LLC Resonant Converter with Shared Power Switches and Dual Coupled Resonant Tanks to Achieve Automatic Current Sharing

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***Abstract*—In this paper, a novel LLC resonant converter with parallel input and parallel output circuit topology is proposed to achieve the good performance of reduced switch count and medium power compared with conventional parallel half-bridge resonant converter. The proposed LLC resonant converter has two resonant circuits, two resonant circuits use the same power switches to transmit power so that the switch counts are reduced compared with the conventional two-phase LLC resonant converter. The resonant inductors of each resonant circuit are shared to achieve automatic resonant current sharing performance and then to balance the current stress of passive elements, such as transformer, secondary-side rectifier even sough there are components tolerance of each resonant circuit. Mathematical model based on Fundamental Harmonic analysis (FHA) is built. The FHA analysis shows that there is same ZVS and ZCS performance with conventional LLC Converter. Two-phase conventional LLC converter and proposed LLC converter can be analyzed. A 600W experiment prototype is built to verify the feasibility and excellent current sharing performance has been demonstrated. The experimental results are shown that the current sharing error of two tanks is smaller 5% at worst case. The resonant current error of each tank is only 2.5% at total rated load power with the proposed LLC converter.**

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.

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. 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. The second method is DC voltage self-balanced method based on series input capacitors [27, 28, 32]. 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 be achieved under +10% tolerance of resonant inductor, which is not very good. The third method is using three-phase three-wire structure for three-phase LLC resonant converter based on 120° phase-shift, which has good load current sharing near resonant frequency [30, 31]. The load current will not share very well when the number of parallel modules is more than three. Therefore, from the above review, it is noted that the existing technologies cannot

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provide cost effective, flexible current sharing performance for multi-phase LLC resonant converters.

The authors have proposed passive impedance matching technology to achieve automatic current sharing [33, 34]. Two realization methods have been introduced. One is common inductor[35], the other is common capacitor[36].

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 automatic 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 analysis of conventional multi-phase LLC resonant converter is given in Section II. Section III discusses current sharing analysis of the proposed common inductor multi-phase 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 both the conventional method and the proposed method. And the paper is concluded in Section VI.

II. WORING PRINCIPLE OF THE PROPOSED LLC RESONANT CONVERTER

In this section, a new LLC resonant converter with dual resonant tanks is proposed. It has two shared power switches and dual resonant tanks. Part A introduces the proposed converter and several terms' definitions. Section B shows the operation mode of the proposed LLC resonant converter.

A. Proposed LLC Resonant Converter with Dual Coupled Resonant Tanks

The proposed LLC resonant converter with dual coupled resonant tanks is shown in 0. It has two power switches Q1 and Q2 and two resonant tanks with one common inductor L_s. The term i_{Ls} is the common inductor current. The #1 resonant tank consists of the common inductor L_s, resonant capacitor C_{r1}, and magnetizing inductor L_{m1}. And the #2 resonant tank is composed of common inductor L_s, resonant capacitor C_{r2} and magnetizing inductor L_{m2}.

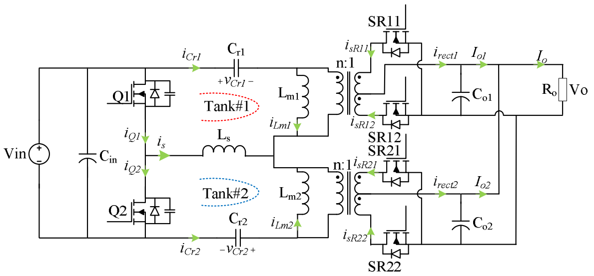


Fig.1 LLC resonant converter with dual coupled resonant tanks

Two high-frequency transformers are used to transmit power from primary side to secondary side. n in 0 is transformer turn ratio. To achieve high efficiency for low output voltage, high current applications, the Synchronous Rectifier (SR) is used to replace diode rectifiers. SR11 and SR12 work to transmit power for the first resonant tank. SR21 and SR22 flow the secondary current to transmit the second resonant tank energy.

