J Electr Eng Technol.2018; 13(1): 143-151
http://doi.org/10.5370/JEET.2018.13.1.143

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

A Novel Hybrid Converter with Wide Range of Soft-Switching and No Circulating Current for On-Board Chargers of Electric Vehicles

Van-Long Tran*, Dai-Duong Tran*, Van-Tuan Doan*, Ki-Young Kim* and Woojin Choi†

Abstract – In this paper, a novel hybrid configuration combining a phase-shift full-bridge (PSFB) and a half-bridge resonant LLC converter is proposed for the On-Board Charger of Electric Vehicles (EVs). In the proposed converter, the PSFB converter shares the lagging-leg switches with half-bridge resonant converter to achieve the wide ZVS range for the switches and to improve the efficiency. The output voltage is modulated by the effective-duty-cycle of the PSFB converter. The proposed converter employs an active reset circuit composed of an active switch and a diode for the transformer which makes it possible to achieve zero circulating current and the soft switching characteristic of the primary switches and rectifier diodes regardless of the load, thereby making the converter highly efficient and eliminating the reverse recovery problem of the diodes. In addition an optimal power sharing strategy is proposed to meet the specification of the charger and to optimize the efficiency of the converter. The operation principle the proposed converter and design considerations for high efficiency are presented. A 6.6 kW prototype converter is fabricated and tested to evaluate its performance at different conditions. The peak efficiency achieved with the proposed converter is 97.7%.

Keywords: Hybrid converter, Lithium battery, On-board charger (OBC), Zero current switching (ZCS), Zero voltage switching (ZVS)

1. Introduction

Due to the depletion of the petroleum and climate change, Electric Vehicles (EVs) and Plug-in Hybrid Electric Vehicles (PHEVs) have become realistic solutions for future transportation. Several manufacturers have successfully commercialized them such as Toyota Prius Plug-in Hybrid, Nissan Leaf, and etc. As a result, battery charger has developed as an associated technology at a rapid rate in response to the expected market demand for electric vehicles. There are two kinds of charging systems for the electric vehicles, DC charging systems and AC charging systems. While the DC charging systems are installed at fixed locations, the AC charging systems are mounted inside the vehicles and charge the battery by connecting it to the grid. However, since the charging infrastructure is not widely installed all over the area most of the vehicles have their own On-Board Chargers (OBCs) inside the vehicles. Therefore, most of the researches so far mainly focus on developing the OBCs. Both of charging systems are classified as Level 1, Level 2 and Level 3 according to their levels of power and the OBCs belong to the AC Level 2 charging system. In case of typical 3.3 kW AC Level 2 OBCs, it takes about 4 to 6 hours to fully charge a depleted 16 kWh Lithium battery pack in PHEV with a single-phase 208 to 240 V supply [1]. However, owing to the upcoming demands for the longer driving distance and shorter charge time, it is preferred to use high power OBCs. The OBCs are typically consisting of an AC-DC converter with a power factor correction and a DC-DC converter to charge a battery pack. In order to maximize the efficiency and performance of the vehicles it is critical to minimize the volume and weight of the charger, the charge time and the expense for the charge. Hence, it is important to find out the suitable topology for each part of the charger to satisfy the aforementioned criteria. In this paper we will focus on the DC-DC converter of the OBC since it plays the most crucial function of it.

The phase shift full bridge (PSFB) topology is a suitable option for high input voltage and high output power converter since it offers soft-switching capability for the primary switches [2-6]. However, it also suffers from three main issues such as limited ZVS range for the lagging-leg switches, circulating current and its associated losses, and high ringing voltage across the secondary rectifier. To increase the ZVS turn-on range for the lagging-leg switches, an external inductor is used to store the sufficiency inductive energy [5, 6]. However, it prolongs the time requirement for the current to change its polarity, thereby increasing the duty-cycle-loss on secondary side. As a consequence, the transformer with a higher turn ratio is needed to compensate for the duty-cycle-loss, which contributes to a higher conduction loss. The circulating

† Corresponding Author: Dept. of Electrical Engineering, Soongsil University, Korea. (cwj777@ssu.ac.kr)
* Dept. of Electrical Engineering, Soongsil University, Korea. (tranvanlong988@gmail.com, dai-duong.tran@vub.ac.be, doantuan85@gmail.com, com123490@naver.com)
Received: December 1, 2016; Accepted: August 2, 2017

current during the freewheeling interval is another concern of the PSFB converter since it contributes to an increase in the conduction loss. Several methods have been proposed to reduce it [7, 8]. One method uses the reverse avalanche breakdown voltage of the leading-leg switch to reset the primary current [7] and the other uses the dc blocking capacitor and a saturated inductor to reduce the circulating current [8]. However, none of the above methods can completely eliminates the circulating current at the primary side and the ZVS turn-on of the lagging leg switches is available only in a limited range. In addition, it is difficult to achieve the significant improvement in terms of the efficiency due to the losses generated in the additional circuit.

Another approach for high voltage and high power application is the resonant converters whose output voltage is modulated by the frequency control. Due to its high efficiency at the fixed-resonant frequency, the resonant converters are often used for dc-bus power supply since there would be almost no switching losses [9-11]. However, when the wide range of voltage gain is required, the switching frequency needs to be changed in a wide range, and hence the resonant converter becomes less practical in that case. To overcome the above mentioned disadvantages of the resonant converter, several studies have proposed the phase-shift control scheme operating at a fixed-frequency [12, 13]. However, the circulating current which contributes to a severe conduction loss during the freewheeling period is unavoidable.

