Two-phase Three-Dimension Common Inductor LLC Resonant Converter with Automatic Current Sharing

Hongliang Wang, *Senior Member*, *IEEE,* Yang Chen, Bo Sheng, Yan-Fei Liu, *Fellow*, *IEEE*，P.C.Sen*, Life Fellow, IEEE*
Department of Electrical and Computer Engineering
Queen's University, Kingston, Canada
hongliang.wang@queensu.ca, yang.chen@queensu.ca, bo.sheng@queensu.ca, yanfei.liu@queensu.ca, senp@queensu.ca

***Abstract*—Two-phase Three-dimension (3D) common inductor LLC resonant converter is proposed to achieve automatic current sharing. The series inductor of each phase are connected by a Coupled impedance which is inductor, capacitor or short-circuit. A Coupled index is indicated to analyze the current sharing performance under three types converter based on the Fundamental Harmonic Analysis (FHA). The previous method only work at Coupled index equals to 1 and 0, However, the Coupled index can be design any value in (-∞, +∞) for two-phase 3D common inductor LLC converter, and the current sharing performance is better if the Coupled index is designed in negative value. Four steady-state operations under Coupled index is 1, 0.5, 0, -1 are discussed to verify the current sharing improving. 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 converter.**

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

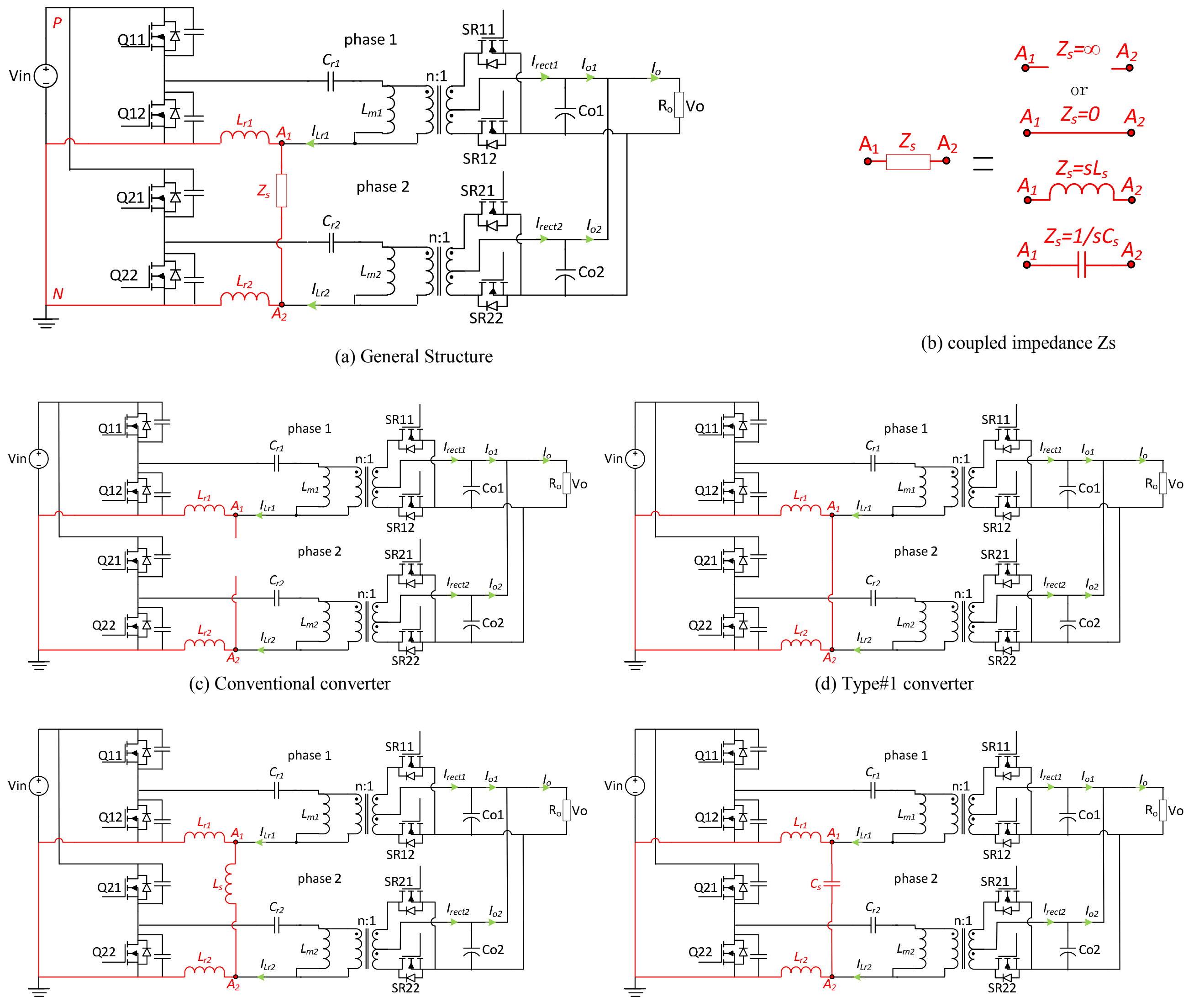
I. INTRODUCTION

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, multiphase parallel technique is a good choice [2, 3]. However, there is the deviation of current stress in each LLC unit owning to components tolerances of each phase [4, 5]. Small component tolerances will cause large current imbalance. Thus, the key problem is load sharing.

