# An Integrated Magnetic-based IPOP LLC Resonant Converter

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ABSTRACT

This paper proposes an integrated magnetic current balancing transformer (IMCBT) that allows the current to be shared naturally between phases of an input parallel output parallel (IPOP) LLC converter. In this design, resonant inductors are integrated into transformer; simultaneously, there is a strong coupling between the inductors to minimize the difference of phase currents. Therefore, the proposed structure reduces the number of magnetic components and ensures balanced operation between phases. A 2 kW prototype is constructed to validate the proposed structure.

## 1. Introduction

The IPOP LLC resonant converter, as depicted in Fig. 1(a), effectively increases the power of system without increasing the current rating of switches and components[1]. However, due to the mismatch in the parameter of resonant tanks ($L_{rX}$, $C_{rX}$, $L_{mX}$, X = {A, B}), the tank currents ($i_{rA}$, $i_{rB}$) experienced unbalanced conditions. A current balancing transformer (CBT) connects two resonant tanks, allowing the tank currents to be shared automatically[1]. Resonant inductors can also be integrated into the CBT[2] to reduce the magnetic volume. However, this structure is not feasible when the leakage inductance of transformer is used as the resonant inductor.

This paper proposes an integrated magnetic current balancing transformer (IMCBT) for the IPOP LLC converter, which utilizes the leakage inductance of transformer as the resonant inductor. It also allows high coupling between leakage inductances. Thereby achieving natural current sharing and reducing the number of magnetic components.

## 2. The IMCBT-based IPOP LLC converter

### 2.1 Structure of the proposed IMCBT

The IMCBT shown in Fig. 1(b) uses U-shape ferrite cores; each phase includes two primary windings connected in series ($N_{p1}$, $N_{p2}$) and a secondary winding ($N_s$). The $N_s$ and $N_{p2}$ are wound on the same outer leg with minimized leakage inductance. $N_{p1}$ is placed on the separated inner leg to increase leakage inductance and is utilized as a resonant inductor. An air gap ($l_g$) is inserted into the structure to provide the required magnetizing inductance. Inner legs are connected without air gap to create high coupling between resonant inductors.

### 2.2 Current balancing mechanism of the IMCBT

Reluctance model and cantilever model of the IMCBT are shown in Fig. 1(c), Fig. 2(a), and Fig. 2(b), respectively. As can be seen from Fig. 2(b), with the sufficiently large magnetizing inductance ($L_{mb}$) of the IMCBT, tank currents ($i_{rA}$, $i_{rB}$) are forced to be equal regardless of the difference in the parameter of resonant tanks.