Recently the hybrid converter combining a PSFB converter and a Half Bridge LLC (HB LLC) converter has been proposed for the high voltage and high power applications [14-16]. The main advantage of the hybrid topology is its lower current stress of the components in the primary side of the converter due to the parallel input connection of the two converters and its lower voltage stress of the components in the secondary side of the converter due to the series connection of the rectifier of each converter [17]. Furthermore, since the additional transformer is connected to the shared lagging-leg, the magnetizing current can be increased. Hence, it contributes to obtaining a sufficient inductive energy to guarantee the wide ZVS range for the lagging-leg switches. However, the conduction loss and the turn-off switching loss at the lagging-leg switches still exist since the circulating current is not eliminated in these topologies.

In this research, a novel hybrid PSFB-HB LLC converter is proposed for the On-Board Charger of the EVs as shown in Fig. 1. The proposed topology utilizes the magnetizing inductance of the transformer for the HB LLC converter to achieve the wide ZVS range for the lagging-leg switches and employs an additional switch and a diode in the secondary side of the PSFB converter to eliminate the circulating current and to achieve soft switching of the rectifier diodes. Therefore it has no reverse recovery problem in the rectifier diodes. The outputs of the two converters are connected in series and the output voltage is regulated by the effective duty cycle of the PSFB converter. The ZVS turn-on of the lagging-leg switches is possible all over the load range thanks to the HB LLC converter. In addition, due to the separate freewheeling path formed by switch S_5 and diode D_9 in the secondary side, the circulating current can be completely eliminated and the voltage at the secondary rectifier of the PSFB converter can be clamped to zero volts. The optimal power sharing strategy is also proposed to maximize the efficiency of the proposed hybrid converter while satisfying the specification of the charger and implementing the CC/CV charge method by assigning the suitable power for each converter.

In the Section 2, the circuit description and the operation principle of the proposed converter are explained. In the Section 3, design considerations for high efficiency operation of the converter are presented. In the Section 4, a 6.6 kW hardware prototype is fabricated, and tested to verify the performance of the proposed converter. Finally, the conclusions are given in the Section 5.

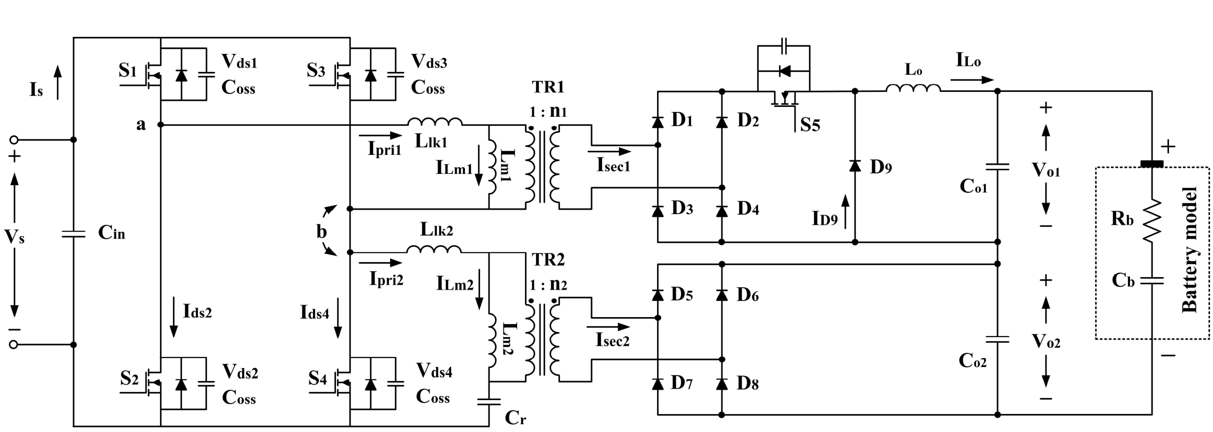


Fig. 1. Proposed hybrid phase shift full bridge-half bridge LLC converter

2. Circuit Description and Operation Principle

Fig. 1 shows the circuit diagram of the proposed hybrid converter for the OBC of EV. It consists of a traditional PSFB converter with a switch S_5 and diode D_9 to create an additional freewheeling circuit and a HB LLC converter which shares two switches S_3 and S_4 in the lagging-leg. The outputs of the two converters are connected in series to provide a high voltage suitable for charging the EV battery pack. Since the proposed hybrid converter operates at the fixed resonant frequency, the HB LLC converter delivers power to the load without switching losses.

Fig. 2 shows the key waveforms of the proposed hybrid converter. As shown in Fig. 2 the primary switches operate as conventional PSFB converter and the secondary switch turns on only during the effective duty cycle. Due to the secondary switch operation, the circulation current can be eliminated in the proposed converter. Fig. 3 shows the mode of operation of the proposed hybrid converter. Each mode will be described by using the key waveforms shown in Fig. 2 and the equivalent circuit at each mode as shown in Fig. 3. For the simplicity of the analysis it is assumed that all the devices and components are ideal except for the output capacitors of the switches C_{oss}.

