

Unbalanced three-phase interleaved LLC resonant converter: current phase angle balancing technique

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ABSTRACT

Resonant power supplies have the advantage over traditional pulse width modulation (PWM) converters due to their soft switching capabilities. In addition, the output current ripple can be reduced by using three phase interleaving structure. However, this structure also suffers from some disadvantages, such as resonant current imbalance. Most previous solutions have been focused on hardware as adding extra power switches, increasing the cost and volume of the converter. There are not many software solutions due to the difficulty in modeling unbalance three-phase. This paper will propose a smoothly resonant current balancing solution for the three-phase interleaved LLC structure which is based on controlling directly resonant current phase angles (CPAB). This proposed method shows better current balance and response than the old trigonometric current balancing (TCB) method. The proposed technique is also verified by a 48 V 3.6 kW prototype converter and its experimental results.

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1. INTRODUCTION

LLC resonant converters are increasingly popular in many applications, especially those requiring high efficiency and high power density. Interest is due to its preeminent characteristics, which includes zero-voltage switching (ZVS) of the primary side MOSFET and zero-current switching (ZCS) of the secondary diodes. By soft switching, the resonant converters are able to operate at higher frequencies, which increases the power intensity for the smaller component sizes ([1]-[5]). For high power converters, the interleaving resonance structure is of most interest. The influence of resonant parameter mismatch and the improvement of current balancing are discussed in ([6]-[11]). When component tolerance occurs between two modules, different gain characteristics will arise at a synchronous operating frequency. This will lose the advantage of interleaving control and will cause large output voltage ripples.

Various possible solutions for implementing an alternating resonant converter have been studied in ([12]-[17]). However, auxiliary power switches had to be added ([12]-[14]) or increased loss due to soft switching loss by phase shift [15]. Another method is to add a power stage to regulate the output voltage, increasing the loss, increasing the cost and volume of the converter ([16]-[18]). The interleaved LLC resonant converter presented in [12] adds variable inductors to compensate for gain characteristic mismatch. A previous work [13] proposed an automatic current balancing technique based on a magnetic coupling. Topologies using a

magnetic coupling for current balancing are prone to bulkiness due to the large number of magnetic components. Luo *et al.* [14], studied the switch-controlled capacitor method was used to control the output current sharing on each module. However, auxiliary power switches had to be added, increasing the cost and volume of the converter. Figge *et al.* [15], proposed the output voltage is regulated by variable frequency control of the primary switch, while the time delay control used to control the secondary side switch is to correct load current imbalances between inverters. In [16] and [17], the output voltage of the power factor correction (PFC) stage is used to compensate the parameter mismatch between two resonant modules. The PFC must be placed before each module of the resonator. The use of separate PFCs or pre-regulators may be cost-constrained for some applications. Lin *et al.* [18], studied the current sharing method requires an additional power stage to regulate the output voltage but this method causes lower conversion efficiency.

Due to the natural tolerances between the resonant components, modeling an interleaved three-phase LLC resonant circuit is difficult because of the large number of state variables. The usual approach to avoid unbalanced currents in a multi-phase resonant converter (set of single-phase converters) is to control the phases separately ([19]-[21]). Unfortunately, such a method cannot be applied on a three-phase resonant converter, because interleaved modulation of the phases cannot be achieved with different switching frequencies for the phases.

The influence of the tolerances between the resonant phases on the current sharing characteristics of the three-phase LLC is analyzed in [4] and [22]. Normally, a 10% tolerance in the value of the passive component (Cr, Lr and Lm) can be expected. Arshadi *et al.* [22], studied the trigonometric current balancing (TCB) technique is proposed to decrease the resonant current imbalance. However, adjusting indirectly the phase deviation angle between the resonant current vectors based on performing compensation of input voltage phase angles leads to poor current balance response in case of large tolerance of resonant components. In addition, a sudden large change in the switching angle between the inverter phases can affect the quality of the voltage control loop of the three-phase interleaved LLC resonant.

In this paper, an innovation method is proposed to improve the current balance with controlling directly the angles between the resonant current vectors to 120 degrees through the tuned PI controller. Simulation and experimental results show that the current balance of proposed method is better than that of the old TCB method. The cause of unbalanced sharing current among phases and its effect is analyzed in part 2. The proposed current balancing method is presented in part 3. Then the simulation and experiment results are shown in part 4. And finally, the conclusion is given in part 5.

2. CURRENT SHARING

The interested three-phase LLC resonant converter consists of three half-bridge DC-AC inverter modules, three resonant modules and three single-phase transformers connected in floated star point at primary side. This structure has been shown many advantages due to the inherent current-balancing characteristics between the phases ([23]-[25]). On the secondary side of the transformer are three half-bridge rectifier modules.

The proposed control structure of three-phase LLC converter with floating star connected is considered as Figure 1:

- One voltage controller is to stabilize the output voltage by the variable switching frequency.
- One phase current balancing controller performs the current phase angle balancing (CPAB) with PI regulator.

From equivalent circuit of the three-phase converter (Figure 2), we can find the equations according to Kirchhoff's laws 1 and 2 as follows:

$$\begin{cases} V_2 - V_1 + Z_1 I_1 - Z_2 I_2 = 0 \\ V_3 - V_1 + Z_1 I_1 - Z_3 I_3 = 0 \\ I_1 + I_2 + I_3 = 0 \end{cases} \quad (1)$$

Where the impedance of each phase Z_t can be calculated as (2):

$$Z_t = (L_r \omega - \frac{1}{C_r \omega} + \frac{L_{mt} R_{act}^2 \omega}{R_{act}^2 + L_{mt}^2 \omega^2})j + \frac{L_{mt} R_{act}^2 \omega}{R_{act}^2 + L_{mt}^2 \omega^2}, t = 1, 2, 3 \quad (2)$$

with the equivalent load reflected to primary of each phase.

$$R_{aci} = \frac{6}{\pi^2} N^2 R_o \quad (3)$$

Analyzing the influence of the difference between the resonant components is quite complicated because there are many variables. Instead, this can be considered in terms of the maximum and minimum values of the resonant frequency when there is a tolerance of the resonant components due to fabrication, typically $\pm 10\%$. In [22], the influence of each resonance components on the current balance characteristics has been analyzed in detail and has some key points as follows:

- Changes in L_{rt} and C_{rt} have the same effect on the phase angle and amplitude of the impedance. By changing L_{rt} and C_{rt} in the same direction will cause the most deviation in the value of the impedance.
- Changes in L_{mt} have the opposite effect on impedance phase angle compared to the effects of L_{rt} and C_{rt} . By changing L_{mt} and L_{rt} in opposite directions will result in the most amount of deviation in the value of impedance phase.
- The impedance phase angle and amplitude are much more sensitive to changes in the values of L_{rt} and C_{rt} than those of L_{mt} .