There are three methods to achieve current sharing for multiphase LLC converter [6-13]. In the first one, 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. A two-phase common inductor LLC resonant converter has been reported with automatic current sharing [14-16]. And forth more, a passive impedance matching concept was introduced for multi-phase resonant converter [17, 18]. A passive element, such as an inductor [14-16]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, two-phase three-dimension (3D) common inductor LLC resonant converter is proposed. Three types of the topologies are introduced and mathematical models and analysis based on FHA is used. It is possible that two-phase 3D common inductor LLC converter has better current sharing at light load than the topology [14-16]. A 600W, 12V two-phase LLC converter prototype based on short-circuiting impedance is built to verify the feasibility and demonstrate the advantages.

II. TWO-PHASE 3D COMMON INDUCTOR RESONANT CONVERTER

Fig.1 shows two-phase 3D common inductor LLC resonant converter. Lr1, Lr2, Cr1, Cr2, Lm1 and Lm2 are the series inductor, series capacitor and magnetizing inductor of each phase, respectively. The series inductors of each phase are connected to point N. and the point A1 and point A2 are connected by Coupled impedance Zs. Fig.1 (b) shows the Coupled impedance Zs. There are four possible way to construct Coupled impedance Zs. If there is open circuit between point A1 and point A2, Fig.1 (a) is equivalent to a two-phase conventional LLC resonant converter without current sharing as shown in Fig.1 (c). The point A1 and point A2 are shorted, it is called type #1 topology in this paper as shown in Fig.1 (d) which has been reported to achieve good current sharing[14-16]. Zs=0. Once Coupled impedance Zs is instead of an extra inductor Ls, the topology from Fig.1 (a) is called type #2 one as shown in Fig.1 (e). Similarly, the Coupled impedance Zs can be instead of an extra capacitor Cs. Type #3 converters as shown in Fig.1 (f) can be derived from Fig.1 (a).



(a) General Structure

(b) coupled impedance Zs

(c) Conventional converter

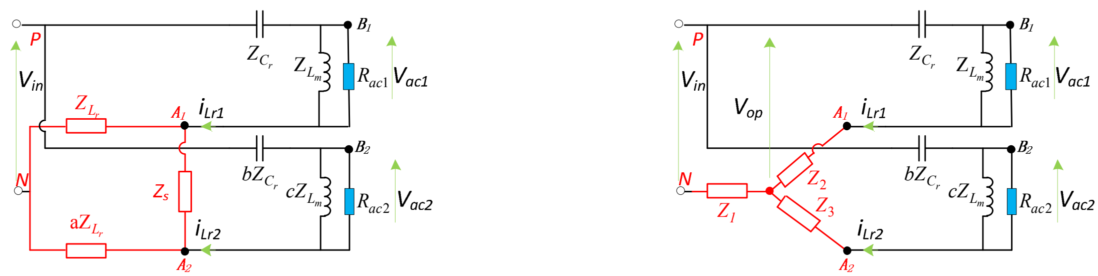
(d) Type#1 converter

(e) Type #2 converter

(f) Type#3 converter

Fig.1 Multi-phase CRT resonant converter

The phase 1 is as the reference. In phase 2, a, b and c is tolerance index of series inductor Lr, series capacitor Cr, and magnetizing inductor. The index d describes index of the Coupled inductor, e describes the index of Coupled capacitor.



(a) FHA circuit with Δ-style

(b) FHA circuit with Y-style

Fig.2 Equivalent circuit of proposed converter

Z_{Lr}, Z_{Cr}, and Z_{Lm} are impedance of series inductor, series capacitor, and magnetizing inductor, respectively. The parameter is (1).

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

FHA is utility to estimate the current sharing performance. A decoupled method has been reported [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 3D common inductor LLC resonant converter are shown in Fig.2.

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. (2).

