A Passive-Impedance-Matching Concept for Multi-phase Resonant Converter

Hongliang Wang, *Senior Member, IEEE*, Yang Chen, Yan-Fei Liu, *Fellow,IEEE*

Department of Electrical and Computer Engineering

Queen's University

Kingston, Canada

hongliang.wang@queensu.ca, yang.chen@queensu.ca, yanfei.liu@queensu.ca

***Abstract*— A passive impedance matching (PIM) concept is proposed for multi-phase resonant converters application. The new concept can achieve load current sharing between every unit automatically. A passive element such as an inductor or a capacitor is connected in the common branch of the two units (or multi-units), such that several sets of equivalent positive resistors and negative resistors are distributed into these units accordingly. The equivalent virtual resistors are of variable value, which automatically adjust the DC gain in each unit to achieve load sharing. Three equivalents LLC resonant converters with virtual variable resistor are analyzed. The theoretical analysis result shows that the first and third types have good load current sharing performance. A 600W, 12V two-phase LLC converter prototype is built based on the first type. The prototype verified the feasibility and demonstrated advantages of PIM multiphase resonant converter.**

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][2]. 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 [3][4][5]. 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 [6][7][8]. Small component tolerances will cause large current imbalance. Thus, the key problem is load sharing.

Three technologies have been used to achieve current sharing in multiphase LLC converter. One is the active method in which passive components tolerance can be compensated by adjusting the variable capacitor [6][9] or inductor [10] 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[11][12]. 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. Besides, it is hard for modularization design since the DC voltage stress is reduced with module number increased. 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[13][14].It is only suitable for three-phase - the load current does not share when the number of module exceeds three. In a nutshell, existing studies have limitation on cost, complex control, modularization and dynamic performance.

In this paper, a passive impedance matching concept is proposed for multi-phase resonant converter. A passive element, such as an inductor or a capacitor, is put in the common branch of the multiple units. A set of virtual resistors (positive and negative) are yielded through the common branch inductor or capacitor, which changes the gain curve in different converter. Three resonant converters with variable resistor have been analyzed. A 600W, 12V two-phase LLC converters prototype based on sharing resonant inductor is built to verify the feasibility and demonstrate the advantages. The paper is organized as follows. Section II introduces virtual impedance concept; Section III analyzes the three resonant converters with variable resistor. Section IV shows the experimental results. Conclusion is given in Section V.

II. VIRTUAL IMPEDANCE CONCEPT

Fig.1 shows the basic circuit about the common branch impedance. Fig.1 (a) shows that K current source units $I_1(s)$, $I_2(s)$... $I_k(s)$ in parallel are connected to the common branch. The voltage of common impedance Z_s is V_s. The total current is defined as $I_s(s)$

$$I_s(\mathrm{s}) = \sum_{1}^{k} I_j(\mathrm{s}) \tag{1}$$

The impedance Z_s can be separated into Z_{s1}, Z_{s2}... Z_{sk} for each unit based on current $I_1(s)$, $I_2(s)$... $I_k(s)$ to achieve 'virtual open' multiple units, which is shown in Fig.1(b).Three kinds of passive elements (inductors, capacitors and resistors) can be selected as impedance Z_s. Resistors will introduce power loss and lower efficiency of converter. Thus, inductors and capacitors are better candidates in this application. Fig.1(c) and Fig.1 (d) illustrate two examples of sharing an inductor and a capacitor in the common branch.

Fig.1 (e) is the vector plot of sharing an inductor in Fig.1 (c). Vector $I_s(s)$ is composed of vector $I_1(s)$ and $I_2(s)$. The current $I_1(s)$ is leading current $I_2(s)$, so the impedance angle of $Z_1(s)$ is smaller than 90^0 and that of $Z_2(s)$ is larger than 90^0. In consequence, impedance $Z_1(s)$ is equivalent to an inductor k_1L_s and a positive resistor R_{s1} connected in series. Similarly, impedance $Z_2(s)$ is equivalent to one inductor k_2L_s and a negative resistor R_{s2} connected in series. Where k_1, k_2 is the coefficient parameters. They can be found from (2).