From the above analysis results show that the current deviation in the worst case when two phases have the largest resonant frequency and the other phase has the smallest resonant frequency with typical tolerance $\pm 10\%$.

$$\begin{cases} f_r(\min) = \frac{1}{2\pi\sqrt{(L_r+10\%)(C_r+10\%)}} \\ L_m(\min) = L_m - 10\% \\ f_r(\max) = \frac{1}{2\pi\sqrt{(L_r-10\%)(C_r-10\%)}} \\ L_m(\max) = L_m + 10\% \end{cases} \quad (4)$$

In item 3, the new current balancing method (CPAB) was developed and compared with the trigonometric current balancing method (TCB in [22]).

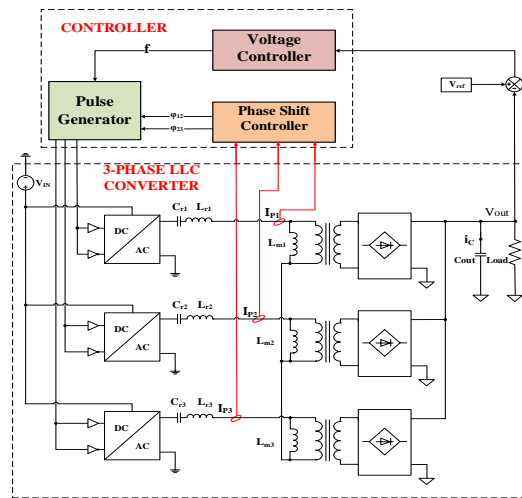


Figure 1. Three-phase interleaved LLC resonant converter with voltage and current balancing control structure

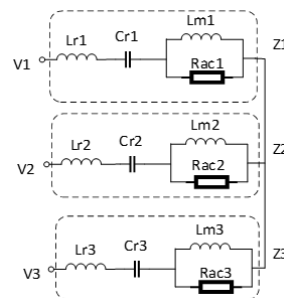


Figure 2. The equivalent circuit of three-phase LLC converter

3. CURRENT BALANCING TECHNIQUE

3.1. Trigonometric current balance (TCB)

The TCB method for the three-phase LLC star-connected resonant circuit on the primary side has been proposed and analyzed in [22]. Figure 3(a) shows that when we only shift the input voltage between the phases by 120 degrees, the phase current vector module will be significantly different. Based on the law of sine, if the phase angles between the current vectors are equal 120 degrees, the resonant currents will be equalized as Figure 3(b). Therefore, we can adjust the phase angle of the inverter voltage vectors to control the current balance. The PWM modulation method cannot be used here because of the limitation of soft-switching gain.

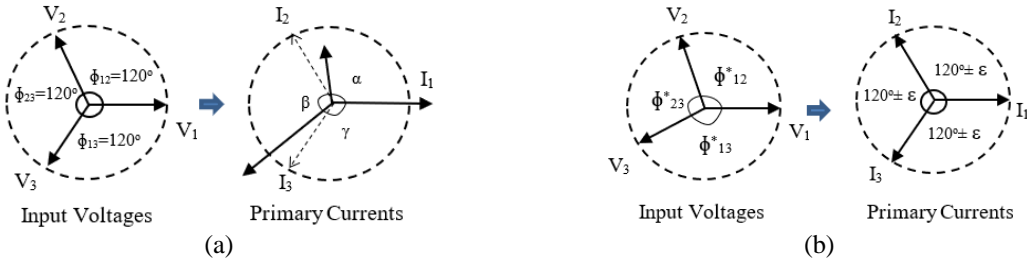


Figure 3. Balancing currents with changing the phase-shift of the input voltages: (a) basic 120 degrees phase-shifted input voltages and (b) balancing currents with changing the phase-shift of input voltages

The offset phase angle between the current vectors (α , β , and γ) is easily calculated from trigonometric triangle.

$$\begin{cases} \alpha = \pi - \arccos\left(\frac{I_1^2 + I_2^2 - I_3^2}{2I_1I_2}\right) \\ \beta = \pi - \arccos\left(\frac{I_1^2 + I_3^2 - I_2^2}{2I_1I_3}\right) \\ \gamma = \pi - \arccos\left(\frac{I_2^2 + I_3^2 - I_1^2}{2I_2I_3}\right) \end{cases} \quad (5)$$

ϕ'_{xy} are the new phase angles of the inverter voltage vectors, and ϕ_{xy} are the old phase angles in (6):

$$\begin{cases} \phi_{12}^* = \phi_{12} + (120^\circ - \alpha) \\ \phi_{23}^* = \phi_{23} + (120^\circ - \beta) \\ \phi_{13}^* = \phi_{13} + (120^\circ - \gamma) \end{cases} \quad (6)$$

Figure 4 shows the TCB control structure with estimating the phase angles between current vectors and adjusting indirectly the corresponding input voltage phase angle, and Figure 5 shows the CPAB structure with adjusting directly the current phase angles to set value 120 degree through PI algorithm. The indirect phase-shift of inverter legs can be considered as an "open-loop" control since no feed-back loop is used. Moreover, because the phase deviation between current and voltage at each phase is changed with the variable switching frequency and load, the indirect control of the current phase angle by simply compensating the voltage phase angle may lead to untimely current balance response. In addition, the voltage control performance of the interleaving circuit is strongly affected when the phase-shift at the inverter legs is suddenly too large. The method proposed in the next section (CPAB) gives better current-balancing characteristics by directly controlling the angle between the resonant current vectors to 120 degrees.

