전기자동차용 온보드 충전기를 위한 새로운 하이브리드 컨버터

Novel Hybrid Converter for the On-Board Charger of Electric Vehicle

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ABSTRACT

This paper introduces a novel hybrid converter combining a full-bridge soft switching converter and a full-bridge LLC converter. In this topology all the primary switches can achieve ZVS and ZCS all over the operation range. An additional switch and a diode are added in the secondary side of full-bridge converter to eliminate the circulating current and to provide a separate freewheeling path. The hybrid structure makes it possible to deliver the power to the secondary all the time of operation, thereby improving the efficiency. The proposed topology is suitable for the applications such as on-board chargers for electric vehicles and high power dc-dc converters. A 6.6-kW prototype converter was implemented and 97.5% efficiency was obtained through the experiments.

Index Terms – Hybrid converter, Soft switching full bridge converter, Full bridge LLC converter, Circulating current, ZVZCS operation.

1. Introduction

Recently, hybrid converters are popularly used in high voltage and high power applications [1-2]. Conventional hybrid converter is composed of a phase shift full bridge converter and a half bridge LLC converter [3-4]. However, this topology has several drawbacks as follows: limited ZVS range, circulating current at the primary side, ZCS for only lagging-leg switches, and hard-switching of the rectifier diodes in the secondary side of phase shift full bridge converter. In this paper a novel hybrid converter composed of a soft switching full bridge (SSFB) converter and a full bridge LLC (FBLLC) converter is proposed to overcome the drawbacks mentioned above. ZVS for all the primary switches can be achieved all over the operation range by using the magnetizing current of transformer in the LLC converter. Since the ZVS can be achieved with no leakage inductance requirement, the duty cycle loss can be minimized. In addition ZCS turn-off of all the primary switches can be achieved regardless of the load. The PWM for the full bridge converter can be achieved by the secondary switch while the duties of the primary switches are fixed at 50%. All the rectifier diodes can also achieve the ZVZCS due to the additional switch in secondary side and the resonant operation.

2. Operating principle of the proposed converter

The circuit topology of the proposed converter is shown in Fig. 1. Primary switches are shared by the SSFB and FBLLC converter. Secondary side of the SSFB converter is composed of the rectifier diodes (D_1, D_2, D_3, and D_4) and an additional switch S_5 and a diode D_5. The secondary side of the FBLLC converter is the same as the traditional FBLLC converter. Each converter has its own transformer of which turns ratio is $1\ n_1$ and $1\ n_2$, respectively. The operation of the converter can be divided into 6 switching modes in a period. The key waveforms are shown in Fig.2 and each mode of operation can be explained as follows.

Mode 1 ([t_0~t_1]): At t_0, S_1 and S_4 are turned off and the current $i_{pri2}(t)$, which is equal to the magnetizing current of Tr_2, starts to charge the output capacitors of S_1 and S_4 and discharge those of S_2 and S_3.

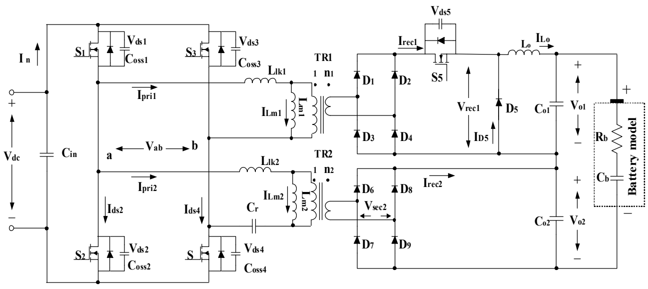

Fig. 1. Proposed hybrid dc-dc converter for the on-board charger of EV

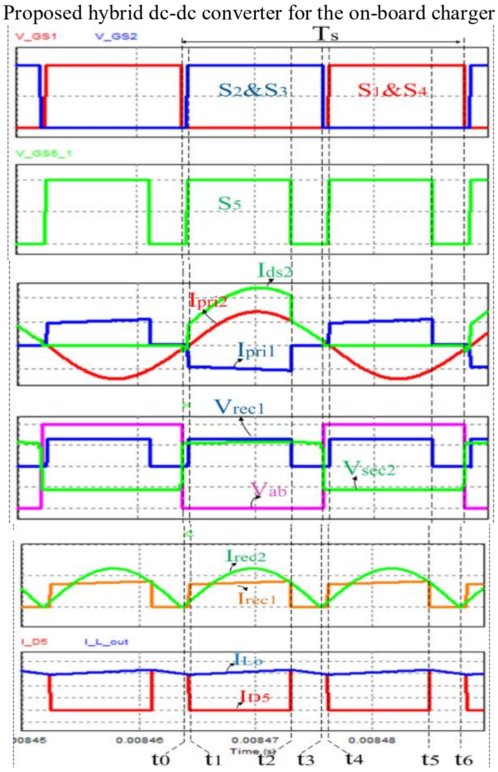

Fig. 2. Key waveforms of the proposed converter

Mode 2 ([t_1~t_2]): At t_1, S_2, S_3 and S_5 are turned on. Here the switches S_2 and S_3 are turned on with ZVS. The power is delivered to the secondary through both SSFB and FBLLC converter.

Mode 3 ([t_2~t_3]): Secondary switch S_5 is turned off at t_2 and the freewheeling current flows through the diode D_5.

Mode 4 ([t_3~t_4]): The switches S_2 and S_3 are turned off at t_3. No switch is conducting during this time and only small magnetizing current flows through Tr_1 and Tr_2.

$$i_{pri2}(t) = I_2 \cos\omega\left(\frac{T_s}{2} - t_3 + t\right) \tag{1}$$

Mode 5 ([t_4~t_5]): At t_4, S_1, S_4 and S_5 are turned on. The power is transferred through both SSFB and FBLLC converter.