$$\frac{(sk_1L_s + R_{s1})(sk_2L_s + R_{s2})}{(k_1 + k_2)sL_s + (R_{s1} + R_{s2})} = sL_s \tag{2}$$

The circuit in Fig.1(c) can be replaced by the circuit in Fig.1 (g). In the same analysis, two separated impedances can be given by virtual open. The circuit in Fig.1 (d) can be replaced by the circuit in Fig.1 (h). Where k_1, k_2 is the coefficient parameters. They can be found from (3).

$$\frac{(\frac{1}{sk_1C_s} + \mathrm{R}_{s1})(\frac{1}{sk_2C_s} + R_{s2})}{(\frac{1}{k_1} + \frac{1}{k_2})\frac{1}{sC_s} + (R_{s1} + R_{s2})} = \frac{1}{sC_s} \tag{3}$$

No matter for the sharing inductor or capacitor, an equivalent circuit with virtual positive resistor and negative resistor can always be derived. Three different LLC converters with variable resistors will be analyzed.

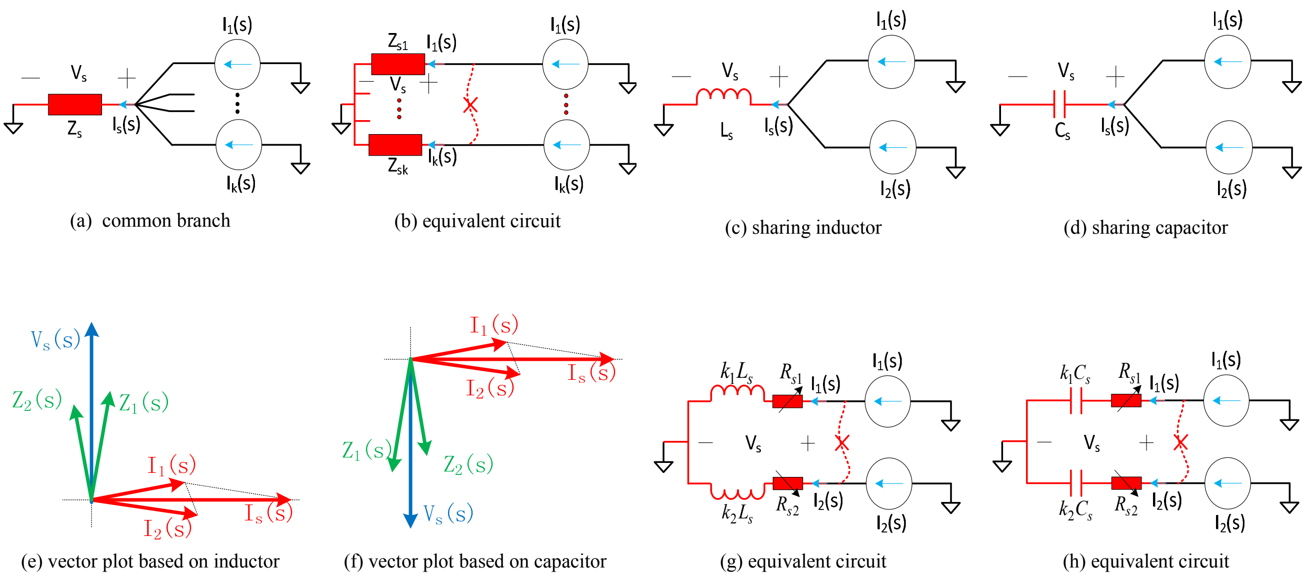


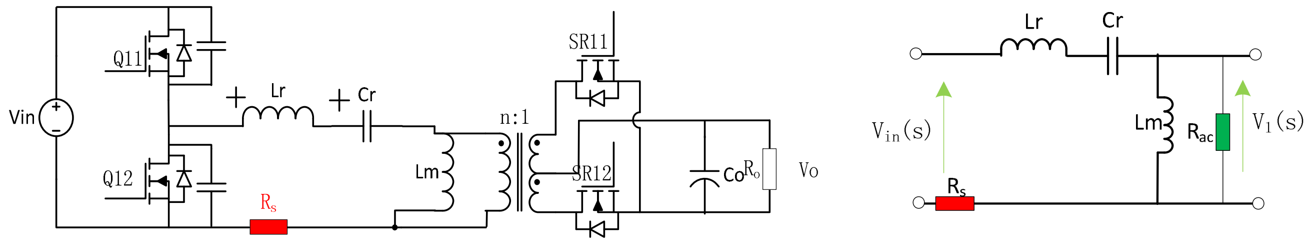
Fig.1 basic circuit about the common branch

