

Automatic Current-Sharing Method for Multi-Phase LLC Resonant Converter

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Abstract— an automatic current sharing method is proposed for multi-phase LLC resonant converter for high power application. There are two types, one is common inductor, and the other is common capacitor. Automatic current sharing is achieved by using a common component for all LLC resonant stages. The proposed method can automatically share the load current without any additional circuit and control strategy. The current share performance of the proposed 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 has been achieved.

Keywords— Resonant converter, Circulating current, multi-phase;

I. INTRODUCTION

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, multiphase parallel technique is a good choice to solve this problem [3][4][5]. However, due to the tolerance of resonant components, the output currents will be different [6][7][8]. A small component tolerance 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, which is shown in Fig. 1 and Fig. 2 respectively. Excellent load sharing performance can be achieved. 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.

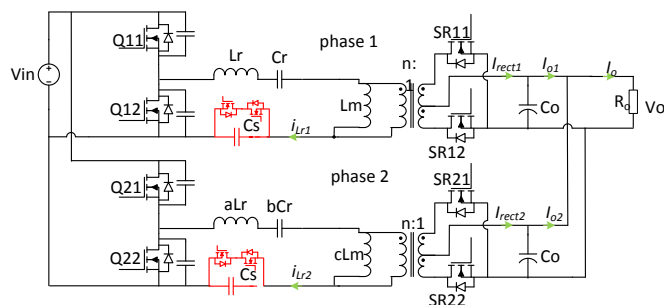


Fig. 1. Switched capacitor multi-phase LLC converter

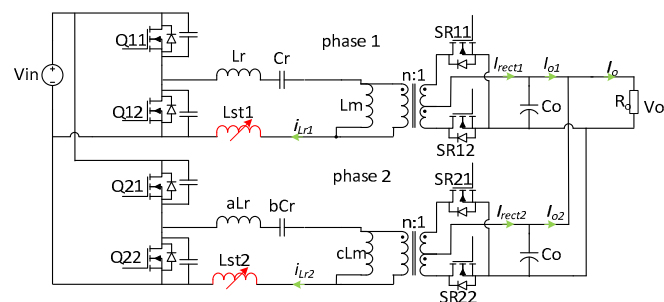


Fig. 2. Variable inductor multi-phase LLC converter

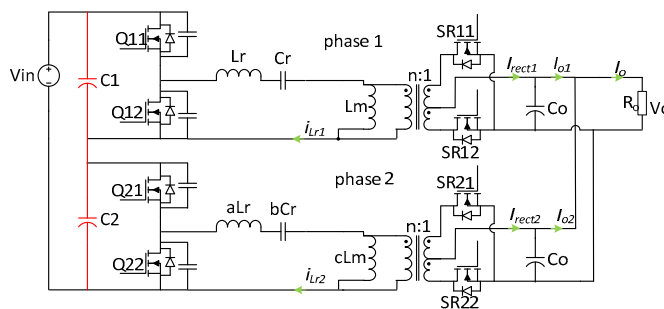


Fig. 3. Series DC-capacitor multi-phase LLC converter

Two-phase LLCs is made as an example to explain the principle, 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 as shown in Fig. 4, 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. Therefore, the existing technologies cannot provide cost effective, flexible current sharing technologies for multi-phase LLC resonant converters.

