A General Multi-phase Coupled-Resonant-Tank Resonant Converter

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***Abstract*— A general multi-phase Coupled-Resonant-Tank (CRT) converter is proposed to achieve automatic current sharing. There are Y-style or Δ-style structures. The series inductor (or capacitor) of each phase are connected by a Coupled impedance which is inductor, capacitor or short-circuit. For easy understanding, a two-phase CRT LLC resonant converter is made as an example to analyze the current sharing performance. There are three types including eight topologies derived from CRT LLC converter. The coupled impedance of each phase can be instead of open-circuit, short-circuit and other inductor or capacitor. The Fundamental Harmonic Analysis (FHA) is utility to estimate the current sharing performance. A 600W, 12V two-phase LLC converter with short-circuit coupled impedance prototype is built. The prototype verified the feasibility and demonstrated advantages of the proposed concept.**

Keywords— Resonant Converter; Multi-phase; Coupled Resonant Tank; Current Sharing;

I. INTRODUCTION

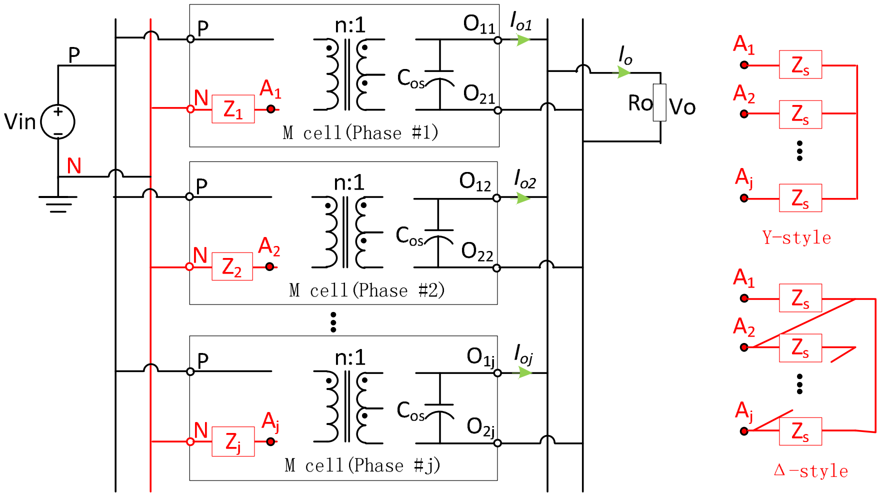
LLC resonant converter has been widely used due to its high efficiency achieved by zero voltage switching (ZVS) on the primary-side MOSFETs and zero current switching (ZCS) on secondary-side diodes [1]. For high power applications, current stress of power devices increase with the power rating, so multiphase parallel technique is a good choice to solve this problem [2, 3]. But, components tolerances may cause each LLC unit to have different resonant frequency. This will lead to the deviation of current stress in each LLC unit [4, 5]. Small component tolerances will cause large current imbalance. Thus, the key problem is load sharing.

There are Decoupled-Resonant-Tank (DRT) [6-13] and Coupled-Resonant-Tank (CRT) technologies [14-21] to achieve current sharing for multiphase LLC converter. Three methods has been reported in multi-phase DRT resonant converter, one is the active method in which passive components tolerance can be compensated by adjusting the variable capacitor [6-8]or inductor [9] in an additional circuit. This method has prefect load sharing performance, but it has large cost, complex control and non-excellent dynamic performance because of sensing the circulating current and controlling the additional switches. The second method is self-balanced DC voltage based on series bus capacitors [10, 11]. Take two-phase LLC converter as an example, the mid-point voltage is changed according to two unit's power. Thus, the system has low cost and good load current sharing performance. However, it has poor reliability because the DC gain is halved when one unit is broken. The third method is built in three-phase three-wire structure for three-phase LLCs, which has good load current sharing near resonant frequency as all of three-phase resonant current is zero [12, 13]. In a nutshell, existing studies have limitation on cost, complex control, modularization and dynamic performance. The authors has developed passive impedance matching concept for multi-phase resonant converter [14, 21]. A passive element, such as an inductor [16-18]or a capacitor [19, 20], are connected together to get common branch (short-circuiting impedance). A set of virtual resistors (positive and negative) are yielded through the common branch inductor or capacitor. In this paper, the passive impedance matching concept is extended into three-dimension (3D) operation. The Y-type and Δ-type constructs are introduced. The coupled impedance is introduced, and is not only short-circuiting impedance but also other inductance or capacitance. A 600W, 12V two-phase LLC converter prototype based on short-circuiting impedance is built to verify the feasibility and demonstrate the advantages.

