11th International Conference on Power Electronics-ECCE Asia
May 22 - 25, 2023 / ICC Jeju, Jeju, Korea

A Natural Current Sharing in LLC Resonant Converter and Analysis of the Current Sharing Error

Taewoo Kim[1], Jeongchan Park[1], Donghyeon Yu[1], Joonsu Kim[1], and Gun-Woo Moon[1]
[1] Electrical engineering, KAIST, Daejeon, Republic of Korea

***Abstract*-- Input-parallel and output-parallel (IPOP) converters are commonly used to share the high output current. However, unbalanced current occurs because they have a voltage gain difference due to the tolerance of the components. Therefore, IPOP converters require expensive current sensors and complex controls for current sharing. To improve these drawbacks, this paper proposes a novel LLC resonant converter capable of natural current sharing. The proposed converter can achieve current sharing without expensive current sensors and complex controls. In addition, it can have small current sharing errors. Furthermore, the structure of proposed converter is implemented simply through the secondary-side point connection without additional components. Finally, the feasibility of the proposed converter is verified by the experimental results with a 100 V/20 A 2000 W lab prototype converter.**

***Index Terms*—Current sharing error, Input-parallel output-parallel converters, Unbalanced current, Voltage gain difference.**

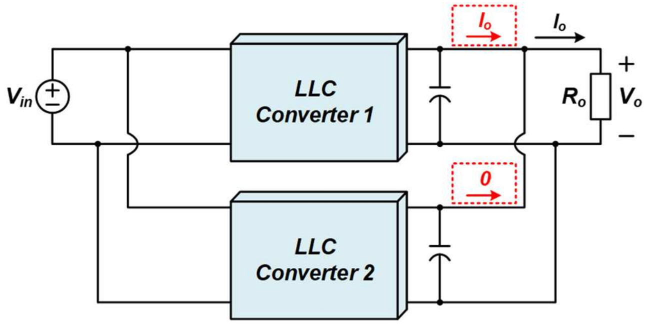
I. Introduction

Generally, input-parallel and output-parallel (IPOP) converters are widely used in high-current applications. They can increase the overall power of the system and achieve a high efficiency to divide the converter's currents. However, IPOP converters have a problem that current imbalance occurs [1]. Therefore, extreme current can flow through the one converter and destroy it, as shown in Fig. 1.

Fig. 2 shows the causes of unbalanced current. IPOP converters ideally have the same voltage gain, but as shown in Fig. 2, the voltage gains between converter units are slightly different due to the tolerance of components. As a result, an extremely unbalanced current flows through one converter in order to have the same voltage gain.

Unbalanced current deteriorates the reliability of the IPOP converters because it increases the current stress of components. Therefore, a current sharing method using current feedback loop has been proposed [2]. It can control the unbalanced current by sensing the current of each converter unit. However, the research in [2] requires expensive current sensors and complex controls.

Many studies have been suggested to solve the unbalanced current problem [3]-[11]. The papers [3]-[6] perform closed-loop current control by adding a new control variable to achieve current sharing. The switching frequency control [3] and phase-shift modulation control [4] are used in the *LLC* resonant converter. The new control variables compensate for the tolerance of components to achieve current sharing. The switch-controlled capacitor [5] and saturable inductor [6] are used in the *LLC* resonant converter. They control the gain of the resonant tank through an additional capacitor or inductor. Thus, the current sharing can be achieved by changing the impedance of converter's resonant tank. The aforementioned papers have a small current sharing error by using a new control variable. That is, they can achieve excellent current sharing performance. However, the



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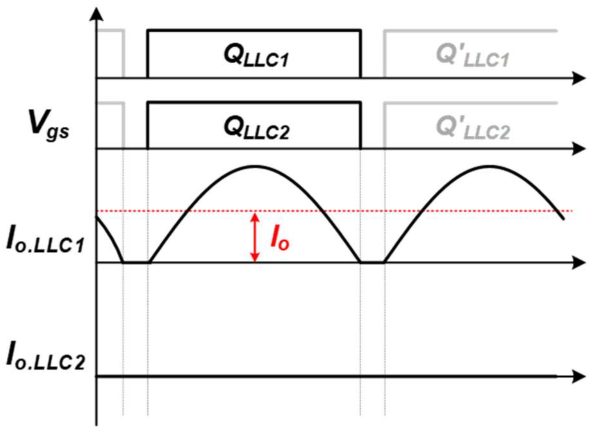

