (a, b, c) = (1.05, 1.05, 1.05)	26	24	4%	24.3	25.7	2.8%
Type b: (a, b, c) = (0.95, 1.05, 1.05)	26	24	4%	24.3	25.7	2.8%
Type c: (a, b, c) = (1.05, 0.95, 1.05)	25.5	24.5	2%	25.5	24.5	2%
Type d: (a, b, c) = (1.05, 1.05, 0.95)	24.5	25.5	2%	24.4	25.6	2.4%

Fig. 15 shows the PSIM simulation waveforms of resonant current and rectifier current of common inductor two-phase LLC converter at 340V input condition. The results are very similar to the 400V operation results. The conclusion for 400V results can also be applied to the 340V operation that very good current sharing is achieved for all tolerances cases.

Table VI shows the load current data comparison of FHA calculation and PSIM simulation for common inductor two-phase LLC converter at 340V input condition.

The simulation results match well with the FHA calculation. At worst case $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$, the load current error between the two phases (σ_{load}) is only 2.8%, while the worst case for conventional two-phase LLC is 98% (almost no sharing).

C. Error of FHA analysis and PSIM simulation

It is noted that computer simulation result by PSIM is more accurate than the FHA analysis. From Table III and Table V, it is observed that the deviation between the PSIM result and the FHA analysis is larger for conventional two-phase LLC converter than that of the common inductor LLC converter shown in Table IV and Table VI.

The deviation between PSIM simulation and FHA calculation is caused by the neglected high order harmonics in FHA method. So at given load current, the voltage gain calculated by FHA is lower than the actual case since only the fundamental harmonic is considered. Thus, in order to achieve the same output voltage, the switching frequency predicted by FHA method is always lower than the actual switching frequency predicted by PSIM simulation. In other words, the actual operating switching frequency will be higher than the switching frequency predicted by the FHA method.

Fig. 16 shows the current sharing error changing with switching frequency in conventional two-phase LLC converter. The parameter tolerance between phase 1 and phase 2 are that $L_{r2} = 1.05\ L_{r1}$, $C_{r2} = 1.05\ C_{r1}$, and $L_{m2} = 1.05\ L_{m1}$ (worst case). Take 400 V operation as an example, in FHA method, the predicted switching frequency is 185 kHz, at which the current sharing error is 64%. The actual switching frequency measured in PSIM is 220 kHz, and the current sharing error is 100%. It could be observed that for conventional LLC converter, the current sharing error has a steep curve versus switching frequency. In other words, a small change of switching frequency will cause a large change of output current. Thus, the deviation between FHA and PSIM results is relatively large.

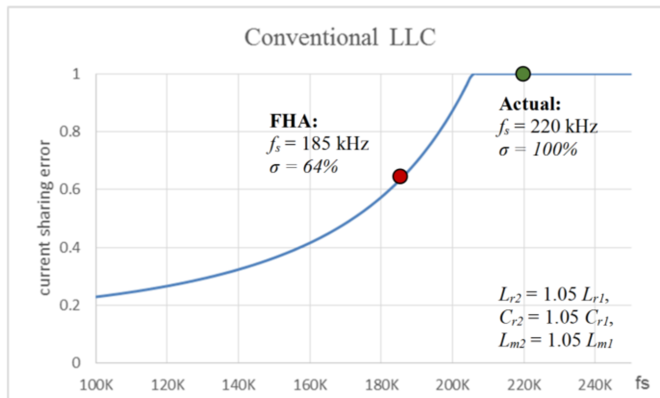

Fig. 16. Current sharing error vs. fs of conventional two-phase LLC converter

Fig. 17 shows the current sharing error changing with switching frequency in common inductor two-phase LLC converter. Still use 400 V operation as an example, the FHA predicted switching frequency is around 190 kHz and the current sharing error is 4%. The actual switching frequency in PSIM simulation is 220 kHz, at which the corresponding current sharing error reduces to 6% in Fig. 17. The value "6%" is not exactly same with the actual current sharing error as 2% shown in Table IV. The reason is that Fig. 17 is still from FHA prediction. The key point here is that the curve is rather flat. Thus the deviation between FHA and the PSIM results is small.