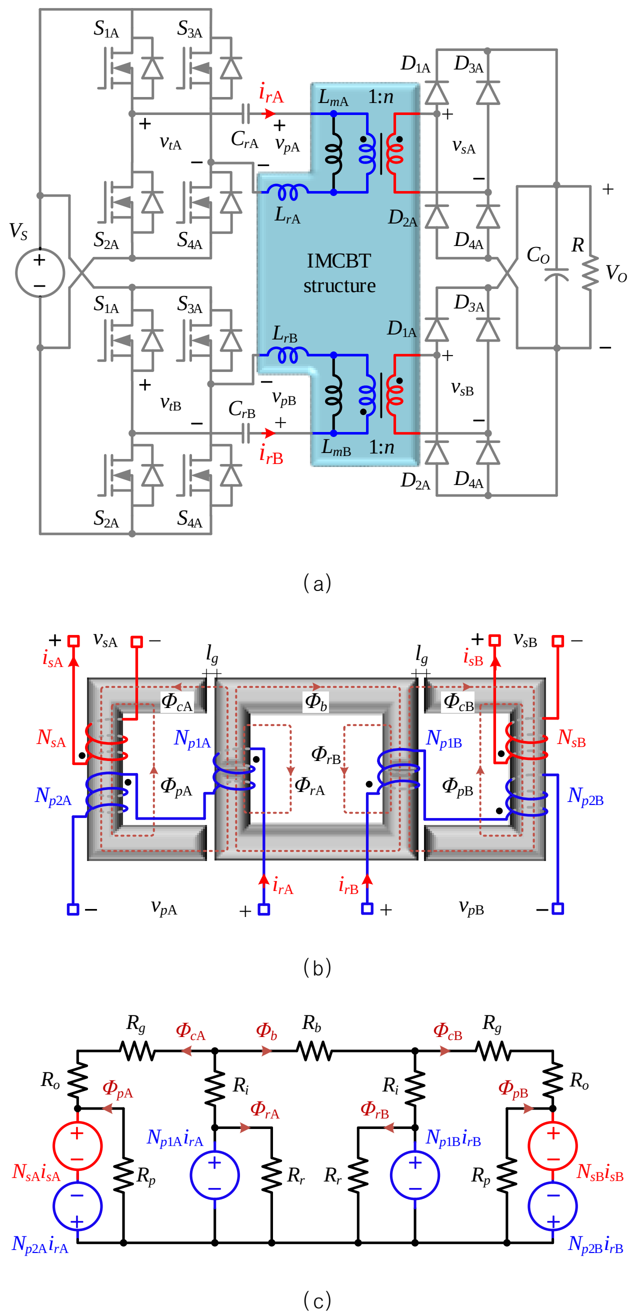


Fig. 1. The proposed IMCBT for the IPOP LLC converter. (a) Topology. (b) Structure of the IMCBT. (c) Reluctance model of the IMCBT.

### 2.3. Experimental results

A 2kW prototype is fabricated with the parameters as

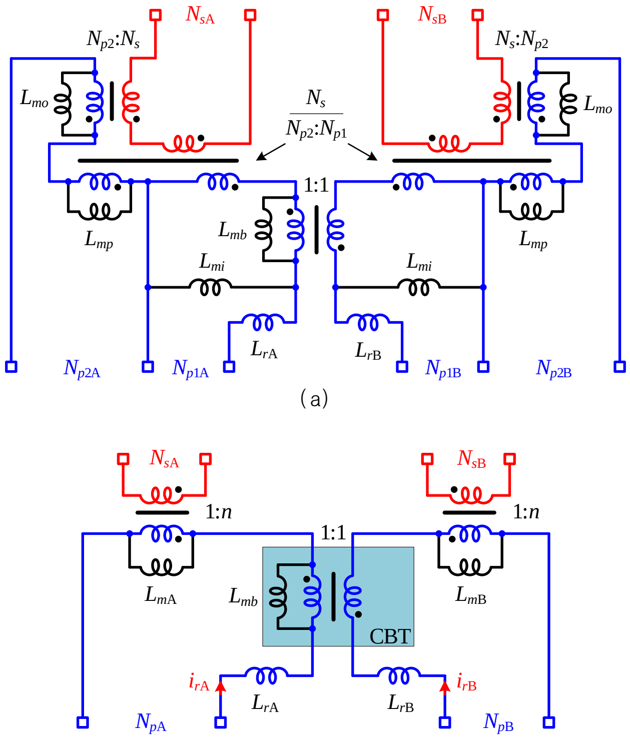


Fig. 2. Cantilever model of the IMCBT. (a) Complete model. (b) Simplified model.

Table 1: Electrical parameter of the IMCBT-based IPOP LLC converter

| | | | |
|---|---|---|---|
| Input voltage, $V_S$ | 320 $V$ | Resonant inductance, $L_r$ | 28 $\mu H$ |
| Output voltage, $V_O$ | 100 $V$ | Magnetizing inductance, $L_m$ | 234 $\mu H$ |
| Output power, $P_O$ | 2 $kW$ | IMCBT core | EE5555A |
| Switching frequency, $f_s$ | 90 $kHz$ | Turns ratio, $N_{p1}$: $N_{p2}$:$N_s$ | 12:36:15 |
| Resonant capacitance, $C_r$ | 0.1 $\mu F$ | Air gap, $l_g$ | 3 $mm$ |

shown in Table 1. A photograph of the IMCBT is shown in Fig. 3. The experimental results in Fig. 4 illustrate the natural current balancing function of the proposed structure.