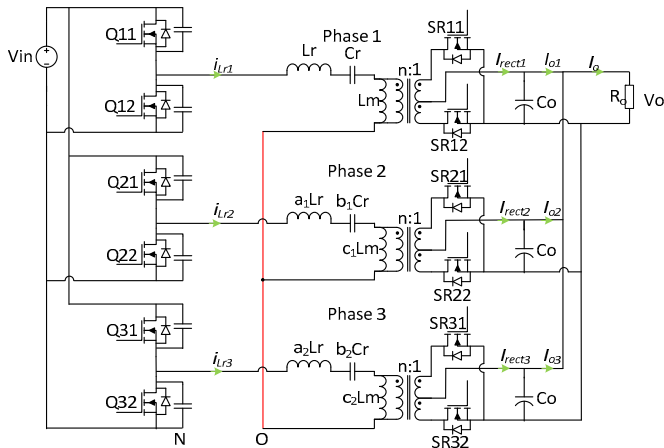


Fig. 4. Three-phase three-wire converter

In this paper, a new common component multi-phase LLC resonant converter is proposed to achieve automatic load sharing. In this method, the resonant inductor [16] or capacitor 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. This technology is simple and no additional cost and complex control method are needed. Section II describes the load sharing characteristic with/ without the proposed common component method. Section III provides simulation and experimental results of a two-phase 600W prototype with common component current sharing method; and Section IV is conclusion.

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

A. Conventional two-phase resonant converter

For simplicity, the two-phase LLC converter without sharing method is shown in Fig. 5. Where 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 I_{o2} are the resonant current, rectifier current and load current of two phases.

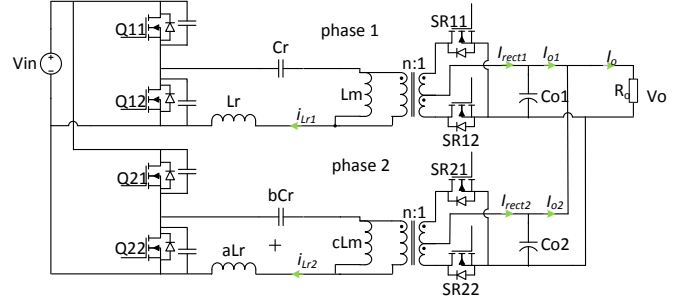


Fig. 5. Conventional two-phase LLC resonant converter

For simple understanding, switches Q11 and Q21 has same drive signal. Q12 and Q22 has same drive signal. V_o , P_o , R_o are the output voltage, total output power and total load resistor of two phase. The load resistor can be expressed as follows.

$$R_o = \frac{V_o^2}{P_o} \quad (1)$$

In steady-state, the total load power P_o is separated P_{o1} of phase one, P_{o2} of phase two.

$$P_o = P_{o1} + P_{o2} \quad (2)$$

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

$$\begin{cases} R_{o1} = \frac{V_o^2}{P_{o1}} \\ R_{o2} = \frac{V_o^2}{P_{o2}} \end{cases} \quad (3)$$

The coefficient k is defined as the phase one load power proportion of total load power

$$P_{o1} = kP_o \quad (4)$$

According to (3) (4), load power P_{o2} of phase two is expressed as

$$P_{o2} = (1-k)P_o \quad (5)$$

Combining (1), (2), (3), (4) and (5) gives (6)

$$[R_{o1} \quad R_{o2}] = \begin{cases} [\infty \quad R_o] & k=0 \\ \left[\begin{array}{cc} R_o/k & R_o/(1-k) \end{array} \right] & k \in (0,1) \\ [R_o \quad \infty] & k=1 \end{cases} \quad (6)$$

Fig. 6 is the equivalent circuit based on Fundamental Harmonic Analysis (FHA). The primary-side equivalent ac resistors R_{ac1} and R_{ac2} are shown as follows.

$$\begin{cases} R_{o1} = \frac{1}{k} R_o, R_{o2} = \frac{1}{(1-k)} R_o, k \in [0,1] \\ R_{ac} = \frac{8n^2}{\pi^2} R_o, R_{ac1} = \frac{8n^2}{\pi^2} R_{o1}, R_{ac2} = \frac{8n^2}{\pi^2} R_{o2} \end{cases} \quad (7)$$

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.