As shown in 0, i_{Q1}, i_{Q2}, i_{SR11}, i_{SR12}, i_{SR21} and i_{SR22} are the currents respectively in Q1, Q2, SR11, SR12, SR21 and SR22; the currents i_{Cr1} and i_{Cr2}, i_{Lm1} and i_{Lm2}, i_{rect1} and i_{rect2}, i_{o1} and i_{o2}, $C_{o1,}$ and C_{o2} are the resonant current ,magnetizing current , rectifier current, output current and output capacitor of two resonant tanks, respectively.

B. Working Principle of the Proposed LLC Resonant Converter

Some assumptions are made before analyzing the working principle of the proposed LLC resonant converter.

1. Switches Q1 and Q2 have the same parasitic capacitance.
2. Resonant capacitance $C_{r1}=C_{r2}=C_r$.
3. Magnetizing inductance $L_{m1}=L_{m2}=L_m$.
4. Transformers T1 and T2 are identical and turn ratios are both n.

Based on the assumptions mentioned above, the equivalent resonant inductance of each tank is twice of common inductance. Thus, the two resonant tanks have the same resonant frequency as shown in (1).

$$f_r = \frac{1}{2\pi\sqrt{2L_sC_r}} \tag{1}$$

The proposed LLC resonant converter has eight operation modes during one switching period. The key waveforms of the proposed LLC resonant converter are shown in 0. The detailed eight operation modes of the proposed LLC resonant converter are expressed in 0.

Mode 1 [$t_0 \rightarrow t_1$]: Q1 is on and Q2 is off. This mode starts at t_0 when Q1 turns on. Q2 keeps off. The drain voltage of Q2 equals to Vin. The body diode of switch Q1 is on as the common inductor current i_{Ls} is negative at t_0. So the switch Q1 achieves ZVS performance. The SR12 and SR21 are on to flow rectifier current. The voltages of magnetizing inductors are clamped by output voltage. Thus, the currents i_{Lm1} and i_{Lm2} in the magnetizing inductors decrease. The power is transferred from input voltage Vin to output load R_0.

Mode 2 [$t_1 \rightarrow t_2$]: Q1 is on and Q2 is off. Mode 2 starts at t_1 when i_{Ls}= 0, i_{Cr1}= 0 and i_{Cr2}= 0. The drain voltage of Q2 equals to Vin. The current in the common inductor is positive after t_1. The SR12 and SR21 keep on. The voltages of magnetizing inductors are clamped by output voltage. Thus, the currents i_{Lm1} and i_{Lm2} in the magnetizing inductors decrease. This mode ends when $i_{Lm1}= i_{Cr1}$, and $i_{Lm1}= i_{Cr1}$.

Mode 3 [$t_2 \rightarrow t_3$]: Q1 is on and Q2 is off. i_{SR12} and i_{SR21} become zero and $i_{Lm1}= i_{Cr1}$, $i_{Lm1}= i_{Cr1}$. There is no power transmitted from the primary side to secondary side of transformer. The voltages of magnetizing inductors are no longer clamped by output voltage. The resonant current flows into the magnetizing inductor.

