A Two-Phase Interleaved Single-Stage Isolated Boost-Half-Bridge AC-DC Converter using a Transformer with Flux Cancellation

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ABSTRACT

This paper proposes a two-phase interleaved bridgeless single-stage ac-dc converter with magnetic integration that can achieve CCM power factor correction without input current sensing. All switches achieve ZVS turn-on and all diodes achieve ZCS turn-on for the whole grid cycle. SDAB-based modulation strategy is applied which results in simple power control and wide range output voltage. A flux cancellation method to integrate the interleaved transformer is firstly proposed in this paper to reduce the core size and loss. Experimental results on a 1.7-kW, 50kHz prototype are given to verify the principle and advantages of the proposed ac-dc converter.

1. Introduction

Nowadays, electric vehicles (EVs) and light-electric-vehicles(LEVs) are becoming popular solutions to reduce fossil fuel consumptions. One of the key components in the EVs/LEVs is the onboard battery charger (OBC). In general, there are two approaches of OBC, two-stage and single-stage. The single-stage topology has become a research trending topic because it can achieve higher power density compared to the two-stage topology [1].

A voltage-fed single-stage topology for EV OBC is proposed in [2]. A sinusoidal charging scheme without electrolytic capacitor is used. All semiconductor devices can achieve ZCS turn-on and off. However, it has a high component count, using a diode bridge, and need an extra input filter Therefore, it is lowering the power density and efficiency. A current-fed EV battery charger is proposed in [3]. The switches achieve ZVS turn-on and diodes achieve ZCS turn-off. The topology only uses 6 switches, but it requires 12 diodes including input diode bridge. Moreover, it requires two separate interleaved transformers which decrease the power density.

In [4], a bridgeless interleaved isolated single-stage ac-dc converter has been proposed by the author which has the following features: 1) wide range ZVS turn-on for all of the switches and ZCS turn-off for all of the diodes, 2) wide output voltage range, 3) open-loop CCM PFC operation, 4) switching ripple-free grid current, and 5) totem-pole

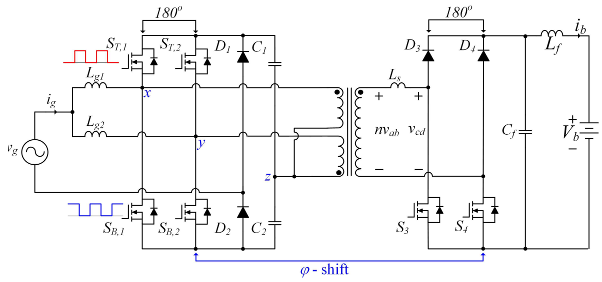


Fig.1 Circuit diagram of the proposed ac-dc converter

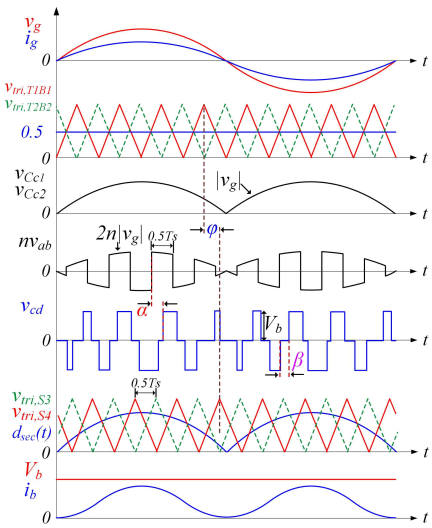


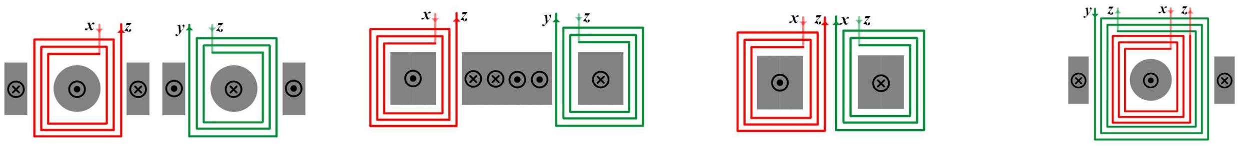
Fig.2 Key waveforms of the proposed ac-dc converter

structure in CCM without reverse-recovery issue. However, it uses two separate cores for the interleaved transformer.