Mode 1([t_0~t_1]): Before t_0, the switch S_3 is on and the secondary switch S_5 is off. At t_0, the switch S_3 is turned off with a small magnetizing current I_{Lm2} of the transformer TR_2. The current I_{pri2} charges the output capacitor of the switch S_3 and discharge that of the switch S_4. Then, the body diode of the switch S_4 starts to conduct and with ZVS turn-on condition. In the secondary circuit the freewheeling current of the output inductor is bypassed through the diode D_9. In order to guarantee the ZVS operation of lagging leg switches, the minimum dead time t_{dead} is required and it can be expressed as (1).

$$t_{dead} = t_1 - t_0 = 2C_{oss}\frac{V_s}{\left|I_{Lm2}\left(t_0\right)\right|} \tag{1}$$

Mode 2([t_1~t_2]): The switch S_4 turns on with ZVS at t_1 and the switch S_5 also turns on at the same time. The input voltage V_{dc} applies to the primary side of TR_1 and the primary current starts to rise and reaches the reflected output inductor current at t_2. In the secondary side of the PSFB circuit, the load current commutates from the diode D_9 to the switch S_5. In the HB LLC resonant capacitor C_r starts to resonate with the leakage inductance L_{lk2} of transformer TR_2.

Mode 3([t_2~t_3]): At t_2, the power is transferred to the load through the switch S_1, S_4 and S_5 of the PSFB converter together with HB LLC converter. The primary current of the PSFB transformer I_{pri1} increases with a slope as shown in (2).

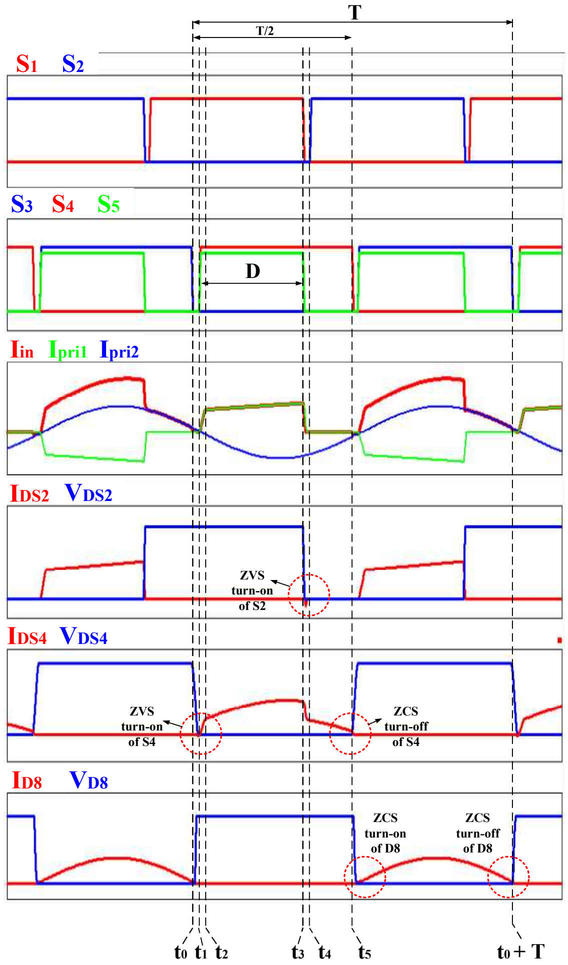


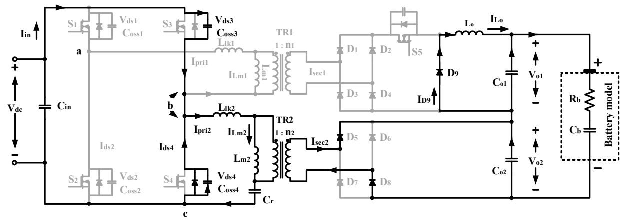
Fig. 2. Key waveforms of the proposed hybrid converter

$$\frac{di_{pri1}}{dt} = \frac{n_1 V_s - V_{o1}}{L_o / n_1} \tag{2}$$

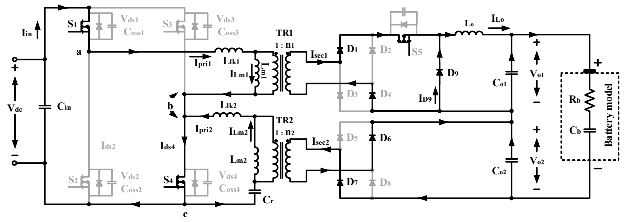
Hence, the current flowing through switch S_4 is sum of the monotonously increasing primary current I_{pri1} and the sinusoidal primary current I_{pri2} as shown in Fig. 2.

Mode 4([t_3~t_4]): At t_3, switches S_1 and S_5 both are turned off. The output capacitance of the switch S_1 is charged and that of the switch S_2 is discharged. Since the voltage across the switch S_2 is reduced to zero and ZVS turn-on condition for the switch S_2 can be obtained in this mode 4. The load current starts to commutate from the switch S_5 to the diode D_9. The current flowing through the switch S_4 becomes equal to I_{pri2} at t_4.

