An Algorithm to Analyze Circulating Current for Multi-Phase Resonant Converter

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***Abstract*— an algorithm based on new circulated current model is proposed to analyze the circulating current in the multi-phase LLC converter. First of all, a virtual-open concept is introduced and LLC phases are decoupled from each other, Thus, A circulating current model can be achieved from fundamental harmonic approximation (FHA). Secondly, the ac voltages on the equivalent resistor of different phases are assumed same magnitude but different angle viewing from the primary-side. From mentioned above, current sharing error can be calculated, two types calculated results are shown under two-phase independent LLC converter and two-phase common inductor LLC converter. Simulation results from different input voltage levels, different resonant component tolerances, and different total load are compared. A two-phase 600W prototype is built to verify the effectiveness of the proposed analysis method**

I. INTRODUCTION

LLC resonant converter has been widely used due to high performance, such as the 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, multiphase parallel technique is a good choice to reduce the high current stress [3-5].

However, due to the resonant component tolerances (such as less than 5%), LLC converter may have unequal output currents among phases [6-8]. Small component tolerances can cause drastic current imbalance. Thus, an accurate method is needed to analyze the inter-phase circulating current.

There are several literatures analyzing circulating current [9-12]. In [9-10], these methods rely on simulation to get the circulating current information. In [11], the secondary rectifier circuits are equivalent to two ac resistors for the two-phase LLC converter. However, the ac voltages on the equivalent resistors are assumed to have same magnitude and angle. The rectifier circuit is equivalent three ac resistor voltages for three-phase LLC converter, it also exist coupling parameter for each phase, Thus, it is hard to get decoupled circulating current for each phase [12].

In this paper, an algorithm to analyze the inter-phase circulating current for multi-phase LLC resonant converter is proposed. The primary ac voltages of phases are of same voltage magnitude but different angle. The circulating current model can be derived by viewing the primary ac voltage of each phase decoupled. Circulating current error can be calculated with any combination of component tolerances. Section II describes circulating current analysis method. Section III shows experimental results of a 600W prototype; and Section IV gives the conclusion.

II. CIRCULATING CURRENT ANALYSIS METHOD

Mathematical model of LLC converter is needed for analyzing the current sharing characteristics of multi-phase LLC converter. For simplicity, two-phase LLC converter is analyzed in this paper. Conventional two-phase LLC resonant converter is shown in Fig.1. Lr, Cr, Lm are respectively the resonant inductor, resonant capacitor, magnetizing inductor of Phase one. Parameters aLr, bCr and cLm are the resonant inductor, resonant capacitor, magnetizing inductor of phase two. Of phase two, in which a, b and c indicate the resonant component tolerances as compared with Phase one. n is transformer turn ratio. iLr1, iLr2, Irect1, Irect2, Io1, and Io2 are the resonant current, rectifier current and load current of two units. Fig. 1(b) shows the equivalent circuit of the two-phase LLC resonant converter. The output resistor R is divided into R_1 and R_2. The values of R_1 and R_2 are decided by the steady-state load current, considering the output DC voltage V_O is well regulated and same for the two phase. The impedance error k is defined in Eq. (1). Fig. 1(c) shows the FHA equivalent circuit of Fig.1 (b).

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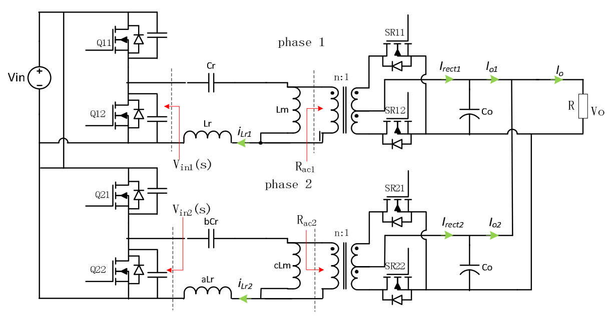
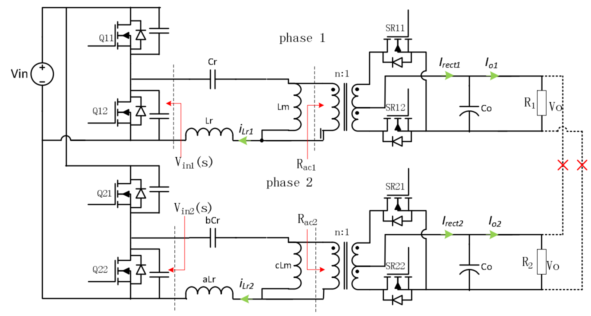
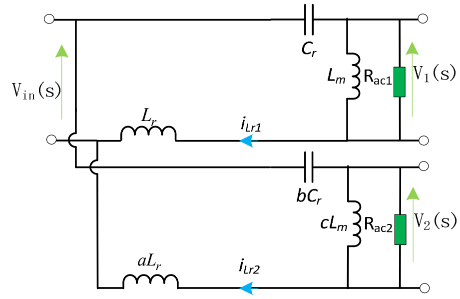