III. ANALYSIS OF THREE LLCS WITH VARIABLE RESISTOR

From the analysis in the above section, the common branch impedance is equivalent to the new impedance network with virtual positive resistor or negative resistor. For easy understanding, LLC resonant converter is made as an example. Three LLC converters with virtual resistors based on different common branch will be analyzed next. The first common branch is series branch; the second one is parallel branch and the last one is the primary-side branch of transformer.

A. FIRST LLC CONVERTER WITH VARIABLE RESISTOR

Fig.1 shows the first LLC with a virtual resistor, R_s. If the value of resistor R_s is zero, the converter in Fig.2 (a) is traditional LLC converter. Fig.2 (b) shows the equivalent circuit based on fundamental harmonic analysis (FHA).



(a) first LLC Converter with virtual resistor

(b) FHA equivalent circuit

Fig.2 first LLC converter with virtual resistor

The gain expression of the first LLC converter with resistor is shown in (4):

$$G_{DC} = \frac{nV_o}{V_{in}/2} = \left|\frac{V_1(s)}{V_{in}(s)}\right| = \frac{1}{\sqrt{[\frac{1}{m}(\frac{f_r}{f_s})^2 - \frac{(1+m+mk)}{m}]^2 + [(\frac{k}{mQ}+Q)(\frac{f_r}{f_s}) - Q(\frac{f_s}{f_r})]^2}} \quad (4)$$

Where

$$Q = \sqrt{\frac{L_r}{C_r}}\frac{1}{R_0}, f_r = \frac{1}{2\pi\sqrt{L_r C_r}}, m = \frac{L_m}{L_r}, R_{ac} = \frac{8n^2}{\pi^2}R_o, k = \frac{R_s}{R_{ac}},$$

$$f = \frac{f_s}{f_r}$$

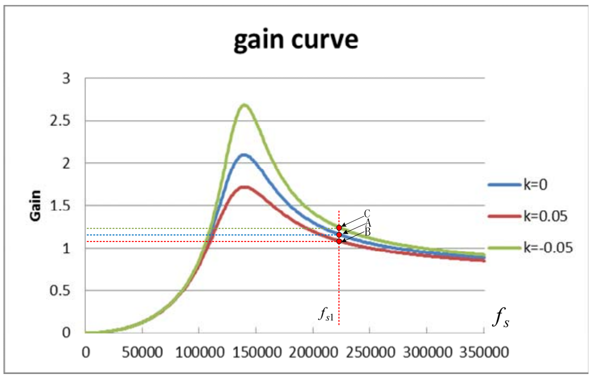


Fig.3 gain curve of first LLC converter with resistor

Fig.3 shows gain curve with different switching frequency. *k*=0 represents the traditional LLC converter gain curve; *k*=0.05 represents an LLC converter with a positive resistor; *k*=-0.05 represents an LLC converter with a negative resistor. The gain value reduces significantly when *k* increases from zero to positive at switching frequency f_{s1}. Likewise, the gain value increases significantly when k decreases from zero to negative at switching frequency f_{s1}. Thus, adding virtue resistors into the series branch can improve the performance of load current sharing significantly.