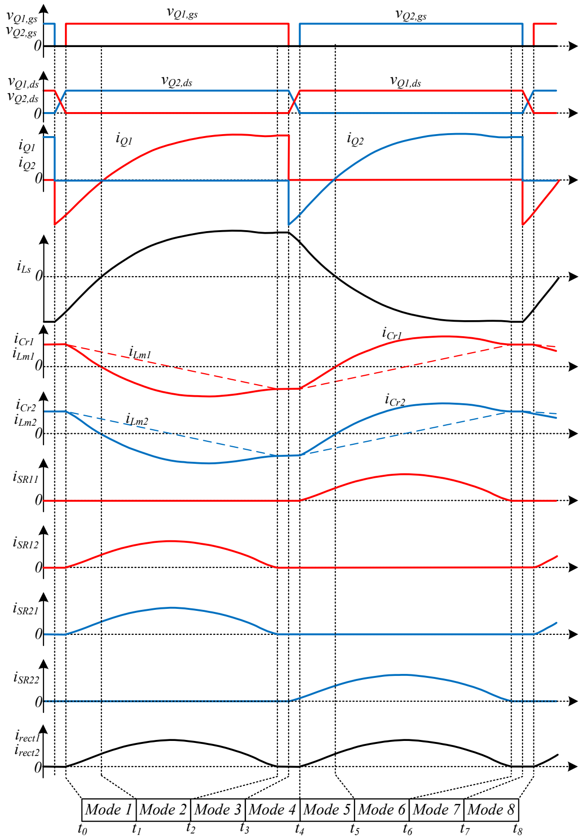
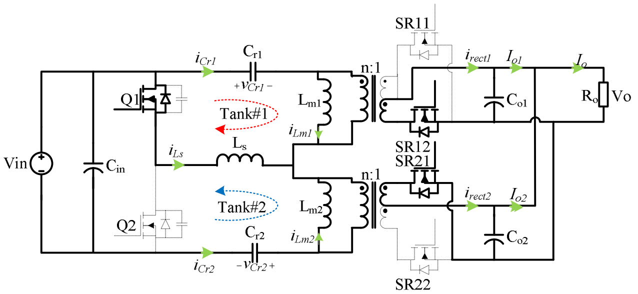


Fig.2 Key waveforms of the proposed LLC resonant converter

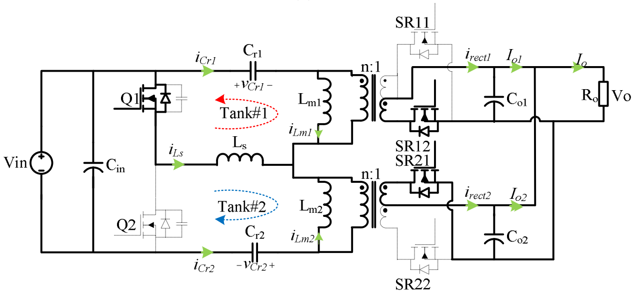
Mode 4 [$t_3 \rightarrow t_4$]: This is the dead time during which both Q1 and Q2 are off. At $t= t_3$, i_{Ls} is larger than zero. At the same time, the parasitic capacitor of Q1 is charged and parasitic capacitor of Q2 is discharged. The body diode of Q2 is on when the drain-source voltage of Q2 decreases to zero.

Mode 5 [$t_4 \rightarrow t_5$]: Q1 is off and Q2 is on. At $t= t_4$, i_{Ls} is delivered from body diode of Q2 so that no significant energy is lost during the turn on transient. ZVS performance is achieved for Q2. SR11 and SR22 transfer the energy from power source Vin to output load R_0. The voltages of magnetizing inductors are clamped by output voltage. This mode ends when $i_{Ls}= 0$.

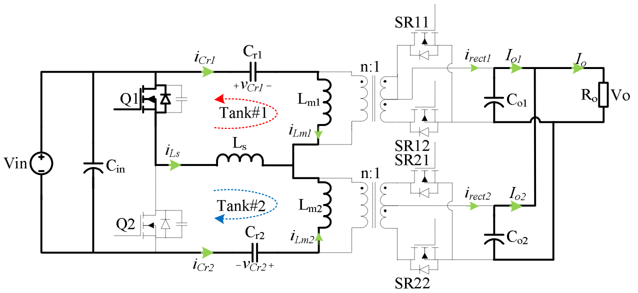
Mode 6 [$t_5 \rightarrow t_6$]: Q1 is off and Q2 is on. i_{Ls} becomes positive at $t= t_5$. Mode 6 starts at t_5 when $i_{Ls}= 0$, $i_{Cr1}= 0$ and $i_{Cr2}= 0$. The drain voltage of Q1 equals to Vin. The current



