1단 방식 인터리브드 토템폴 AC-DC 컨버터를 위한 변압기-계통인덕터 통합형 자성체

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Integrated magnetic of transformer–grid inductor for single-stage interleaved totem-pole AC-DC converter

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ABSTRACT

This paper proposes a 4-leg magnetic of high-frequency transformer and grid inductor integration for the single-stage interleaved totem-pole AC-DC converter. This proposal offers a considerable reduction in core volume and core count, resulting in higher power density and lower production cost. To verify this method, a 3.7kW single-phase single-stage AC-DC converter was built and tested. Compared to the separated grid inductor-transformer structure, the integrated one achieves a 22% decrease in core material volume and a 61% reduction in total volume. The experiment results present an achievement of 97.2% peak efficiency of the converter.

1. Introduction

The onboard charger (OBC) allows EVs to charge when connected to an AC grid outlet. Typically, a two-stage topology including a PFC and an isolated DC-DC converter is employed for OBC implementation. In the DC-DC stage, popular configurations such as resonant CLLC converters[1] as in Fig. 1 and phase-shift full bridge converters[2] obtain excellent performance. However, the decrease in efficiency caused by hard switching in traditional PFC circuits and the use of bulky low-lifespan electrolytic capacitors in the DC link compromise OBC reliability and increase its size.

To address these challenges, the realization of single-stage AC-DC architectures[3], [4]was proposed. By integrating the PFC stage and DC-DC stage, the single-stage system can achieve smaller footprint, higher efficiency, and enhanced reliability. In [4], authors introduced a 11kW single-stage electrolytic capacitor-less AC-DC converter for OBC application by combining an interleaved totem-pole circuit with a DAB converter as in Fig. 2. The single-stage AC-DC converter replaces electrolytic capacitors with small film capacitors, further enhancing power density, efficiency, and reliability.

However, the magnetic components which constitutes

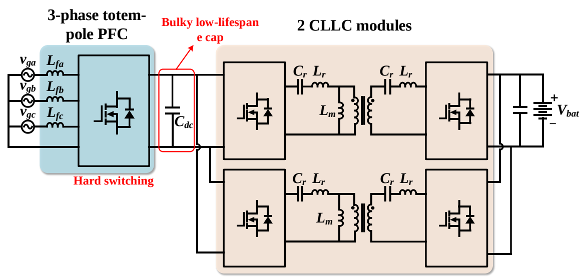


Fig.1 Conventional 11kW two-stage AC-DC converter

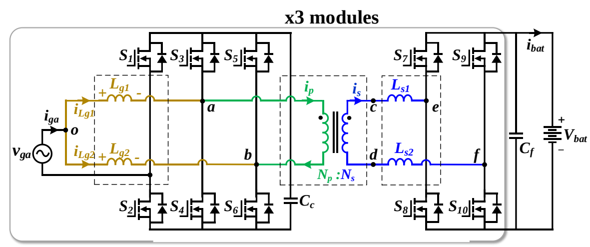


Fig.2 Proposed phase module of 11kW single-stage AC-DC converter

about 50% total volume limit the power density of the converter[4]. In this article, to enhance the power density of single-stage AC-DC converter, an improved integration of the high-frequency transformer and two grid inductors is presented, a 4-leg magnetic concept based on a UI-shape core is utilized for this proposal. This integration approach reduces the number of magnetic components, magnetic loss, and overall volume.

2. Proposed integrated magnetic structure

Fig. 3 shows the operation waveforms of proposed single-stage AC-DC converter. It is noticed that grid inductors and transformer have the same operating frequency, therefore, grid inductors can be integrated into transformer. As a result, inductor cores are eliminated. This is beneficial compared to two-stage AC-DC converter where operating frequency of grid-side filter inductor is different from high-frequency transformer.

Fig. 4 shows the single-stage AC-DC converter with the integrated transformer-grid inductor structure. Especially,