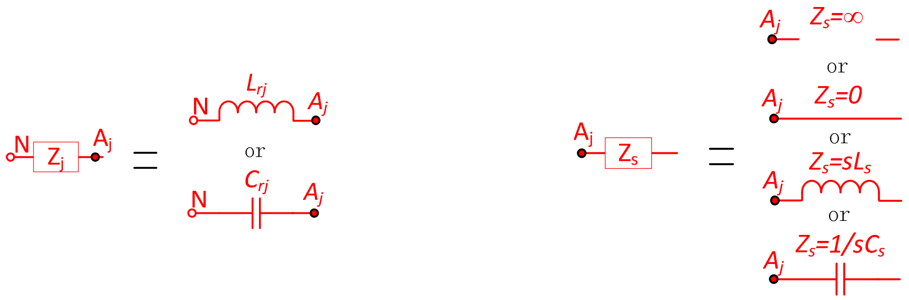
II. MULTI-PHASE CRT RESONANT CONVERTER

A. Coupled-Resonant-Tank Concept

Fig.1 shows the multi-phase CRT resonant converter. In Fig.1 (a), the series impedance Z1, Z2…Zj of each phase are connected by the coupled impedance Zs. There are Y-style and Δ-style structure. The series impedance Zj, j=1, 2… is a series inductor or series capacitor as shown in Fig.1 (b). The coupled impedance Zs is constructing of four different impedances in Fig.1 (c). Once coupled impedance is open-circuit impedance Zs=∞, there are several impendent units to parallel together. The common inductor or common capacitor concepts has been introduced if the coupled impedance is short-circuit impedance Zs =0. There are another two possible that coupled impedance is extra inductance Zs=sLs or extra capacitance Zs=1/sCs.



(a) General Structure



(b) Unit of impedance Zj

(c) Unit of impedance Zs

Fig.1 Multi-phase CRT resonant converter

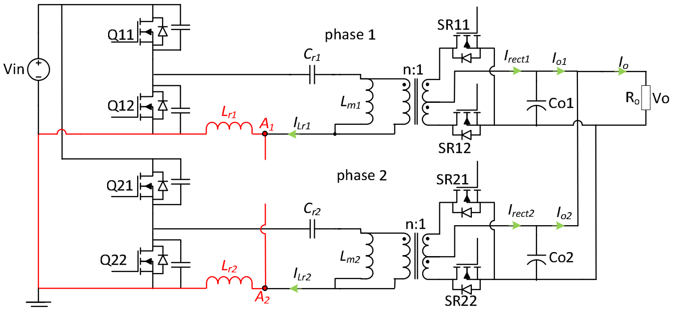
B. *Two-phase CRT LLC Resonant Converter*

To better understanding, two-phase CRT LLC resonant converter is made as an example to analyze the current sharing performance. Fig.2 shows total eight two-phase CRT LLC resonant converters. Fig.2 (a) and Fig.2 (b) show the two-phase conventional LLC resonant converter which is as special example of CRT LLC resonant converter under coupled impedance Zs=∞. Fig.2 (c) and Fig.2 (d) show the two-phase common inductor or capacitor LLC resonant converters under coupled impedance Zs=0, these are called Type #1 in this paper. In Type #2 as shown in Fig.2 (e) and Fig.2 (f), the series impedance Zj and coupled impedance Zs are both chosen inductors and capacitors. Two inductors work in Fig.2 (e) and two capacitors work in Fig.2 (f). Fig.2 (g) and Fig.2 (h) show the type #2 CRT resonant converters. The series impedance Zj is inductance and the coupled impedance Zs is capacitance as shown in Fig.2 (g). The series impedance Zj is capacitance and the coupled impedance Zs is inductance in Fig.2 (h).

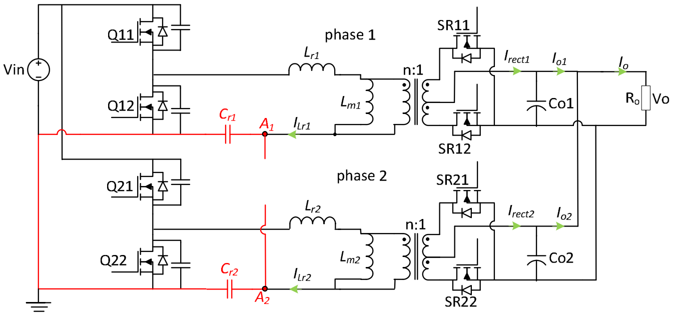
The component tolerance is defined as (1). a, b and c is tolerance index of series inductor Lr, series capacitor Cr, and, magnetizing inductor. d describes index of the coupled inductor, e describes the index of coupled capacitor.