（a）circuit structure



（b）equivalent circuit



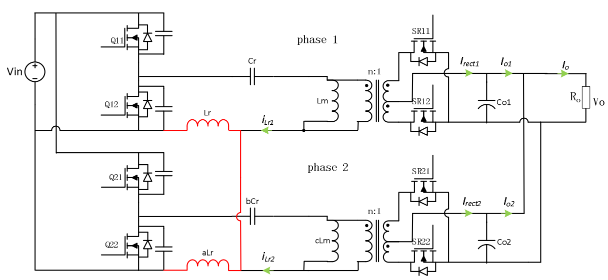
(c) FHA equivalent circuit

Fig.1 two-phase independent LLC resonant converter

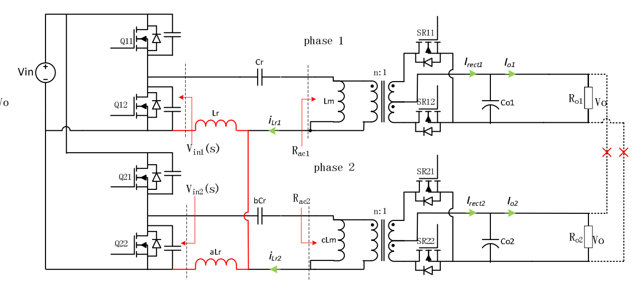
The impedance error k is defined in Eq. (1). Fig. 1(c) shows the FHA equivalent circuit of fig.1 (b).

$$R_1 = \frac{1}{k} R, R_2 = \frac{1}{(1-k)} R, k \in [0,1] \tag{1}$$

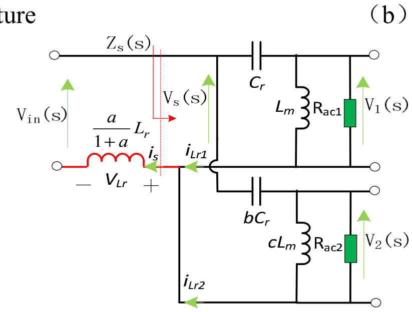
Two-phase common inductor LLC converter is shown in Fig.2 [13]. Similar analysis, the equivalent circuit and FHA circuit are shown in Fig.2 (a), Fig.2 (b).



（a）Common inductor circuit structure



（b）equivalent circuit



(c) FHA equivalent circuit

Fig.2 Two-phase common inductor LLC resonant converter

V1 and V2 are of same magnitude but different angle. The ac voltage angles are always different at parameter tolerances. The relationship is shown Eq. (2).

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

The ac loads Rac1 and Rac2 are defined in Eq. (3).

$$R_{ac1} = \frac{8n^2}{\pi^2} R_1, R_{ac2} = \frac{8n^2}{\pi^2} R_2 \tag{3}$$

For two-phase independent LLC converter, the transfer function $V_1(s)$, $V_2(s)$ are in Eq. (4) from Fig.1(c).

$$\begin{cases} V_1(\mathrm{s}) = G_1(\mathrm{s})V_{in}(\mathrm{s}) \\ V_2(\mathrm{s}) = G_2(\mathrm{s})V_{in}(\mathrm{s}) \end{cases} \tag{4}$$

For two-phase common inductor converter, the transfer function $V_3(s)$, $V_4(s)$ are in Eq. (5) from Fig.2(c).

$$\begin{cases} V_3(\mathrm{s}) = \dfrac{R_{ac1}//sL_m}{R_{ac1}//sL_m + 1/sC_r}(V_{in}(s)+V_{Lr}(s)) \\ V_4(\mathrm{s}) = \dfrac{R_{ac2}//scL_m}{R_{ac2}//scL_m + 1/sbC_r}(V_{in}(s)+V_{Lr}(s)) \end{cases} \tag{5}$$