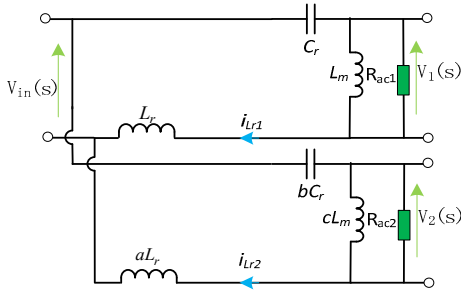


Fig. 6. FHA circuit of conventional two-phase LLC

In steady-state operation, the gain of each phase is same. Thus, there are same magnitude values of ac voltage. The ac voltage angles are always different at parameter tolerance. The relationship is shown in (8).

$$|V_1(s)| = |V_2(s)| \quad (8)$$

According to Fig. 6, the transfer function of $V_1(s)$, $V_2(s)$ are shown in (9).

$$\begin{cases} V_1(s) = \frac{R_{ac1} // sL_m}{R_{ac1} // sL_m + sL_r + 1/sC_r} V_{in}(s) \\ V_2(s) = \frac{R_{ac2} // sL_m}{R_{ac2} // sL_m + saL_r + 1/sbC_r} V_{in}(s) \end{cases} \quad (9)$$

Manipulating (7), (8), (9), the impedance sharing error k complies a uniform in (10):

$$Ak^2 + Bk + C = 0 \quad (10)$$

For conventional two-phase LLC converter, the parameter A , B , C can be expressed in (11):

$$\begin{cases} A = \omega^2(1-b^2)c^2L_m^2 - \omega^4(2ab-2b^2)c^2L_rL_m^2C_r \\ \quad + \omega^6(a^2-1)b^2c^2L_r^2L_m^2C_r^2 \\ B = -2\omega^2c^2L_m^2 + 4\omega^4abc^2L_rL_m^2C_r - 2\omega^6a^2b^2c^2L_r^2L_m^2C_r^2 \\ C = \omega^2c^2L_m^2 - 2\omega^4abc^2L_rL_m^2C_r + \omega^6a^2b^2c^2L_r^2L_m^2C_r^2 \\ \quad + (1-b^2c^2)R_{ac}^2 - \omega^2[(2ab-2b^2c^2)L_r + (2bc-2b^2c^2)L_m]C_rR_{ac}^2 \\ \quad + \omega^4(ab-bc)[(ab+bc)L_r^2 + 2bcL_rL_m]C_r^2R_{ac}^2 \end{cases} \quad (11)$$

The value of the current sharing error k can then be derived in (12):

$$k = \begin{cases} -\frac{C}{B} & A=0, B \neq 0 \\ \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} & A \neq 0, \sqrt{B^2 - 4AC} \geq 0 \end{cases} \quad \text{and } k \in [0,1] \quad (12)$$

B. Common component two-phase resonant converter

A Common components two-phase resonant converter is proposed in Fig. 7 and Fig. 8. A common inductor is used in Fig. 7. Two resonant capacitors are connected together in Fig. 8.

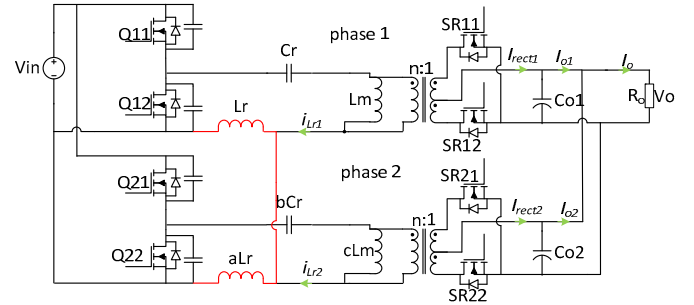


Fig. 7. Common inductor two-phase d LLC resonant converter

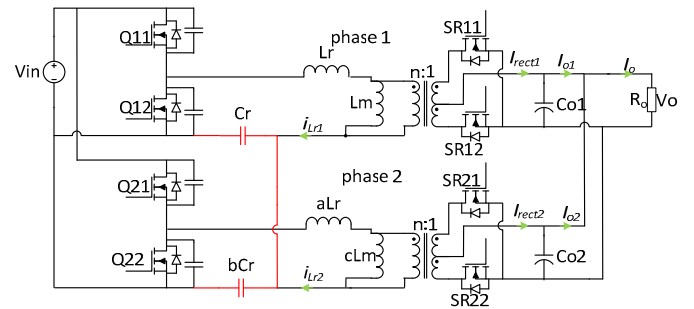


Fig. 8. Common capacitor two-phase d LLC resonant converter

The FHA circuit of common inductor two-phase LLC converter is in Fig. 9. Fig. 10 shows FHA circuit of common capacitor two-phase LLC converter.