$$\begin{cases} L_{r1} = L_r, \quad L_{r2} = aL_r \\ C_{r1} = C_r, \quad C_{r2} = bC_r \\ L_{m1} = L_m, L_{m2} = cL_m \\ L_s = dL_r, C_s = eC_r \\ Z_{L_r} = sL_r, Z_{C_r} = 1/sC_r, Z_{Lm} = sL_m \end{cases} \tag{1}$$

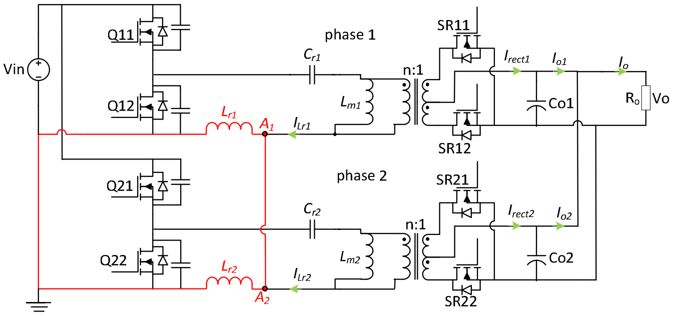
Fig.3 shows the relationship of each type two-phase CRT resonant converter. The coupled impedance Zs=∞ (Fig.2 (a) and Fig.2 (b)) is marked as four points A, B, C, D in real axis and imaginary axis. Point E marks that the coupled impedance Zs=0 (Fig.2 (c) and Fig.2 (d)). Fig.2 (a) (or Fig.2 (b)) is a special example of Fig.2 (e) (or Fig.2 (h)) under index d=0 (or Fig.2 (f) and Fig.2 (g) under e=∞).



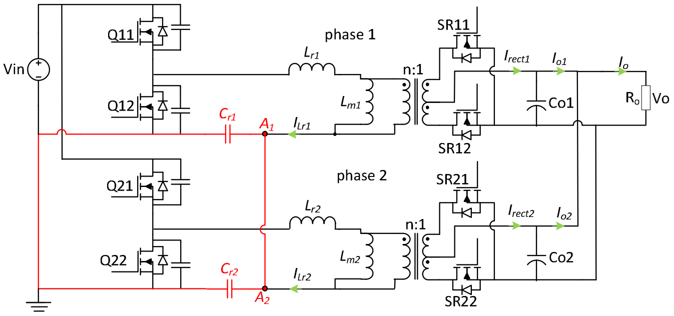
(a) Two-phase conventional LLC resonant converter



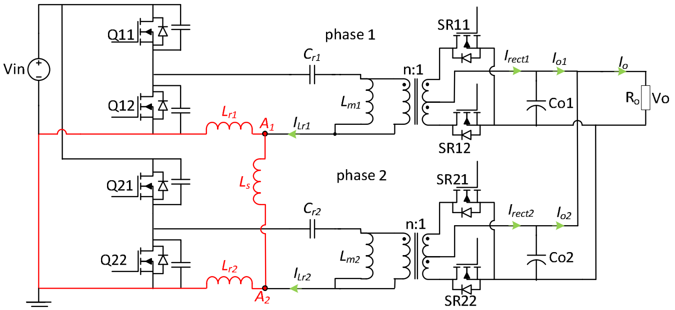
(b) Two-phase conventional LLC resonant converter