According to Eq. (1) to (5), the follow relationship can be found：

$$Ak^2 + Bk + C = 0 \tag{6}$$

The coefficient under two-phase independent LLC converter is shown in Eq. (7),

$$\begin{aligned} A &= \omega^2(1-\mathrm{b}^2)c^2L_m^{\ 2} - \omega^4(2ab-2b^2)c^2L_rL_m^{\ 2}C_r \\ &+\omega^6(a^2-1)b^2c^2L_r^{\ 2}L_m^{\ 2}C_r^{\ 2} \\ B &= -2\omega^2c^2L_m^{\ 2} + 4\omega^4abc^2L_rL_m^{\ 2}C_r \\ &-2\omega^6a^2b^2c^2L_r^{\ 2}L_m^{\ 2}C_r^{\ 2} \\ C &= \omega^2c^2L_m^{\ 2} - 2\omega^4abc^2L_rL_m^{\ 2}C_r + \omega^6a^2b^2c^2L_r^{\ 2}L_m^{\ 2}C_r^{\ 2} \\ &+(1-\mathrm{b}^2\mathrm{c}^2)R^2 - \omega^2[(2ab-2b^2c^2)L_r + (2bc-2b^2c^2)L_m]C_rR^2 \\ &+\omega^4(ab-bc)[(ab+bc)L_r^{\ 2} + 2bcL_rL_m]C_r^{\ 2}R^2 \end{aligned} \tag{7}$$

The coefficient under two-phase common inductor is shown in Eq. (8),

$$\begin{cases} A = \omega^2(1-b^2)c^2L_m^{\ 2} \\ B = -2\omega^2c^2L_m^{\ 2} \\ C = \omega^2c^2L_m^{\ 2} + (1-b^2c^2)R^2 - 2\omega^2(bc-b^2c^2)L_mC_rR_{ac}^{\ 2} \end{cases} \tag{8}$$

Then, impedance error k can be expressed as in Eq. (9),

$$k = \begin{cases} -\dfrac{C}{B} & A=0, B\neq 0 \\ \dfrac{-B\pm\sqrt{B^2-4AC}}{2A} & A\neq 0, \sqrt{B^2-4AC}\geq 0 \end{cases} \quad and\ k\in[0,1] \tag{9}$$

The impedance error k is effective when k is between 0 and 1. Otherwise only one unit will provide the load power.

According to (9),

The load current sharing error σ is defined in (10),

$$\sigma = abs\left(\frac{I_{01}-I_{02}}{I_{01}+I_{02}}\right) = abs(1-2k), \mathrm{k}\in[0,1] \tag{10}$$

The resonant current sharing error is defined in (11)

$$\sigma_{resonant} = \frac{abs(rms(\mathrm{i}_{Lr1}) - rms(\mathrm{i}_{Lr2}))}{abs(rms(\mathrm{i}_{Lr1}) + rms(\mathrm{i}_{Lr2}))} \tag{11}$$

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.

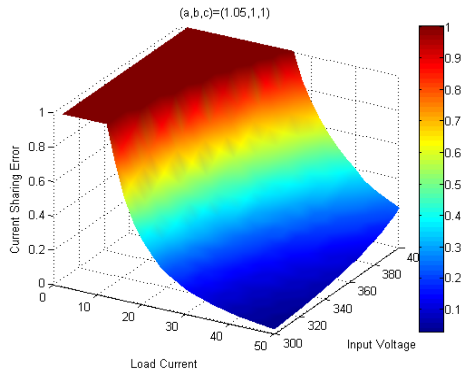
Tab.1 Parameters

Lr	Cr	Lm	n	fr	Vo	Po(total)
29µH	12nF	95µH	20	270KHZ	12V	600W

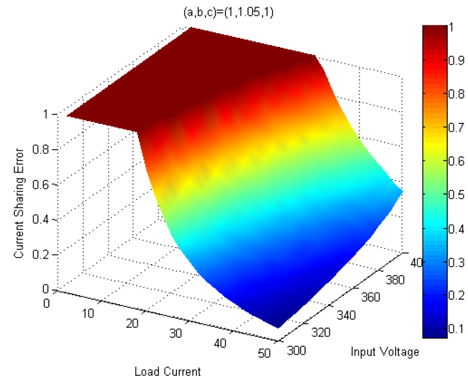
As the resonant inductance, resonant capacitance is increased of phase two, the resonant frequency is reduced , thus, the gain value of phase two will be increased if the load resistor doesn’t changed based on virtual open concept. Actually, phase two will provide more power than phase one. And then keep the same between phase one and phase two. Similarly, phase two provide more power than phase on with magnetic inductance of phase two increasing. Thus, the worst situation is that parameters a, b, c is increased or deduced at same time.