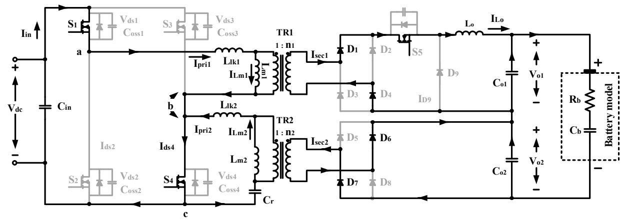
Mode 5([t_4~t_5]): At t_4, the switch S_2 is turned on with ZVS condition and the output inductor current I_{LO} freewheels through the diode D_9. The circulating current can be eliminated since the freewheeling current does not flow through the secondary winding of the transformer TR_1. In the primary side circuit only the resonant current circulates through the switch S_4 and the primary winding of the transformer TR_2. At t_5, the switch S_4 can achieve nearly ZCS turn-off since the resonant current I_{DS4} equals to the



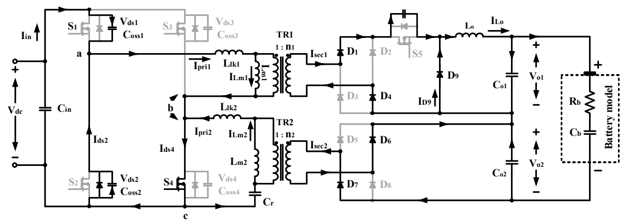
(a) Mode 1 [t_0~t_1]



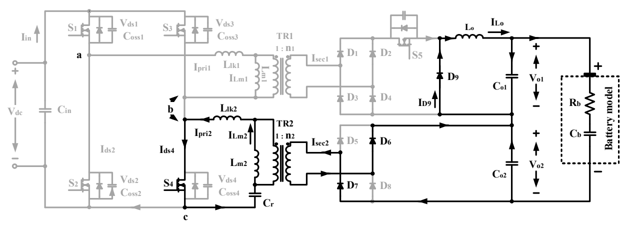
(b) Mode 2 [t_1~t_2]



(c) Mode 3 [t_2~t_3]



(d) Mode 4 [t_3~t_4]



(e) Mode 5 [t_4~t_5]

Fig. 3. Mode of operation of the proposed converter

magnetizing current I_{Lm2} of the transformer TR_2. Since the other half of the operation is symmetrical to the one described above from Mode 1 to Mode 5, it is omitted here.

3. Design Considerations for High Efficiency

In this chapter design considerations for high efficiency operation of the hybrid converter is presented. The power for each converter needs to be assigned optimally to achieve maximum efficiency. In order to take the advantage of the switching loss free characteristics of the HB LLC converter, it is required to select the output voltage of the HB LLC converter as high as possible. The power rating of the hybrid charger is 6.6.kW, the input voltage ranges from 380 to 400V, output voltage ranges from 250 to 420V and the output current is 15.7A.

3.1 Optimal power assignment for each converter

In order to maximize the efficiency of the hybrid converter, it is necessary to design the output voltage (hence the output power) of the HB LLC converter as high as possible. Since the output voltage of the hybrid converter varies from 250V to 420V during the CC charge, it could be an option to assign a constant 250V for the HB LLC converter and the rest of varying voltage from 250V to 420V for the PSFB converter. However, it is not possible to operate the hybrid converter in such a way since the HB LLC converter is not able to control the current due to the fixed frequency operation. Therefore, the CC charge needs to be implemented by the PSFB converter by controlling the effective duty cycle. It requires some voltage margin to control the inductor current and hence the minimum operating voltage (minimum duty cycle) needs to be defined. In the meantime the PSFB converter is designed to have a maximum effective duty cycle in the CV charge. However, it is not desirable to design the converter to have a maximum allowable duty for the maximum output voltage because the turn ratio of the transformer becomes smaller than unity thereby contributing to a lower efficiency.

Therefore, the turns-ratio of the PSFB transformer n_1 is calculated by the following procedure first. Then, the turns-ratio of the HB LLC transformer n_2 can be calculated accordingly. The output voltage of the PSFB converter can be expressed as (3), where D is the effective duty cycle of the PSFB converter.

$$V_{o1} = n_1 D V_s \tag{3}$$

The effective duty cycle D is selected as 0.25~0.7 according to the above mentioned considerations.

The minimum output voltage of the PSFB converter with the maximum input voltage and the minimum duty cycle can be expressed as (4). Hence, the turns-ratio of the PSFB transformer can be easily derived as (5).

$$V_{o1(\min)} - V_{o2} \geq n_1 D_{\min} V_{s(\max)} \tag{4}$$

$$n_1 \leq \frac{V_{o1(\min)} - V_{o2}}{D_{\min} V_{s(\max)}} \tag{5}$$

Similarly, the maximum output voltage of the PSFB converter with the minimum input voltage and the maximum duty can be expressed as (6). Hence the turns-ratio of the PSFB transformer can be easily derived as (7).