B. SECOND LLC CONVERTER WITH VARIABLE RESISTOR

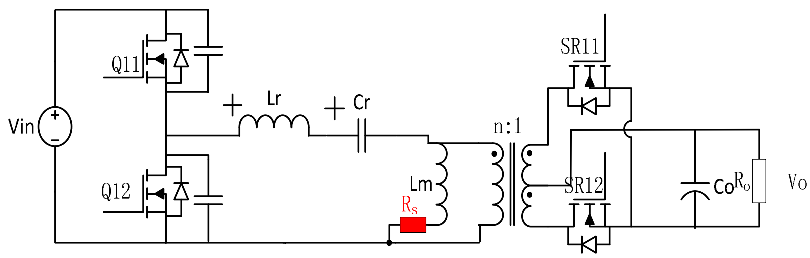
Fig.4 shows the second LLC with a virtual resistor. A resistor R_s is added into parallel branch. If the value of resistor R_s is zero, the converter in Fig.4 (a) is a traditional LLC converter.Fig.4 (b) shows the FHA equivalent circuit.

The gain expression of the first LLC converter with resistor is shown in (5):

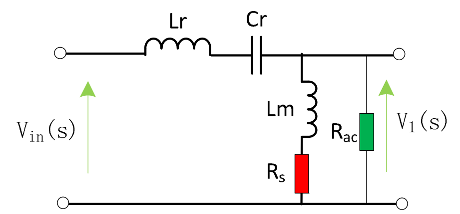
$$G_{DC}=\frac{nV_o}{V_{in}/2}=\left|\frac{V_1(s)}{V_{in}(s)}\right|$$
$$=\frac{\sqrt{m^2(\frac{f_s}{f_r})^4+\frac{k^2}{Q^2}(\frac{f_s}{f_r})^2}}{\sqrt{[1+k-(1+k+m)(\frac{f_s}{f_r})^2]^2+\{(\frac{f_s}{f_r})[\frac{k}{Q}+mQ-mQ(\frac{f_s}{f_r})^2]\}^2}} \quad (5)$$

Where

$$Q=\sqrt{\frac{L_r}{C_r}}\frac{1}{R_0},f_r=\frac{1}{2\pi\sqrt{L_rC_r}},m=\frac{L_m}{L_r},R_{ac}=\frac{8n^2}{\pi^2}R_o,k=\frac{R_s}{R_{ac}},$$
$$f=\frac{f_s}{f_r}$$



(a) second LLC Converter with virtual resistor



(b)FHA equivalent circuit

Fig.4 second LLC converter with virtual resistor

Fig.5 shows gain curve with switch frequency. k=0 represents the traditional LLC converter gain curve; k=0.05 represents an LLC converter with positive resistor; k=-0.05 represents an LLC converter with a negative resistor. The gain value almost doesn't change no matter increasing or decreasing k at switching frequency f_{s1}. Thus, adding virtue resistors into the parallel branch cannot improve the performance on current load sharing.

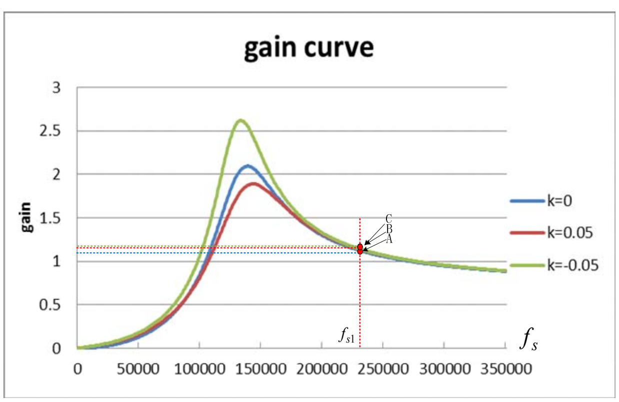


Fig.5 gain curve of second LLC converter with resistor

C. THIRDRESONANT CONVERTER WITH VARIABLE RESISTOR

A CLL resonant converter has been reported [15][16] and it has similar performance with traditional LLC converter. A CLL resonant converter has a passive inductor in the primary-side of transformer. Thus, this topology can be used to build virtual resistor for multi-phase CLL application. Fig.6 shows the second LLC with virtual resistor. A resistor R_s is added into parallel branch. If the value of resistor R_s value is zero, the converter in Fig.6 (a) is the traditional LLC converter. Fig.6 (b) shows the equivalent circuit based on fundamental harmonic analysis (FHA).