Fig.3 shows load current sharing error with different parameter tolerance under two-phase independent LLC converter. Fig.3 (a), (b), (c) shows the current sharing error at +5% Lr, +5% Cr, +5% Lm, respectively. The current sharing error is almost reduced with total load current increasing and input voltage increasing. The worst situation of current sharing error is shown in Fig.3 (d), which three resonant parameters have +5% increasing. The current sharing error is 60% at 50A load current, 400V input voltage. Fig.4 shows the load current sharing error with different parameter tolerance under two-phase common inductor LLC converter. Fig.3 (a), (b), (c) shows the current sharing error at +5% Lr, +5% Cr, +5% Lm, respectively.

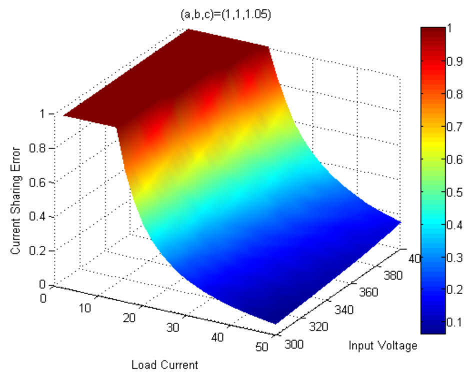
The current sharing error is reduced with total load current increasing and input voltage increasing. The worst situation of current sharing error is shown in Fig.3 (d), which three resonant parameters have +5% increasing. The current sharing error is about 5% at 50A load current, 400V input voltage.



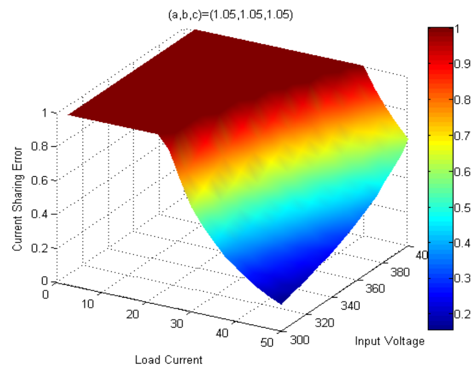
(a) +5% Lr parameter tolerance



(b) +5% Cr parameter tolerance

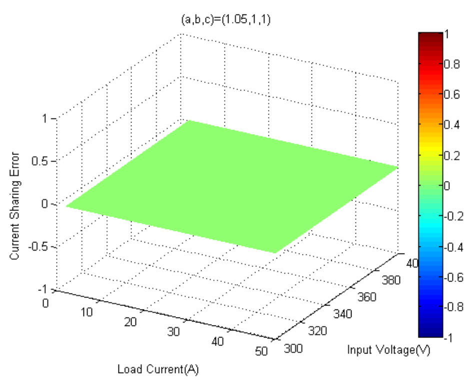


(c) +5% Lm parameter tolerance

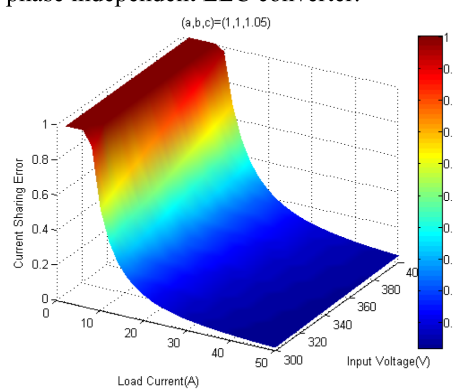


(d) +5% Lr, +5% Cr, and +5% Lm parameter tolerance

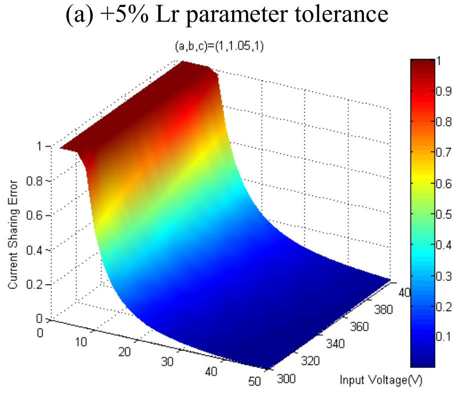
Fig.3 current sharing error under two-phase independent LLC converter.