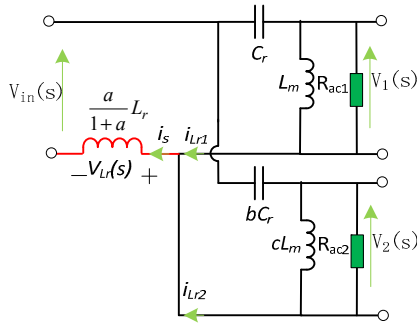


Fig. 9. FHA circuit of common inductor two-phase LLC converter

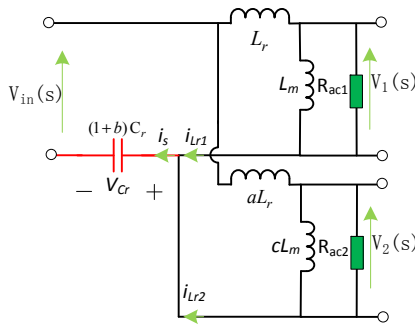


Fig. 10. FHA circuit of common capacitor two-phase LLC converter

Similar analysis of conventional two-phase LLC, the parameter A , B , C of common inductor two-phase LLC converter can be expressed in (13):

$$\begin{cases} A = \omega^2(1-b^2)c^2L_m^2 \\ B = -2\omega^2c^2L_m^2 \\ C = \omega^2c^2L_m^2 + (1-b^2c^2)R_{ac}^2 - 2\omega^2(bc-b^2c^2)L_mC_rR_{ac}^2 \end{cases} \quad (13)$$

The parameter A , B , C of common capacitor two-phase LLC converter can be expressed in (14):

$$\begin{cases} A = \omega^4(a^2-1)c^2L_r^2L_m^2 \\ B = -2\omega^4a^2c^2L_r^2L_m^2 \\ C = \omega^4a^2c^2L_r^2L_m^2 + \omega^2[(a^2-c^2)L_r^2 + 2(ac-c^2)L_rL_m]R_{ac}^2 \end{cases} \quad (13)$$

C. Circulating current analysis

The load current sharing error is defined as (14)

$$\sigma_{load} = \frac{|I_{01} - I_{02}|}{|I_{01} + I_{02}|} = abs(1-2k), k \in [0,1] \quad (14)$$

The resonant current sharing error is expressed as (15)

$$\sigma_{Resonant} = \frac{|rms(i_{Lr1}) - rms(i_{Lr2})|}{|rms(i_{Lr1}) + rms(i_{Lr2})|} \quad (14)$$

Tab.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).

TABLE I. NOMINAL PARAMETER VALUE

Resonant inductor L_r	29 μ H
Resonant capacitor C_r	12 nF
Magnetizing inductor L_m	95 μ H
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

The worst case is three parameters of phase two have +5% parameter tolerances.

Fig. 11 shows load current sharing error σ of two phase LLC converter at worst case in conventional two-phase LLC converter. The load current sharing error is changed under different load current and input voltage. The load current sharing error almost equals 1 when the total load current is smaller than 40A at 400V input voltage, which means almost only one phase provides total load power. The load current sharing error is 63% the current sharing error is about 2% at 50A load current, 400V input voltage.

Fig. 12 shows load current sharing error σ of two phase LLC converter at worst case in common inductor two-phase LLC converter. The load current sharing error is changed under different load current and input voltage. The load current sharing error almost equals 1 when the total load current is smaller than 13A at 400V input voltage. However, this situation is not be cared because of light load. The current sharing performance is good under heavy load. The load current sharing error is 4 % the current sharing error is about 2% at 50A load current, 400V input voltage.