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

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

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

Fig.2 (b) is another circuit from Fig.2 (a) from Δ-style to Y-style. Three impedances Z1, Z2 and Z3 are (4).

$$\begin{cases} Z_1 = \dfrac{aZ_{Lr}^{\ 2}}{(1+a)Z_{Lr} + Z_s} \\ Z_2 = \dfrac{Z_{Lr}Z_s}{(1+a)Z_{Lr} + Z_s} \\ Z_3 = \dfrac{aZ_{Lr}Z_s}{(1+a)Z_{Lr} + Z_s} = aZ_2 \end{cases} \quad (4)$$

The equivalent Coupled impedance Z2 and Z3 are defined as (5)

$$\begin{cases} Z_2 = gL_r s \\ Z_3 = agL_r s \end{cases} \quad (5)$$

Where coupled index g can be calculated in (6).

$$g = \begin{pmatrix} 1 & Con. \\ 0 & Type\#1 \\ g(d) = \dfrac{d}{1+a+d} & Type\#2 \\ g(e) = \dfrac{1}{1-(1+a)eL_rC_r\omega^2} \approx \dfrac{1}{1-(1+a)e} & Type\#3 \end{pmatrix} \quad (6)$$

Fig.3 shows the coupled index g range of proposed converter. Coupled index g=1 means two phases are independent. There is no current sharing. Type #1 topology in Fig.2 (b) operates if g=0. For Type #2 topology in Fig.2 (c), g (d) increases from 0 to 1with parameter d changed from 0 to ∞. Thus, conventional converter and type #1 converter are made as the special example of type #2 converter at d=0, and d=∞. Similarly, g (e) can be positive or negative under different e from (6), such as g<0 or g≥1, Thus, Type #3 converter can achieve attractive performance under different design. Further analysis will be provided in next part. Four operations under H_1, H_2, H_3 and H_4 will be discussed. H5 point doesn't be discussed in this paper. It is noted that coupled index g of proposed converter can be covered from -∞ to +∞ under required design.

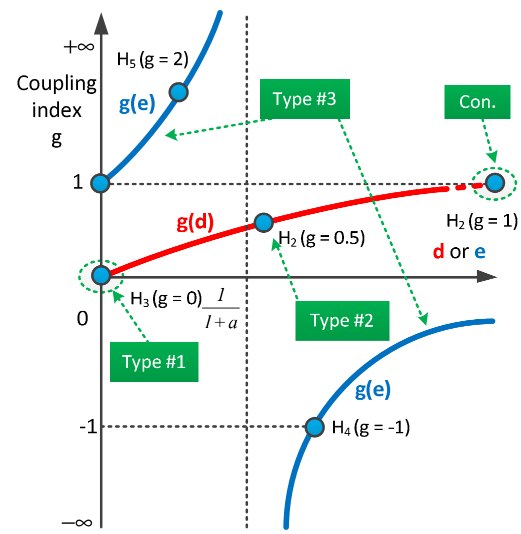


Fig. 3 Coupled index g range of proposed converter

III. Mathematic Model and Current Sharing Analysis

As the output side of each phase arc connected together, there is same voltage gain of each phase. The load index k can be calculated.

$$Ak^2 + Bk + C = 0 \quad (7)$$

The coefficient is shown in following

$$\begin{cases} A = (cL_m\omega - abcgL_rL_mC_r\omega^3)^2 - b^2c^2(L_m\omega - gL_rL_mC_r\omega^3)^2 \\ B = -2(cL_m\omega - abcgL_rL_mC_r\omega^3)^2 k \\ C = (R_{ac} - bcR_{ac}L_mC_r\omega^2 - abgR_{ac}L_rC_r\omega^2)^2 \\ \quad + (cL_m\omega - abcgL_rL_mC_r\omega^3)^2 \\ \quad - b^2c^2(R_{ac} - R_{ac}L_mC_r\omega^2 - gR_{ac}L_rC_r\omega^2)^2 \end{cases} \quad (8)$$

The load current sharing error is defined as follows

$$\sigma = abs(1-2k) \quad (9)$$

The resonant current sharing error is defined in (10), where *$rms(i_{Lr1})$, $rms(i_{Lr2})$* are the root mean square (RMS) value of resonant current i_{Lr1} and i_{Lr2}.

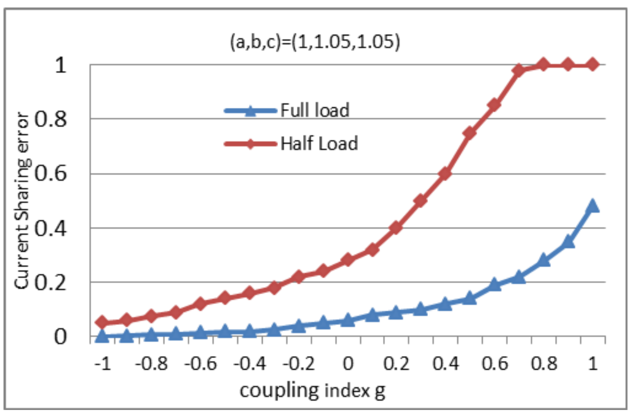
$$\sigma_{Resonant} = abs\left(\frac{rms(i_{Lr1}) - rms(i_{Lr2})}{rms(i_{Lr1}) + rms(i_{Lr2})}\right) \quad (10)$$

Tab.1 shows the nominal parameter value. The series inductors of each phase are parallel by coupling impedance. The influence of tolerance of series inductor is limited. Thus, a =1 is calculated the current sharing error under different b and c. 5% component tolerance is consider to analyze the current sharing error.