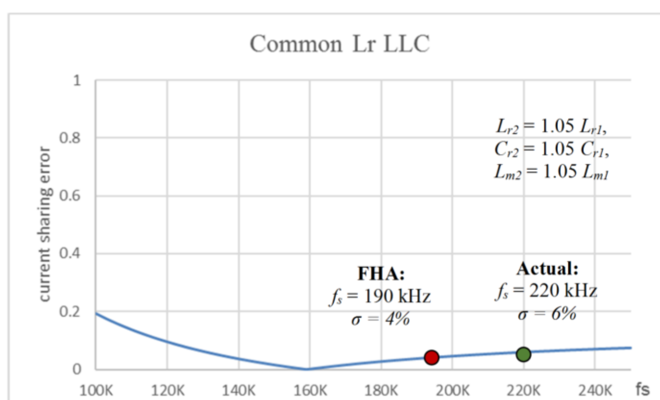

Fig. 17. Current sharing error v.s. fs of common inductor LLC converter

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D. Simulation Results of Experimental Prototype Parameters

The parameters and tolerances based on experimental prototype is shown in Table VII. It is the worst case as the tolerance direction on L_r and L_m are opposite. The leakage inductor of transformer is now taken into consideration. The design total power is 600 W (300 W * 2).

TABLE VII. EXPERIMENTAL PROTOTYPE PARAMETERS

	Resonant Inductor L_r	Resonant capacitor C_r	Magnetizing inductor L_m
Phase 1	22.5 μH	12.3 nF	95 μH
Phase 2	24.5 μH (+8.9%)	12.7 nF (+3.3%)	92 μH (-3.2%)