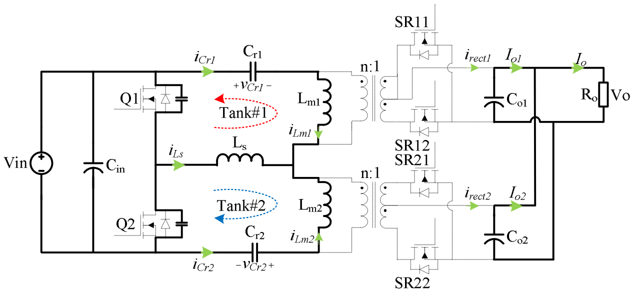
(a) Mode 1



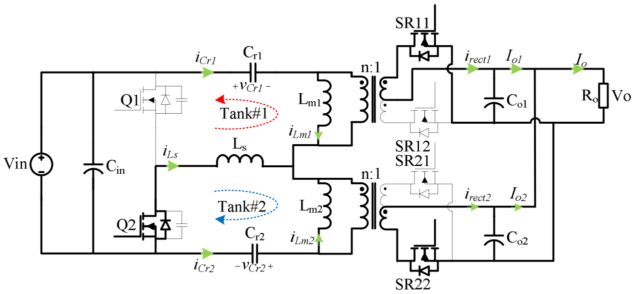
(b) Mode 2



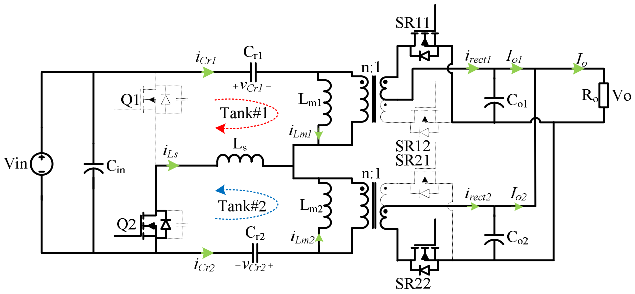
(c) Mode 3



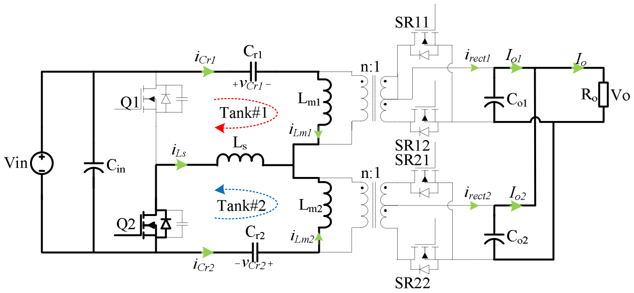
(d) Mode 4



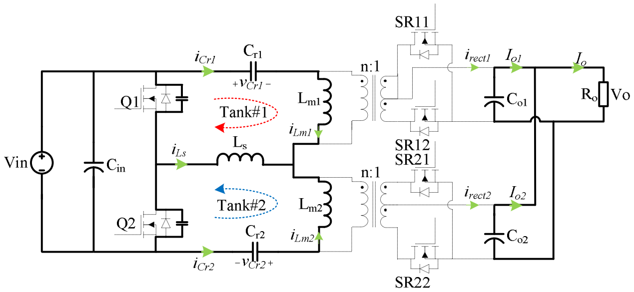
(e) Mode 5



(f) Mode 6



(g) Mode 7



(h) Mode 8

Fig.3 Operation modes of the porosed LLC resonant converter with dual coupled resonant tanks

of common inductor is negative after t_5. The SR11 and SR22 keep on. The voltages of magnetizing inductors are clamped by output voltage. Thus, the currents i_{Lm1} and i_{Lm2} in the magnetizing inductors increase. This mode ends when $i_{Lm1}= i_{Cr1}$ and $i_{Lm1}= i_{Cr1}$ at $t= t_6$.

Mode 7 [t_6→t_7]: Q1 is off and Q2 is on. i_{SR12} and i_{SR21} become zero. $i_{Lm1}= i_{Cr1}$ and $i_{Lm1}= i_{Cr1}$. There is no power transmitted from the primary side to secondary side of transformer. The voltages of magnetizing inductors are no longer clamped by output voltage. The resonant current flows into the magnetizing inductor.