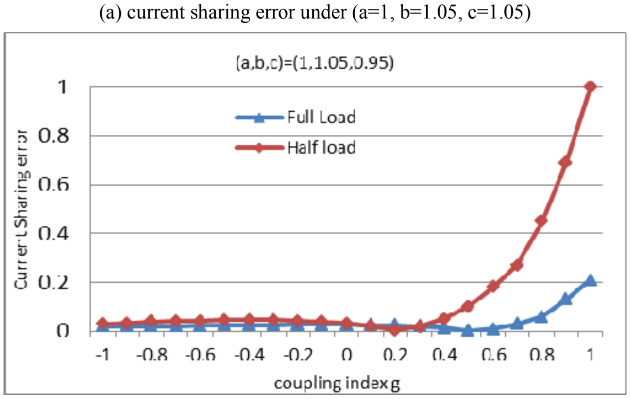
Tab.1 Nominal parameter value

Input voltage	340V – 400V
Resonant inductor L_r	29 μH
Resonant capacitor C_r	12 nF
Magnetizing inductor L_m	95 μH
Transformer ratio n	20
Resonant frequency f_r	270 kHz
Output voltage V_o	12V (rated voltage)
Total output load P_o	full load power 600W
	half load power 300W

Fig.5 shows current sharing error with Coupled index g changing. In Fig.5 (a), a=1, b=1.05 and c=1.05. The current sharing error decreases with Coupled index g decrease. The error is reduced from 28% to 5% at half load if g is changed from 0 (Type #1 converter) to -1 (Type #3 converters). Type #3 has better current sharing performance than type #1 and type #2 converters. Forth more, the good current sharing can also achieved at light load. Fig.5 (b) shows the current sharing error under a=1, b=1.05 and c=0.95. From Fig.5, the worst case is that a=1, b=1.05 and c=1.05.



(a) current sharing error under (a=1, b=1.05, c=1.05)



(a) current sharing error under (a=1, b=1.05, c=0.95)

Fig.5 Current sharing error vs. Coupled index g

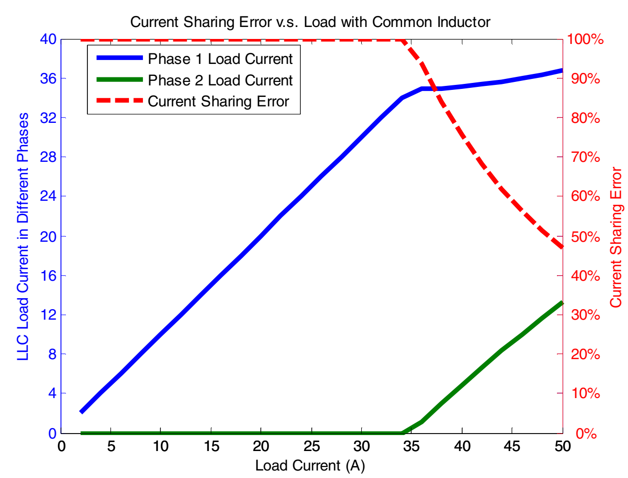
Fig.6 shows the current sharing error with different load current. It is obvious that the current sharing performance at light load is improved when the Coupled index g decreases from 1→0.5→ 0 →-1.

In Fig.6 (a), g=1, the tolerances of resonant inductance and resonant capacitor is larger than 1, the resonant frequency of phase 2 is deviated the one of phase 1, Thus, there is large current sharing error. When the total load current is smaller than 34A, only phase 2 provides the total load power, and the load current sharing error is 100%. Load current of phase 1 is 36A when total load current is 50A.

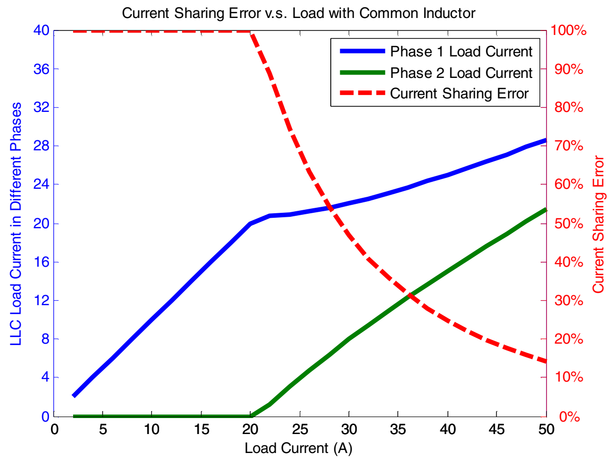
In Fig.6 (b), g=0.5, the tolerances of resonant inductance and resonant capacitor is larger than 1, the resonant frequency of phase 2 is deviated the one of phase 1, Thus, there is large current sharing error. When the total load current is smaller than 20A, only phase 2 provides the total load power, and the load current sharing error is 100%. Load current of phase 1 is 28A when total load current is 50A.