The gain expression of the first LLC converter with resistor is shown in (6):

$$G_{DC}=\frac{nV_o}{V_{in}/2}=\left|\frac{V_1(s)}{V_{in}(s)}\right|$$
$$=\frac{(\frac{f_s}{f_r})^2}{\sqrt{[\frac{(1+k)}{m}-(1+k)(\frac{f_s}{f_r})^2]^2+\{\frac{m-1}{m}Q(\frac{f_s}{f_r})[1-(\frac{f_s}{f_r})^2]\}^2}} \quad (6)$$

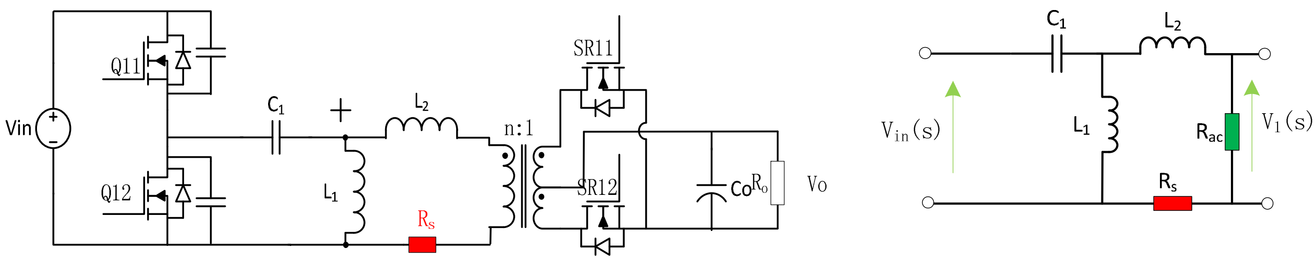
Where

$$L_{eq}=\frac{L_1L_2}{L_1+L_2}, f_r=\frac{1}{2\pi\sqrt{L_{eq}C_1}}, Q=\sqrt{\frac{L_{eq}}{C_1}}\frac{1}{R_{ac}}, m=L_1/L_{eq},$$

$$R_{ac}=\frac{8n^2}{\pi^2}\mathrm{R}_o, \mathrm{k}=\frac{R_s}{R_{ac}}$$

Fig.7 shows gain curve with switch frequency. k=0 represents the traditional LLC converter gain curve k=0.05 represents the LLC converter with a positive resistor; k=-0.05 represents the LLC converter with a negative resistor.

The gain value reduces significantly when k increases from zero. Likewise, the gain value increases significantly when k decreases from zero to negative. Thus, in this situation adding virtue resistors can improve the performance on current load sharing.



(a) third LLC Converter with virtual resistor

(b) FHA equivalent circuit

Fig.6 third LLC converter with virtual resistor

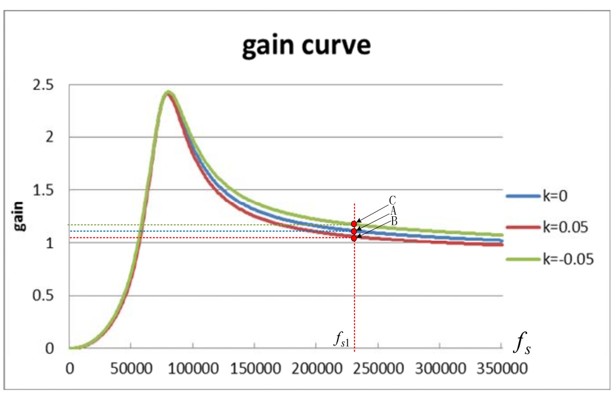


Fig.7 gain curve of third CLL converter with resistor

IV. Experimental Results

A 600W two-phase LLC converter in section II (A) is built to verify the feasibility and demonstrate the advantages of the proposed method. The experiment prototype is shown in Fig.8[17]. Fig.8 (a) shows two-phase LLC resonant converter sharing series inductor. Fig.8 (b) shows FHA equivalent circuit based on Fig.8 (a). According to passive impedance matching concept, the equivalent circuit based on separated impedance is shown in Fig.8 (c). Assuming the virtual opening when the separated impedance is distributed by the equivalent current $i_{Lr1}(s)$ and $i_{Lr2}(s)$. Thus, another equivalent circuit can be achieved as shown in Fig.8 (d). A virtual positive and negative resistor R_{s1} or R_{s2} are added into the series branch. From the FHA circuit at Fig. 8 (d), Two-phase LLC converter shown in Fig. 8 (a) has be transferred into Fig. 8 (e). The virtual resistors, R_{s1} and R_{s2}, have a different sign. One is positive resistor, other is a negative resistor.