Fig. 13 shows load current sharing error σ of two phase LLC converter at worst case in common capacitor two-phase LLC converter. The load current sharing error is changed under different load current and input voltage. The load current sharing error almost equals 1 when the total load current is smaller than 8A at 400V input voltage. However, this situation is not be cared because of light load. The current sharing performance is good under heavy load. The load current sharing error is 2 %

at the current sharing error is about 2% at 50A load current, 400V input voltage.

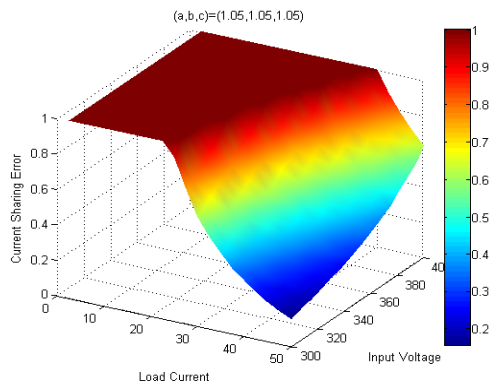


Fig. 11. Current sharing error in conventional two-phase LLC converter

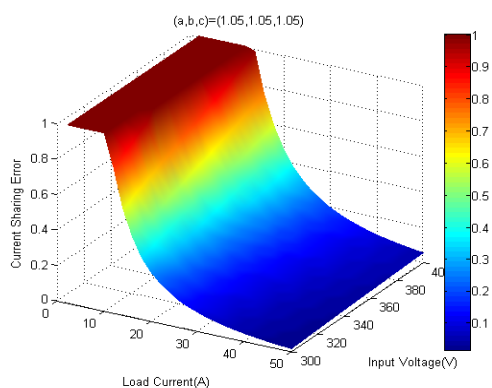


Fig. 12. Current sharing error in common inductor two-phase LLC converter

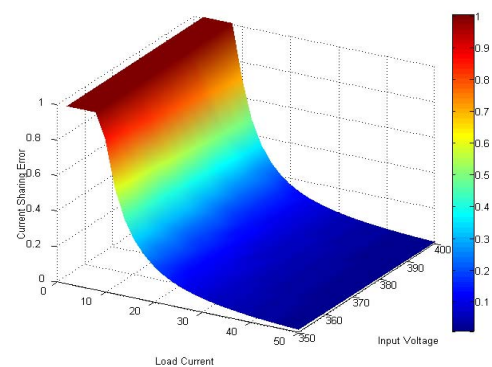


Fig. 13. Current sharing error in common capacitor two-phase LLC converter

III. EXPERIMENTAL RESULTS

To demonstrate the advantages of the proposed method, the 600W two-phase LLC converter prototype

is built and tested. The prototype parameters are listed in Tab. 2.

Tab.2 Prototype parameters

Switching frequency	180kHz-300kHz
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)	24.5μH(Phase1) 22.5μH(Phase2)
Leakage Inductance(Le)	6.5μH(Phase1) 6 μH(Phase2)
Magnetizing Inductance(Lm)	95μH(Phase1) 92μH(Phase2)

Fig. 14 and Fig. 15 show the experiment waveform of conventional two-phase LLC converter at 15A, 25A load current, respectively.