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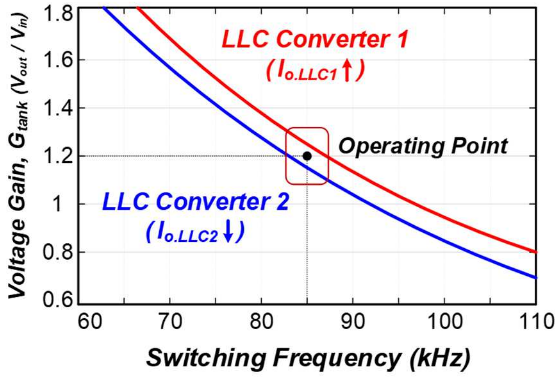
Fig. 1. Unbalanced current of IPOP converters. (a) Circuit Diagram. (b) Key waveforms.

TABLE I
Comparison of the Researches

	[7]	[8]	[9]	[10]	[11]	Proposed
Method	Inductor coupling	Transformer coupling	Current·sec balance	Common inductor	Common capacitor	Variable voltage sources
Current sharing	Good	Good	Excellent	Normal	Normal	Excellent
Circuit complexity	Resonant inductor design	Transformer design	Flying capacitor, gate driver			



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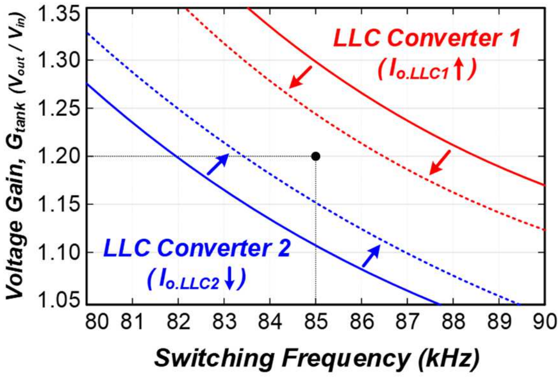

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Fig. 2. Causes of unbalance current. (a) Key graph. (b) Enlarged operating point.

papers [3]-[6] require expensive current sensors and complex controls. In addition, in [5]-[6], they require additional switches, capacitors, or inductors. As a result, the aforementioned papers increase the overall cost of the system.

To improve theses drawbacks, natural current sharing methods have been proposed [7]-[11]. They can achieve current sharing using topological features without expensive current sensors and complex controls. In [7]-[8], the coupling of resonant inductors [7] and transformers [8] is used for current sharing. In [9], the flying capacitor is used for current sharing. In [10]-[11], the common inductor and capacitor are used for current sharing. As a result, the researches in [7]-[11] can achieve current sharing through simple magnetic coupling or circuit

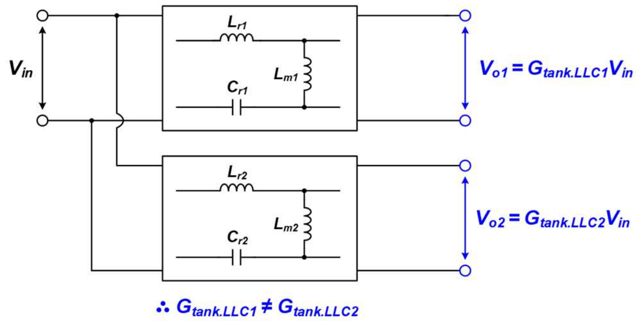


Fig. 3. Concept of proposed converter.