In Fig.6 (c), g=0, the tolerances of resonant inductance and resonant capacitor is larger than 1, the resonant frequency of phase 2 is deviated the one of phase 1, Thus, there is large current sharing error. When the total load current is smaller than 14A, only phase 2 provides the total load power, and the load current sharing error is 100%. Load current of phase 1 is 26.5A when total load current is 50A.

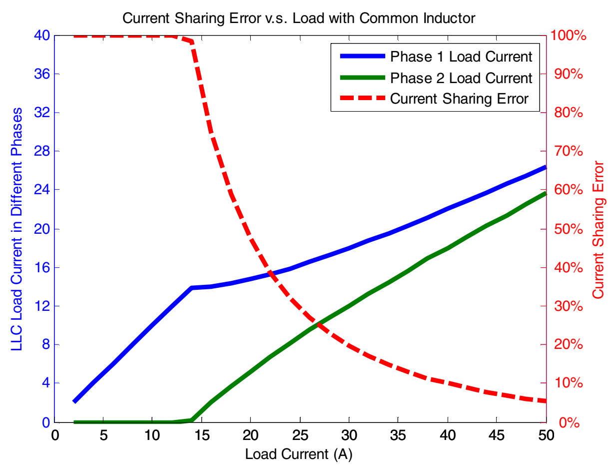
In Fig.6 (d),g=-1, the tolerances of resonant inductance and resonant capacitor is larger than 1, the resonant frequency of phase 2 is deviated the one of phase 1, Thus, there is large current sharing error. When the total load current is smaller than 6A, only phase 2 provides the total load power, and the load current sharing error is 100%. Load current of phase 1 is 25A when total load current is 50A. Good current sharing performance can be achieved.



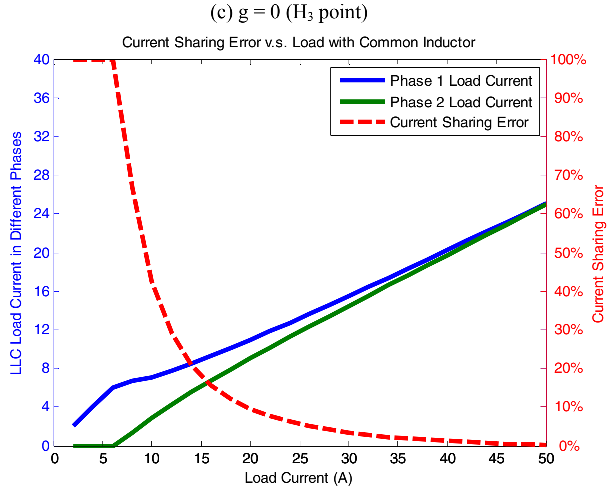
(a) g = 1 (H_1 point)



(b) g = 0.5 (H_2 point)



(c) g = 0 (H_3 point)



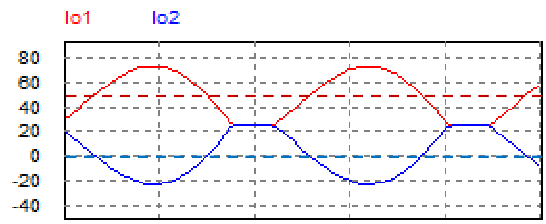
(d) g = -1 (H_4 point)

Fig.6 load current of each phase and current sharing error vs. total load current under a=1, b=1.05, c=1.05

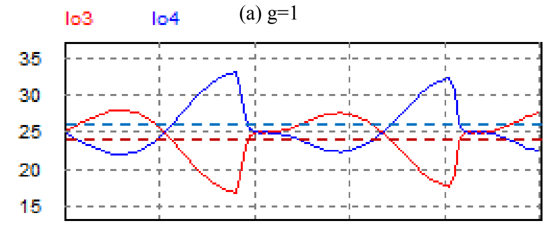
IV. PSIM Simulation Results

Further to verify and compare the current sharing performance, in this section, PSIM simulation results under full power and half power will be provided.

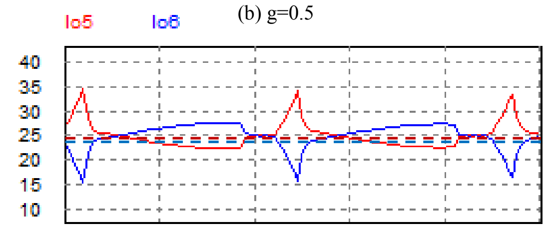
Fig.7 shows the load current of each phase at full power under different coupled index g. In Fig.7 (a),g=1, only phase one provides the total power. In Fig.7 (b), g=0.5, the average current of phase one，phase two is 24A，26A，good current sharing performance can be achieved. The average current of each phase is 24.7A and 25.3A during g=0 as shown in Fig.7 (c). In Fig. (d), the average current of each phase is 25.2A and 24.8A. Thus, the best current sharing performance is achieved when g = -1.