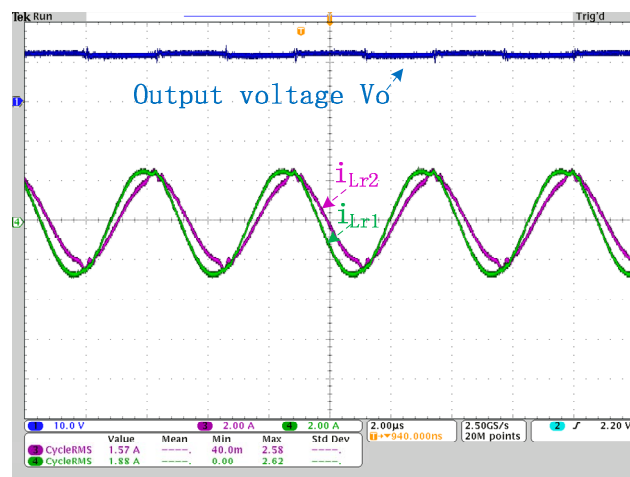


Fig. 14. Waveform of conventional two-phase LLC converter at 15A

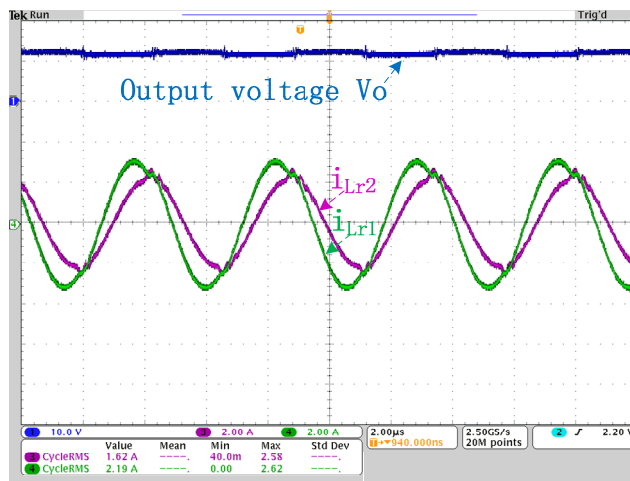


Fig. 15. Waveform of conventional two-phase LLC converter at 25A

Channel 1 is the output voltage. Channel 3, channel 4 are the resonant current of two phases. The resonant current $i_{Lr,2}$ is almost triangular waveform, which means

phase two almost doesn't provide the power for output load.

Fig. 16 and Fig. 17 show the experiment waveform of common inductor two-phase LLC at 25A, 50A load current, respectively. The resonant current i_{Lr1} and i_{Lr2} are almost same, which also means that the load current is shared by two phases. A very small angle difference between them is shown at different load.