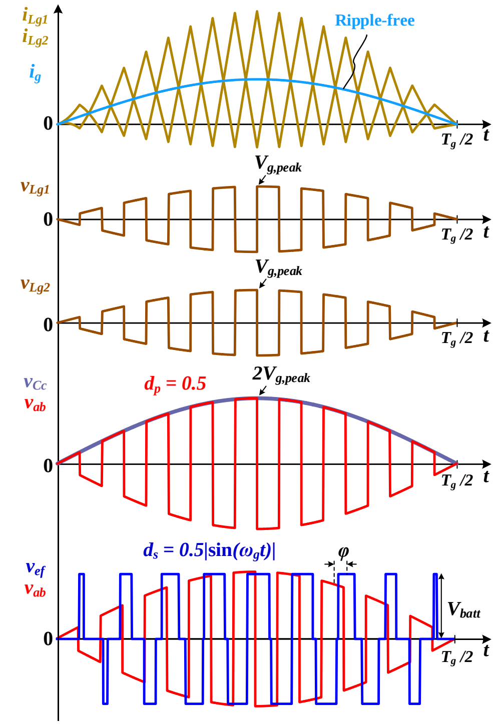


Fig.3 Operating waveforms of the single-stage AC-DC converter

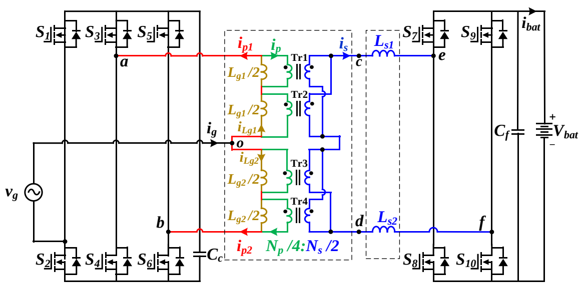
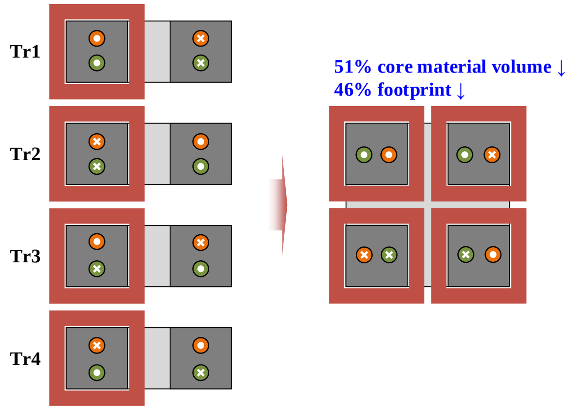


Fig.4 Single-stage AC-DC converter with integrated transformer-grid inductor magnetic structure

the integrated transformers are broken down into elemental ones (*Tr1~Tr4*) to reduce voltage-second applied on them. Accordingly, i_{Lg1} and i_{Lg2} now perform as magnetizing currents, the integrated transformer winding current now is i_{P1}/i_{P2}.

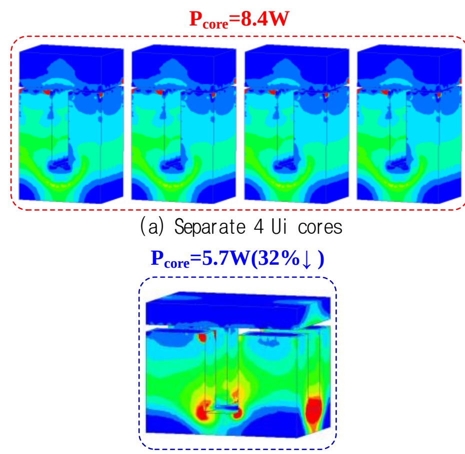
$$i_{P1} = i_{Lg1} - i_S \qquad (1)$$
$$i_{P2} = i_{Lg2} + i_S$$

Conventionally, UI-shape core can be utilized to implement integrated transformers *Tr1~Tr4* as in Fig. 5(a). However, the number of components may increase the production cost and make the system bulky. In this paper, a 4-leg core is proposed to implement the integrated magnetic structure, as shown in Fig. 5(b). Based on the customized design, core material volume and footprint of the proposed 4-leg core is reduced by 51% and 46% compared to separate 4 UI cores, respectively. To evaluate the advantage of the proposal, a 3D Finite Element Analysis (FEA) simulation based on Ansys Maxwell is done as Fig. 6. The result shows that by using single 4-leg core, the core loss is reduced by 32.1% compared to 4 separate UI cores.



(a) Separate 4 Ui cores (b) Single integrated 4-leg core

Fig.5 Implementation of proposed integrated magnetic structure



(b) Single integrated 4-leg core

Fig.6 Comparison of core loss based on Ansys Maxwell

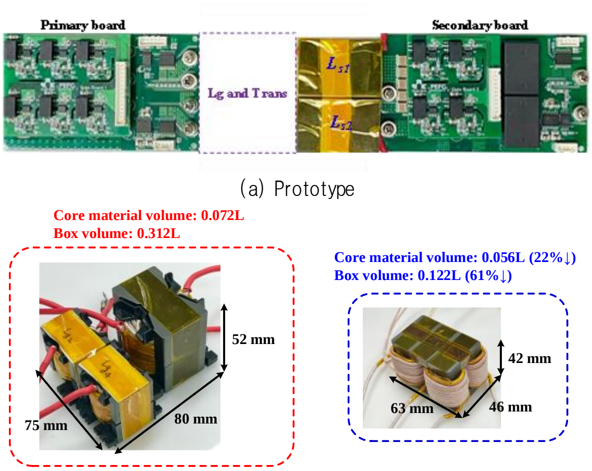
3. Experiment results

To validate the effectiveness of the improved integrated magnetic structure, a prototype of the single-stage phase module of 3.7kW AC-DC converter was constructed, as shown in Fig. 7. It is noted that the proposed integrated magnetic reduces 22% core material and 61% box volume compared to the separate one. The specifications are listed as follows:

Table I Operating parameters

Rated power	3.7kW
Grid voltage	220V (RMS)
Battery voltage	350-850V
Switching frequency	150kHz

Fig. 8 displays the operational waveforms of the converter utilizing the proposed integrated core at rated power. It is highlighted that the converter maintains similar operational characteristics, including ripple-free grid current and power factor correction operation, when compared to the original topology. The efficiency comparison of converter with separate inductor and transformer cores and proposed integrated magnetic single core is illustrated in Fig. 9. The peak efficiency with proposed magnetic structure is 97.2%, which increases 0.3% compared to the converter with separate magnetic structure.



(a) Prototype

(b) Separate magnetic (c) Proposed integrated magnetic

Fig.7 3.7kW single-stage phase module prototype

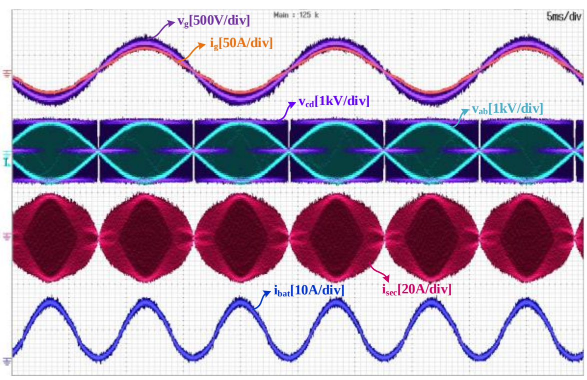


Fig.8 Experimental waveforms at 3.7kW and 600V battery

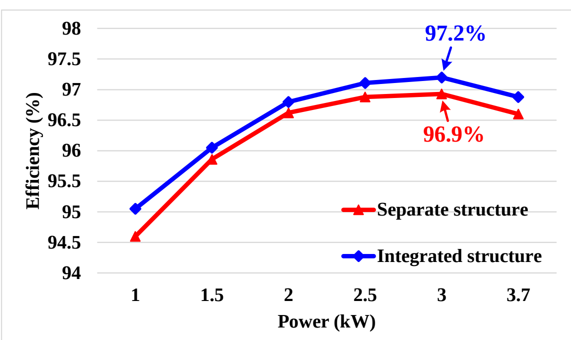
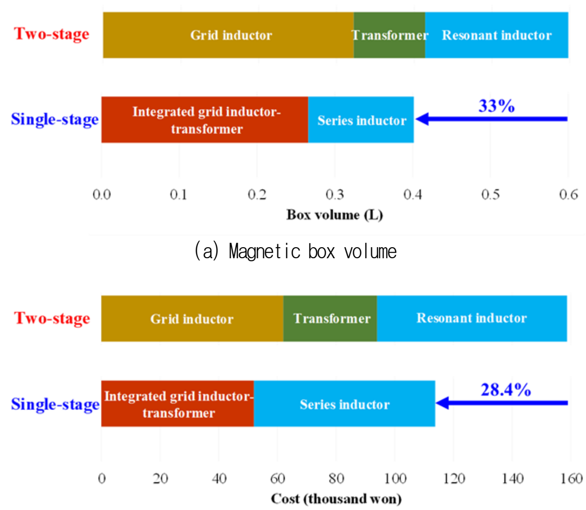


Fig.9 Measured efficiency (Yokogawa WT3000)

In addition, a magnetic volume and cost comparison between the two-stage and single-stage AC-DC converter is shown in Fig. 10. Compared to the two-stage converter, the single-stage one reduces 33% magnetic box volume and 28.4% magnetic cost. It is noted that in the two-stage converter, the powder core is used for filter inductor which is expensive compared to ferrite core.

4. Conclusion

In this paper, a new method is presented to integrate grid inductors into the high-frequency transformer for a single-stage interleaved totem-pole AC-DC converter. The detailed analysis and construction of the proposed magnetic structure,



(a) Magnetic box volume

(b) Magnetic cost

Fig.10 Comparison of total magnetic box volume and material cost

utilizing four separate UI cores and a single 4-leg core, are given. Additionally, this technique enhances power density and reduces the number of magnetic components, thereby simplifying manufacturing and reducing costs. A single-phase 3.7kW prototype was assembled, achieving a peak efficiency of 97.2%, and the test results confirm the effectiveness of the proposed magnetic concept.

이 논문은 Infineon의 전력반도체 지원을 받아 수행된 연구임. 본 과제(결과물)은 교육부와 한국연구재단의 재원으로 지원을 받아 수행된 3단계 산학연협력 선도대학 육성사업(LINC 3.0)의 연구 결과입니다.

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