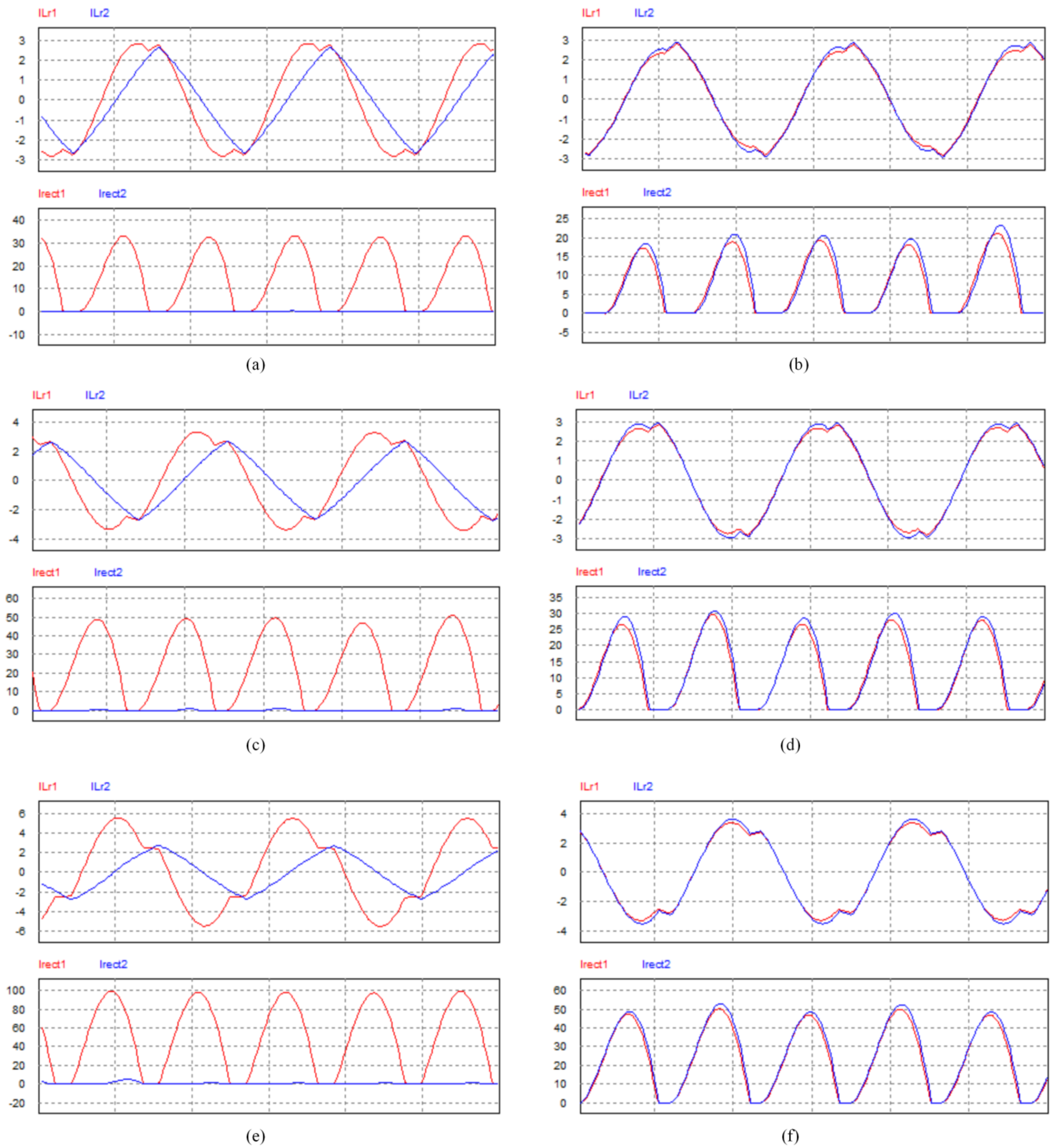

Fig. 18. Simulation for conventional and common inductor two-phase LLC converter at 400V input and different load conditions
(a) Conventional LLC converter at 400V input and total 15A load (b) common inductor LLC converter at 400V input and total 15A load
(c) Conventional LLC converter at 400V input and total 25A load (d) common inductor LLC converter at 400V input and total 25A load
(e) Conventional LLC converter at 400V input and total 50A load (f) common inductor LLC converter at 400V input and total 50A load

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TABLE VIII. CURRENT SHARING ERROR AT EXPERIMENTAL PARAMETER TOLERANCE

Total current	Phase	Conventional two-phase LLC				Common inductor two-phase LLC			
		I_{Lr_rms}	$\sigma_{resonant}$	I_{rect_ave}	σ_{load}	I_{Lr_rms}	$\sigma_{resonant}$	I_{rect_ave}	σ_{load}
15A	Phase 1	2.1A	13.5%	14.8A	97.3%	1.9A	2.6%	7.15A	*4.7%*
	Phase 2	*1.6A*		*0.2A*		*2.0A*		*7.85A*	
25A	Phase 1	2.41A	18.7%	24.7A	97.6%	2.18A	2.7%	12A	4%
	Phase 2	1.65A		0.3A		2.3A		13A	
50A	Phase 1	3.61A	36%	49.5A	98%	2.4A	2.6%	24.3A	2.8%
	Phase 2	1.69A		0.5A		2.53A		25.7A	

Fig. 18 shows the simulation waveforms of conventional and proposed two-phase LLC converter at 400V input and total 15A, 25A and 50A load current, repetitively. A common inductor two-phase LLC converter could achieve significantly improved load current sharing.

Table VIII shows the resonant current sharing error $\sigma_{resonant}$ and load current sharing error σ_{load} base on the prototype parameters and tolerances of conventional two-phase LLC converter and common inductor two-phase LLC converter at 400V and different load conditions.

The load current sharing error is almost 100% in conventional two-phase LLC resonant converter, which means only one phase provides total power. The load current sharing error is reduced to around 2.8% in common inductor two-phase LLC resonant converter at full load.