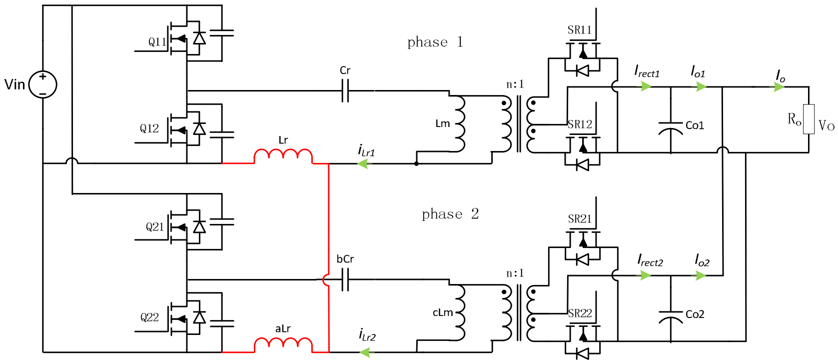
The resonant current sharing error is defined as follows

$$\sigma_{resonant}=\frac{|rms(\mathrm{i}_{Lr1})-r\,\mathrm{ms}(\mathrm{i}_{Lr2})|}{|rms(\mathrm{i}_{Lr1})-rms(\mathrm{i}_{Lr2})|} \tag{7}$$

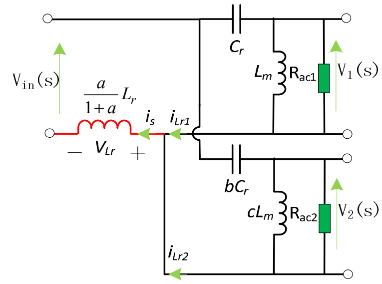
The prototype parameter is shown in Table.1. The rated power of each phase is 300W. Output voltage is 12V. The leakage inductances value of each phase are 6uH, 6.5uH, respectively. Series inductances are 22.5uH and 24.5uH, respectively. Series capacitances are 12nF and 13nF, respectively.

Fig.9 shows the resonant current waveform at 180W, 300W operation without load sharing method. The phase two i_{Lr2} is almost a triangular waveform. Phase one converter resonant current, delivers nearly all of power to load. As only phase one provides total load power, it is not possible to provide the experiment results at total load 600W because phase one will be over-current and damage.

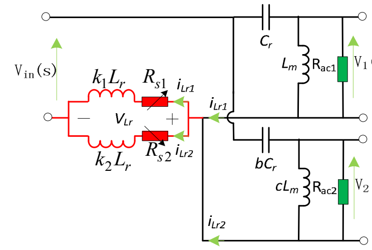
Fig.10 shows the resonant current waveform at 180W, 300W operation with propose method. The resonant current iLr1, iLr2 are almost same. There is only a small angle difference. Thus, the load current can shared. The experiment results at total load 600W load current is shown in Fig. 10 (c).



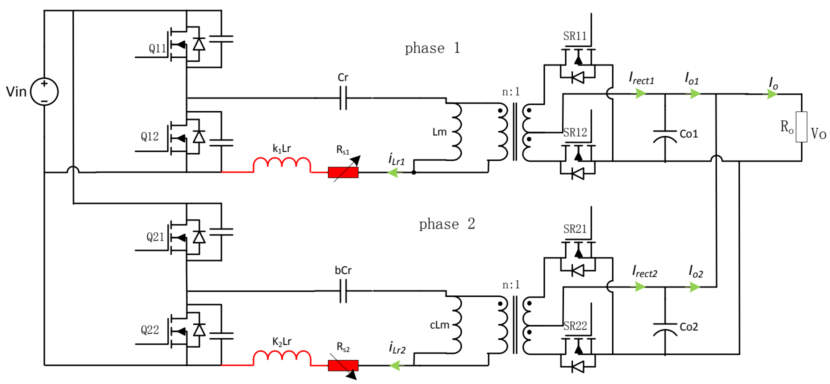
(a) two-phase LLC with first common branch using inductor