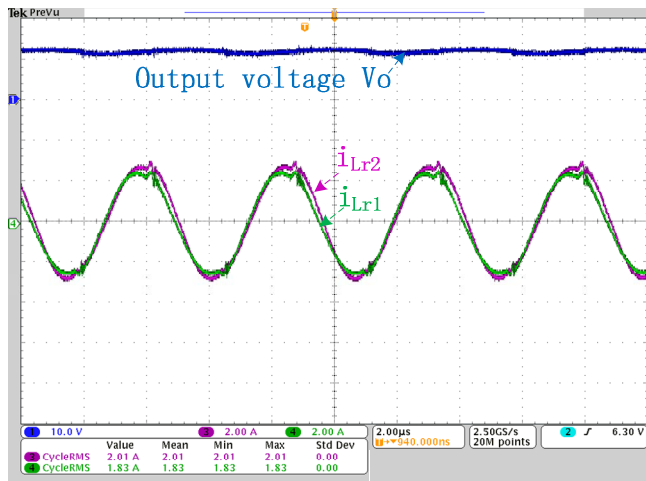


Fig. 16. Waveform of common inductor two-phase LLC at 25A

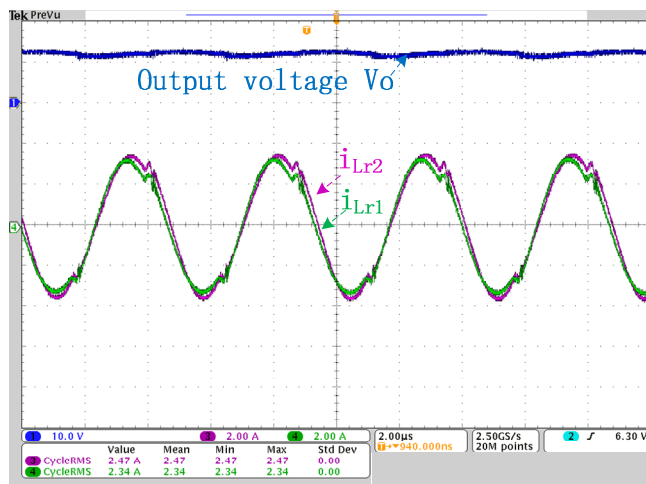


Fig. 17. Waveform of common inductor two-phase LLC at 50A

Fig. 18 and Fig. 19 show the experiment waveform of common capacitor two-phase LLC converter at 25A, 50A load current, respectively. The resonant current i_{Lr1} and i_{Lr2} are almost same, which also means that the load current is shared by two phases.

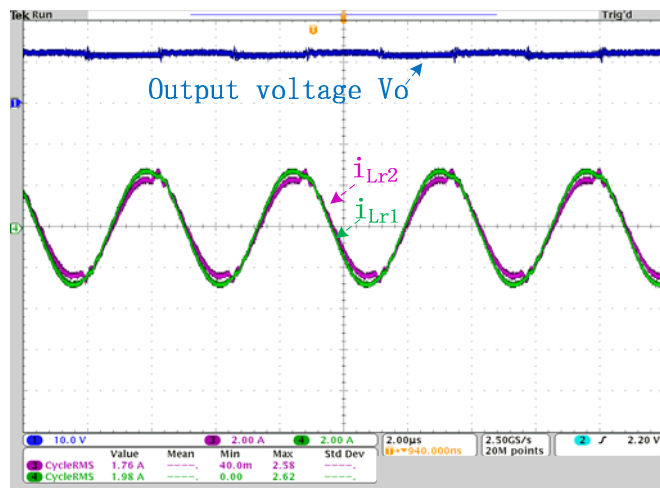


Fig. 18. Waveform of common capacitor two-phase LLC at 15A

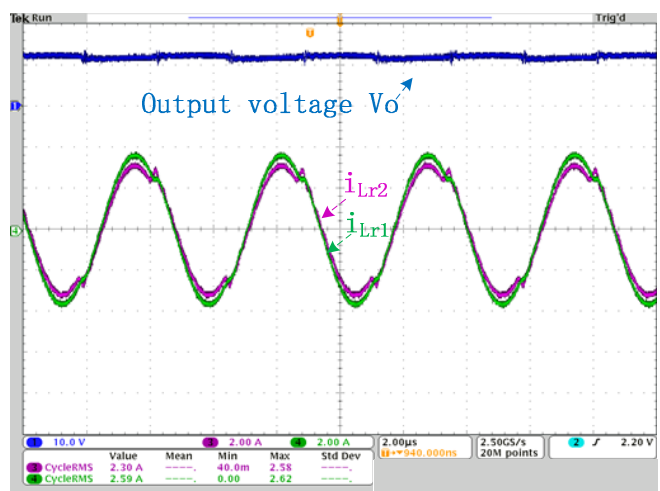


Fig. 19. Waveform of common capacitor two-phase LLC at 50A

The detailed resonant current error of conventional two-phase LLC converter is shown in Fig. 20.

