A Common Inductor Multi-Phase LLC Resonant Converter

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***Abstract*—In this paper, a new common inductor current sharing method is proposed for multi-phase LLC resonant converter for high power application. Automatic current sharing is achieved by using a common resonant inductor for all the LLC resonant stages, by connecting the resonant inductors in each phase in parallel. The proposed method can automatically share the load current without any additional circuit and control strategy. The current share performance of the proposed common inductor current share 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 (less than 0.5% current sharing error at full load) has been achieved.**

I. INTRODUCTION

Resonant converter is attractive for isolated DC/DC application, such as flat-panel TVs, laptop adapters, server computers, and so on, because of its attractive features: smooth waveforms, high efficiency and high power density. Furthermore, 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][2]. For high power applications, the current stress of power devices increases with the power rating. 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 noted that a small component tolerance (such as less than 5%) can cause significant current imbalance. Therefore, current sharing is mandatory in order to achieve multiphase operation for LLC converter..

Three methods have been used to achieve current sharing for multiphase LLCs. The first one is the active method which adjusts the equivalent resonant capacitor [9], [10] or inductor [11] to compensate the components' tolerances using additional MOSFETs. Excellent load sharing performance can be achieved. The circuit diagram for switched capacitor is shown in Fig.1. The circuit diagram for variable inductor is shown in Fig.2. However, these methods suffer from high cost, complex control and non-excellent dynamic performance because of sensing circuit and controlling additional switches. The second one is the DC voltage self-balanced method based on series capacitors [12][13], which is shown in Fig.3. Two-phase LLCs is made as an example to explain the principle, the mid-point voltage is changed according to two phase's power. Thus, the system has low cost and good load current sharing performance. However, it is hard to achieve modularization design as the DC voltage stress is reduced with module number increased. The third one is based on three-phase three-wire structure for three-phase LLCs based on 120° phase-shift method, which has good load current sharing near resonant frequency as all of three-phase resonant current is zero [14][15]. However, it is only suitable for three LLC modules in parallel. The load current will not share when the numbers of parallel modules is more than three.

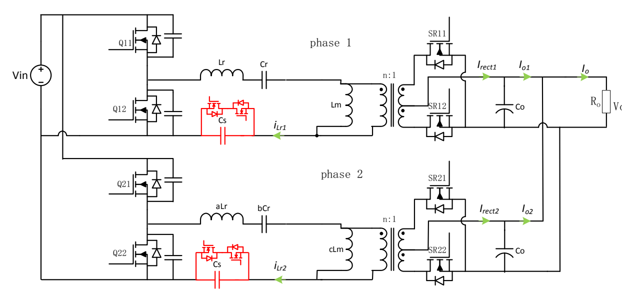

Fig.1 switched capacitor multi-phase LLC converter

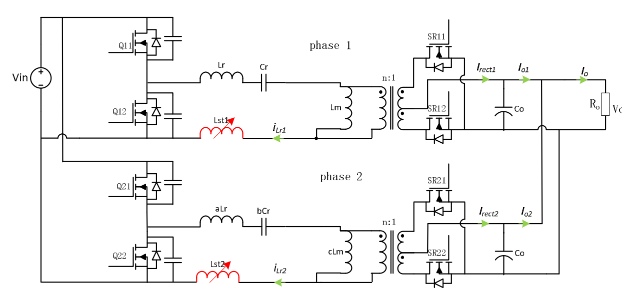

Fig.2 variable inductor multi-phase LLC converter

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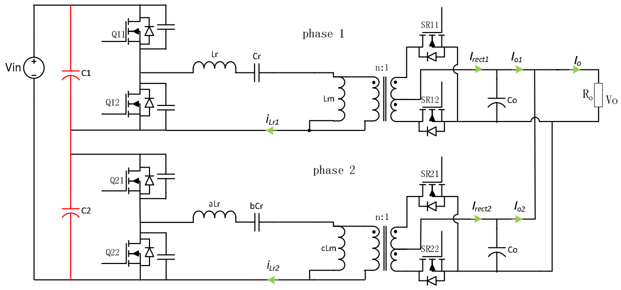