3.2. Current phase angle balancing technique (CPAB)

Instead of "open loop" control like the conventional TCB method mentioned above, a "close loop" control method with PI regulator has been developed by directly controlling the phase angle between the resonant currents to the set value of 120 degrees. The new control structure is illustrated in the Figure 5 and Figure 6. Below are the steps of the proposed current phase angle balancing technique (CPAB):

- Initially, the phase angles of input voltages are set to be 120° . If the circuit is unbalanced, this will lead to unbalanced currents between the phases according to the law of sines.
- The angles between the current vectors (α , β , and γ) are estimated by using (5).
- New switching angles ϕ_{12} , ϕ_{23} based on above angle feedback are calculated by PI regulators R01 and R02.

- After new switching angles are estimated, the inverter legs are shifted respectively via phase shift modulator as Figure 5, and then the controller goes back to step two. With this technique, the angles between resonant currents can be updated smoothly to 120 degrees, later result in resonant current balance perfectly.

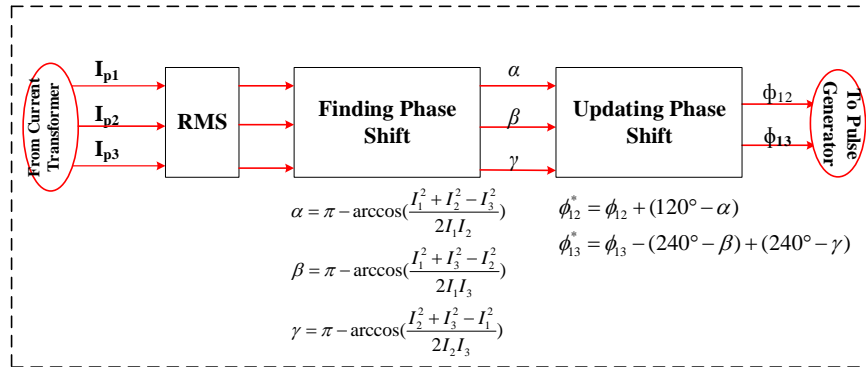


Figure 4. Current balancing structure TCB

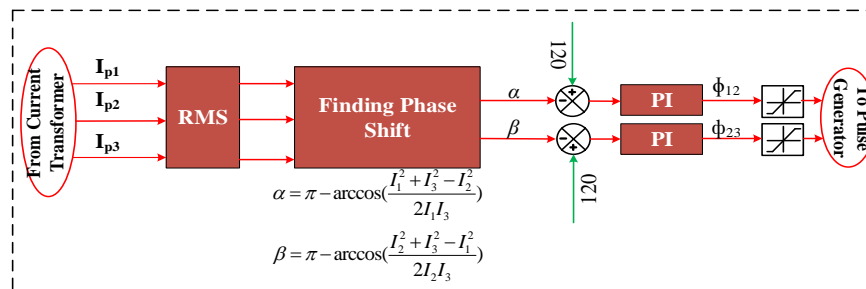


Figure 5. Current balancing structure CPAB

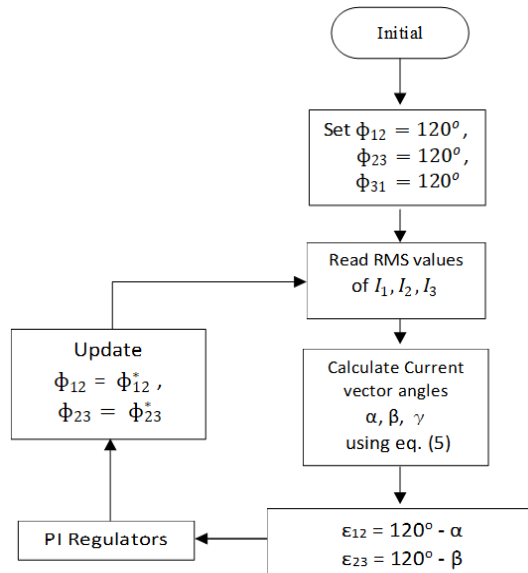


Figure 6. Flowchart of CPAB technique

4. SIMULATION AND EXPERIMENT

In order to analysis the proposed CPAB technique, the experimental tests and simulations have been done. A 3.6 kW three phase LLC resonant converter with the proposed control technique has been tested

under different conditions. Table 1 represents the main parameters of the model. The model (Figure 7) uses two PI controllers and a phase-shift calculator based on the proposed technique to control the output voltage and to equalize the currents in three phases.