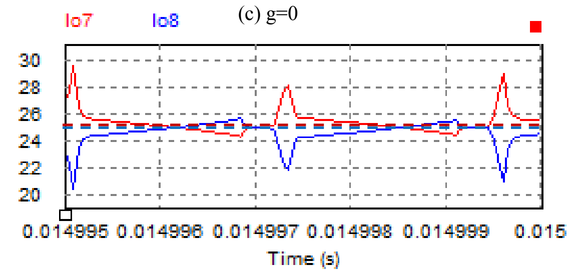
(a) g=1



(b) g=0.5



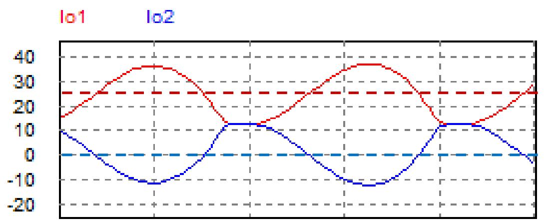
(c) g=0



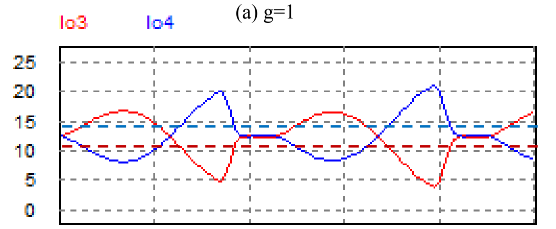
(d) g=-1

Fig.7 Simulation Waveform at different coupled index g under full power

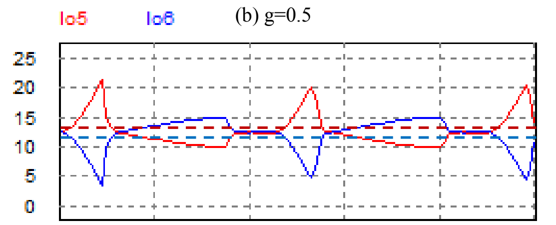
Fig.8 shows the load current of each phase at half power under different coupled index g. In Fig.8 (a), g=1, only phase one provides the total power. In Fig.8 (b), g=0.5, the average current of phase one，phase two is 12.2A，12.8A，good current sharing performance can be achieved. The average current of each phase is 12.6A and 12.4A during g=0 (Fig.1 (d)) as shown in Fig.7 (c). In Fig. (d), the average current of each phase is 12.55A and 12.45A. Thus, the best current sharing performance is achieved when g=-1.



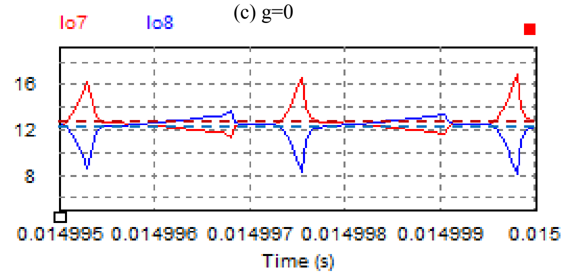
(a) g=1



(b) g=0.5



(c) g=0



(d) g=-1

Fig.7 Simulation Waveform at different coupled index g under half power

Fig.8 shows the current sharing error under different load current. There is best current sharing performance during g=-1.

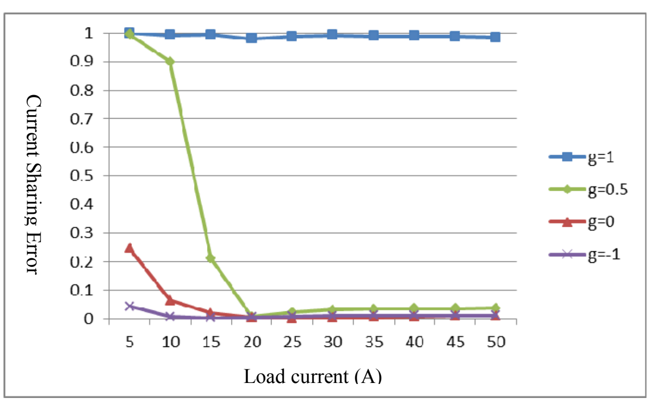


Fig.8 Current shairng error under load current at different g

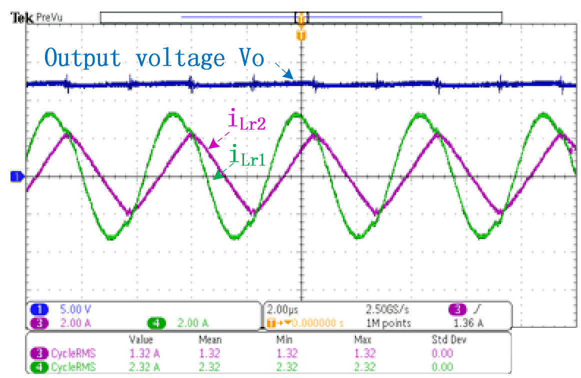
V. Experimental Results

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.