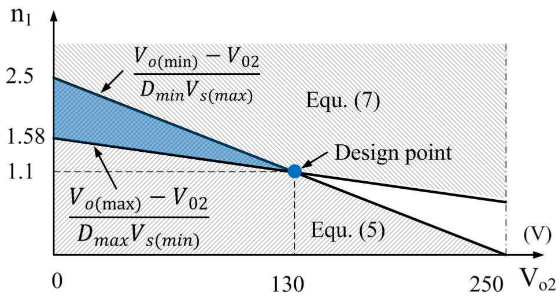


Fig. 4. Relationship between the PSFB transformer turn ratio n_1 and output voltage of the LLC converter

$$V_{o1(\max)} - V_{o2} \le n_1 D_{\max} V_{s(\min)} \tag{6}$$

$$n_1 \ge \frac{V_{o1(\max)} - V_{o2}}{D_{\max} V_{s(\min)}} \tag{7}$$

Therefore, Fig 4 can be drawn to show the relationship between n_1 and V_{o2} by using Equs. (5) and (7). It is seen in the Fig. 4 that both conditions in Equs. (5) and (7) are only satisfied in the shaded region. Hence, the output voltage for the LLC converter to optimize the efficiency of the proposed hybrid converter is found to be 130V, and the transformer turn ratio of the PSFB converter and the HB LLC can be calculated as 1.1 and 0.7, respectively.

3.2 Soft switching turn-on condition for the leading leg switches

In order to obtain the high efficiency of the converter it is essential to achieve soft-switching for all the switches during the entire charge process. Since the lagging leg switches can operate with no switching loss due to the perfect resonant operation, only the ZVS condition for leading-leg switches needs to be considered. The ZVS condition for leading-leg switches is achieved in the Mode 4 (Fig. 3(d)). The ZVS turn-on condition for the switch S2 can be achieved if its parasitic capacitor is completely discharged and the parasitic capacitor of the switch S_1 is charged by the energy stored in the leakage inductances before the switch S_2 is turned on. Therefore the total inductive energy stored in the leakage inductances should be greater than the energy required to charge and discharge the output capacitor of the switches S_1 and S_2. In the circuit formed in Mode 4 (Fig. 3(d)) the total capacitive energy can be expressed as (8) and the total inductive energy can be expressed as (9), respectively. The inductive energy includes the energy stored in the magnetizing inductance of the transformer TR_1, in the output inductor and in the leakage inductance of TR_1. Where L_{m1}, I_{m1} and C_{OSS} are the magnetizing inductance, the magnetizing current and the effective output capacitance of each switch, respectively.

$$E_c = C_{oss} \times V_s^2 \tag{8}$$

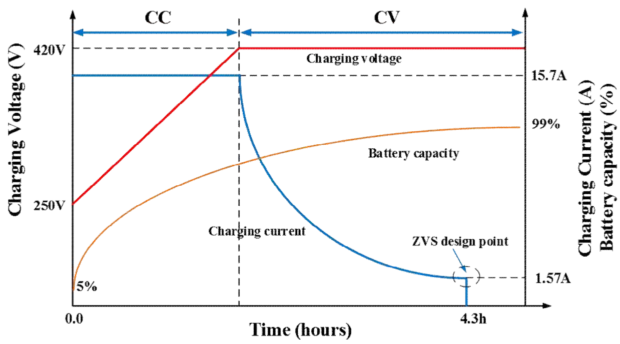


Fig. 5. CC/CV charge characteristics of the battery and the ZVS design point of the proposed on-board charger

$$E_L = \frac{1}{2} L_{m_1} I_{m_1,pk}^2 + \frac{1}{2} L I_{L_o,\max}^2 + \frac{1}{2} L_{lk_1} (I_{m_1,pk} + \frac{I_{L_o,\max}}{n_1})^2 \tag{9}$$

Fig. 5 shows the CC/CV charge profile of the battery pack of EV. In order to guarantee the ZVS of the leading leg switches during the entire charge operation, the PSFB transformer should be designed to satisfy the ZVS condition, $E_L > E_C$, at the end of CV charge where the output current is the lowest in value, 1.57[A].

4. Experimental Results

Fig. 6 shows the prototype 6.6kW hybrid on-board charger. All the parameters for the circuit is shown in Table 1. In order to show the soft switching capability of the proposed hybrid converter, it is enough to show it during the CV mode. Hence, the waveforms in Fig. 7 to Fig. 12 are all captured at light load condition (400V input voltage, 420V output voltage, 3.15A output current and corresponding output power of 1.3kW (19.7% load)) during the CV charge.

Fig. 7 shows the primary current waveforms of the two transformers and the input current waveform. Since the proposed converter operates at the resonant frequency, the primary current waveform of the HB LLC converter is sinusoidal. The circulating current in the PSFB converter is successfully eliminated, resulting in no conduction loss due to it at the primary side.