In Table VIII, it is observed that resonant current sharing error is generally lower than load current sharing error due to the existence of the current sharing error in the primary side. However, at heavy load, when the resonant current sharing error is low (such as smaller than 5%), the load current sharing error becomes very reasonable. Thus, it is believed that good resonant current sharing guarantees good load current sharing at heavy load.

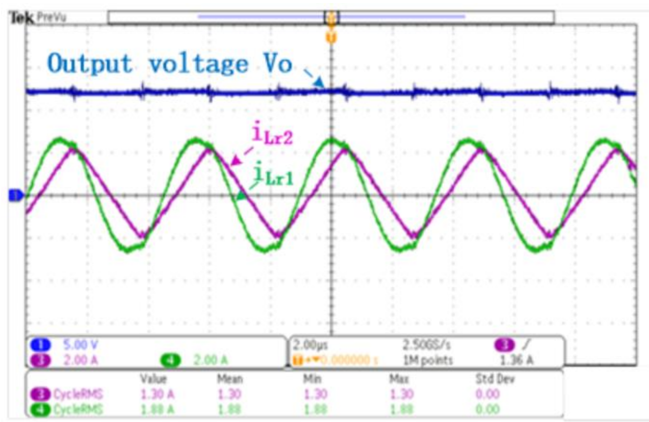
V. EXPERIMENTAL RESULTS

A 600W two-phase LLC converter prototype using common inductor 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. 8. The resonant tank parameter is designed based on traditional design method for single-phase LLC resonant converter. Thus, the design of proposed multi-phase LLC resonant converter is same as single-phase LLC converter. The prototype parameters are shown in Table IX. In experimental prototype, the current on the secondary side is very high, and the PCB track should be as short as possible. Thus it is not appropriate or easy to measure the load current of each phase directly. As mentioned above, good resonant current sharing means good load current sharing. Resonant currents are measured as current sharing performance evaluation.

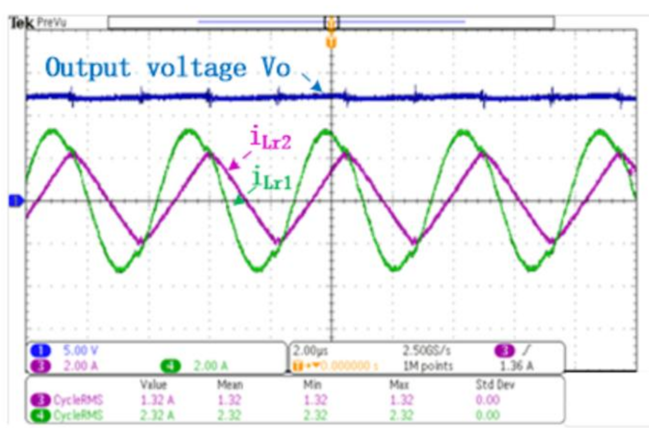
Fig. 19 shows the experiment waveform of conventional two-phase LLC converter at 15A, 25A total load current. Channel 1 is the output voltage. Channel 3, channel 4 are the resonant current of two phases. The resonant current i_{Lr2} is almost triangular waveform (as magnetizing current for the transformer), which means phase 2 doesn't provide the power for output load in Fig. 19 (a) and Fig. 19 (b).

TABLE IX. PROTOTYPE SPECIFICATIONS

Switching frequency	180 kHz-270 kHz
Input Voltage	340 V-400 V
Output Voltage	12V
Output Power	300W * 2
Transformer Ratio *n*	20:1
Output Capacitance	1790μF
Series Capacitance (*Cr*)	12nF 13nF
Resonant Inductance (*Lr*)	22.5μH(Phase1) 24.5μH(Phase2)
Leakage Inductance (*Le*)	6μH(Phase1) 6.5μH(Phase2)
Magnetizing Inductance (*Lm*)	95μH(Phase1) 92μH(Phase2)
Output Capacitance	1790μF (100μF * 8 + 330μF * 3)
Half-bridge MOSFET	IPB60R190C6
SR MOSFET	BSC011N03LS