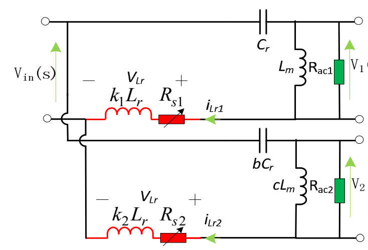
(b) FHA equivalent circuit



(c) equivalent circuit based on separated impedance



(e) equivalent two-phase LLC converter with virtual positive and negative resistor

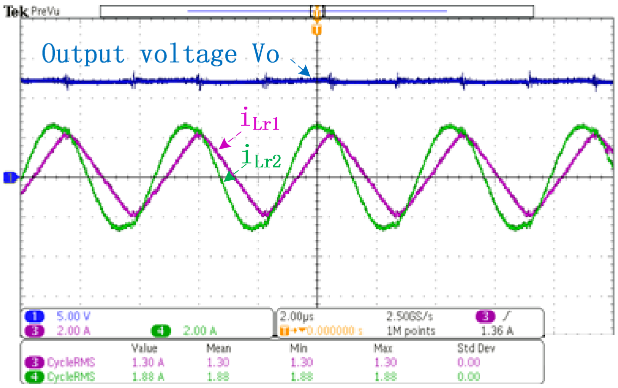


(d) equivalent circuit with independent impedance

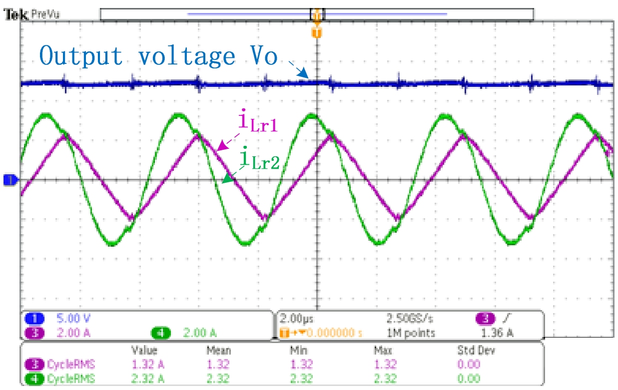
Fig.8 two-phase first LLC converter by sharing resonant inductor

Tab.1 Prototype parameters

Switching frequency	180kHz-300kHZ	Output Capacitance	1790μF
Input Voltage	340V-400V	Series Capacitance(Cr)	12nF(phase1) 13nF (phase 2)
Output Voltage	12V	Resonant Inductance(Lr)	22.5μH(Phase1) 24.5μH(Phase2)
Output Power	300W × 2	Magnetizing Inductance(Lm)	95μH(Phase1) 92μH(Phase2)
Transformer Ratio n	20:1	Leakage Inductance(Le)	6μH(Phase1) 6.5μH(Phase2)