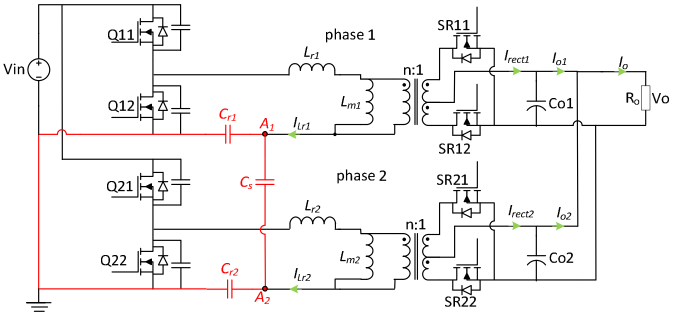
(c) Type#1 based on common inductor



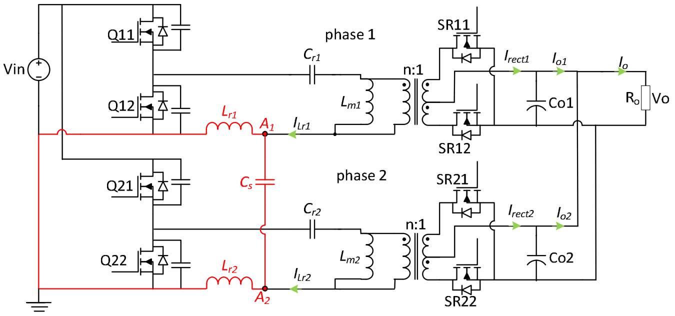
(d) Type#1 based on common capacitor



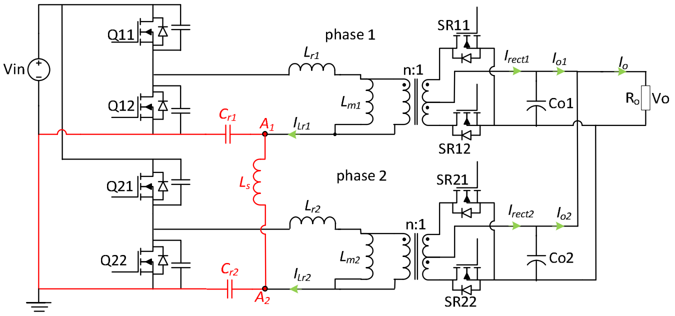
(e) Type#2 based on common inductor



(f) Type#2 based on common capacitor



(g) Type#3 based on common inductor



(h) Type#3 based on common capacitor

Fig.2 Two-phase CRT LLC resonant converter

Similarly, Fig.2 (a) is special example of Fig.2 (e) and Fig.2 (h) under index $d=\infty$, Fig.2 (f) and Fig.2 (g) under $e=0$.

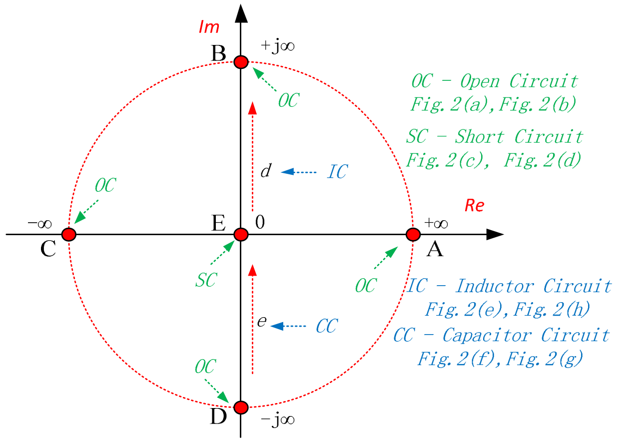


Fig.3 basic circuit about the common branch

III. CURRENT SHARING ANALYSIS OF TWO-PHASE CRT LLC RESOANT CONVERTER

FHA is utility to estimate the current sharing performance. A decoupled method has been reported in reference [15], which can decouple the coupled resonant tank to decoupled resonant tank based on virtual-open and virtual-short. The total equivalent circuits of two-phase CRT LLC resonant converter are shown in Fig.4.

The output resistor R is divided into R_1 and R_2. The values of R1 and R2 are decided by the steady-state load current, considering the output DC voltage Vo is well regulated and same for the two phases. The impedance error k is defined in Eq. (1).

$$R_1=\frac{1}{k}R, R_2=\frac{1}{(1-k)}R, k\in[0,1] \tag{2}$$

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

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

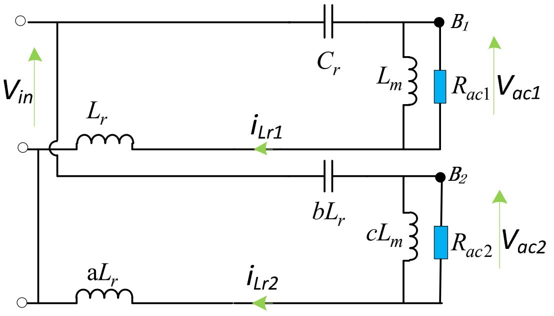
The impedance error k is effective when k is between 0 and 1. Otherwise only one unit will provide the load power.

The load current sharing error σ is defined in (4),

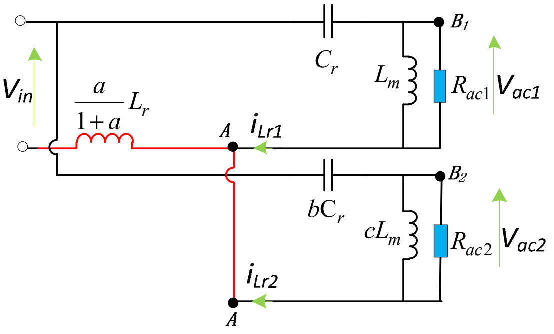
$$\sigma = abs(\frac{I_{01}-I_{02}}{I_{01}+I_{02}}) = abs(1-2k), k\in[0,1] \tag{4}$$

The resonant current sharing error is defined in (5)