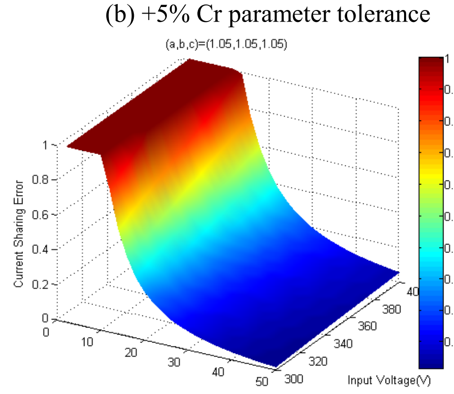
(a) +5% Lr parameter tolerance



(b) +5% Cr parameter tolerance



(c) +5% Lm parameter tolerance

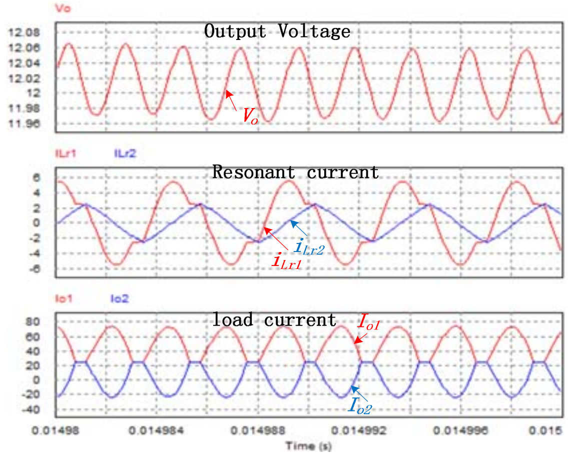


(d) +5% Lr, +5% Cr, and +5% Lm parameter tolerance

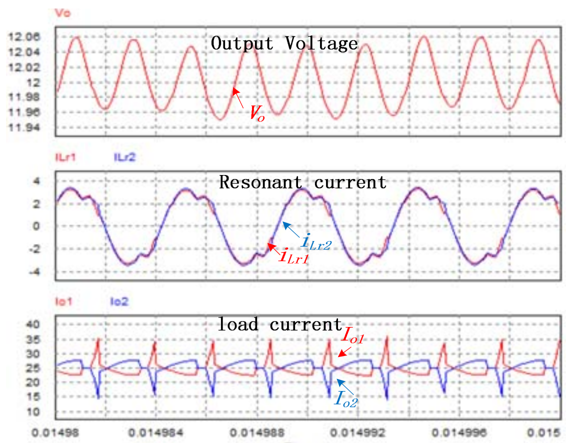
Fig.4 current sharing error under two-phase common inductor LLC converter.

III. SIMULATION AND EXPERIMENT RESULTS

From Section II, the simulation results under 400V input voltage, 60A load current are shown in Fig.5, which parameters (a, b, c) equals to (1.05, 1.05, 1.05).



(a) Waveforms under two-phase independent LLC converter



(b) Waveforms under two-phase common inductor LLC converter

Fig.5 simulation waveforms at the worst case.

Fig.5 shows simulation waveform under the worst case (a, b, c) = (1.05, 1.05, 1.05). Fig. 5(a) shows the simulation waveform under two-phase independent LLC converter. Output voltage is 12V. There is large difference between resonant current of each phase. Load current of each phase is 48.5A，1.5A. Thus, almost only phase one provides total load power. The simulation waveform of two-phase common inductor LLC converter is shown in Fig.5 (b).The resonant current and load current are been shared.

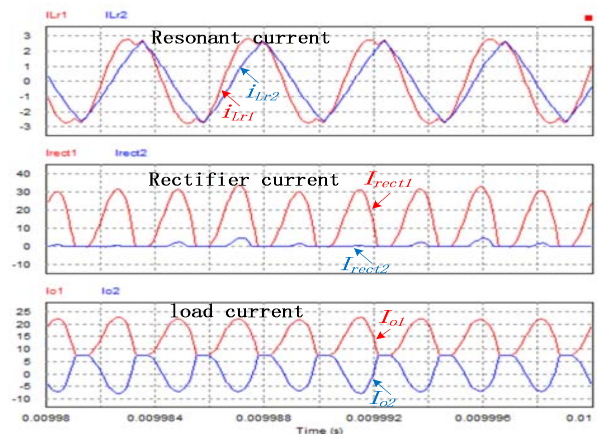
As output capacitor are connected together in industry product, it is hard to get the load current of each phase. However, the resonant current of each phase can also influence the current sharing performance. Thus, the resonant current sharing error can be used to estimate circulating current performance based on Fig.5.

2*300W LLC converter is built to verify of proposed method. To compare the different component tolerances. The circuit diagram is shown in Fig.5 (a). The prototype parameters are shown in Table 2.