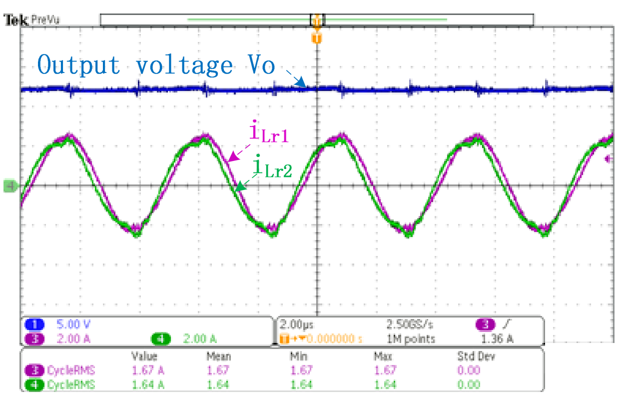
(a) Steady state at 180W load



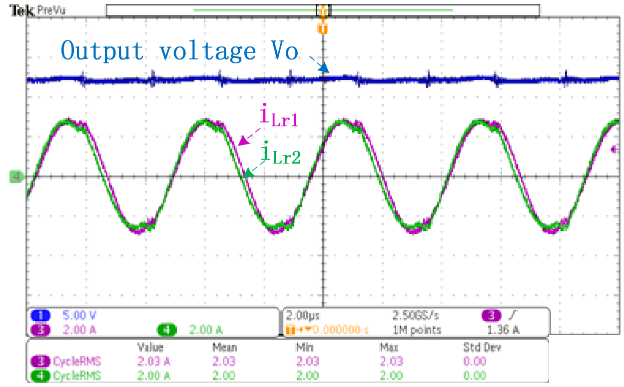
(b) Steady state at 300W load

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

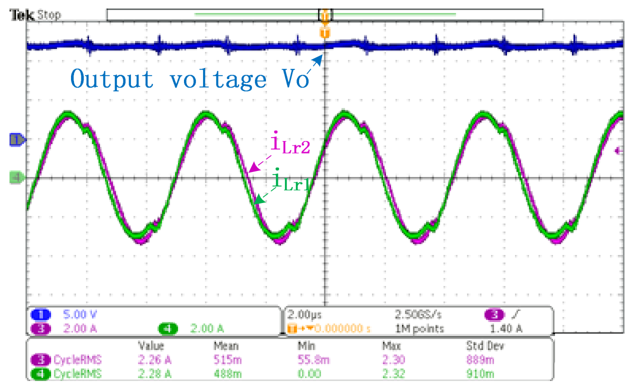
Fig.9 experiment waveform of two-phase conventional LLC converter



(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 one; Ch4: resonant current of phase two.

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

To express the resonant current sharing error between the two phases according to (7), the resonant current and resonant current sharing error are shown in Fig. 11, Fig. 12. The resonant current sharing error increases from 10% to 28% with load power from 60W to 300W according to Fig.11. The resonant current sharing error reduced from 5.5% to 0.44% when load power changes from 60W to 600W in Fig.12. The current sharing performance is better with load increasing, which is useful parallel operation. The resonant current sharing error reduces 63 times and is only 0.44% at 600W total load power. Circulating current is significantly reduced using PIM multiphase resonant converter.

Fig.11 resonant current of two-phase conventional LLC converter

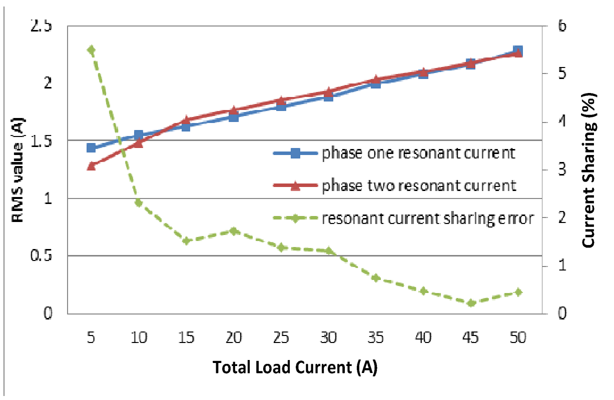


Fig.12 resonant current of two-phase proposed LLC converter

V. CONCLUSION

A passive impedance matching concept is proposed in this paper to achieve load sharing automatically for multi-phase resonant converter. The new concept views the impedance network as passive components in addition with virtual positive resistors and negative resistors. The first and third type of converters can achieve nearly perfect load sharing. Besides, the new concept does not require active control. A 600W two-phase LLC converter sharing the common series inductor is built to verify the feasibility and demonstrate the advantages of the proposed method. The experiment results show that the resonant current sharing error reduces 63 times and is only 0.44% at 600W total load power. This passive impedance matching concept for parallel technique can be extended any phases that is more than two, and any resonant converters, such as series resonant converter, parallel resonant converter, LCC and so on.

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