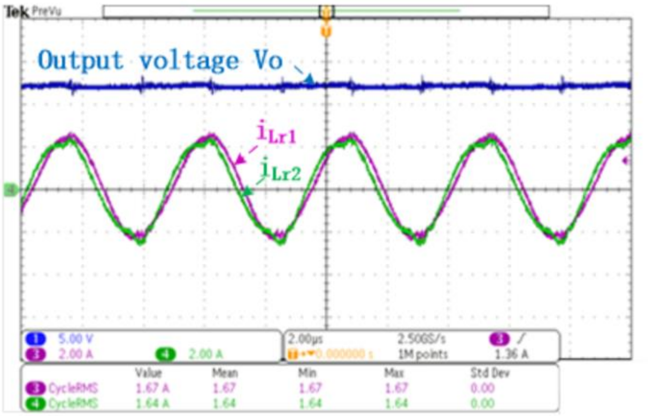
(a)



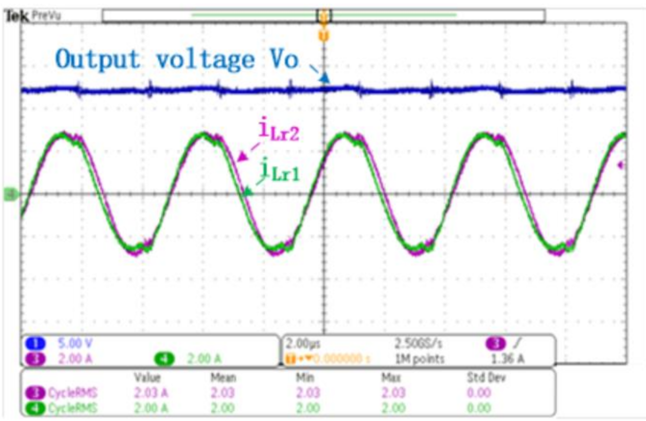
(b)

Fig. 19. Experimental waveform of conventional two-phase LLC converter (a) Steady state at 15A load (b) Steady state at 25A load
Ch1: output voltage; Ch3: resonant current of phase 2;
Ch4: resonant current of phase 1.

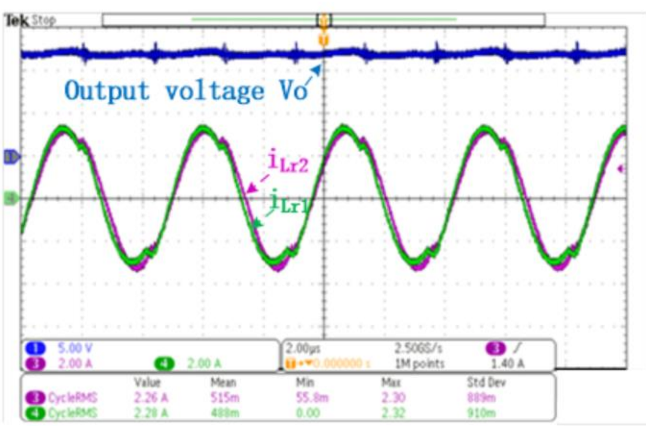
Fig. 20 shows the experiment waveform of proposed common inductor two-phase LLC converter. The resonant current i_{Lr1} and i_{Lr2} is almost same at 15A, 25A and 50A load. A very small angle difference between them is shown at different load.



(a)



(b)



(c)

Fig. 20. Experimental waveform of common inductor LLC converter
(a) Steady state at 15A load (b) Steady state at 25A load
(c) Steady state at 50A load Ch1: output voltage;
Ch3: resonant current of phase 2; Ch4: resonant current of phase 1.

To show the current sharing performance, the resonant current and resonant current sharing error are shown in Fig. 21 and Fig. 22 for both conventional and proposed converter.