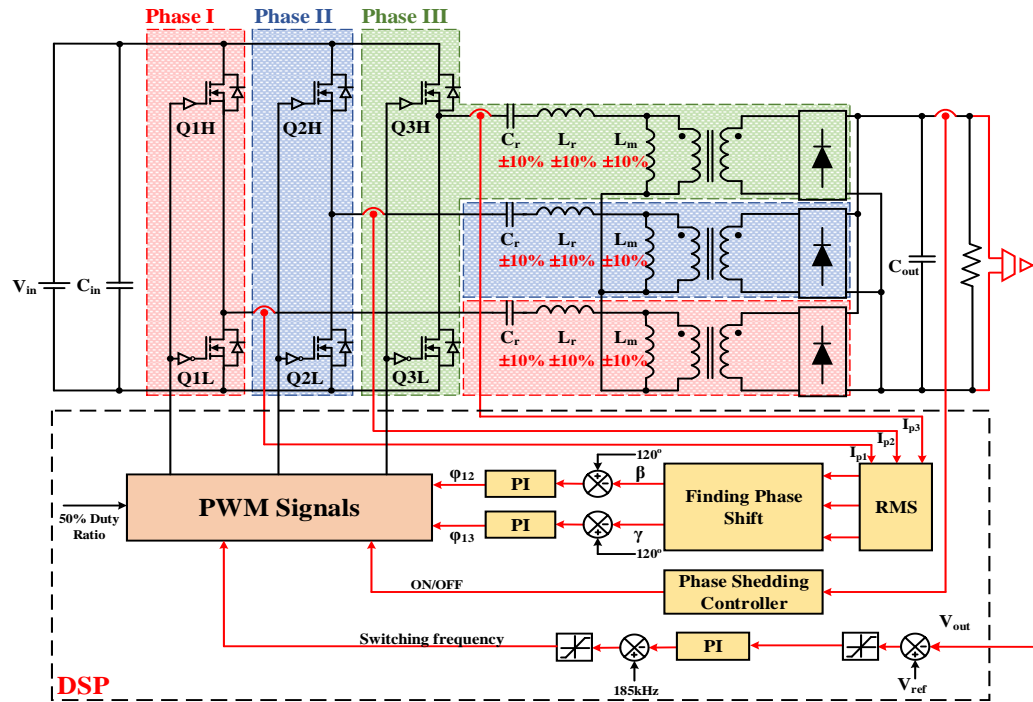


Figure 7. CPAB simulation diagram

Table 1. The main parameters of the simulation model

Parameters	Values
V_{in} / V_{out}	340-400VDC / 48VDC
$P_{out} (max)$	3.6kW
$I_{out} (max)$	70A
Turns ratio	4/1
f_r	185kHz
$L_r - C_r - L_m$	$5\mu H - 150nF - 30\mu H$

The simulation scenario is as follows: one phase has a tolerance of resonant components of -10%, the other phases is +10%. The load is changed in a step-up from 50% to 100% nominal value at 0.02s and a step-down from 100% to 50% at 0.04s. The simulation results are presented in 4 cases as follow:

- Ideal conditions with balance resonant components, not using current balance controller (ideal).
- Non-ideal condition, not using current balance controller (non-ideal).
- Non-ideal condition, using TCB structure (TCB).
- Non-ideal condition, using the proposed CPAB structure (CPAB).

The simulation results will be sorted in the order.

Figure 8 simulates the phase difference between current vectors in the cases (a) of ideally balanced circuit, (b) unbalanced circuit without control and (c) with TCB control and with (d) CPAB control. From simulation results (Figure 8), it is shown that the CPAB method achieves better current balancing than the TCB method. The phase deviation between the resonant currents is 0.4 degrees with CPAB, which is less than half of one with TCB, and much lower than the case without current balance control (9.5 degrees). The difference of current phase is lower than 0.5 degree which is equivalent to result of ideal condition.

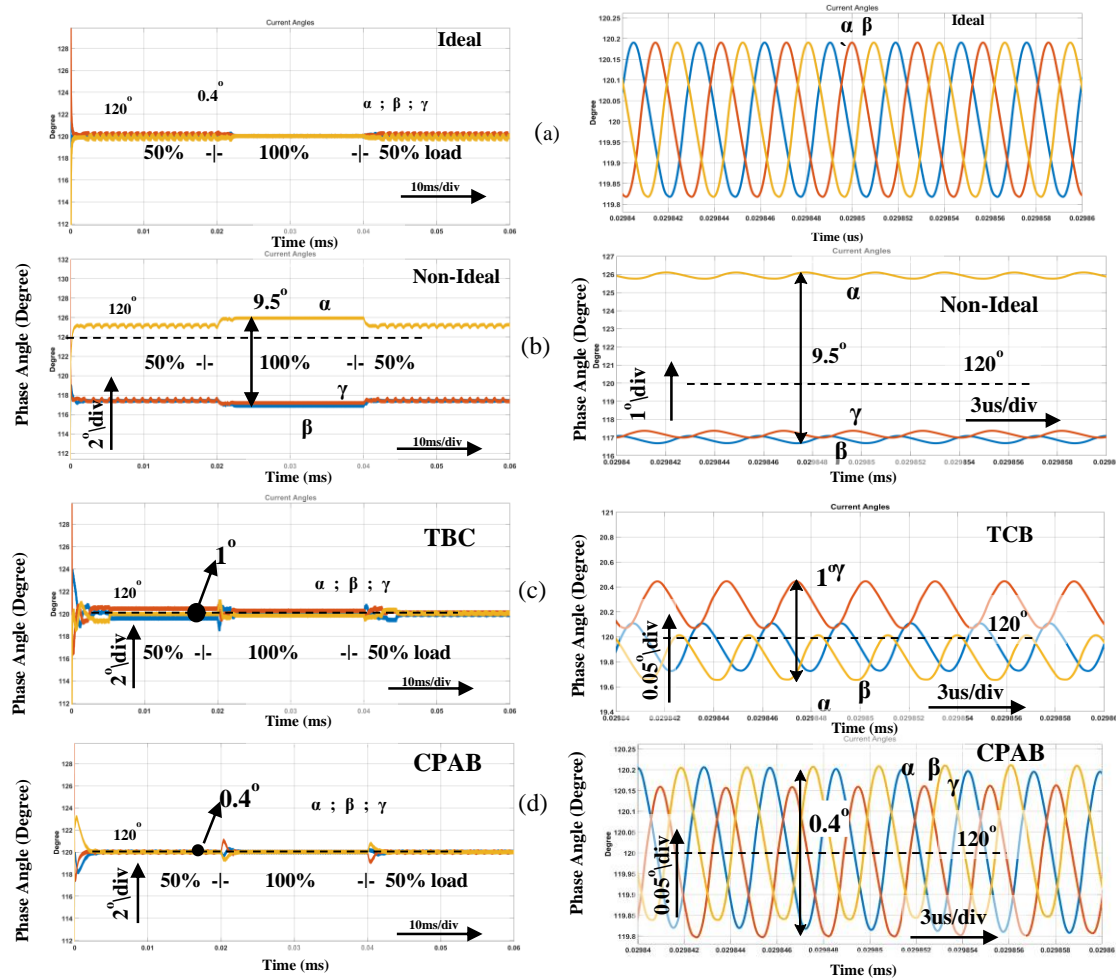


Figure 8. Phase angles between resonant currents and large zoom with tolerance resonant components $\pm 10\%$ in case of (a) ideal, (b) non-ideal, (c) TCB, and (d) CPAB

Figure 9 shows the current phase angle deviation and phase current unbalance when using TCB (Figures 9(a) and 9(b)) and when using CPAB (Figures 9(c) and 9(d)) in case of load change from half to full load and vice versa. Notably, in the case of a large tolerance of the resonant components ($\pm 20\%$), the TCB algorithm could not bring the current phase difference to 120 degrees, while the new CPAB algorithm managed perfectly to set value 120 degrees as Figure 9. And moreover, CPAB achieves better response to load changes than TCB.