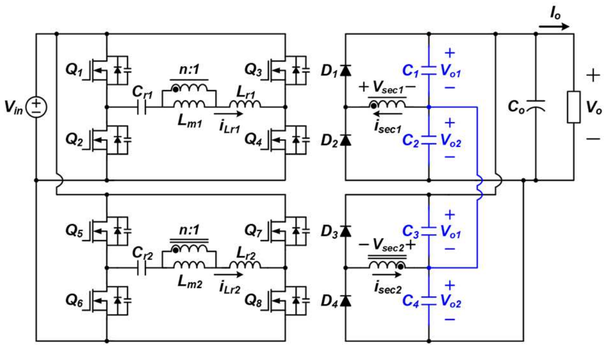
connections. However, they have drawbacks in terms of current sharing performance, and circuit complexity. Detailed comparisons are summarized in Table I.

This paper proposes a novel LLC resonant converter with natural current sharing. Its structure is based on variable voltage sources and secondary-side point connection. The proposed converter achieves current sharing without expensive current sensors and complex controls. In addition, it can have excellent current sharing by using variable voltage sources. Finally, the proposed converter does not increase the circuit complexity through simple secondary-side point connection.

The contents of this paper are as follows: Section II describes the mode analysis of the proposed converter. It focuses on the circuit diagram and mode analysis of the proposed converter. Section III describes the simulation result of IPOP converters. The theoretical analysis will be verified through simulation results. Section IV describes the experimental result of IPOP converters. It focuses on the design specification and key waveforms. Lastly, conclusion is presented in Section V.

II. Mode Analysis of the Proposed Converter

The concept of the proposed converter is shown in Fig. 3. The conventional IPOP converters have an unbalanced current problem due to the same voltage gain. However, the proposed converter makes it possible to have different voltage gains between each converter unit. Therefore, it can naturally solve the unbalanced current problem. The detailed equations can be demonstrated as follow:



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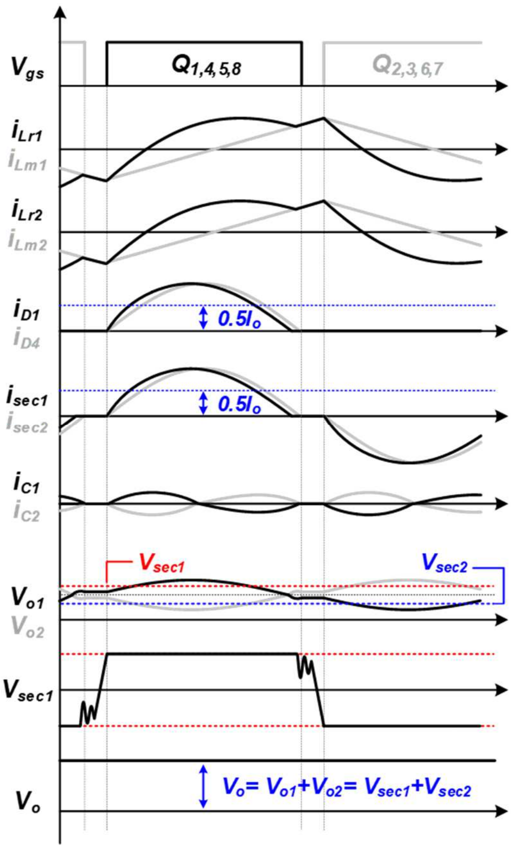

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Fig. 4. Proposed converter. (a) Circuit diagram. (b) Key waveforms.

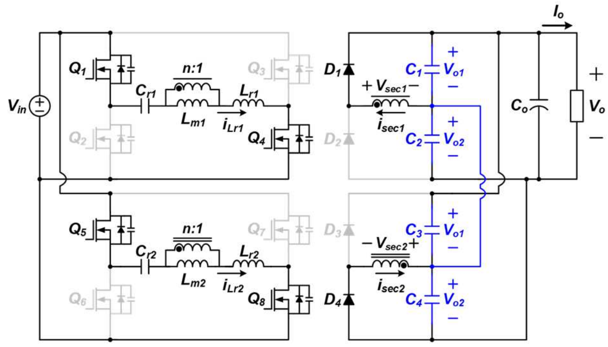
$$V_{o.conv} = G_{tank.LLC1.conv} V_{in} = G_{tank.LLC2.conv} V_{in}, \quad (1)$$