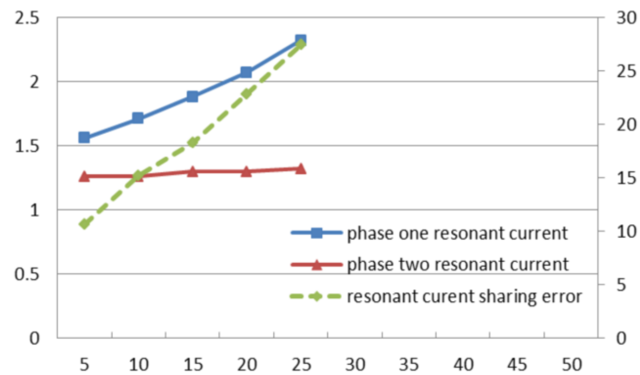


Fig. 21. Resonant current of conventional two-phase LLC converter

The resonant current sharing error increases from 10% to 28% for load power from 5A to 25A for conventional two phase LLC converter in Fig. 21. The resonant current sharing error is reduced from 2.3% to 0.44% for the proposed current sharing method when load power changes from 5A to 50A in Fig. 22. The resonant current sharing error can be significantly reduced using the proposed method. Good current sharing performance can be achieved based on common inductor two-phase LLC converter.

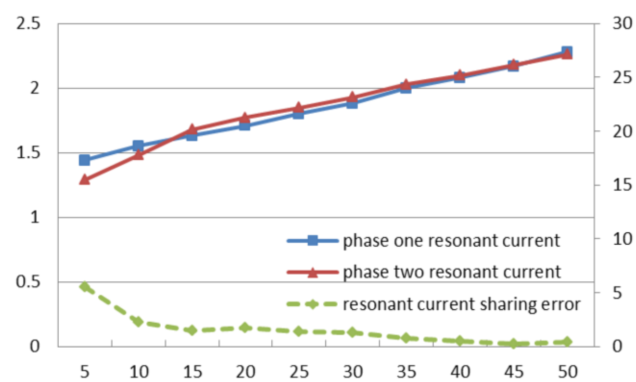


Fig. 22. Resonant current of proposed two-phase LLC converter

VI. Conclusion

A new, common inductor current sharing strategy for multi-phase LLC resonant converter is proposed. The series resonant inductors 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 both conventional and proposed two-phase LLC converter. The analysis results shows that the current sharing error is significantly reduced using the proposed method. A two-phase LLC converter prototype with 300W per phase is built using the common inductor current sharing method. The simulation and experiment results show that the circulating resonant current reduces 63 times and is only 0.44% at 600W total load power with the proposed method.

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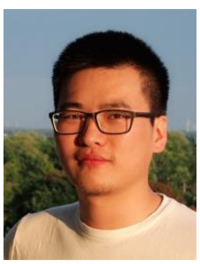
Hongliang Wang (M'12-SM'15) received the B.Sc. degree in electrical engineering from Anhui University of Science and Technology, Huainan, China in 2004, and received the Ph.D. degree in electrical engineering from Huazhong University of Science and Technology, Wuhan, China in 2011.

From 2004 to 2005, he worked as an electrical engineer of Zhejiang Hengdian Thermal Power Plant. From 2011 to 2013, he worked as a senior system engineer of Sungrow Power Supply Co., Ltd. He is a Post-Doctoral Fellow at Queen's University since 2013.

His research in the area of power electronics, including digital control, modulation and multilevel topology of inverter for photovoltaic application and micro-grids application; resonant converters and server power supplies, and LED drivers. He has published more than 50 papers in conferences and journals. He is the inventor/co-inventor of 41 China issued patents, 15 US patents and 6 PCT patents pending.

Dr. Wang is currently a senior member of China Electro-Technical Society (CES); a senior member of China Power Supply Society (CPSS). He serves as a member of CPSS Technical Committee on Standardization; a member of CPSS Technical Committee on Renewable Energy Power Conversion; a vice-chair of Kingston Section, IEEE; a session chair of ECCE 2015; a TPC member of ICEMS2012； a China Expert Group Member of IEC standard TC8/PT 62786.