Fig.3 series DC-capacitor multi-phase LLC converter

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

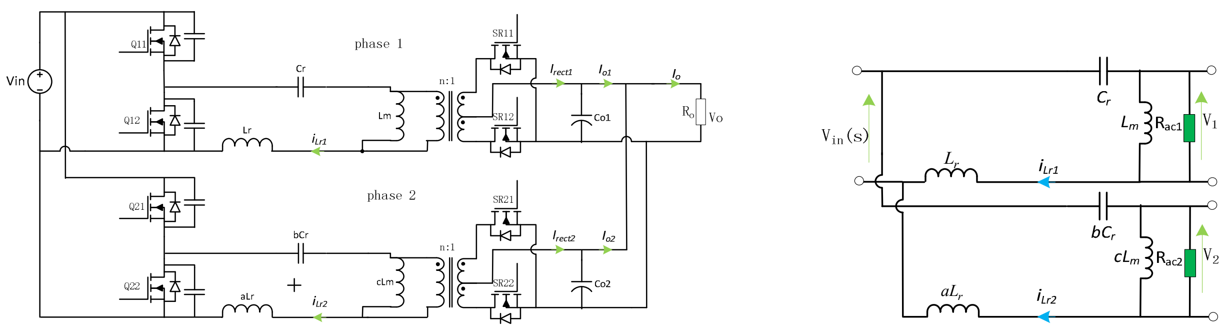
In this paper, a new common inductor multi-phase LLC resonant converter is proposed to achieve automatic load sharing. In this method, the resonant inductor in each LLC phase is connected in parallel. As a result, the load current is automatically shared. This technology is simple and no additional cost and complex control method are needed. It can be expanded to any number of phases. Section II describes the load sharing characteristic with/ without the proposed common inductor method. Section III provides simulation and experimental results of a two-phase 600W prototype with common inductor current sharing method; and Section IV is conclusion.

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 of LLC converter. For simplicity, two-phase LLC converter without sharing method is show in Fig.4. L_r, C_r, L_m are the series inductor, series capacitor, magnetic inductor and transformer turn ratio of phase one. aL_r, bC_r, cL_m are the series inductor, series capacitor, magnetic inductor of phase two. The values, a, b, c indicate that the resonant parameters for these two phases are different. n is transformer turn ratio. i_{Lr1}, i_{Lr2} , I_{rect1}, I_{rect2}, I_{o1}, and Io2 are the resonant current, rectifier current and load current of two phases. Fig.4 (b) is the equivalent circuit based on Fundamental Harmonic Analysis (FHA).In steady-state, the load resistor Ro is separated Ro1 and Ro2 according to each load current. The primary-side equivalent ac resistors Rac1 and Rac2 are shown as follows.

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

k is the impedance sharing error, 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.



（a）circuit structure

(b) FHA equivalent circuit

Fig.4 two-phase conventional LLC resonant converter

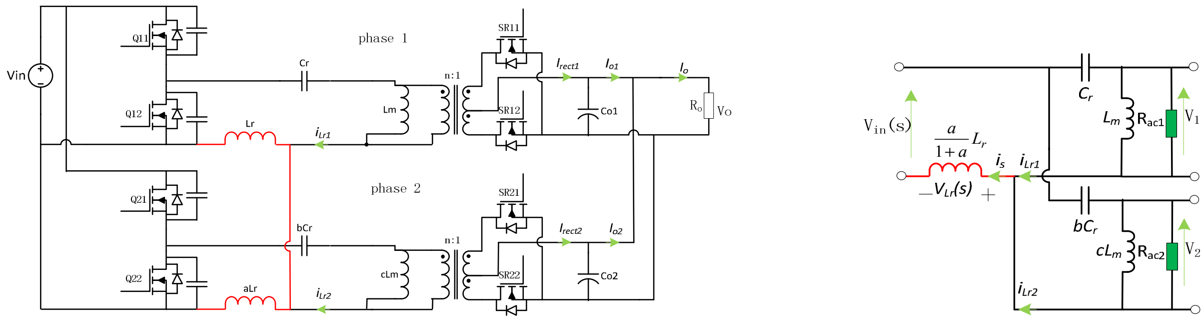
Fig. 5 shows proposed two-phase LLC resonant converter with current sharing. The only difference is that the series resonant inductors of the two LLC converters are connected together, as shown with red line. Fig.5 (b) shows the FHA equivalent circuit.