The resonant current balance and output capacitor current ripples are compared in case of Ideal and non-ideal, TCB, CPAB with tolerances of resonant components $\pm 10\%$ (Figure 10 and Figure 11 (see Appendix)). The output capacitor current ripples with proposed CPAB is 14 A, approximately the Ideal case. And peak difference between resonant currents in case of CPAB is below 0.6 A, showing the high applicability of the CPAB technique.

Figure 12 shows the output voltage response and output power response of the dc-dc converter. The overshoot and undershoot of output voltage met the design requirements (< 0.5 V) as Figure 12(a) when the output power suddenly change as shown in Figure 12(b). Figure 13 shows the prototype, and the specifications of this platform are presented in Table 1. The experimental and simulation results are presented in cases of the balanced circuit, unbalanced circuit with applied TCB control, and with applied CPAB control.

Figure 14 shows the experimental flow results with TCB (Figures 14(a)-(c)) and with CPAB (Figures 14(d)-(f)) in the cases: below the resonant frequency (below f_r), at the resonant frequency (at f_r) and above the resonant frequency (above f_r). Experimental results, with common tolerances of resonant components, show that the balance of resonant phase currents with CPAB technique is more effective. Furthermore, with CPAB, the phase angle between the resonant currents is controlled approximately 120

degrees. Depending on the deviation in the normal values of the currents, this also results in slightly lower efficiency and significant reduction in the output capacitor current ripple. Table 2 shows that the difference between the measured r.m.s. current values of the resonant phases by applying the CPAB algorithm is lower than that of the old TCB algorithm. In real experiment, the converter with CPAB also achieves soft switching ZVS with stable output voltage and low voltage ripples (as Figure 15 and Figure 16). The difference value of approximately 1A are just acceptable, but enough to verify the improved CPAB technique.

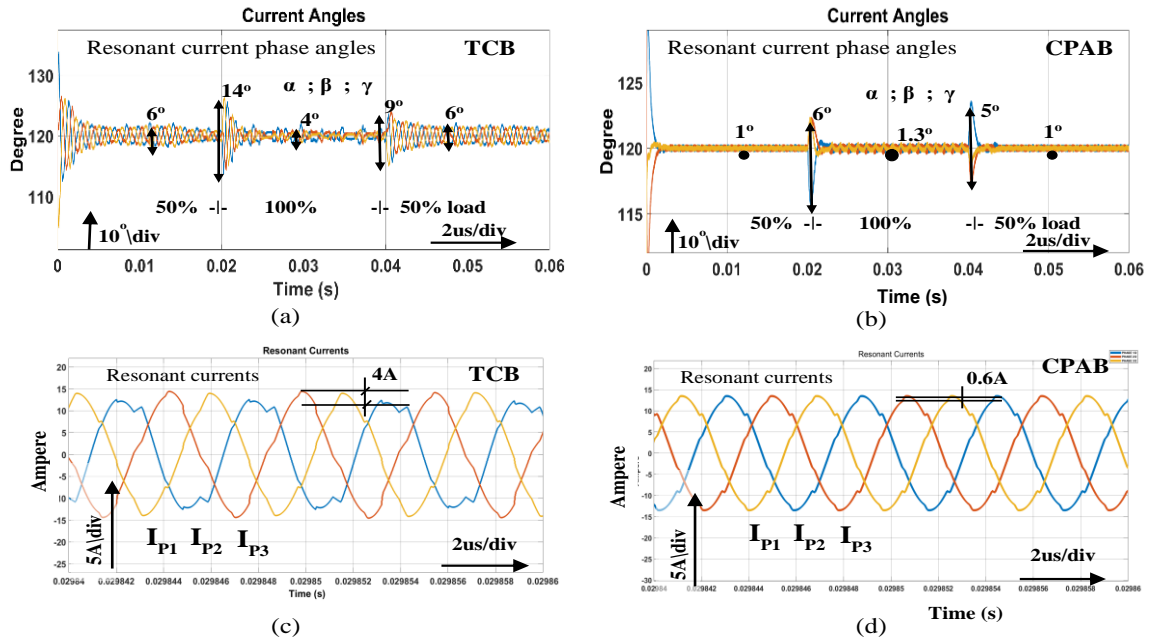


Figure 9. In case of tolerance resonant components $\pm 20\%$: (a) resonant current phase angles with using TCB vs (b) resonant current phase angles with using CPAB and (c) resonant currents with using TCB vs (d) resonant currents with using CPAB

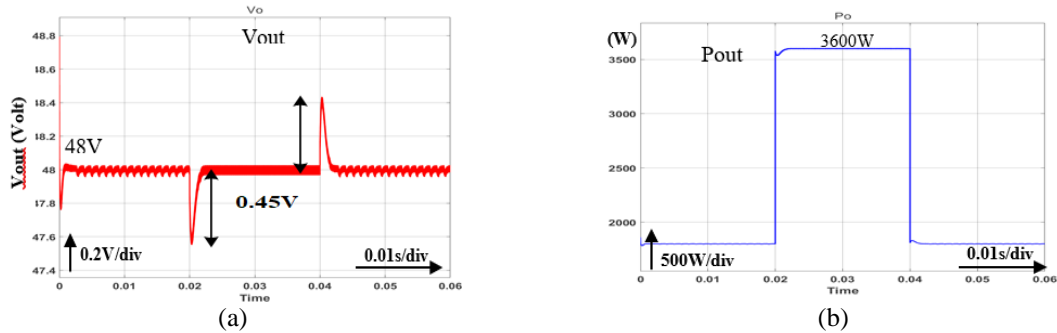


Figure 12. Output voltage and power of the converter: (a) output voltage and (b) output power

Experimental setup:

- Power circuit: Based on SiC MOSFET
- Control circuit: DSP TMS320F28379D
- DC voltage: 400 VDC
- Output power: 3600W
- Output voltage: 48V
- Specific parameter: shown in Table 1

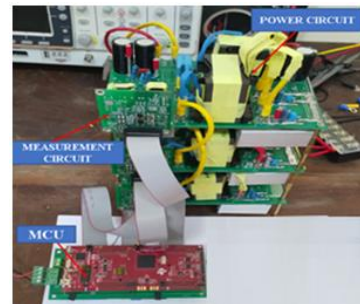


Figure 13. 3.6 kW experimental model

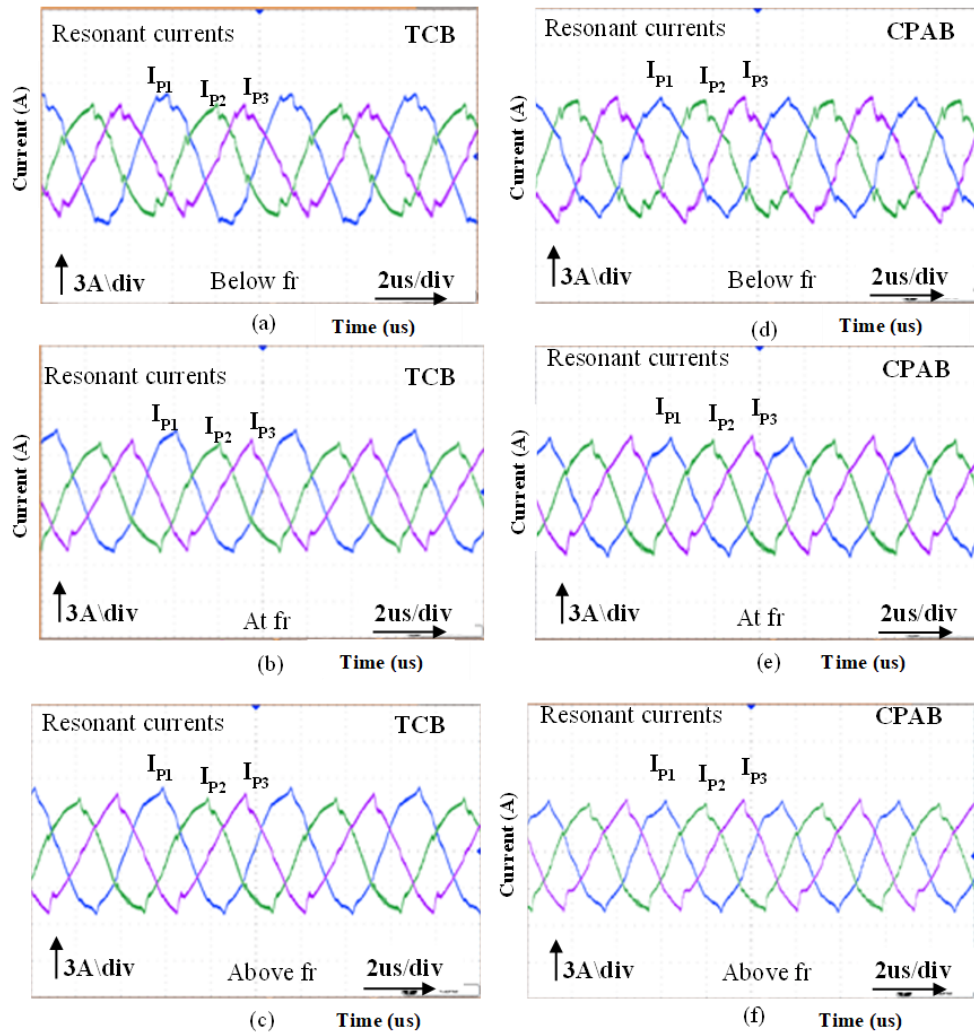


Figure 14. Experimental results: three-phase resonant currents: (a), (b), (c) with TCB control and (d), (e) (f) with CBAP control: (a), (d) at below frequency; (b), (c) at frequency; and (e), (f) above frequency

Table 2. Experimental results: RMS three-phase resonant currents with TCB and with CPAB

Switching frequency	With TCB			With CPAB		
	Phase1	Phase2	Phase3	Phase1	Phase2	Phase3
Below resonant	7.45A	7.15A	6.75A	7.35A	7.1A	6.85A
At resonant	7.30A	7.12A	6.87A	7.24A	7.12A	7.02A
Above resonant	7.12A	6.97A	6.80A	7.10A	6.98A	6.86A

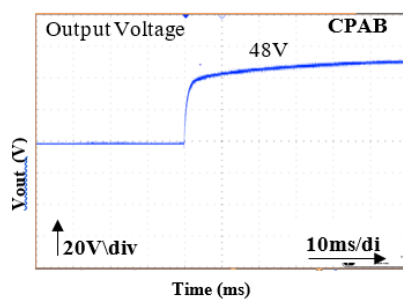


Figure 15. Output voltage

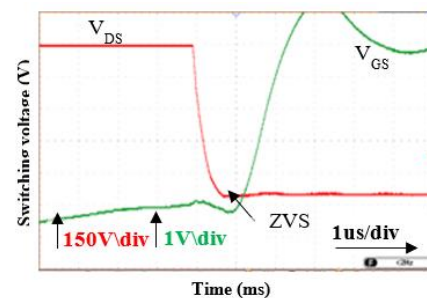


Figure 16. Zero voltage switching

5. CONCLUSION

In this paper, the new technique (current phase angle balancing (CPAB)) is proposed to improve the unbalanced behavior of the three-phase converters. This proposed technique achieves the resonant current balance by controlling directly the current phase angles. The results of simulation and experiment of the interleaved three-phase LLC resonance model show that the resonant current balance is better achieved than those of the previous TCB method. Notably, in the case of a large tolerance of the resonant components (20%), the TCB algorithm could not bring the current phase difference to 120 degrees, while the new CPAB algorithm managed perfectly to set value 120 degrees. The results also show that the current ripples on output capacitor is significant decreased. Therefore, being able to use smaller output capacitor filter will result in lower power loss and better heat distribution. The solution proposed in this paper may be applied to commercialized products.