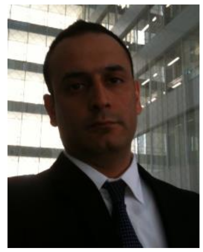


Yang Chen (S'14) received his B.Sc. in electrical engineering in 2011, and his M.Sc. degree in 2013, both from Beijing Institute of Technology, Beijing, China. He is currently working toward the Ph.D. degree at Queen's University, Kingston, Canada. His research interests include topology, control, and design of resonant converters in AC-DC and DC-DC fields, power factor correction technology, and digital control.

Yan-Fei Liu (M'94-SM'97-F'13) received his Bachelor and Master degree from the Department of Electrical Engineering from Zhejiang University, China, in 1984 and 1987 and PhD degree from the Department of Electrical and Computer Engineering, Queen's University, Kingston, ON, Canada, in 1994.

He was a Technical Advisor with the Advanced Power System Division, Nortel Networks, in Ottawa, Canada from 1994 to 1999. Since 1999, he has been with Queen's University, where he is currently a Professor with the Department of Electrical and Computer Engineering. His current research interests include digital control technologies for high efficiency, fast dynamic response dc–dc switching converter and ac–dc converter with power factor correction, resonant converters and server power supplies, and LED drivers. He has authored over 200 technical papers in the IEEE Transactions and conferences, and holds 20 U.S. patents. He is also a Principal Contributor for two IEEE standards. He received Premier's Research Excellence Award in 2000 in Ontario, Canada. He also received the Award of Excellence in Technology in Nortel in 1997.

Dr. Liu serves as an Editor of IEEE Journal of Emerging and Selected Topics of Power Electronics (IEEE JESTPE) since 2013, an associate Editor for IEEE Transactions on Power Electronics since 2001, and a Guest Editor-in-Chief for the special issue of Power Supply on Chip of IEEE Transactions on Power Electronics from 2011 to 2013. He also served as Guest Editor for special issues of JESTPE: Miniaturization of Power Electronics Systems in 2014 and Green Power Supplies in 2016. He serves as Co-General Chair of ECCE 2015 held in Montreal, Canada, in September 2015. He will be the General chair of ECCE 2019 to be held in Baltimore, USA. He has been the chair of PELS Technical Committee on Control and Modeling Core Technologies since 2013 and chair of PELS Technical Committee on Power Conversion Systems and Components from 2009 to 2012.



Jahangir Afsharian received the B.S and M.S degree in electrical engineering from Ryerson University, Toronto, Canada, in 2006 and 2009, respectively. From 2009 to 2011, he was a Research and Development (R&D) Engineer in the Communications and Power Industries (CPI), Georgetown, ON, Canada, where he was involved on the design of resonant converter LCC and high voltage transformer for x-ray medical equipment. From end of 2011 to present, he is a Senior Electrical Engineer in the Advanced Development Group, Murata Power solution, where he is involved in the power electronics ac_dc power-factor-correction and dc_dc converter. His current research interests include three-phase Matrix based rectifier for battery charger and data center applications. He is also currently working toward the Ph.D. degree at the Ryerson University, Toronto, Canada.

Zhihua (Alex) Yang was born in Hubei, China. He received the B.S. degree from Hubei Institute of Technology, Hubei, China, in 1993, and the M. S. degree from Queen's University, Kingston, On, Canada, in 2005, both in electrical engineering.

He worked as a design engineer with Wuhan Zhouji Telecom Power Supply Corporation from 1993 to 2002. He has been a design engineer with the Advanced Research center, Paradigm Electronics, Inc., Canada during 2005 ~ 2007. He joined Murata Power Solutions Inc. located in Markham, Ontario, Canada in 2007. Since then he has been worked as a design engineer, senior design engineer, and principal design engineer. He is currently holding the position of Director of Product Development in Murata power solutions. Inc. His research interest is in high switching frequency, high power density and high efficiency switching mode power suppliers.