## 3. Conclusion

The IMCBT in this paper allows:

1. Achieving the natural current balancing between phases of the IPOP LLC converter.
2. Utilizing the leakage inductance of transformer as the resonant inductor.
3. No additional magnetic component is required.

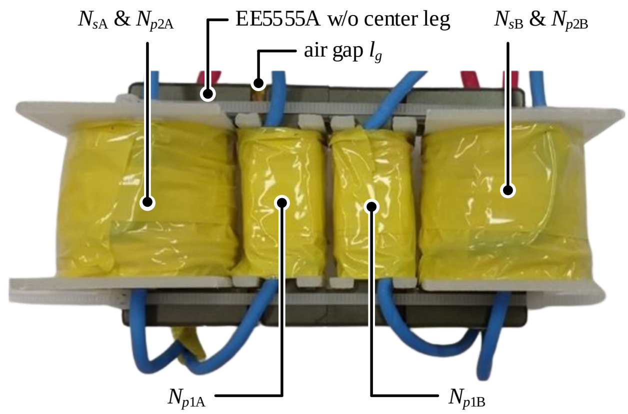


Fig. 3. Photograph of the proposed IMCBT.

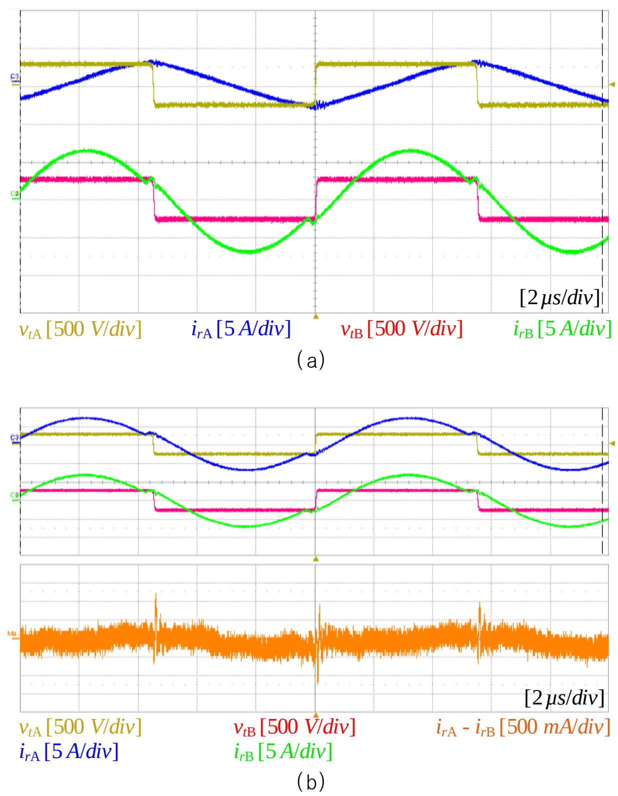


Fig. 4. Experimental results of the IMCBT-based IPOP LLC converter. (a) Two cores are separated. (b) Two cores are combined.

## References

[1] C. Liu et al., “Magnetic-Coupling Current-Balancing Cells based Input-parallel Output-parallel (IPOP) LLC Resonant Converter Modules for High-Frequency Isolation of DC Distribution Systems,” *IEEE Trans. Power Electron.*, vol. 31, no. 10, pp. 6968–6979, Oct. 2016.

[2] U. Ahmad, H. Cha, and N. Naseem, “Integrated Current Balancing Transformer Based Input-Parallel Output-Parallel *LLC* Resonant Converter Modules,” *IEEE Trans. Power Electron.*, vol. 36, no. 5, pp. 5278–5289, May 2021.