$$G_{tank.LLC1.conv} = G_{tank.LLC2.conv}, \quad (2)$$

$$V_{o1.prop} = G_{tank.LLC1.prop} V_{in}, \quad V_{o2.prop} = G_{tank.LLC2.prop} V_{in}, \quad (3)$$

$$G_{tank.LLC1.prop} \neq G_{tank.LLC2.prop}, \quad (4)$$

where $V_{o.conv}$ is a output voltage of conventional IPOP converters, $G_{tank.LLC.conv}$ is a voltage gain of conventional IPOP converters, $V_{o.prop}$ is a output voltage of proposed converters, $G_{tank.LLC.prop}$ is a voltage gain of proposed converters, and V_{in} is a input voltage of converters.



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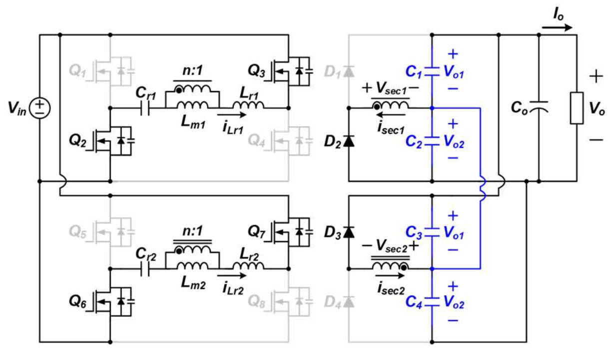


(b)

Fig. 5. Mode analysis of proposed converter. (a) Mode1 [$t_1 - t_2$]. (b) Mode2 [$t_3 - t_0$].

Fig. 4 shows the circuit diagram and key waveforms of the proposed converter. The proposed converter is implemented through capacitors $C_1 \sim C_4$ with low capacitance and secondary side point connection, as shown in Fig. 4(a). The capacitors $C_1 \sim C_4$ with low capacitance are defined as variable voltage sources because they allow each converter unit to have a different voltage gain while charging and discharging the capacitors. The voltage variable sources can improve current sharing performance by lowering the capacitance. As a result, the proposed converter has natural current sharing capability and operates the same as conventional IPOP converters with voltage doubler rectifier. As shown in Fig. 4(b), the proposed converter can achieve natural current sharing. A small unbalanced current flows into the variable voltage sources to compensate for the voltage gain difference.

Detailed analysis and characteristics are illustrated as shown in Fig. 5. The assumptions are as follows:

1) All parasitic components are ignored except for those shown in Fig. 4(a).
2) All switches and diodes are ideal except for output capacitors and junction capacitors.
3) The sinusoidal voltages V_{o1}, V_{o2} of variable voltage sources are approximated as square waveforms.

Mode 1 [$t_1 - t_2$] : Mode 1 starts when switches $Q_{1,4,5,8}$ are turned on. The currents resonate and deliver power to the output. V_{o1} is matched to converter 1 with higher

TABLE II
DESIGN SPECIFICATION

Input Voltage, V_{in}	200 ~ 400 V
Output Voltage, V_o	100 V
Output Power, P_o	2000 W
Transformer turn ratio, n	8
Resonant Frequency, f_r	100 kHz
Resonant Capacitance, C_r	36 nF
Resonant Inductance, L_r	48 uH
Magnetizing Inductance, L_m	160 uH

voltage gain and V_{o2} is matched to converter 2 with lower voltage gain by voltage variable sources. Both converters have almost the same current and consequently conduction losses are reduced.

Mode 2 [$t_3 - t_0$] : Mode 2 starts when switches $Q_{2,3,6,7}$ are turned on. The currents resonate and deliver power to the output. V_{o2} is matched to converter 1 with higher voltage gain and V_{o1} is matched to converter 2 with lower voltage gain. Voltage variable sources are charged and discharged naturally according to the voltage gain of each converter. Therefore, the currents of IPOP converters are naturally shared.