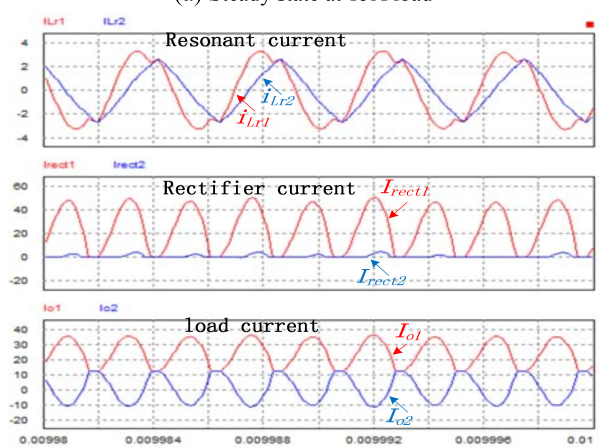
Tab.2 Prototype parameters

Switching frequency	180kHz-270kHZ
Input Voltage	340V-400V
Output Voltage	12V
Output Power	300W × 2
Transformer Ratio n	20:1
Output Capacitance	1790μF
Series Capacitance(Cr)	12nF +5%
Resonant Inductance(Lr)	22.5μH(Phase1) 24.5μH(Phase2)
Leakage Inductance(Le)	6μH(Phase1) 6.5μH(Phase2)
Magnetizing Inductance(Lm)	95μH(Phase1) 92μH(Phase2)

Fig.6 show simulation waveforms of two-phase independent LLC converter without current sharing at 15A, 25A total load. Actually, the designed rated current value is



(a) Steady state at 15A load

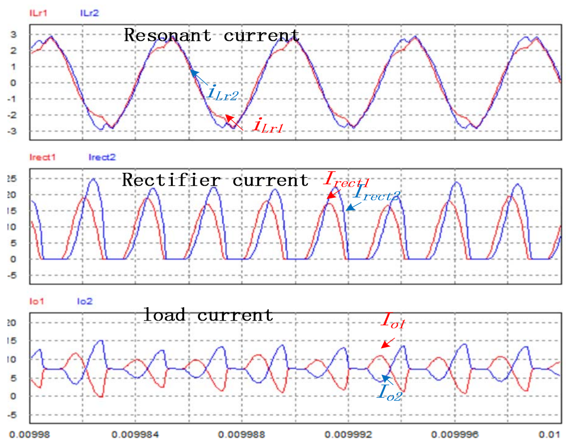


(b) Steady state at 25A load

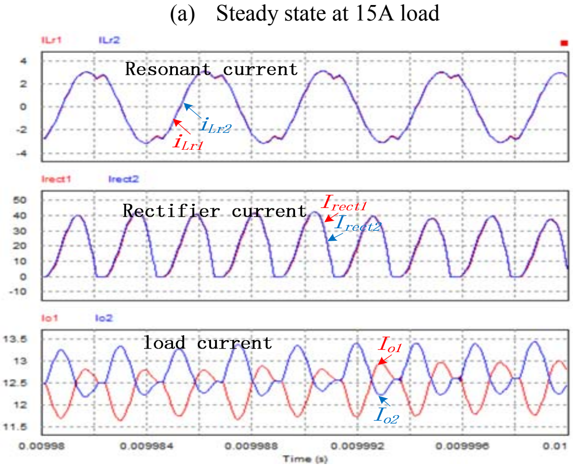
Fig. 6 simulation waveform of two-phase independent LLC converter

25A for each phase, which means that it doesn't provide 50A for two phase parallel converter. In other words, when the total load current is larger than 25A, the second phase loads current will exceed the rated current according to Fig.3.To escape the overcurrent of each phase, the total maximum 25A current experiment is done without current sharing technology method. As the output voltage has switching frequency ripple, The load current Io2 has a high frequency ripple to charge or discharge the output capacitor C_{o2}. Thus, it has negative high frequency current or positive high frequency current. The average load current average value is zero. Thus, only phase one provides the load power.

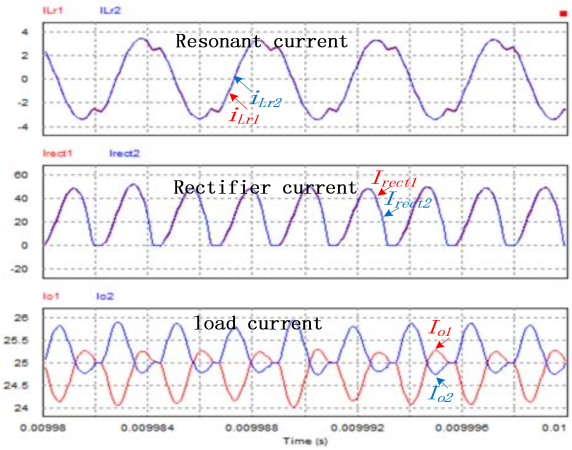
Fig.7 shows simulation waveforms of two-phase common inductor LLC converter at 15A, 25A, 50A total load.