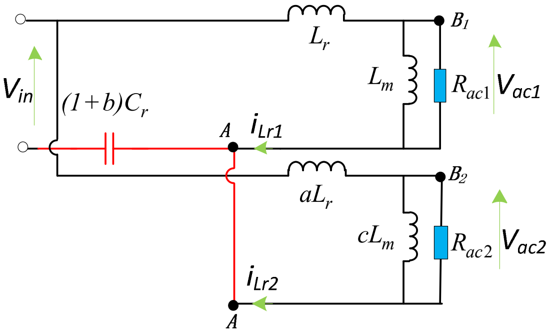
$$\sigma_{resonant}=\frac{abs(rms(i_{Lr1})-rms(i_{Lr2}))}{abs(rms(i_{Lr1})+rms(i_{Lr2}))} \tag{5}$$



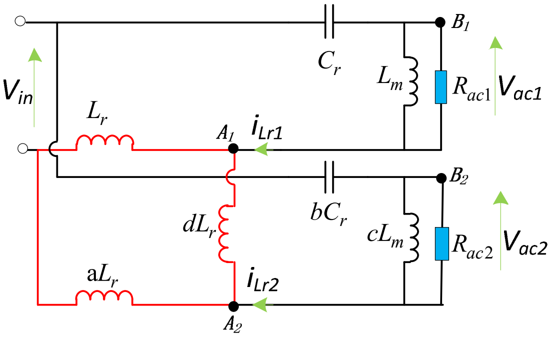
(a) Fig.2 (a) and Fig.2 (b)



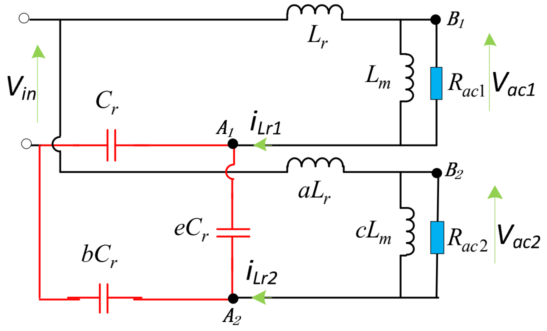
(b) Fig.2 (c)



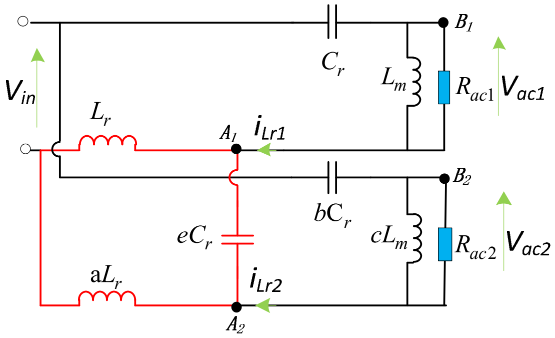
(c) Fig.2 (d)



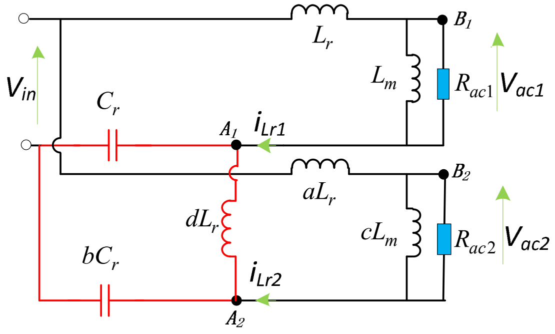
(d) Fig.2 (e)



(e) Fig.2 (f)



(f) Fig.2 (g)



(g) Fig.2 (h)

Fig.4 Total equivalent circuits of Two-phase CRT LLC resonant converter

IV. PSIM SIMULATION RESULSTS

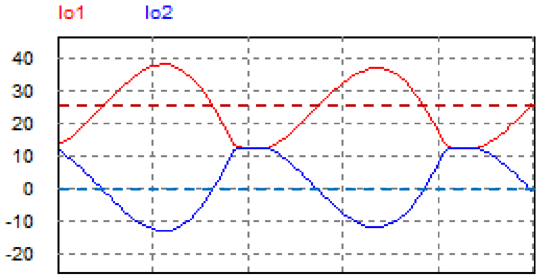
In order to verify and compare the current sharing performance further, in this section, PSIM simulation results of both conventional two-phase LLC converter and the proposed common inductor LLC converter will be provided.

Tab.1 shows the basic parameter of phase 1 and phase 2. The coefficient a, b, c, d and is 1.05, 1.05, 1.05, 2 and 1, respectively.