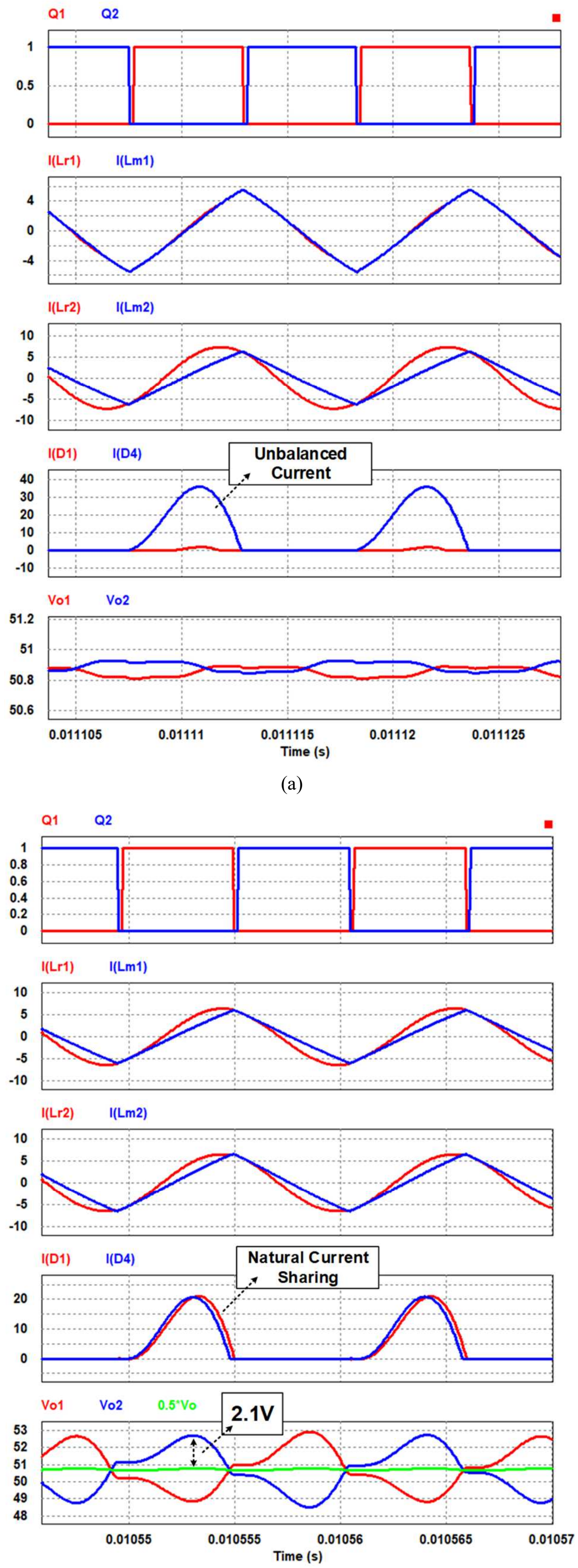
III. SIMULATION RESULT OF IPOP CONVERTERS

Section III verifies the contents described in Section II through PSIM simulation results. The input voltage is 200~400 V, the output voltage is 100 V, the output power is 2000 W, and the detailed resonant tank is designed as shown in TABLE II.

Fig. 6 shows the key waveforms of conventional and proposed converter by PSIM simulation results. It is assumed that the resonant tank has a 10% tolerance and is designed for the following worst-case conditions.

$$\text{Tolerance:} C_{r2} = 1.1C_{r1}, L_{r2} = 1.1L_{r1}, L_{m2} = 0.9L_{m1} \quad (5)$$

As in the theoretical analysis mentioned above, conventional converters have extremely unbalanced current because their voltage gains are different due to the tolerance of the resonant tank. Therefore, most of the current flows in the converter with higher voltage gain and little current flows in the converter with lower voltage gain. However, the proposed converters have almost the same current. A small current flows through the variable voltage sources to charge and discharge the capacitors. The voltage fluctuation of about 2.1 V occurs in the PSIM simulation. Thus, it compensates for the difference in voltage gain between each converter. As a result, the proposed converters have good current sharing performance.