The ac voltage angles are always different at parameter tolerance. The relationship is shown as follows.

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

According to the Fig.4 (b), the transfer function of $V_1(s)$, $V_2(s)$ are shown as follows

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



(a) circuit structure (b) FHA equivalent circuit

Fig.5 two-phase proposed LLC resonant converter

According to the Fig.5 (b), the transfer function of $V_1(s)$, $V_2(s)$ are shown as follows

$$\begin{cases} V_1(\mathrm{s}) = \dfrac{R_{ac1}//sL_m}{R_{ac1}//sL_m + 1/sC_r}(V_{in}(s)+V_{Lr}(s)) \\ V_2(\mathrm{s}) = \dfrac{R_{ac2}//scL_m}{R_{ac2}//scL_m + 1/sbC_r}(V_{in}(s)+V_{Lr}(s)) \end{cases} \tag{4}$$

According to eq. (1), (2) and (3) or (4), the follow relationship can be found:

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

For two-phase proposed LLC converter, the parameter A, B, C can be expressed as follows:

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

For two-phase conventional LLC converter, the parameter A, B, C can be expressed as follows:

$$\begin{cases} A=\omega^2(1-b^2)c^2L_m^{\ 2} \\ B=-2\omega^2c^2L_m^{\ 2} \\ C=\omega^2c^2L_m^{\ 2}+(1-b^2c^2)R^2-2\omega^2(bc-b^2c^2)L_mC_rR_{ac}^{\ 2} \end{cases} \tag{7}$$

The value of the current sharing error is derived expressed below

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

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. The load current sharing error σ_{load} is defined in (9)

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

The resonant current sharing error $\sigma_{Resonant}$ is defined in (10)

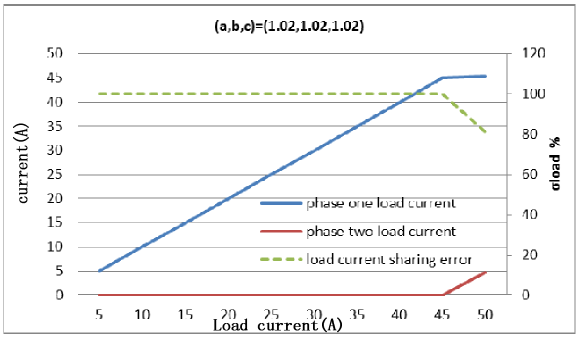
$$\sigma_{Resonant} = \frac{|rms(\mathrm{i}_{Lr1})-r\,\mathrm{ms}(\mathrm{i}_{Lr2})|}{|rms(\mathrm{i}_{Lr1})+rm\mathrm{s}(\mathrm{i}_{Lr2})|} \tag{10}$$

Table.1 shows power train parameters for the current sharing analysis. The full load power for each LLC converter is 12V/25A. Two load conditions are considered full load (12V/50A) and half load (12V/25A total).

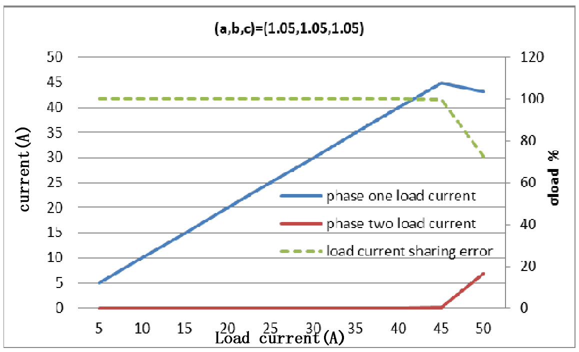
Tab.1 Nominal parameter value

Resonant inductor Lr	29uh
Resonant capacitor Cr	12nF
Magnetic inductor Lm	95uh
Transformer ratio n	20
Resonant frequency fr	270KHZ
Output voltage Vo	12V(rated voltage)
Total Output load Ro	0.24Ω(full power 600W)
	0.48Ω(half power 300W)