Mode 8 [t_7→t_8]: This is the dead time during which both Q1 and Q2 are off. At $t= t_7$, i_{Ls} is smaller than zero. At the same time, the parasitic capacitor of Q1 is discharged and parasitic capacitor of Q2 is charged. The body diode of Q1 is on when the drain-source voltage of Q1 decreases to zero.

C. Dual LLC Resonant Circuits Analysis

There are two resonant tanks in which the inductor Ls is shared by them. The input voltage of the resonant tank is of square waveform. According to Pulse Frequency Modulation (PFM), the duty cycles of Q1 and Q2 both equal to 0.5. The equivalent input voltage of each phase can be calculated according to Fourier series analysis.

$$\begin{cases} v_{in1} = \dfrac{V_{in}}{2} + \displaystyle\sum_{l=1,3,5\ldots}^{\infty} \dfrac{2V_{in}}{j\pi} \sin(2\pi l f_s t) = v_{dc} + v_{ac} \\ v_{in2} = \dfrac{V_{in}}{2} - \displaystyle\sum_{l=1,3,5\ldots}^{\infty} \dfrac{2V_{in}}{j\pi} \sin(2\pi l f_s t) = v_{dc} - v_{ac} \end{cases} \tag{2}$$

Where f_s is the switching frequency, the basic equivalent circuit is shown in 0

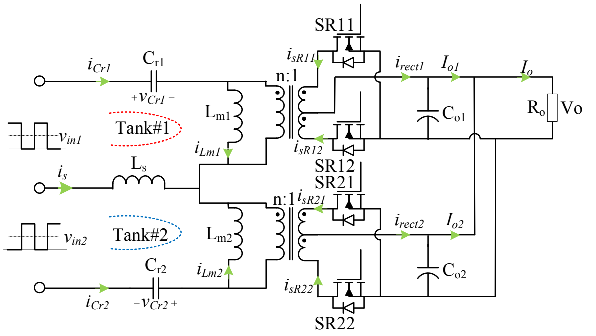


Fig.4 Equivalent circuit of dual resonant tanks

It can be observed from (2), there are two parts of equivalent input voltage of each tank. The first one is DC bias v_{dc}, and the second part is AC value v_{ac}.

Considering the DC value, the impedance of inductor is zero, which means the primary side is shorted. The equivalent circuit under DC bias is shown in 0

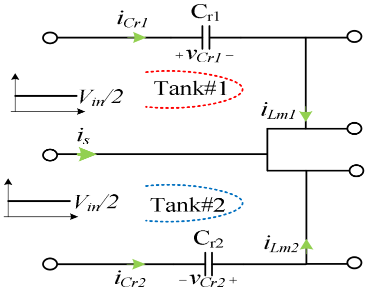


Fig.5 Equivalent circuit of dual resonant tanks under DC voltage source

Thus, the DC voltage of each resonant capacitor can be calculated in (3).

$$\begin{cases} V_{Cr1\_dc} = \dfrac{V_{in}}{2} \\ V_{Cr2\_dc} = \dfrac{V_{in}}{2} \end{cases} \tag{3}$$

The equivalent circuit of dual resonant tanks under AC voltage source is shown in 0.

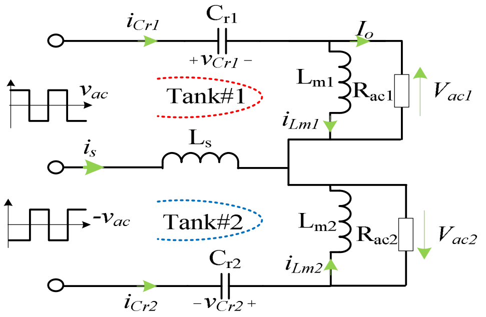


Fig.6 Equivalent circuit of dual resonant tanks under AC voltage source

According to the assumptions mentioned above, there are the same resonant components, such as resonant capacitance and magnetizing inductance. Thus, the load current is shared. The equivalent ac resistance of each tank is expressed as (4).

$$\begin{cases} R_{ac1} = R_{ac2} = 2R_{ac} \\ R_{ac} = \dfrac{8n^2}{\pi^2} R_o \end{cases} \quad (4)$$