(a)

(b)

Fig. 6. PSIM simulation results with 10% tolerance. (a) Conventional converters. (b) Proposed converters.

TABLE III
Component list of converters

	Conventional converter	Proposed converter
Primary switch,	IPW60R099C6 (600V, 99mΩ)	
Secondary diode,	VF30150C (150V, 0.81V_F)	
Resonant capacitor,	Film capacitor Converter 1 : $C_{r1} = 36nF$ Converter 2 : $C_{r2} = 40nF$ (+11.1%)	
Resonant inductor,	PQ32/30 (26) Converter 1 : $L_{r1} = 47.55uH$ Converter 2 : $L_{r2} = 51.94uH$ (+9.2%)	
Transformer,	PQ40/40 (40:5) Converter 1 : $L_{m1} = 156.21uH$ Converter 2 : $L_{m2} = 143.6uH$ (-8.1%)	
Doubler capacitor,	Film capacitor (40uF)	Film capacitor (0.5uF)

IV. Experimental Results

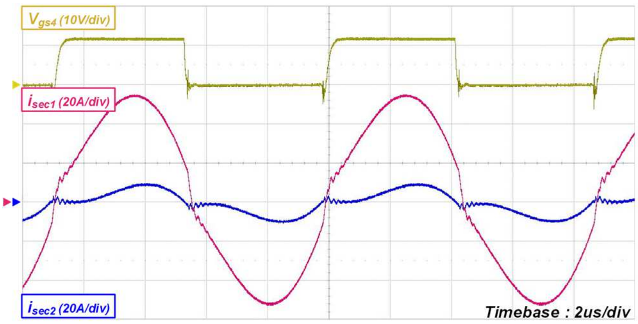
A. Design Specification

To confirm the effectiveness of the proposed converter, 2000W lab prototype experiments were conducted. The detailed component list is summarized in Table III.

B. Experimental Waveforms.

To confirm the effectiveness of the proposed converter, 2000W lab prototype experiments were conducted. The detailed component list is summarized in Table III.

Fig. 7 shows the experimental waveforms of the conventional and proposed converter. In the conventional converter, an unbalanced current flows through one converter unit due to the tolerance of components. Therefore, it causes high current stress and conduction loss. However, in the proposed converter, half current flows in each converter unit through natural current sharing. Thus, it causes low current stress and conduction loss. As a result, the proposed converter can achieve current sharing through variable voltage sources with small capacitance and secondary-side point connection.



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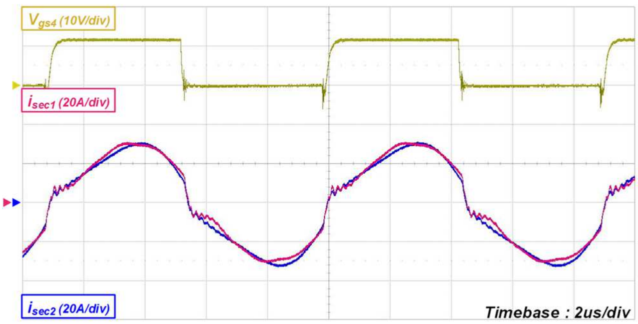

(b)

Fig. 7. Experimental waveforms. (a) Conventional converters. (b) Proposed Converters.

V. Conclusion

In this paper, the LLC resonant converter based on variable voltage sources is proposed. The proposed converter has excellent current sharing performance without additional component. In addition, it can perform the phase-shedding similar to the conventional converter. As a result, the proposed converter has low current stress and conduction loss thanks to the natural current sharing. Compared with previous studies, the proposed converter can improve most of the drawbacks that occurred in previous studies. Therefore, the proposed converter is suitable for high-current applications.

Acknowledgment

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT)(No.2021R1A5A1031868).

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