(a) Steady state at 15A load



(b) Steady state at 25A load.



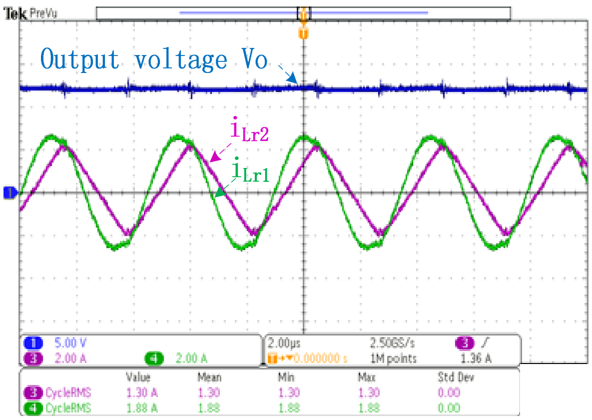
(c) Steady stat at 50A load

Fig.7 simulation waveform of two-phase common inductor LLC converter

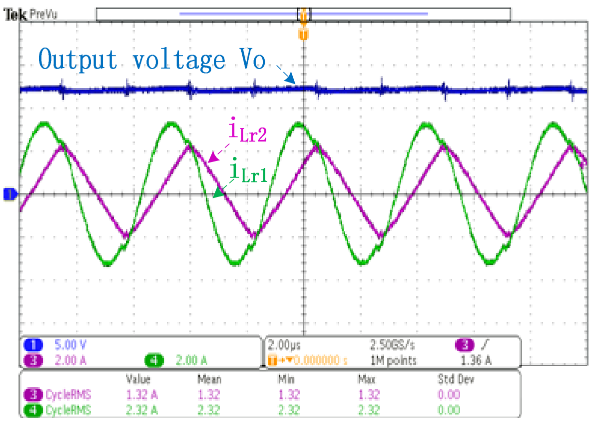
The load current difference is reduced from 15A to 3A between Fig.6 (a) and Fig.7 (a). The load current difference is reduced from 25A to 0.5A between Fig.6 (b) and Fig. 7(b). Fig.7 (c) shows the good load sharing for total 50A load. As the output voltage has switching frequency ripple, The load current Io2 has a high frequency ripple to charge or discharge the output capacitor C_{o2}. Thus, it has negative high frequency current or positive high frequency current. The average load current average value is almost same in Fig.7 (b), (c). Thus, almost two phase units provide same load power.

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.6, Fig.7. It is hard to sense the load current of two phase because output capacitor are connected together closely. The resonant current sharing error is used to estimate the circulating current performance in experiment results.

Fig.8 shows the experiment waveform of two-phase conventional LLC converter. Channel 1 is the output voltage. Channel 3, channel 4 are the resonant current of two phases. The resonant current i_{Lr1} is almost triangulate waveform, which means phase one almost doesn't provide the power for output load. Fig.9 shows the experiment waveform of two-phase proposed LLC converter. The resonant current i_{Lr1} and i_{L2} is almost same. A very small angle difference between them is shown at different load.



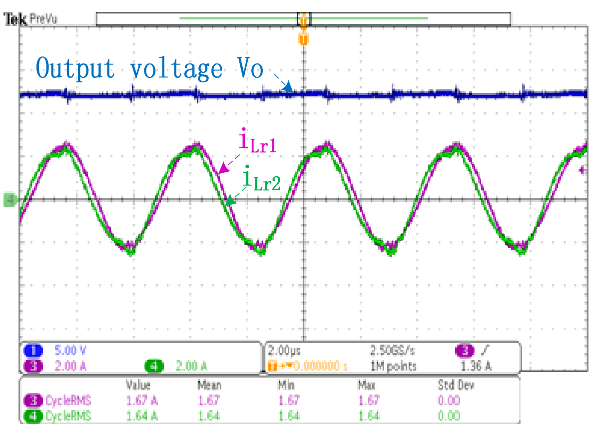
(a) Steady state at 180W load



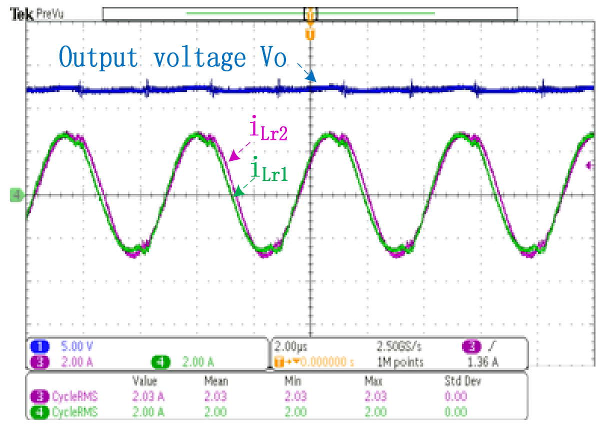
(b) Steady state at 300W load

Ch1: output voltage; Ch3: resonant current of phase two; Ch4: resonant current of phase one.

