전기자동차 충전기용 10kW 하이브리드 컨버터

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A 10kW Hybrid Converter for the Electric Vehicle Charge Application

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ABSTRACT

A hybrid converter for the on-board charger consisting of a soft switching full bridge (SSFB) and a half bridge (HB) LLC resonant converter is proposed. The proposed topology adopts an additional switch and a diode at the secondary side of SSFB converter to guarantee the wide ZVS range of primary side switches and to eliminate the circulating current. The output voltage is regulated by controlling the duty cycle of secondary side switch. The effectiveness of the proposed converter was experimentally verified using a 10-kW prototype circuit. The experimental results show 96.8% peak efficiency.

Index Terms – High efficiency, hybrid resonant and PWM power conversions, hybrid-switching circuit, minimized circulating current, zero-voltage-switching (ZVS).

1. Introduction

Phase-shift full bridge is one of the most widely used topology for high power conversion application due to their soft switching characteristics, but its limited ZVS (Zero-Voltage-Switching) range and the circulating current causing a conduction loss are considered as its main drawbacks. The other topology is an LLC resonant converter which exhibit very high-efficiency at its resonant frequency. However, it is not easy to control and to optimize the design due to its wide switching frequency range, especially for the charge application. Recently, several kinds of hybrid converter topologies for the on-board charger have been introduced to overcome above mentioned drawbacks. In this paper, a new hybrid topology which combines a soft switching full bridge (SSFB) converter and a half-bridge LLC (HBLLC) converter. In the SSFB topology, an additional switch and a diode are employed in the secondary side for freewheeling thereby possessing following advantages: high DC conversion ratio with negligible duty loss, ZVZCS of the primary switches and wide ZVS range, high efficiency with no circulating current, especially at the light load, small size of the passive components in the secondary and a simple switching scheme.

2. Operating principle of the proposed converter

The circuit diagram of the proposed converter is shown in Fig. 1. In this converter, diagonally opposite switches (S_1 and S_4) and (S_2 and S_3) from each leg are switched as pairs and the secondary side switch S_5 is synchronized with the primary switch operation with a small delay at both ends. During the delay between the primary switches and the secondary switch, primary current reaches zero, which make it possible for the primary switches to turn on with ZVS and turn off with ZCS.

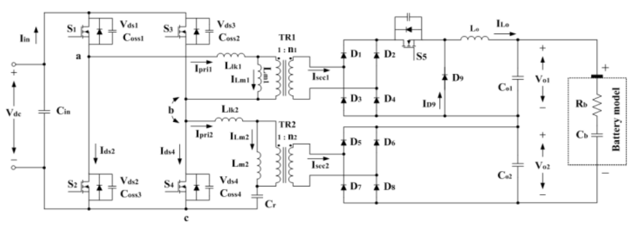

Fig. 1. Proposed hybrid dc-dc converter for the on-board charger

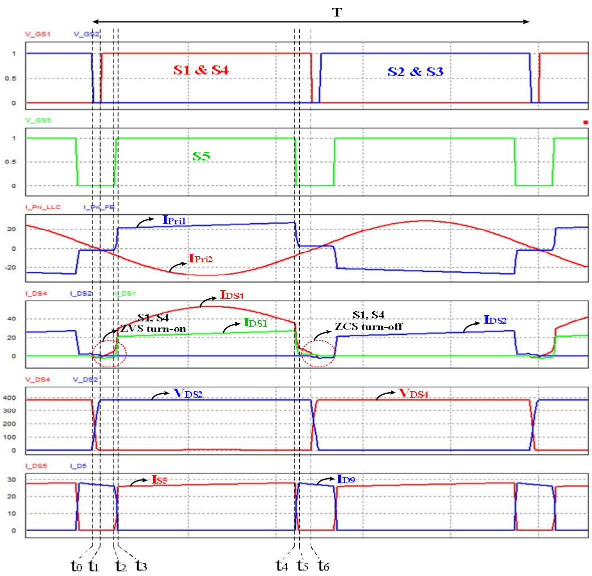

Fig. 2. Key waveforms of the proposed converter

There are six operating modes within each half switching cycle.