The resonant tank parameters are calculated in (5).

$$\begin{cases} C_{r1} = C_{r2} = C_r \\ L_{m1} = L_{m2} = L_m \end{cases} \quad (5)$$

The voltage gain based on First Harmonic Analysis (FHA) is shown in (6).

$$G_{DC} = \frac{nV_o}{V_{in}/2} = \frac{1}{\sqrt{[\frac{1}{m}(\frac{f_r}{f_s})^2 - \frac{(1+m)}{m}]^2 + Q^2(\frac{f_r}{f_s} - \frac{f_s}{f_r})^2}} \quad (6)$$

The existing k-q design method is used for the proposed LLC resonant converter[37]. A set of related parameters based on load power 300W of each resonant tank is designed and shown in **Error! Reference source not found.**

TABLE I. VALUES OF RELATED PARAMETERS

common inductor *Ls*	14.5 µH
Resonant capacitor C_r	12 nF
Magnetizing inductor L_m	95 µH
Switching frequency fs	160kHZ--250kHZ
Transformer ratio *n*	20
Resonant frequency f_r	270 kHz
Output voltage V_o	12V (rated voltage)
Total Output load R_o	Rate load 0.24Ω

III. CURRENT SHARING ANALYSIS UNDER COMPONENTS TOLERANCE

0shows the load current sharing error changing with switching frequency under four different tolerances. (*b*, *c*) means that $C_{r2}= b\ C_{r1}$ and $L_{m2}=c\ L_{m1}$. Case 1 is (*b*, *c*)=(1.05, 1), case 1 is (*b*, *c*)=(1, 1.05), case 1 is (*b*, *c*)=(1.05, 1.05) and case 5 is (*b*, *c*)=(1.05, 0.95).

The maximum value of load current sharing error is 7.5% when the switching frequency is between 150kHZ and 250kHZ. Good current sharing performance of each resonant tank can be achieved using proposed LLC resonant converter.

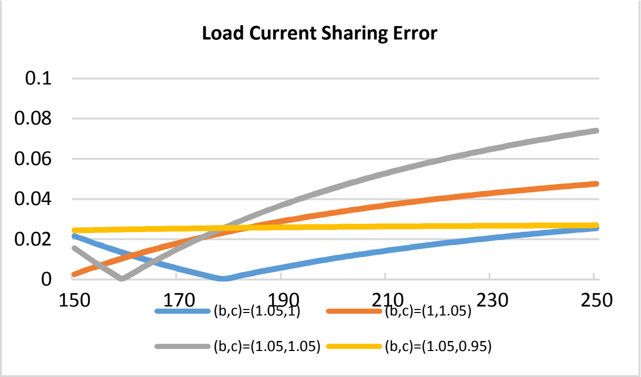
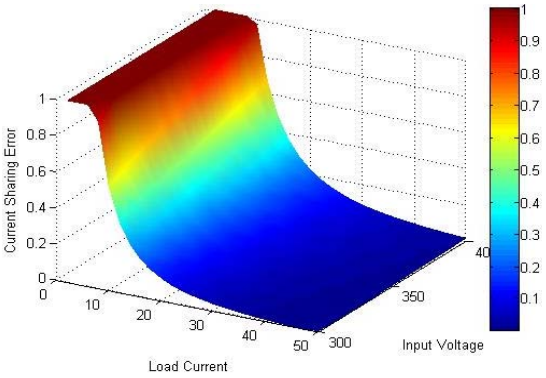


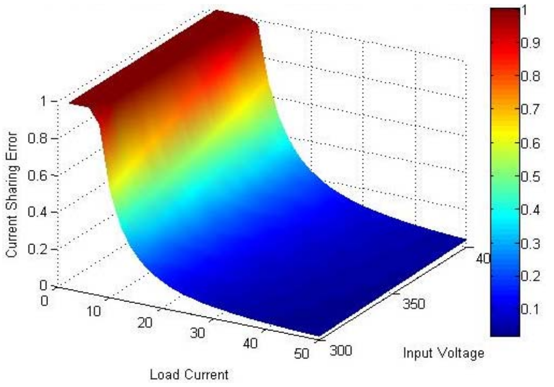
Fig.7 Load current sharing error of proposed LLC resonant converter V.S. switching frequency

To demonstrate the load current sharing performance of each tank of the proposed LLC converter in different input and load conditions, the load current sharing error σ_{load} is calculated with FHA method based on the set of parameters shown in 0. The parameters are shown in 0is assigned to tank #1 as the reference, while parameters of tank #2 will have ±5% tolerances.