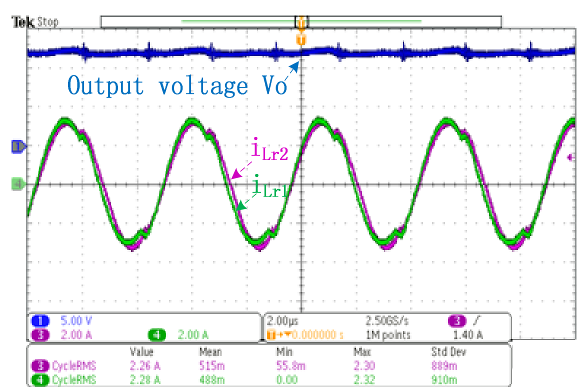
Tab.2 Prototype parameters

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) 6.5 μH(Phase2)
Magnetizing Inductance(Lm)	95μH(Phase1) 92μH(Phase2)

Fig.9 shows the experiment waveform of two-phase conventional and type #1 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 LLC converter. The resonant current iLr1 and iL2 is almost same, which means that the load current is shared by two phases.



(a) Steady state at 300W load in Fig.1 (c)

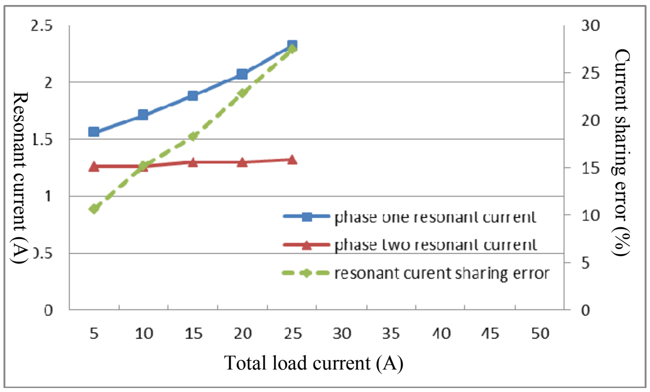


(b) Steady state at 600W load in Fig.1 (d)

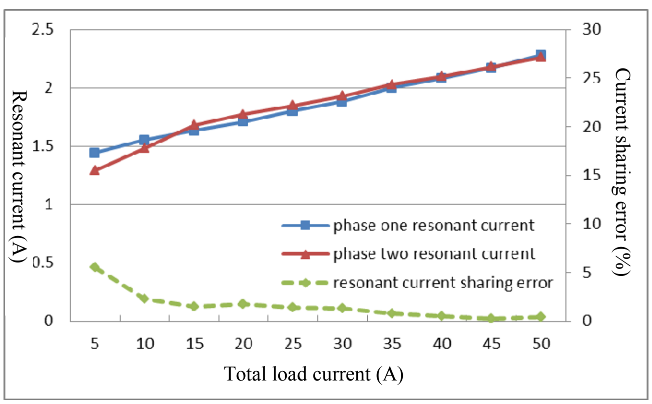
Fig.9 Experimental Waveform

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). The resonant current sharing error is reduced from 2.3% to 0.44% for the proposed current sharing method when load power changes from 5A to 50A in Fig.10 (b). 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.1 (c)



(b) Type #1 converter in Fig.1 (d)

Fig.10 Resonant current sharing error with different topologies

VI. CONCLUSION

A new, two-phase 3D common inductor LLC resonant converter has been proposed. There are three type topologies. A coupling index is indicated to estimate current sharing performance under different topology. Mathematic analysis shows that there is better current sharing performance if the coupling index is designed to negative value. Thus, type #3 converter is the best one of three proposed topologies. 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.

References

[1] B. Yang, "Topology Investigation for Front End DC/DC Power Conversion for Distributed Power System,," Virginia Polytechnic Institute and Stage University, 2003.

[2] Y. Zhang, D. Xu, M. Chen, Y. Han, and Z. Du, "LLC resonant converter for 48 V to 0.9 V VRM," in *Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual*, 2004, pp. 1848-1854 Vol.3.

[3] L. Bing, L. Wenduo, L. Yan, F. C. Lee, and J. D. v. Wyk, "Optimal design methodology for LLC resonant converter," in *Twenty-First Annual IEEE Applied Power Electronics Conference and Exposition, 2006. APEC '06.*, 2006, p. 6 pp.