This paper proposes the first ever flux cancellation method to combine two interleaved high-frequency transformers using a smaller single core. The size and loss of the proposed transformer are 32% smaller compared with the conventional two cores transformer.

2. Flux Cancellation for Interleaved Transformers in the Proposed AC-DC Converter

Fig.1 shows the circuit diagram of the proposed single-stage ac-dc converter with the combined transformer. Fig. 2 shows the operating key waveforms in one grid period.



(a) (b) (c) (d)

Fig.3 Flux cancellation concept for interleaved transformer: (a) conventional two PQ cores transformer (b) integrated four windings transformer using EE core (c) center leg removal because of flux cancellation (d) proposed single PQ core three windings transformer

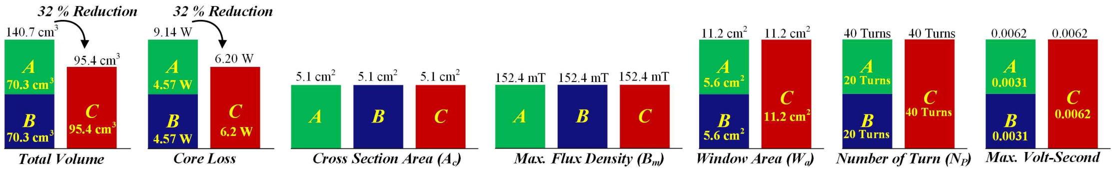


Fig.4 Transformer comparison charts: A and B are conventional two core transformers and C is the proposed transformer.

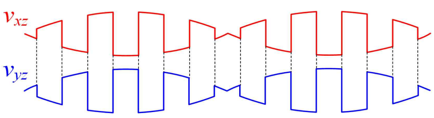


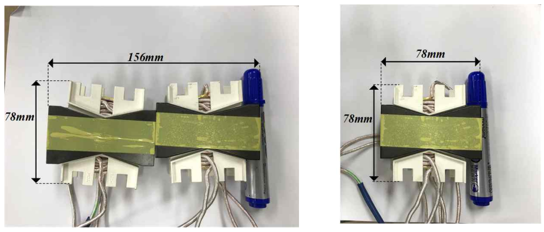
Fig.5 Voltage waveforms of the two interleaved transformers

Primary switches S_T and S_B are complementary switched with fixed 0.5 duty cycle and 180 phase-shift between the legs. Secondary switch S_3 and S_4 are 180° phase-shifted in switching frequency and modulated with duty cycle as defined in (1). The power transfer is done by a phase shift, φ, between the primary and secondary side. More detail of the operating principle of the proposed ac-dc converter can be found in [4].

$$d(t) = m_f \cdot |\sin(2\pi f_g t)| \quad (1)$$

Fig. 3 shows the concept of the proposed interleaved three winding single core transformer. The removal of core legs is possible because of the voltage applied to the two transformers is always opposite with the same magnitude as shown in Fig.5. The dot convention of one transformer has to be reversed, as shown in Fig.1, in order to get the sum of the primary voltage in the secondary side, nV_{ab}, as in Fig. 2. The comparisons between the conventional transformer in Fig. 3(a) with the proposed transformer in Fig. 3(d) are illustrated in Fig. 4 using TDK78 PQ core data with PC40 core material. The proposed and the conventional transformer have the same core-cross section area. The total number of turns is also the same, hence the window area should be doubled for the proposed transformer. The total volume of the proposed transformer is reduced by 32%. By observing (2), the proposed transformer keeps the same value of B_m. Therefore, the $P_{cv}(B_m, f_s)$ in (3) is the same as the conventional transformer and the core-loss reduction is proportional to the volume reduction.

$$B_m = \frac{V \cdot D}{2 \cdot A_c \cdot N_P \cdot f_s} \quad (2)$$



(a) (b)

Fig.6 Transformer photograph: (a) conventional (b) proposed

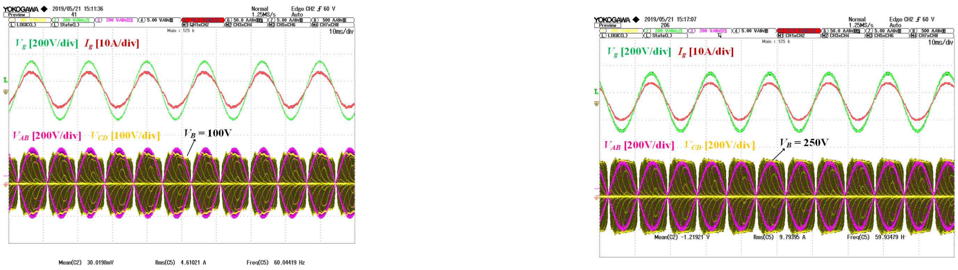
$$P_{core} = V_{core} \cdot P_{CV}(B_m, f_s) \quad (3)$$