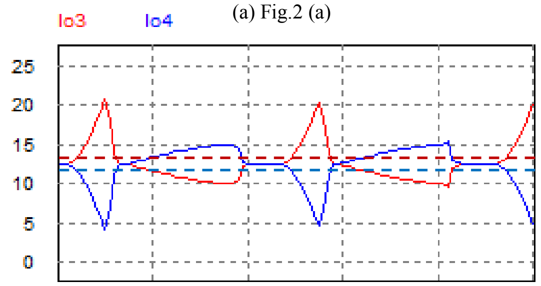
Tab.1 Simulation Parameter

Input Voltage	400V
Output Voltage	12V
Rated Output Power	600W
Transformer Ratio n	20:1
Series Capacitance(Cr)	12nF
Resonant Inductance(Lr)	29µH
Magnetizing Inductance(Lm)	95µH(Phase1)
Coefficient a	1.05
Coefficient b	1.05
Coefficient c	1.05
Coefficient d	2
Coefficient e	1

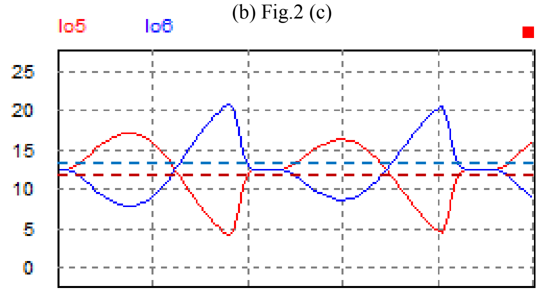
Fig.5 and Fig.6 shows the load current waveform of each phase under half power.



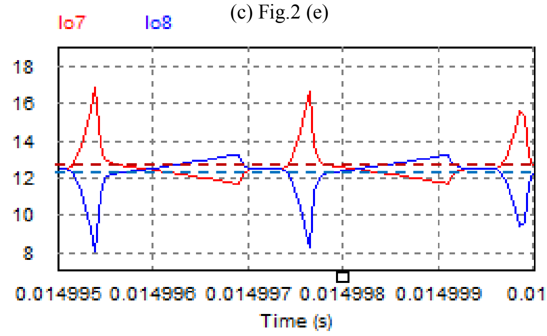
(a) Fig.2 (a)



(b) Fig.2 (c)

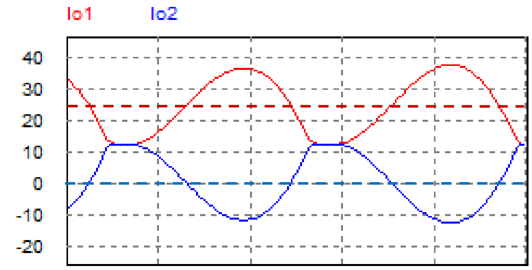


(c) Fig.2 (e)

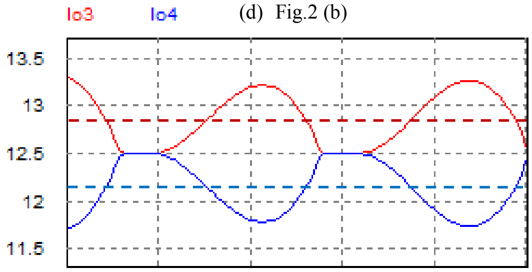


(d) Fig.2 (g)

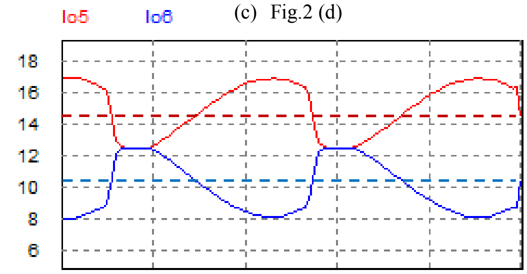
Fig.5 Simulation Waveform of Fig.2 (a), (c), (e), and (g) under half power



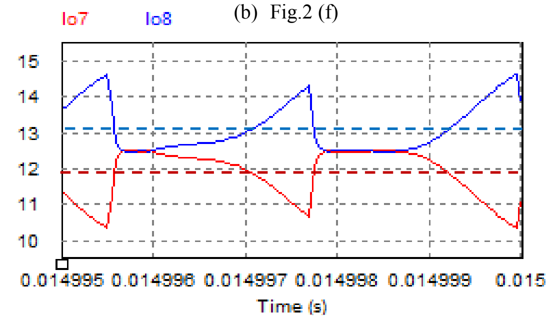
(d) Fig.2 (b)



(c) Fig.2 (d)



(b) Fig.2 (f)



(a) Fig.2 (h)

Fig.6 Simulation Waveform of Fig.2 (b), (d), (f), (h) under half power

Fig.7 and Fig.8 shows the current sharing error under different load current.