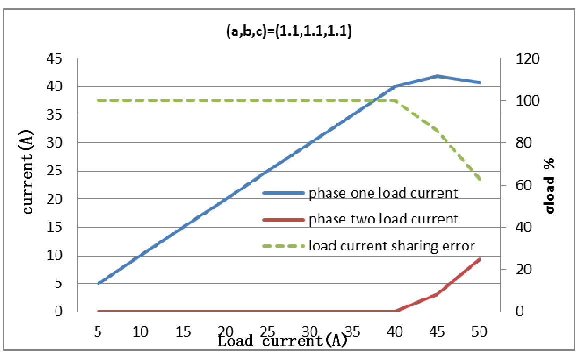
Fig.6 shows load current sharing error σ_{load} of two-phase LLC converter without any current sharing technology under 2%, 5% and 10% different component tolerance. The (a, b, c) = (1, 1, 1) means the second phase has the same parameter as the first phase, which result in the load current be perfectly shared and σ_{load}=0. When (a, b, c) = (1.05, 1.05, 1.05), which means that the resonant component value in second phase is 5% more than the value in phase one. Fig.6 (a) shows the load current and load current sharing error under 2% different component tolerances. Only second phase converter provides load power when the total load current is changed from 5A to 45A, the load current sharing error is 100%. Similarly, fig.6 (b) and (c) shows the same results. Thus, two phase converter without current sharing technology cannot share the load current. Actually, the designed rated current value is 25A for each phase for 50A load current, which means that it cannot provide 50A for two phase parallel converter.



(a) Under +2% tolerance



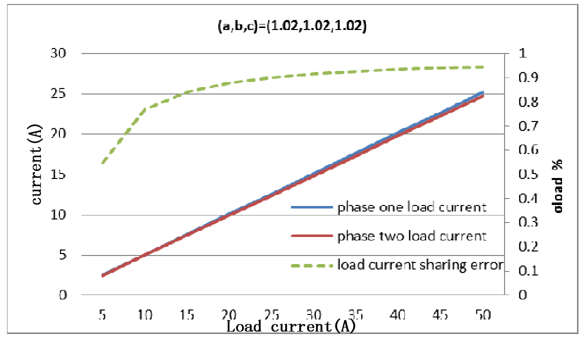
(b) Under +5% tolerance



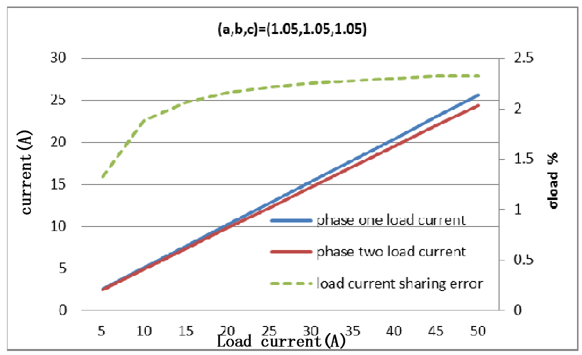
(c) Under +10% tolerance

Fig.6 load current sharing error without current sharing technology under 2%, 5% and 10% different component tolerance.

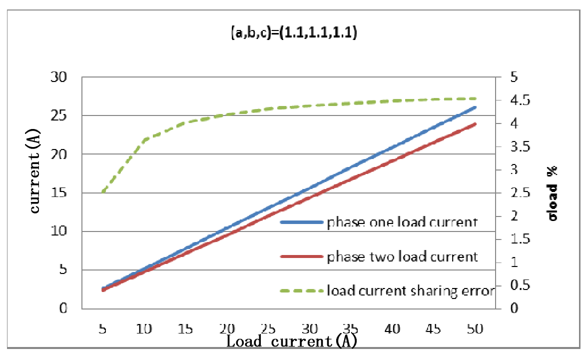
Fig.7 shows load current sharing error σ_{load} of two-phase LLC converter with proposed common inductor current sharing technology under 2%, 5% and 10% different component tolerance. Fig.7 (a) shows the load current and load current sharing error under 2% different component tolerances. The maximum load current sharing error is 0.95%. There is almost same load current between two phases. Similarly, Fig.7 (b) and (c) show the load current and load current sharing error. The maximum load current sharing error is 2.3%, 4.5%, respectively. The load current is almost same for each phase.