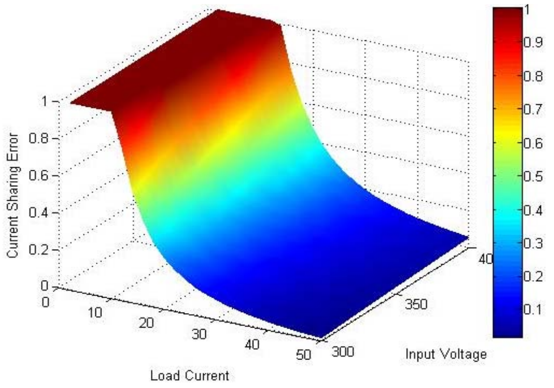
0(a) shows the load current sharing error σ_{load} with +5% tolerance on L_r only (C_{r2}= 1.05 C_{r1}, L_{m2}= L_{m1}). The load current sharing error equals zero at any input voltage and load. The maximum current sharing error is 2% @400V, 50A.



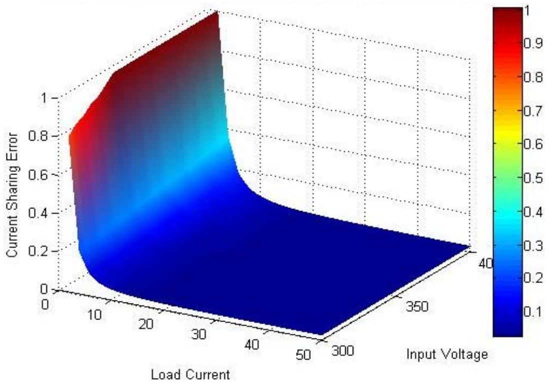
(a) C_{r2}= 1.05 C_{r1}, L_{m2}= L_{m1}



(b) $C_{r2}= C_{r1}$, $L_{m2}= 1.05\ L_{m1}$



(c), $C_{r2}= 1.05C_{r1}$, $L_{m2}= 1.05\ L_{m1}$



(d) $C_{r2}= 0.95C_{r1}$, $L_{m2}= 1.05\ L_{m1}$

Fig.8 Load current sharing error of proposed LLC converter under different input voltage and different load

0(b) shows the load current error σ_{load} with +5% tolerance on C_r only ($C_{r2}= C_{r1}$, $L_{m2}= 1.05\ L_{m1}$). The current sharing error σ_{load} decreases with load increasing and almost keeps constant with input voltage changing between 300V and 400V. The maximum current sharing error is 3% @400V, 50A.

0(c) shows the load current sharing error σ_{load} with +5% tolerance on L_r only ($C_{r2}= 1.05\ C_{r1}$, $L_{m2}= 1.05\ L_{m1}$). The load current sharing error equals zero at any input voltage and load. The maximum current sharing error is 4% @400V, 50A.

0(d) shows the load current error σ_{load} with +5% tolerance on C_r only ($C_{r2}= 0.95\ C_{r1}$, $L_{m2}= 1.05\ L_{m1}$). The current sharing error σ_{load} decreases with load increasing and almost keeps constant with input voltage changing between 300V and 400V. The maximum current sharing error is 2% @400V, 50A.