Mode 6 ([t_5~t_6]): The switch S_5 is turned off and only the FB LLC converter delivers the power to the load. In the SSFB converter the freewheeling current flows through the diode D_5.

3. Design of the proposed converter

3.1. Condition to achieve ZVS turn-on for the primary switches.

The proposed converter can achieve full range of ZVS condition regardless of the leakage inductance value. Thus, it is possible to obtain high efficiency even in the light load condition. In order to achieve the ZVS of the primary switches, however, a dead-time which is enough to discharge the C_{oss} of the switch is required as shown in (2).

$$T_{Dead-Time} \ge \frac{\pi}{2}\sqrt{2L_{m2}C_{oss}} \tag{2}$$

3.2. ZCS turn-off of the primary switches.

By the feature of the proposed converter which shares all the primary switches, turn-off switching losses can also be completely eliminated by the resonant operation of the converter at the resonant frequency.

3.3. Duty cycle loss and voltage gain.

The DC gain of the proposed converter can be calculated by adding up the voltage gain of each converter as (3).

$$V_o = [n_1(D - \frac{1}{T_s}L_{lk1}\frac{n_1 I_{Lo,min}}{V_{dc}}) + n_2]V_{dc} \tag{3}$$

3.4. Elimination of the circulating current

Since the freewheeling current flows thorough the freewheeling diode (D_5) in the secondary side of SSFB, the circulating current in the primary side can be eliminated and hence there is no conduction loss associated with it.

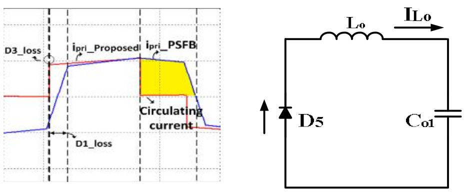

Fig. 3. Elimination of the circulating current by the secondary freewheeling circuit of the SSFB

4. Experimental results

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

TABLE 1
SPECIFICATION OF THE PROPOSED CONVERTER

Power rating (P_o)	6.6 kW
Input voltage (V_{in})	380~400 V
Charge voltage (V_o)	250~420 V
Switching frequency (f_S)	37.5 kHz
Output inductor of SSFB converter (L_o)	450 µH
Magnetizing inductance of the SSFB transformer (L_{m1})	9.56 mH
Turn ratio of the PSFB transformer (n_1)	1: 0.68
Leakage inductance of the HB LLC transformer (L_{lk2})	28 µH
Magnetizing inductance of the LLC transformer (L_{m2})	550 mH
Turn ratio of the HB LLC transformer (n_2)	1: 0.55

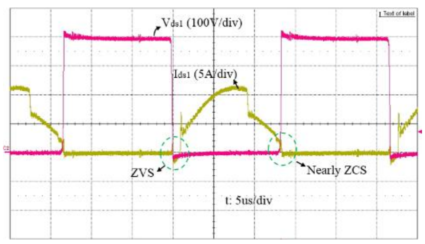

Fig. 4. Current and voltage waveforms of the switch S_1

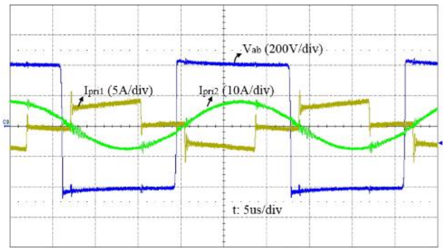

Fig. 5. Current and voltage waveforms of the TR_1 and TR_2

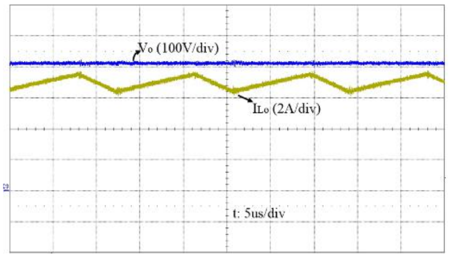

Fig. 6. Output inductor current and output voltage waveforms

Fig. 4 shows voltage and current waveforms of the switch S_1 which shows that both ZVS turn-on and ZCS turn-off are achieved. Fig.5 shows the voltage and current waveforms of the transformer TR_1 and TR_2 at 3 kW. Fig. 6 shows the output inductor current and the output voltage waveforms.

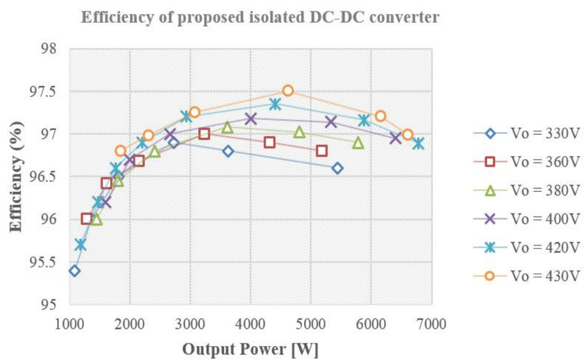

Fig. 7 Efficiency plots of the proposed hybrid converter

As shown in Fig. 7, the efficiency plots of the proposed charger depending on the load and the maximum efficiency is 97.5% at 4.5 kW.

5. Conclusion

In this research a new hybrid converter combining an SSFB converter and a FBLLC is proposed for the wide range of output voltage and high power applications. Experimental results with a 6.6 kW prototype have been presented to verify the validity of the proposed converter.

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