Mode 1 ([t_0~t_1]): At t_0, S_2 and S_3 turn OFF. C_{OSS} of S_2 and S_3 are charged from zero to V_{dc} during ($t_1 - t_0$) and C_{OSS} of S_1 and S_4 are discharged. The sum of the two primary currents flows through the body diode of S_1 and S_4 creating ZVS turn ON condition for S_1 and S_4. In the LLC circuit, since I_{pri2} is equal to I_{Lm2} at t_0, no power is transferred through the LLC circuit. At the same time, the current flowing through the output inductor decreases.

Mode 2 ([t_1~t_2]): At t_1, S_1 and S_4 turn on with ZVS. Because S_5 is still turned off, only LLC part conduct current through diode D_9.

Mode 3 ([t_2~t_3]): Secondary side switch S_5 turns ON at t_2 and takes current from diode D_9. Therefore, current flowing through D_9 decreases to zero. Power starts to be delivered to the load.

Mode 4 ([t_3~t_4]): In this mode, the power is delivered to the load through the switch S_1, S_4 and S_5. The slope of the primary current of full-bridge transformer can be represented as (1).

$$\frac{di_{pri1}}{dt} = (n_1 V_{dc} - V_O)/(\frac{L_O}{n_1}) \qquad (1)$$

The LLC converter also participates in transferring the energy to the secondary side at the resonant frequency where the voltage gain is constant and independent of the load and the inductance ratio L_{m2}/L_{lk2}. Thus, the L_{m2} can be designed relatively large, which leads to a small LLC transformer current, I_{pri2}.

Mode 5 ([t_4~t_5]): When S_5 is turned OFF at t_4, I_{pri1} decreases to almost zero current and C_{OSS} of the switch S_5 is charged. The secondary current of the SSFB is commutated to D_9 and starts to freewheel. At the same time, the HBLLC converter transfers energy to the load through D_9.

Mode 6 ([t_5~t_6]): In the primary side, C_{OSS} of the switch pair S_1/S_4 are charged to V_{dc} and those of S_2/S_3 are discharged. After that, the current flows through body diodes of S_2/S_3 achieving the ZVS turn-on condition for the switch S_2/S_3. At t_6, S_1 and S_4 are turned OFF under ZCS condition.

3. Analysis of the proposed converter

3.1. DC conversion ratio

DC conversion ratio (M) of the proposed converter can be expressed as (2).Where, n_1 is the transformer turns ratio of SSFB, N_s/N_p and D_{sec} is the duty for the secondary switch.

$$M_{SSFB} = 2n_1(D - \Delta D) = 2n_1\left[D - \frac{2n_1 L_{lk1}}{V_{dc}T}\left(\frac{D-D_{sec}}{2} \cdot \frac{V_{01}}{L_o}\frac{T}{2}\right)\right] \quad (2)$$

3.2. Size of the output inductor

The inductance value for the output inductor can be calculated by $L_o = \frac{V_o(1-D)}{\Delta I_{Lo} \cdot f_s}$. Since the switching frequency of the secondary side switch is twice that of the conventional PSFB, the size of the output inductor is reduced by half and it is further reduced if the duty loss is considered as shown in Fig. 3.

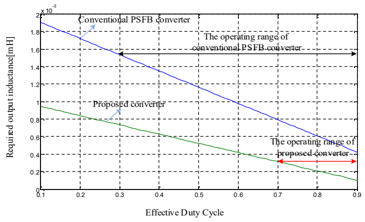

Fig. 3. Comparison of the output inductor in SSFB and PSFB

3.3. Design of the LLC transformer

Since the LLC circuit works at resonant frequency, it only requires to be optimized at that frequency. The L_{m2} can be calculated by using $L_{m2} \leq \frac{t_{dead}T_s}{8(C_{oss1}+C_{oss2})}$ to guarantee the ZVS of the primary switches.

3.4. ZVS/ZCS range for the primary switches

The primary current of the SSFB converter can be represented as (3) since the phase shift is not used in the PWM scheme. The ZVS condition for the primary switches can be guaranteed if the equation (4) is satisfied. From the equation (3) and (4) it can be concluded that the ZVS condition can be satisfied with a certain value of the leakage inductance regardless of the load in the proposed converter.

$$I_p = \frac{V_{dc}}{2(L_{lk}+L_m)} \cdot \frac{T}{2} \quad (3)$$

$$\frac{1}{2}L_{lk}I_p^2 > \frac{1}{2}(2C_{oss})V_{dc}^2 \quad (4)$$

The ZCS condition for the primary switches can be achieved if the primary switch turns off after the secondary switch turns off after a certain period of time, which is represented by (5).

$$t_{ZCS} > \frac{nL_{lk}}{V_{dc}}I_o \quad (5)$$

4. Experimental results and discussions

The specification of the proposed converter can be found in the Table 1.