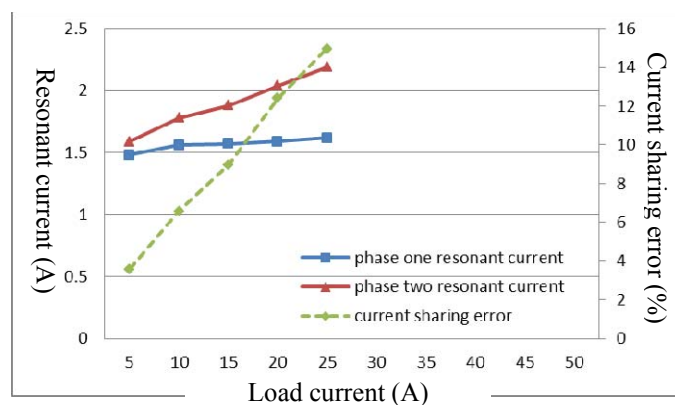


Fig. 20. Resonant current sharing error of conventional two-phase LLC converter

From phase two resonant current (blue line), the current of phase two is almost constant. Thus, almost only phase one provides total load power. The maximum total load current is 25A. Otherwise, phase one will work in overcurrent because of bad current sharing performance. The resonant current sharing error is about 15% at 25A load current.

Fig. 21 shows the resonant current error of common inductor two-phase LLC converter. The difference of two phase resonant current values is almost same. The current sharing performance will be better in heavy load than light load. The resonant current sharing error is about 2.8% at 50A total load current. The maximum resonant current sharing error is about 4.8% at 20A load current.

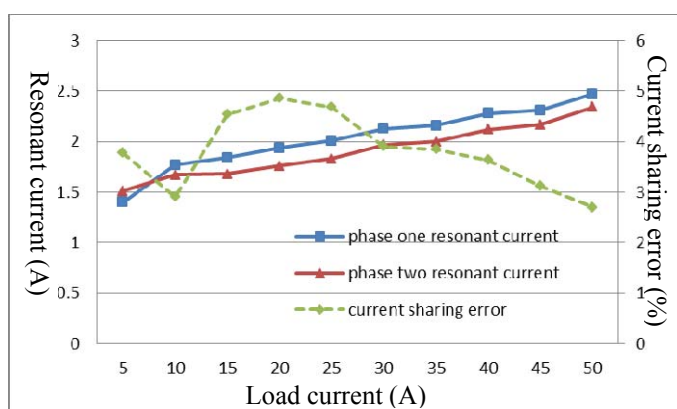


Fig. 21. Resonant current sharing error of common inductor two-phase LLC converter

Fig. 22 shows the resonant current error of common capacitor two-phase LLC converter. The difference of two phase resonant current values is almost same. The current sharing performance will be better in heavy load than light load. The resonant current sharing error is about 6% at 50A total load current. The maximum resonant current sharing error is about 6.5% at 40A load current.

From Fig. 20, Fig. 21 and Fig. 22, the resonant current sharing error is significantly reduced under common components two-phase LLC converter.

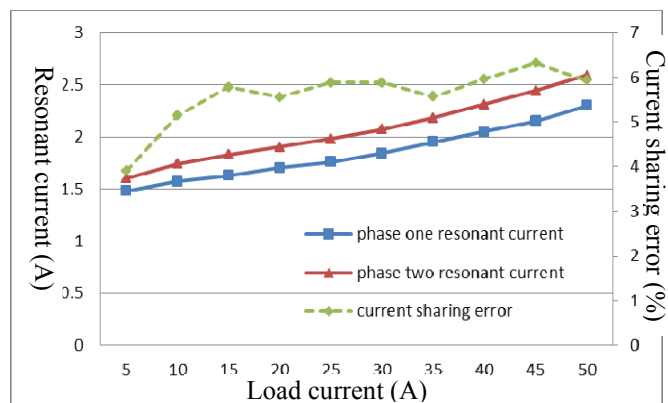


Fig. 22. Resonant current sharing error of common capacitor two-phase LLC converter

IV. CONCLUSION

The common component current sharing strategy for multi-phase LLC resonant converter has been proposed. The series resonant inductors or capacitors in each LLC converter are connected in parallel. No additional components are needed to achieve current sharing. Mathematical model is built based on FHA to analyze the current sharing characteristics of a two-phase LLC converter. The analysis results show that the circulated current is significantly reduced using the proposed method. A two-phase LLC converter prototype with 300W per phase is built using the common inductor or capacitor current sharing method. The experiment results show that the current sharing error has been reduced significantly and the maximum value is about 6%.

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