3. Experimental Results

Fig. 6 show the photograph of the conventional and the proposed transformer. Because of the theoretical size of the proposed transformer is not an off-the-shelf core dimension, the prototype has to reduce the number of turns by half. Therefore, the size is reduced by 50%, but B_m is doubled which leads to a core-loss increase. Fig. 7(a) and (b) shows the experimental result of the converter operation principle, which shows that the proposed converter can operate under a wide output voltage range. The whole grid cycle soft-switching performance is proven in Fig 8(a)-(d). In Fig.8 shows that the transformer voltage waveform match with the theoretical waveform in Fig. 4 which prove that the flux cancellation concept in Fig. 3 can be applied. The performance of the converter in terms of efficiency, %THDi, and power factor are shown in Fig. 9. The graph data is taken at V_b = 200V, 260V, 320V, and 380V.

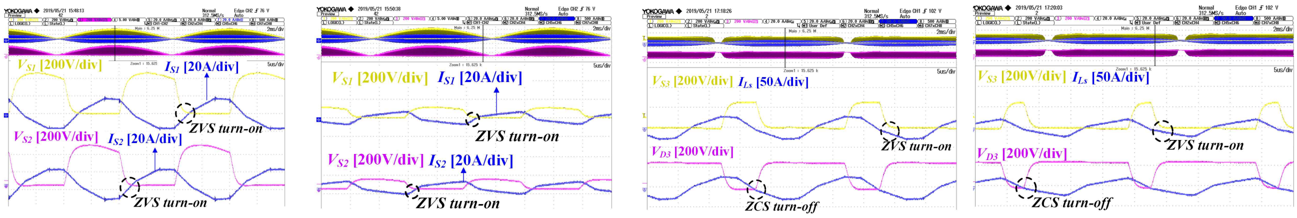
4. Conclusion

A new isolated single-stage ac-dc converter with an integrated interleaved transformer using a flux cancellation method is proposed. The converter is able to achieve CCM PFC operation without the need to sense the input current. Whole grid-cycle ZVS turn-on and ZCS turn-off are



(a) (b)

Fig.7 Experimental results in grid period : (a) Vb = 100V (b) Vb = 250V

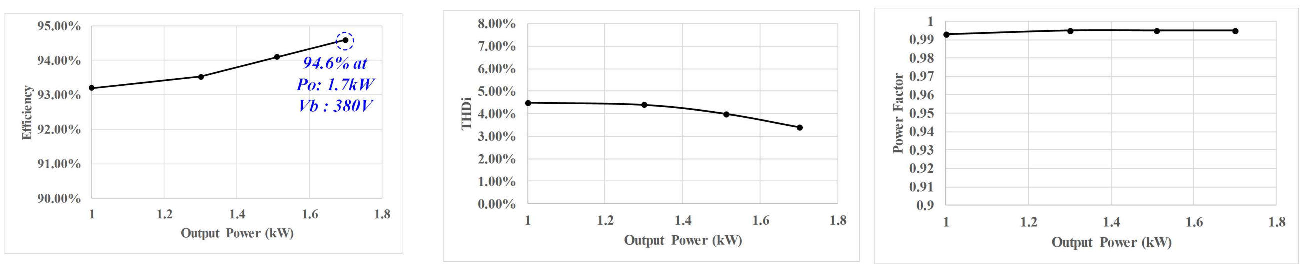


(a) (b) (c) (d)

Fig.8 Experimental waveform of soft-switching performance: (a) primary side at peak v_g (b) primary side at low v_g (c) secondary side at peak v_g (d) secondary side at low v_g

(a) (b)

Fig.9 Primary side voltage waveforms of the proposed transformer: (a) at peak v_g (b) at low v_g



(a) (b) (c)

Fig.10 Proposed converter performance: (a) efficiency (b) %THDi (c) power factor

achieved. Although using a totem-pole structure with CCM operation, there is no reverse-recovery issue. Total volume and core-loss of the transformer can be reduced by 32%. Therefore, higher efficiency and power density are achieved.

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