[4] D. Fu, B. Lu, and F. C. Lee, "1MHz High Efficiency LLC Resonant Converters with Synchronous Rectifier," in *2007 IEEE Power Electronics Specialists Conference*, 2007, pp. 2404-2410.

[5] S. D. Simone, C. Adragna, C. Spini, and G. Gattavari, "Design-oriented steady-state analysis of LLC resonant converters based on FHA," in *International Symposium on Power Electronics, Electrical Drives, Automation and Motion, 2006. SPEEDAM 2006.*, 2006, pp. 200-207.

[6] Z. Hu, Y. Qiu, L. Wang, and Y.-F. Liu, "An Interleaved LLC Resonant Converter Operating at Constant Switching Frequency," *Power Electronics, IEEE Transactions on,* vol. 29, pp. 2931-2943, 2014.

[7] Z. Hu, Y. Qiu, Y.-F. Liu, and P. C. Sen, "A Control Strategy and Design Method for Interleaved LLC Converters Operating at Variable Switching Frequency," *Power Electronics, IEEE Transactions on,* vol. 29, pp. 4426-4437, 2014.

[8] Z. Hu, Y. Qiu, L. Wang, and Y.-F. Liu, "An interleaved LLC resonant converter operating at constant switching frequency," in *Energy Conversion Congress and Exposition (ECCE), 2012 IEEE*, 2012, pp. 3541-3548.

[9] E. Orietti, P. Mattavelli, G. Spiazzi, C. Adragna, and G. Gattavari, "Two-phase interleaved LLC resonant converter with current-controlled inductor," in *Power Electronics Conference, 2009. COBEP '09. Brazilian*, 2009, pp. 298-304.

[10] B. C. Kim, K. B. Park, C. E. Kim, and G. W. Moon, "Load sharing characteristic of two-phase interleaved LLC resonant converter with parallel and series input structure," in *Energy Conversion Congress and Exposition, 2009. ECCE 2009. IEEE*, 2009, pp. 750-753.

[11] F. Jin, F. Liu, X. Ruan, and X. Meng, "Multi-phase multi-level LLC resonant converter with low voltage stress on the primary-side switches," in *Energy Conversion Congress and Exposition (ECCE), 2014 IEEE*, 2014, pp. 4704-4710.

[12] E. Orietti, P. Mattavelli, G. Spiazzi, C. Adragna, and G. Gattavari, "Analysis of multi-phase LLC resonant converters," in *Power Electronics Conference, 2009. COBEP '09. Brazilian*, 2009, pp. 464-471.

[13] E. Orietti, P. Mattavelli, G. Spiazzi, C. Adragna, and G. Gattavari, "Current sharing in three-phase LLC interleaved resonant converter," in *Energy Conversion Congress and Exposition, 2009. ECCE 2009. IEEE*, 2009, pp. 1145-1152.

[14] H. Wang, Y. Chen, and Y. F. Liu, "A passive-impedance-matching concept for multiphase resonant converter," in *2016 IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2016, pp. 2304-2311.

[15] H. Wang, Y. Chen, Z. Hu, L. Wang, T. Liu, W. Liu*, et al.*, "An algorithm to analyze circulating current for multi-phase resonant converter," in *2016 IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2016, pp. 899-906.

[16] H. Wang, Y. Chen, Y.-F. Liu, and S. Liu, "Automatic current-sharing method for multi-phase LLC resonant converter," in *2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia)*, 2016, pp. 3198-3205.

[17] H. Wang, Y. Chen, Y. F. Liu, J. Afsharian, and Z. Yang, "A Passive Current Sharing Method with Common Inductor Multi-Phase LLC Resonant Converter," *IEEE Transactions on Power Electronics,* vol. 9, pp. 6994-7010, 2017.

[18] H. Wang, Y. Chen, Y.-F. Liu, J. Afsharian, and A. Z. Yang, "A common inductor multi-phase LLC resonant converter," in *Energy Conversion Congress and Exposition (ECCE), 2015 IEEE*, 2015, pp. 548-555.

[19] H. Wang, Y. Chen, Z. Hu, L. Wang, Y. Qiu, W. Liu*, et al.*, "A common capacitor multi-phase LLC resonant converter," in *2016 IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2016, pp. 2320-2327.

[20] H. Wang, Y. Chen, Y. Qiu, P. Fang, Y. Zhang, L. Wang*, et al.*, " Common Capacitor Multi-phase LLC Converter with Passive Current Sharing Ability," *IEEE Transactions on Power Electronics,* vol. 1, pp. 370-387, 2018.

[21] H. Wang, Y. Chen, and Y. F. Liu, "A Passive-Impedance-Matching Technology to Achieve Automatic Current Sharing for Multi-Phase Resonant Converter," *IEEE Transactions on Power Electronics,* vol. 12, pp. 9191-9209, 2017.