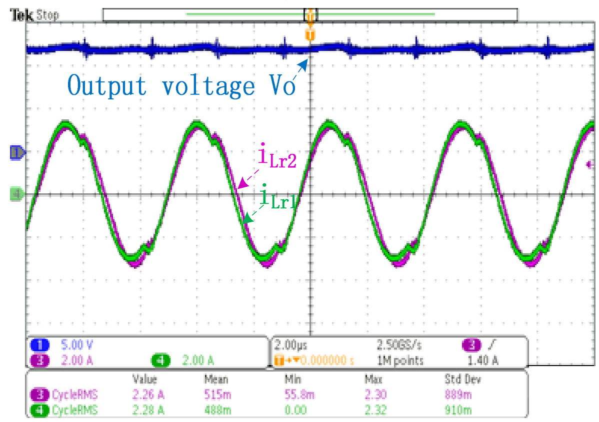
Fig.8 experiment waveform of two-phase conventional LLC converter



(a) Steady state at 180W load



(b) Steady state at 300W load



(c) Steady state at 600W load

Ch1: output voltage; Ch3: resonant current of phase two; Ch4: resonant current of phase one.

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

To express circulating current according to Eq. (11), the resonant current and resonant current sharing errors are shown in Fig.10, Fig.11.

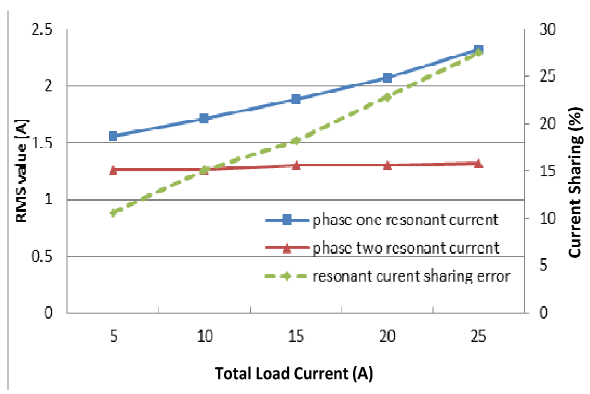


Fig.10 resonant current of two-phase conventional LLC converter

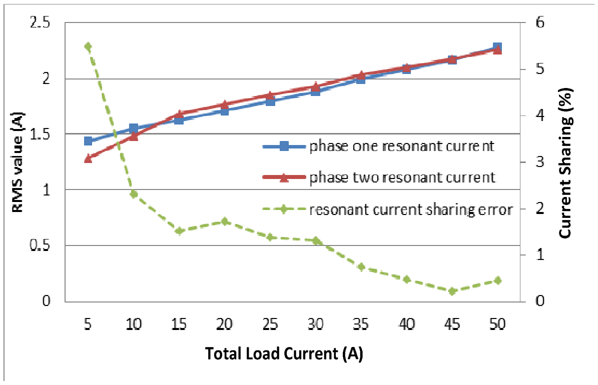


Fig.11 resonant current of two-phase proposed LLC converter

The resonant current sharing error increases from 10% to 28% with load power from 5A to 25A according to Fig.10. The resonant current sharing error is reduced from 2.3% to 0.44% when load power changes from 5A to 50A based on Fig.11.

IV. Conclusion

An analysis algorithm to analyze the circulating current is proposed for multi-phase LLC converter. The equivalent ac resistor voltage is of the same magnitude but different angle based on FHA. The detailed analysis according to the proposed method shows that the worse situation is same direction of deviation between resonant capacitor and magnetizing inductance (one is increased, the other is reduced). There is significant reduction from two-phase independent LLC converter to two-phase common inductor LLC converter according to analysis algorithm. Two-phase LLC converter prototype with 300W each phase is built to verify the effectiveness of proposed analysis method. Simulation and experiment results shows that resonant current sharing error is reduced from 28% to 0.44% when load power changes is 50A.This analysis method can be extended any phases that is more than two, and any resonant converters, such as series resonant converter, parallel resonant converter, LCC and so on.

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