(a) Under +2% tolerance



(b) Under +5% tolerance



(c) Under +10% tolerance

Fig.7 load current sharing error with current sharing technology under 2%, 5% and 10% different component tolerance.

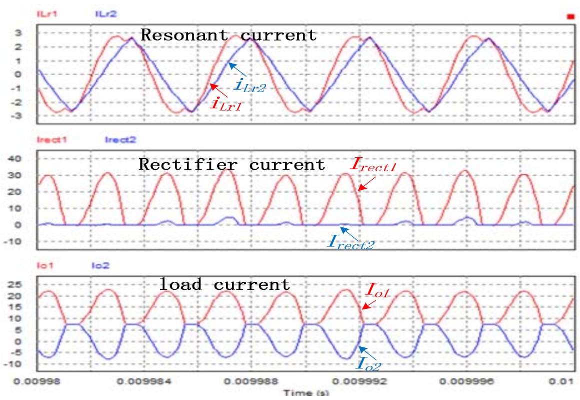
III. Simulation and Experiment Results

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.5 (a). The prototype parameters are shown in Table 2.

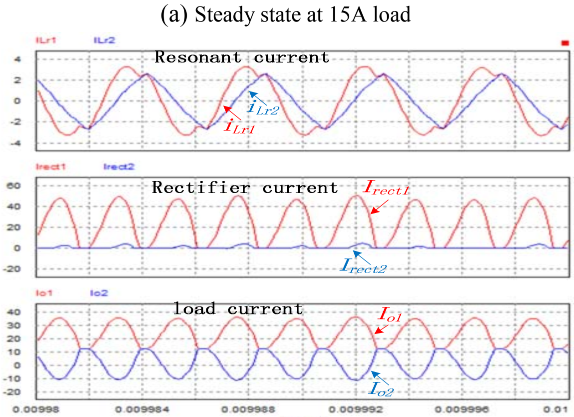
Tab.2 Prototype parameters

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.8 show simulation waveforms of two-phase conventional LLC converter without current sharing at 15A, 25A total load. Actually, the designed rated current



(a) Steady state at 15A load



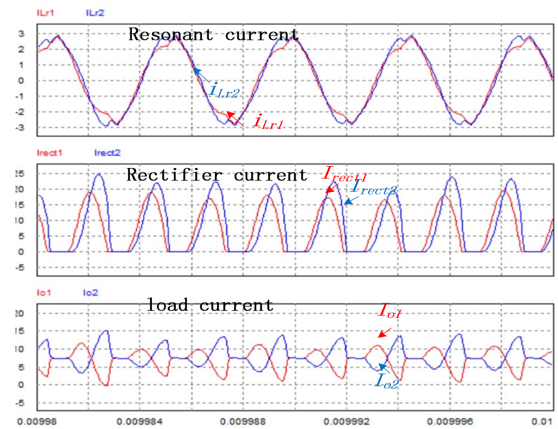
(b) Steady state at 25A load

Fig. 8 simulation waveform of two-phase LLC converter without current sharing technology

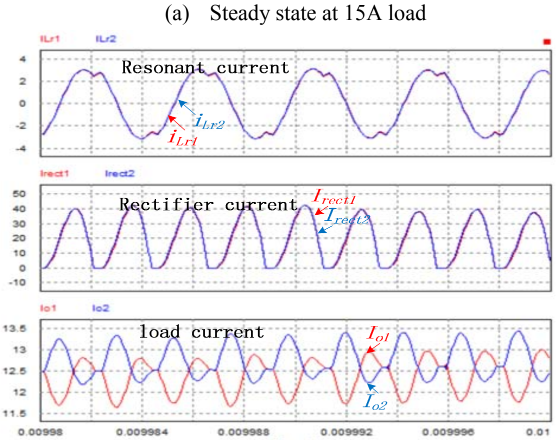
value is 25A for each phase, which means that it doesn't provide 50A for two phase parallel converter. In other words, when the total load current is larger than 25A, the second phase loads current will exceed the rated current according to Fig.3.To escape the overcurrent of each phase, the total maximum 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.