APPENDIX

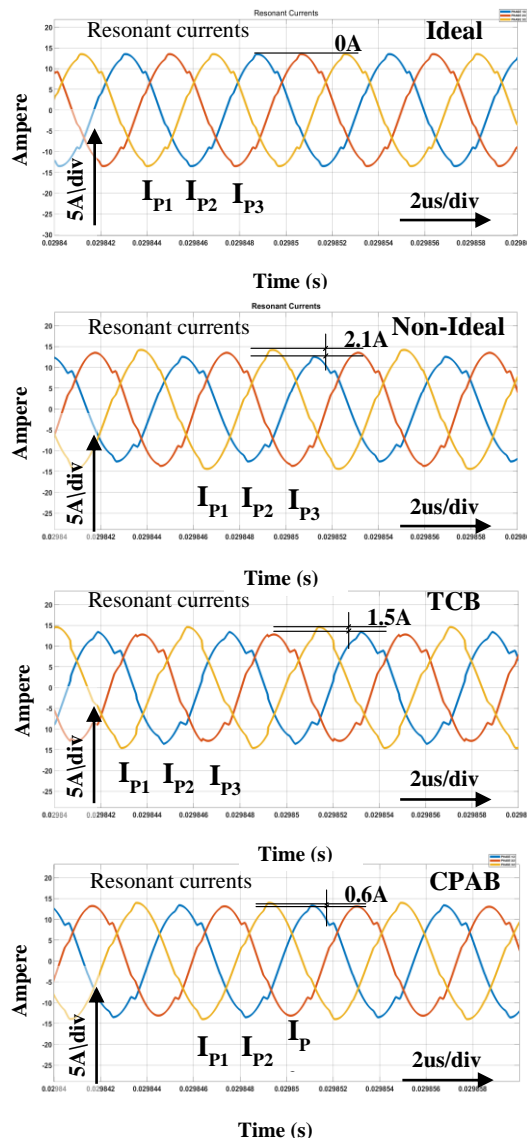


Figure 10. Three-phase resonant currents

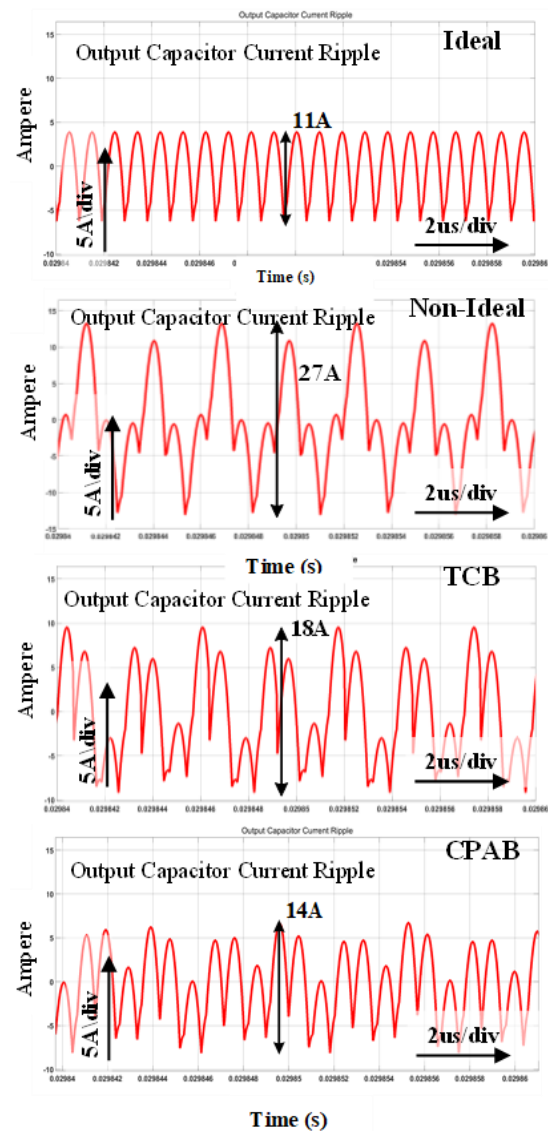


Figure 11. Output current ripples





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REFERENCES

- [1] M. Sato, R. Takiguchi, J. Imaoka, and M. Shoyama, "A novel secondary PWM-controlled interleaved LLC resonant converter for load current sharing," *IEEE 8th Int. Power Electron. Motion Control Conf. IPEMC-ECCE Asia 2016*, 2016, pp. 2276–2280, doi: 10.1109/IPEMC.2016.7512652.
- [2] C. Adragna, S. De Simone, and C. Spini, "A design methodology for LLC resonant converters based on inspection of resonant tank currents," *Conf. Proc. - IEEE Appl. Power Electron. Conf. Expo. - APEC*, no. Mi, 2008, pp. 1361–1367, doi: 10.1109/APEC.2008.4522901.
- [3] R. Beiranvand, M. R. Zolghadri, B. Rashidian, and S. M. H. Alavi, "Optimizing the LLC-LC resonant converter topology for wide-output-voltage and wide-output-load applications," *IEEE Trans. Power Electron.*, vol. 26, no. 11, pp. 3192–3204, 2011, doi: 10.1109/TPEL.2011.2143429.
- [4] Z. Hu, Y. Qiu, L. Wang, and Y. F. Liu, "An interleaved LLC resonant converter operating at constant switching frequency," *IEEE Trans. Power Electron.*, vol. 29, no. 6, pp. 2931–2943, 2014, doi: 10.1109/TPEL.2013.2273939.
- [5] J. Liu, J. Zhang, T. Q. Zheng, and J. Yang, "A Modified Gain Model and the Corresponding Design Method for an LLC Resonant Converter," *IEEE Trans. Power Electron.*, vol. 32, no. 9, pp. 6716–6727, 2017, doi: 10.1109/TPEL.2016.2623418.
- [6] Ö. Ş. Alemdar and O. Keysan, "Design and implementation of an unregulated DC-DC transformer (DCX) module using LLC resonant converter," *IET Conf. Publ.*, vol. 2016, no. CP684, 2016, pp. 1–6, doi: 10.1049/cp.2016.0156.
- [7] T. Shimada, "Current sharing method using secondary voltage ripple for an interleaved LLC resonant converter," *21st Eur. Conf. Power Electron. Appl. EPE 2019 ECCE Eur.*, 2019, doi: 10.23919/EPE.2019.8915456.
- [8] S. Zong, H. Luo, W. Li, X. He, and C. Xia, "Theoretical Evaluation of Stability Improvement Brought by Resonant Current Loop for Parallelled LLC Converters," *IEEE Trans. Ind. Electron.*, vol. 62, no. 7, pp. 4170–4180, 2015, doi: 10.1109/TIE.2014.2385661.
- [9] K. Murata and F. Kurokawa, "An interleaved PFM LLC resonant converter with phase-shift compensation," *IEEE Trans. Power Electron.*, vol. 31, no. 3, pp. 2264–2272, 2016, doi: 10.1109/TPEL.2015.2427735.
- [10] S. A. Arshadi, M. Ordonez, M. Mohammadi, and W. Eberle, "Efficiency improvement of three-phase LLC resonant converter using phase shedding," *IEEE Energy Convers. Congr. Expo. ECCE 2017*, vol. 2017-Janua, 2017, pp. 3771–3775, doi: 10.1109/ECCE.2017.8096666.
- [11] H. Wang, Y. Chen, Y. F. Liu, and P. C. Sen, "A general multi-phase coupled-resonant-tank resonant converter," *Conf. Proc. - IEEE Appl. Power Electron. Conf. Expo - APEC*, vol. 2018-March, 2018, pp. 2183–2190, doi: 10.1109/APEC.2018.8341319.
- [12] E. Orietti, P. Mattavelli, G. Spiazzi, C. Adragna, and G. Gattavari, "Two-phase interleaved LLC resonant converter with current-controlled inductor," *Brazilian Power Electron. Conf. COBEP2009*, 2009, pp. 298–304, doi: 10.1109/COBEP.2009.5347671.