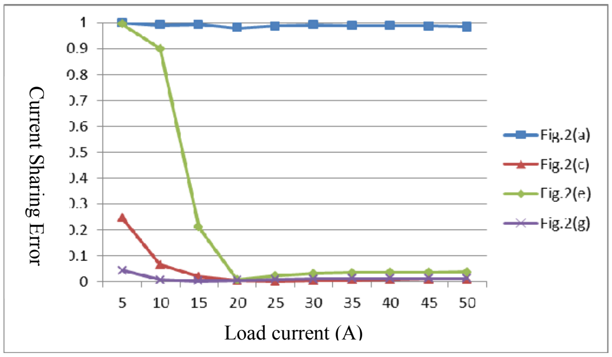


Fig.7 Current sharing error of Fig.2 (a), (c), (e), (g) under different power

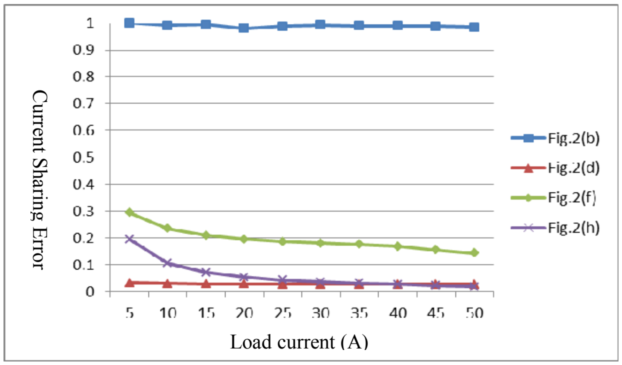


Fig.8 Current sharing error of Fig.2 (b), (d), (f), and (h) under half power

V. EXPERIMENTAL RESULTS

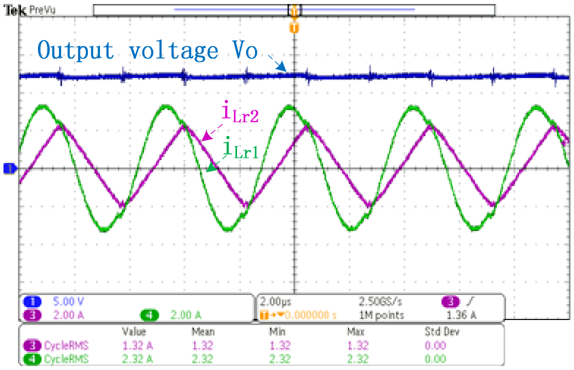
To demonstrate the advantages of the proposed method, the 600W two-phase LLC converter prototype using common capacitor current sharing technology is built and tested. The prototype parameters are listed in Tab. 2.

Tab.2 Prototype parameters

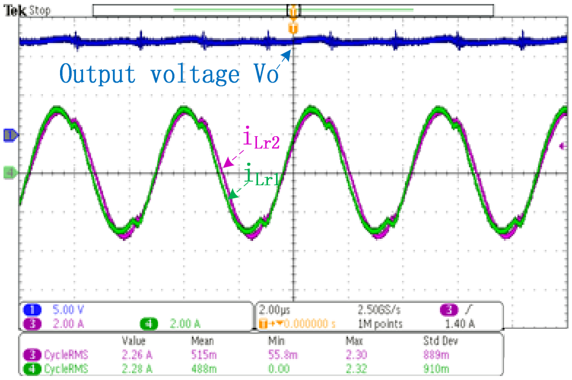
Switching frequency	180kHz-300kHZ
Input Voltage	340V-400V
Output Voltage	12V
Output Power	300W × 2
Transformer Ratio n	20:1
Output Capacitance	1790μF
Series Capacitance(Cr)	12nF ±5%
Resonant Inductance(Lr)	22.5μH(Phase1) 24.5μH(Phase2)
Leakage Inductance(Le)	6μH(Phase1) 6.5μH(Phase2)
Magnetizing Inductance(Lm)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

Fig.9 shows the experiment waveform of two-phase conventional LLC converter and type #1 CRT LLC converter. Channel 1 is the output voltage. Channel 3, channel 4 are the resonant current of two phases. In Fig.9 (a), the resonant current iLr1 is almost triangulate waveform, which means phase one almost doesn't provide the power for output load. Fig.9 (b) shows the experiment waveform of two-phase type #1 CRT LLC converter in Fig.2 (c). The resonant current iLr1 and iL2 is almost same, which means that the load current is shared by two phases. Similarly, Fig.9 (c) shows the experiment waveform of two-phase type #1 CRT LLC converter in Fig.2 (d). Good resonant current sharing performance can be achieved.