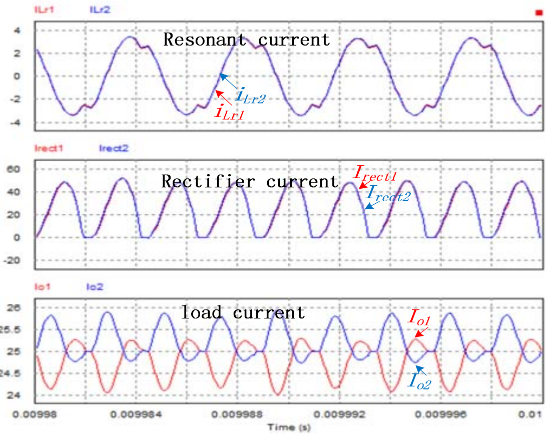
Fig.9 shows simulation waveforms of two-phase LLC converter using the proposed common inductor current sharing method at 15A, 25A, 50A total load. The load current difference is reduced from 15A to 3A between Fig.8 (a) and Fig.9 (a). The load current difference is reduced from 25A to 0.5A between Fig.8 (b) and Fig. 9(b). Fig.9 (c) shows the good load sharing for total 50A load.



(a) Steady state at 15A load



(b) Steady state at 25A load.

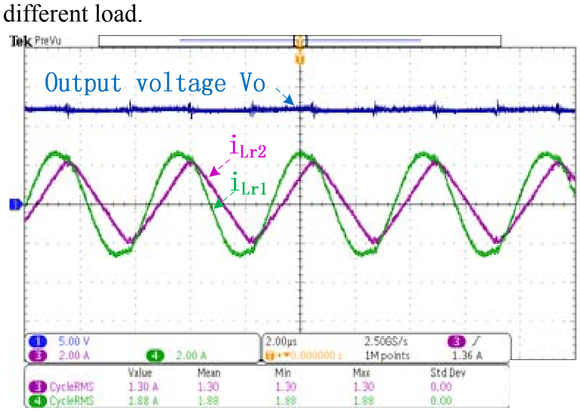


(c) Steady stat at 50A load

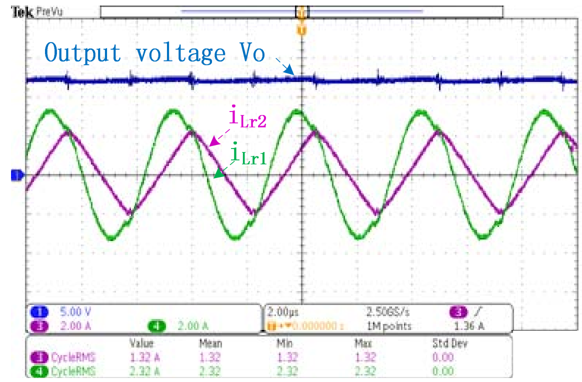
Fig.9 simulation waveform of two-phase proposed LLC converter

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, Fig.9.

Fig.10 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.11 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.