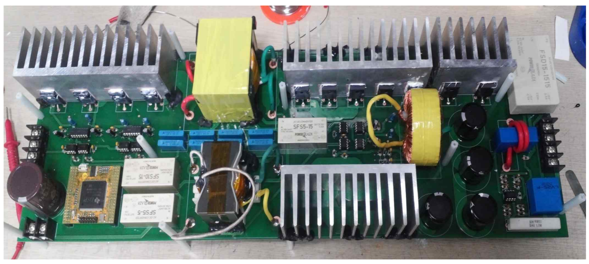


Fig. 6. Hardware prototype of the proposed hybrid on-board charger

Table 1. Specifications of the proposed on-board charger

P_o	Power rating	6.6 kW
V_{in}	Input voltage	380~400 V
V_o	Maximum Output voltage	420 V
I_o	Nominal charge current	15.7 A
f_S	Switching frequency	45 kHz
L_o	Output inductor of the PSFB converter	300 µH
L_{k1}	Leakage inductance of the PSFB transformer	9 µH
L_{m1}	Magnetizing inductance of the PSFB transformer	6 mH
n_1	Turn ratio of the PSFB transformer	1.1
L_{k2}	Leakage inductance of the HB LLC transformer	20 µH
L_{m2}	Magnetizing inductance of the HB LLC transformer	560 µH
n_2	Turn ratio of the HB LLC transformer	0.7
C_{o1}	Output capacitor of PSFB converter	1000 µF
C_{o2}	Output capacitor of HB LLC converter	2000 µF
R_b	Equivalent Series Resistance of the battery	0.011 Ω
C_b	Equivalent capacitance of the battery	350000 F
S_1-S_4	MOSFETs	FCH76N60NF
D_1-D_8	DIODEs	HFA50PA60C

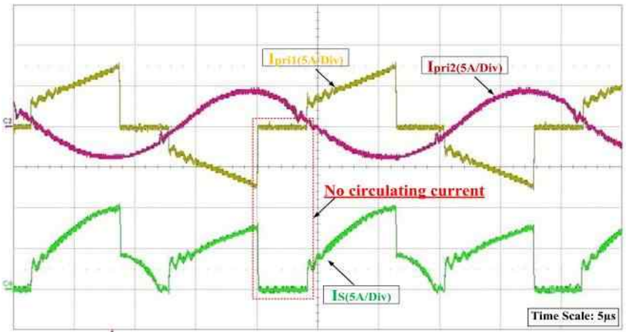


Fig. 7. Primary currents waveforms of the PSFB and LLC converters (upper) and the input current waveforms (lower)

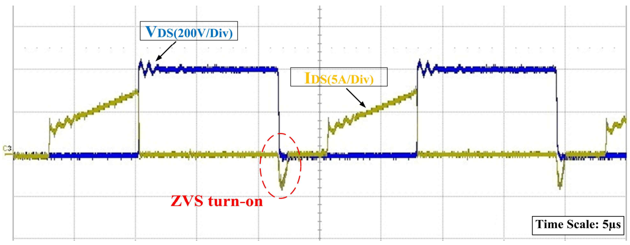


Fig. 8. Voltage and current waveforms of the leading leg switches

Fig. 8 and Fig. 9 show the voltage and current waveforms of a leading-leg switch and a lagging-leg switch of the hybrid converter, respectively. The leading leg switches can achieve ZVS turn-on all over the charge process as shown in Fig. 8. Thanks to the inductive energy stored in the HB LLC converter, the lagging-leg switches can achieve the ZVS turn-on as shown in Fig. 9. In addition its turn-off current is 1.5A which is much smaller than that of

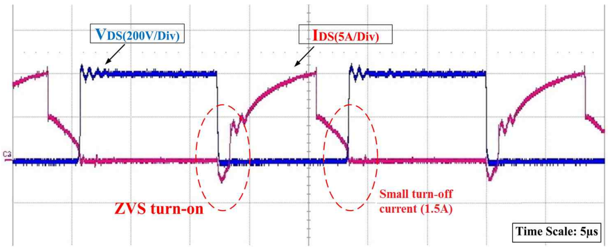


Fig. 9. Current and voltage waveforms of the lagging leg switches

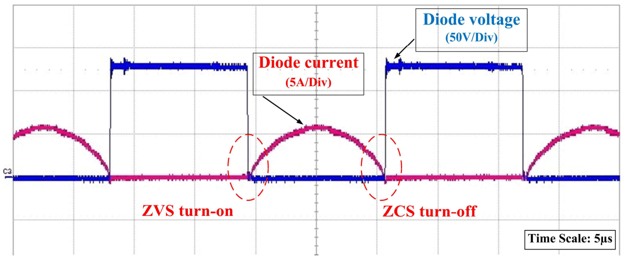


Fig. 10. Diode voltage and current waveforms at the secondary side of the HB LLC converter

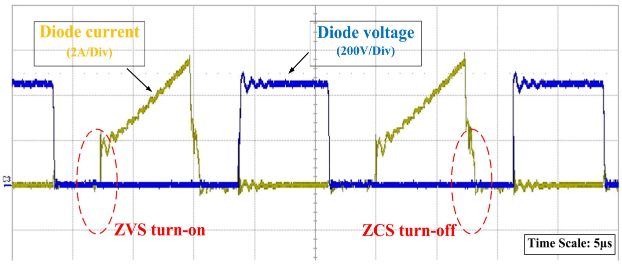


Fig. 11. Diode current and voltage waveforms at the secondary side of the PSFB converter

the conventional PSFB converter.

Fig. 10 shows the voltage and current waveforms of the secondary rectifier diode of the HB LLC converter. Due to the resonance operation, all the rectifier diodes can achieve ZVS turn-on and ZCS turn-off switching. Fig. 11 shows the voltage and current waveforms of the secondary rectifier diode of the PSFB converter. As shown in the Fig. 11, all the rectifier diodes can achieve ZVS turn-on and ZCS turn-off switching, and hence there is no switching losses at the rectifier diodes. Since the freewheeling current does not flow through the rectifier diodes due to the secondary switch S_5 and diode D_9, there is no conduction loss associated with it unlike the conventional converter.