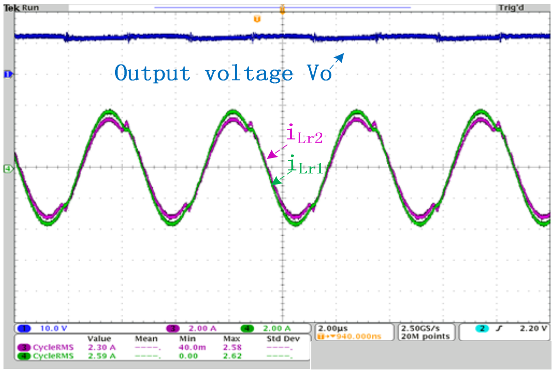
To show the current sharing performance, the resonant current and resonant current sharing error are shown in Fig.10 for both conventional and type#1 LLC resonant converter. The resonant current sharing error increases from 10% to 28% for load power from 5A to 25A for conventional two phase LLC converter in Fig.10 (a).



(a) Steady state at 300W load in Fig.2 (a)



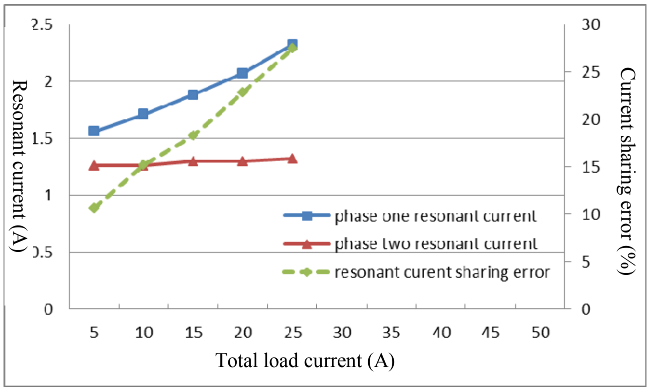
(b) Steady state at 600W load in Fig.2 (c)



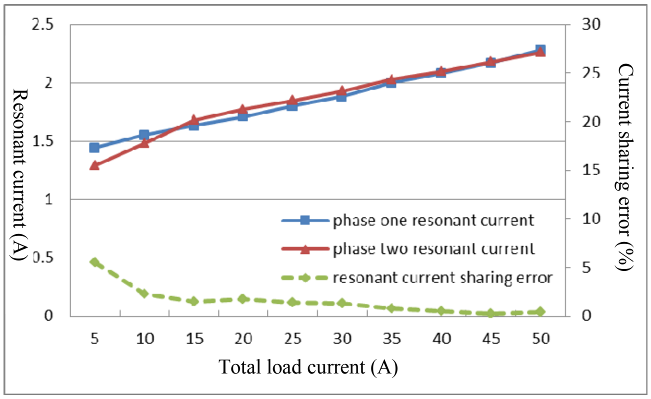
(c) Steady state at 600W load in Fig.2 (d)

Fig.9 Experimental Waveform

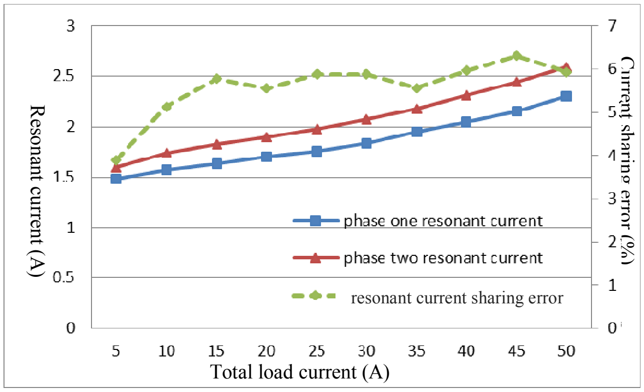
The resonant current sharing error is reduced from 2.3% to 0.44% for type #1 converter with common inductor when load power changes from 5A to 50A in Fig.10 (b). The resonant current sharing error is between 4% and 6.5% for the type#1 converter with common capacitor when load power changes from 5A to 50A in Fig.10 (c).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.



(a) Conventional converter in Fig.2 (a)



(b) Type #1 converter in Fig.2 (c)



(c) Type #1 converter in Fig.2 (d)

Fig.10 Resonant current sharing error with different topologies

I. CONCLUSION

The coupled-resonant-tank for multi-phase resonant converter has been proposed, there are Y-style and Δ-style. Eight two-phase CRT LLC resonant converters are present and the relationship between them is discussed. A decoupled operation based on virtual-open and virtual-short is introduced to get decoupled equivalent circuit based on FHA. A two-phase LLC converter prototype with 300W per phase is built using the conventional method and type #1 method. The experiment results show that the current sharing error has been reduced significantly.

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