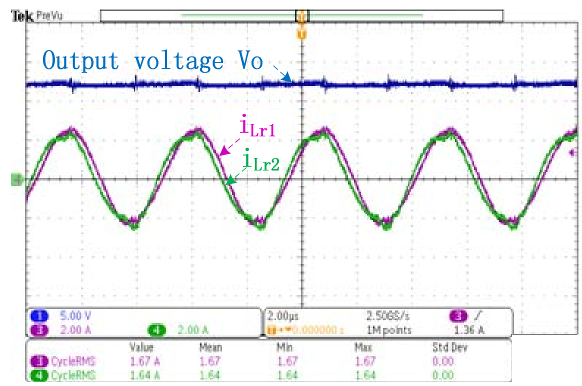
(a) Steady state at 180W load



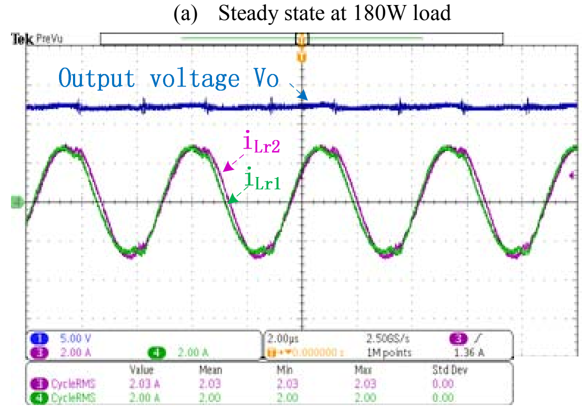
(b) Steady state at 300W load

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

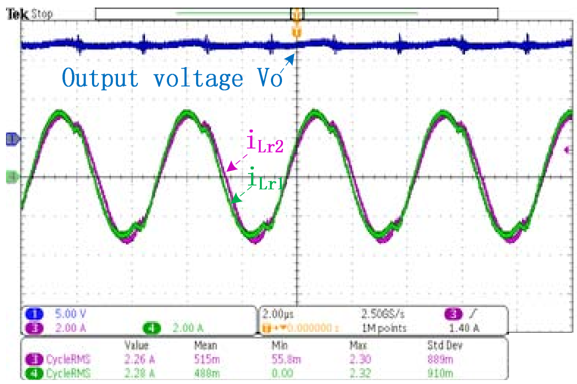
Fig.10 experiment waveform of two-phase conventional LLC converter



(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.11 experiment waveform of two-phase proposed LLC converter

To express circulate resonant current according to Eq. (5), the resonant current and relative circulated resonant current are shown in Fig.12, fig.13.

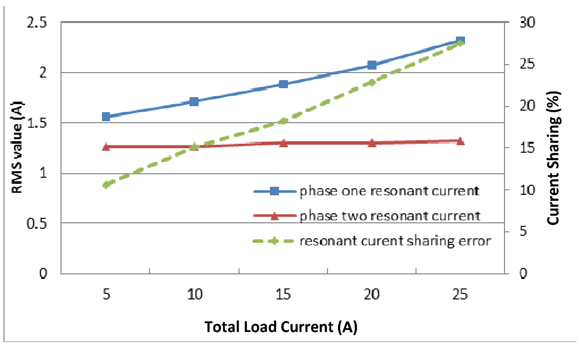


Fig.12 resonant current of two-phase conventional LLC converter

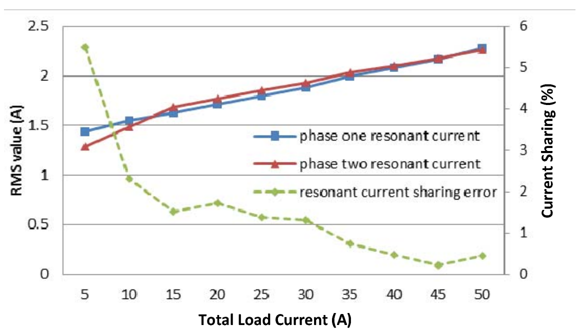


Fig.13 resonant current of two-phase proposed LLC converter

The relative circulated resonant current increases from 10% to 28% with load power from 5A to 25A according to fig.9. The relative circulated resonant current reduced from 2.3% to 0.44% when load power changes from 5A to 50A based on fig.10. Thus, the circulated current is significantly reduced using the proposed method.

IV. 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 a two-phase LLC converter. The analysis results shows that the circulated current is significantly reduce 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 relative circulated resonant current reduces 63 times and is only 0.44% at 600W total load power.

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