Fig. 12 shows the current waveforms at the output inductor and the freewheeling diode D_9 in the secondary side of the PSFB converter. The output inductor current freewheels through the diode D_9 instead of the rectifier diodes. Fig. 13 shows the efficiency of the proposed hybrid converter with different input voltages during the CC/CV charge process for the EV battery pack. The maximum efficiency is 97.7% with 400V input voltage at 4.1 kW.

Table 2. Comparison of hybrid on-board chargers

Perspective	Hybrid topology in [16]	Hybrid topology in [18]	Hybrid topology in [19]	Proposed topology
PSFB transformer reset circuit	None	2 diodes & 1 capacitor	2 diodes & 1 capacitor	1 MOSFET & 1 diode
ZVS turn-on of all the primary switches	Yes	Yes	Yes	Yes
Switching characteristics of the rectified diodes in the PSFB converter	Hard switching turn-on and turn-off	Hard switching turn-on and turn-off	Hard switching turn-on and soft switching turn-off	Soft switching turn-on and turn-off
Circulating current	Large load independent	Medium load dependent	Small load dependent	None load independent
Control method & complexity	PFM+PWM complex	PWM simple	PWM simple	PWM simple
Efficiency	92.2% peak (600W prototype)	98.3% peak (3.7kw prototype)	98.6% peak (4kw prototype)	97.7% peak (6.6kw prototype)

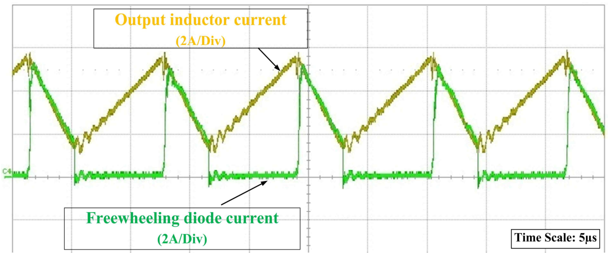


Fig. 12. Output inductor current and freewheeling diode current waveforms of the PSFB converter

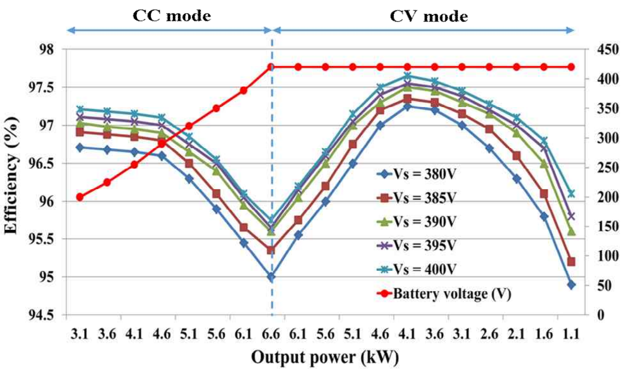


Fig. 13. Measured efficiency of the proposed on-board charger

Table 2 shows the comparison between proposed converter and the other three kinds of hybrid converters in [16, 18], and [19].

All the hybrid converters in the Table 2 use the similar concept to combine of PSFB and HB LLC. However, different techniques for the reduction of the circulating current are applied to the secondary side. In [16], since the topology does not employ the reset circuit, it has a large conduction loss and a large duty loss due to the large circulating current. In [18], though a lossless CDD snubber is applied to reset the circulating current of PSFB transformer, it is difficult to reset it when the load is heavy. In addition, since the transformer can be reset after a 1/4 resonant period, the circulating current cannot be completely eliminated. In [19], a different reset solution with a CDD snubber is introduced. The voltage of LLC converter is used to reset the circulating current of PSFB transformer. However, the voltage stress of secondary side components is higher since the secondary side rectifiers are connected in parallel. In the proposed topology, an active reset circuit composed of a MOSFET and a diode is employed and it provides several advantages such as soft switching of all the secondary PSFB rectifier diodes, zero circulating current all over the load range, and low voltage stress of the secondary side components. Furthermore, the proposed optimal power sharing technique helps maximize the system efficiency and the control of the converter is possible with a simple PWM method. It can be concluded from the Table 2 that the proposed charger is suitable for high power charger applications such as level 2 on board chargers for electric vehicles.

5. Conclusion

In this research a novel soft-switching hybrid converter combining the PSFB and HB LLC resonant converters has been proposed for the on-board charger applications. Experimental results with a 6.6-kW prototype converter has been presented to prove the validity of the proposed converter. The measured peak efficiency was 97.7% at 4-kW load. The main contributions of the proposed converter can be summarized as follows.

a. Reduction in switching losses due to the ZVS turn-on of all the primary switches over the entire charge operation.
b. ZVS turn-on and ZCS turn-off of the rectifier diodes over the entire charge operation, thereby eliminating the losses of the rectifier diodes and the reverse recovery problem.
c. No circulating current and its associated losses due to the active reset circuit employed in the secondary side.
d. Optimal power sharing strategy for each converter which helps maximize the efficiency of the converter.