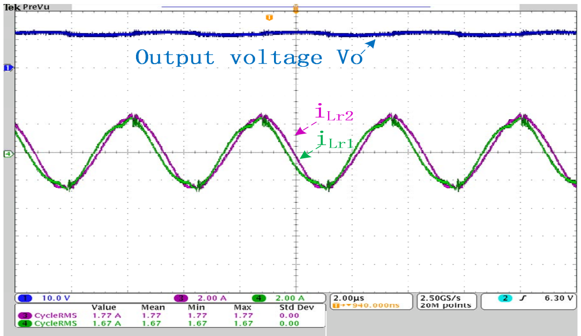
IV. EXPERIMENT RESULTS

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 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 II. 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.

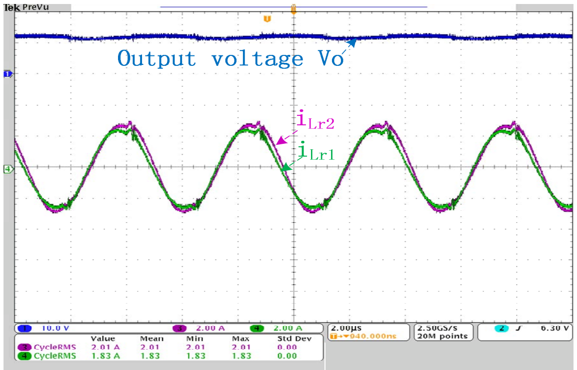
TABLE II. PROTOTYPE PARAMETERS

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(C_r)	12nF 13nF
Resonant Inductance(Ls)	12μH
Leakage Inductance(L_e)	6μH (Tank #1); 6.5μH (Tank #2)
Magnetizing Inductance(L_m)	95μH (Tank #1); 92μH (Tank #2)
Output Capacitance	1790μF)

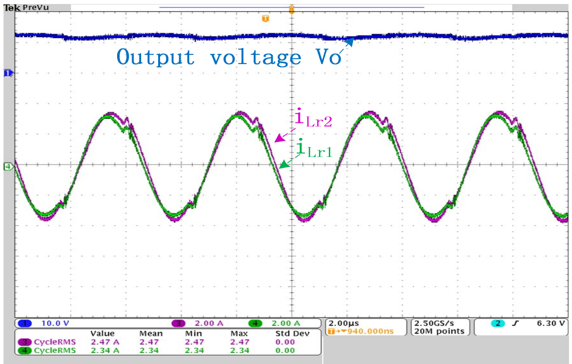
0shows the experiment waveform of proposed LLC converter. The resonant current i_{Lr1} and i_{Lr2} is almost same at10A, 25A and 50A load. A very small angle difference between each tank is shown at different load.



(a) Steady state at 10A 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.

Fig.9 Experimental waveform of proposed LLC converter

To show the current sharing performance of each tank, the resonant current and resonant current sharing error is shown in 0The maximum resonant current sharing error is 4.8% of the proposed current sharing method. The resonant current sharing error can be significantly reduced using the proposed method. Good current sharing performance can be achieved based on proposed LLC converter with two tanks.

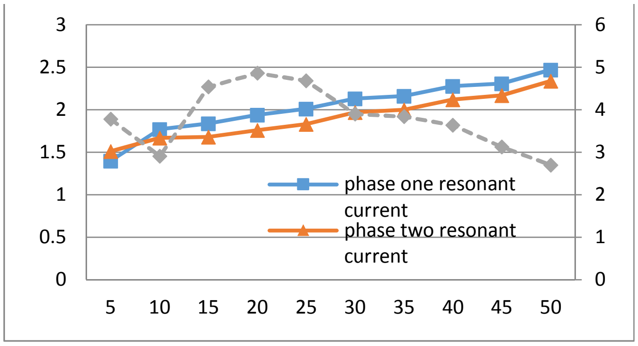


Fig.10 Resonant current error of each tank of proposed LLC converter

V. CONCLUSION

A novel LLC resonant converter with parallel input and parallel output circuit topology is proposed to achieve the good performance of reduced switch count and medium power compared with conventional parallel half-bridge resonant converter. The FHA analysis shows that there is same ZVS and ZCS performance with conventional LLC Converter. The analysis results, simulation results and experimental results are shown that the current sharing error of two tanks is smaller 5% at worst case. The resonant current error of each tank is only 2.5% at total rated load power with the proposed LLC converter.

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