TABLE 1
SPECIFICATION OF THE PROPOSED CONVERTER

Power rating (P_o)	10 kW
Input voltage (V_{in})	380~400 V
Charge voltage (V_o)	420 V
Switching frequency (f_S)	44 kHz
Output inductor of SSFB converter (L_o)	300 µH
Leakage inductance of the SSFB transformer (L_{lk1})	2 µH
Magnetizing inductance of the SSFB transformer (L_{m1})	800 µH
Turn ratio of the PSFB transformer (n_1)	1: 0.9
Leakage inductance of the HB LLC transformer (L_{lk2})	24 µH
Magnetizing inductance of the LLC transformer (L_{m2})	1.2 mH
Turn ratio of the HB LLC transformer (n_2)	1: 0.68

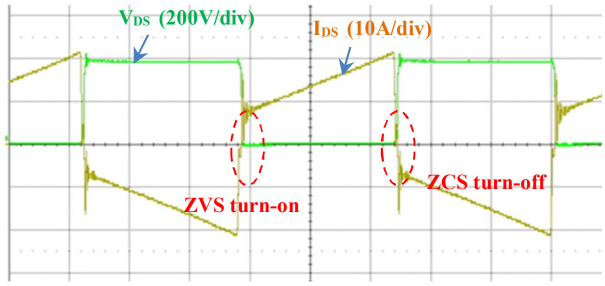

Fig. 4. Current and voltage waveforms of the leading leg switch S2

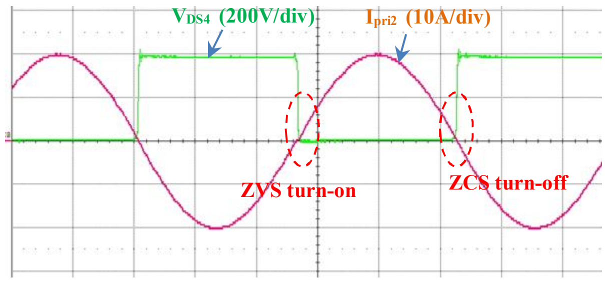

Fig. 5. LLC primary current and voltage of the lagging leg switch S4

Fig. 4 shows the voltage and current waveforms of a leading-leg switch at primary side of the proposed converter. This switch can achieve both ZVS turn-on and ZCS turn-off thank to the delay time in (5) between primary side switches and secondary side switches. As shown in Fig. 4, there is no circulating current, which leads to a reduction of the conduction losses. Fig. 5 shows drain-source voltage of S_4 and the primary current of HB LLC circuit. It shows a perfect ZVS turn-on and ZCS turn-off characteristics of the lagging leg switch S_4.

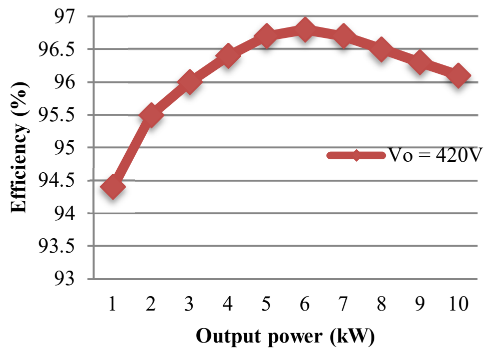

Fig. 6. Measured efficiency of the proposed converter

As shown in the Fig. 6, the efficiency plot of the proposed charger varies from 94.4% to 96.1% according to the load and the maximum efficiency is 96.8% at 6 kW.

5. Conclusion

In this research a novel soft-switching hybrid converter combining an SSFB converter and a HBLLC resonant converter is proposed for the EV On-board charger. Experimental results with a 10 kW prototype have been presented to verify the validity of the proposed converter. The SSFB converter has a wide range of the ZVZCS characteristics and shows high efficiency characteristics, especially at the light load condition.

References

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