- [13] K. I. Hwu and Y. H. Chen, "Applying differential-mode transformer to current sharing with current ripple considered," *IEEE Trans. Ind. Electron.*, vol. 58, no. 7, pp. 2755–2771, 2011, doi: 10.1109/TIE.2010.2080650.
- [14] J. Luo, J. Wang, Z. Fang, J. Shao, and J. Li, "Optimal design of a high efficiency LLC resonant converter with a narrow frequency range for voltage regulation," *Energies*, vol. 11, no. 5, 2018, doi: 10.3390/en11051124.
- [15] H. Figge, T. Grote, N. Froehleke, J. Boecker, and P. Ide, "Paralleling of LLC resonant converters using frequency controlled current balancing," *PESC Rec. - IEEE Annu. Power Electron. Spec. Conf.*, 2008, pp. 1080–1085, doi: 10.1109/PESC.2008.4592073.
- [16] H. Figge, T. Grote, F. Schafmeister, N. Froehleke, and J. Bocker, "Two-phase interleaving configuration of the LLC resonant converter - Analysis and experimental evaluation," *IECON Proc. Industrial Electron. Conf.*, 2013, pp. 1392–1397, doi: 10.1109/IECON.2013.6699336.
- [17] A. K. S. Bhat, S. Member, and R. L. Zheng, "A Three-phase Series-Parallel Resonant and Experimental Results," *IEEE Trans. Ind. Appl.*, vol. 32, no. 4, 1996.
- [18] J. Y. Lin, K. H. Chen, P. H. Liu, H. Y. Yueh, and Y. F. Lin, "Current sharing control of an interleaved three-phase series-resonant converter with phase shift modulation," *Energies*, vol. 14, no. 9, 2021, doi: 10.3390/en14092470.
- [19] Y. Panov, J. Rajagopalan, and F. C. Lee, "Analysis and design of N paralleled DC-DC converters with master-slave current-sharing control," *Conf. Proc. - IEEE Appl. Power Electron. Conf. Expo. - APEC*, vol. 1, 1997, pp. 436–442, doi: 10.1109/apec.1997.581489.
- [20] B. C. Kim, K. B. Park, and G. W. Moon, "Analysis and design of two-phase interleaved LLC resonant converter considering load sharing," *IEEE Energy Convers. Congr. Expo. ECCE 2009*, 2009, pp. 1141–1144, doi: 10.1109/ECCE.2009.5316291.
- [21] T. Jin and K. Smedley, "Multiphase LLC series resonant converter for microprocessor voltage regulation," *Conf. Rec. - IAS Annu. Meet. - IEEE Ind. Appl. Soc.*, vol. 5, no. c, pp. 2136–2143, 2006, doi: 10.1109/IAS.2006.256838.
- [22] S. A. Arshadi, M. Ordonez, W. Eberle, M. A. Saket, M. Craciun, and C. Botting, "Unbalanced Three-Phase LLC Resonant Converters: Analysis and Trigonometric Current Balancing," *IEEE Trans. Power Electron.*, vol. 34, no. 3, pp. 2025–2038, 2019, doi: 10.1109/TPEL.2018.2846526.
- [23] E. Orietti *et al.*, "Analysis of multi-phase LLC resonant converters," *Conf. Proc. - IEEE Appl. Power Electron. Conf. Expo. - APEC*, vol. 2015-May, no. 3, 2009, pp. 464–471, doi: 10.1109/COBEP.2009.5347673.
- [24] M. Salem *et al.*, "Improved topology of three-phase series resonant DC-DC boost converter with variable frequency control," *Alexandria Eng. J.*, vol. 61, no. 2, pp. 1701–1713, 2021, Doi: 10.1016/j.aej.2021.06.078.
- [25] S. A. Arshadi, M. Ordonez, W. Eberle, M. Craciun, and C. Botting, "Three-Phase LLC Battery Charger: Wide Regulation and Improved Light-Load Operation," *IEEE Trans. Power Electron.*, vol. 36, no. 2, pp. 1519–1531, 2021, doi: 10.1109/TPEL.2020.3006422.





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