References

[1] D. Gautam, F. Musavi, M. Edington, W. Eberle, and

W.G. Dunford, “An automotive on-board 3.3kW battery charger for PHEV application,” *Vehicular Power and Propulsion Conf.*, pp. 3466-3474, Sept. 2011.
[2] R. Redl, N. O. Sokal, and L. Balogh, “A novel soft-switching full-bridge dc/dc converter: Analysis, design considerations, and experimental results at 1.5 kW, 100 kHz,” *IEEE Trans. Power Electron.*, vol. 6, no. 3, pp. 408-418, Jul. 1991.
[3] K. Tae-Hoon, L. Seung-Jun and C. Woojin, “Design and control of the phase shift full bridge converter for the on-board battery charger of electric forklifts,” *Journal of Power Electronics*, vol. 12, pp. 113-119, 2012.
[4] Jiashen Tian, Junxia Gao, and Yiming Zhang, “Design of a Novel Integrated L-C-T for PSFB ZVS Converters,” *Journal of Power Electronics*, vol. 17, no. 4, pp. 905-913, Jul. 2017.
[5] Y. Jiang, Z. Chen and J. Pan, “Zero-voltage switching phase shift full-bridge step-up converter with integrated magnetic structure,” *IET Power Elec-tronics*, vol. 3, no. 5, pp. 732-739, Sept. 2010.
[6] I. H. Cho, K. M. Cho, J. W. Kim, and G. W. Moon, "A New Phase-Shifted Full-Bridge Converter With Maximum Duty Operation for Server Power System," *IEEE Transactions on Power Electronics*, vol. 26, no. 12, pp. 3491-3500, Dec. 2011.
[7] K. Chen and T. A. Stuart, “1.6 KW, 110 kHz dc/dc converter optimized for IGBT’s,” *IEEE Trans. Power Electron.*, vol. 8, no. 1, pp. 18-25, Jan. 1993.
[8] G. Cho, J. Sabate, G. Hua, and F. C. Lee, “Zero voltage and zero current switching full bridge PWM converter for high power applications,” *IEEE Trans. Power Electron.*, vol. 11, no. 4, pp. 622-628, Jul. 1996.
[9] Y. C. Ren, M. Xu, J. Sun, and F. C. Lee, “A family of high power density unregulated bus converters,” *IEEE Trans. Power Electron.*, vol. 20, no. 5, pp. 1045-1054, Sep. 2005.
[10] R. L. Steigerwald, “A comparison of half-bridge resonant converter topologies,” *IEEE Trans. Power Electron.*, vol. 3, no. 2, pp. 174-182, Apr. 1998.
[11] B. Lu, W. Liu, Y. Liang, F. C. Lee, and J. D. van Wyk, “Optimal design methodology for LLC resonant converter,” *Proc. IEEE Applied Power Electron. Conf. and Expo.*, pp. 19-23, Mar. 2006.
[12] T. Matysik, “The current and voltage phase shift regulation in resonant converters with integration control,” *IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 1240-1242, Apr. 2007.
[13] S. Zheng and D. Czarkowski, “Modeling and digital control of a phase-controlled series-parallel resonant converter,” *IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 707-715, Apr. 2007.
[14] Najam ul Hassan, Yoon-Jae Kim, Byung-Moon Han, and Jun-Young Lee, “A Hybrid DC/DC Converter for EV OBCs Using Full-bridge and Resonant Con-verters with a Single Transformer,” *Journal of Power Electronics,* vol. 17, no. 1, pp. 11-19, Jan. 2017.
[15] W. S. Yu, J. S. Lai, W. H. Lai, and H. M. Wan, “Hybrid half-and full-bridge converter with high efficiency and full soft-switching range,” *Proc. IEEE Energy Convers. Congr. and Expo.*, pp. 3080-3087, Sep. 2011.
[16] Y. Chen, X. Pei, L. Peng, and Y. Kang, “A high performance dual output dc-dc converter combined the phase shift full bridge and LLC resonant half bridge with the shared lagging leg,” *Proc. Appl. Power Electron. Conf. Expo.*, 2010, pp. 1435-1440.
[17] Van-Long Tran, Sunho Yu, Dai-Duong Tran, and Woojin Choi, “A Novel Hybrid Converter for 6.6 kW On Board Charger,” *ICPE 2015-ECCE Asia*, pp. 1528-1534, Jun 2015.
[18] Chuang Liu, Bin Gu, Jih-Sheng Lai, Mingyan Wang, Yanchao Ji, Guowei Cai, Zheng Zhao, Chien-Liang Chen, Cong Zheng, and Pengwei Sun, “High-Efficiency Hybrid Full-Bridge - Half-Bridge Converter With Shared ZVS Lagging Leg and Dual Outputs in Series,” *IEEE Transactions on Power Electronics*, vol. 28, no. 2, pp. 849-861, Feb. 2013.
[19] B. Gu, C. Y. Lin, B. Chen, J. Dominic, and J. S. Lai, “Zero-Voltage-Switching PWM Resonant Full-Bridge Converter With Minimized Circulating Losses and Minimal Voltage Stresses of Bridge Rectifiers for Electric Vehicle Battery Chargers,” *IEEE Trans-actions on Power Electronics*, vol. 28, no. 10, pp. 4657-4667, Oct. 2013.

Van-Long Tran was born in Haiphong, Vietnam, in 1988. He received his B.S. degree in electrical engineering from Hanoi University of Science and Tech-nology, Hanoi, Vietnam, in 2011. He received his M.S. degree at Soongsil University, Seoul, Republic of Korea, in 2014. His research interests include battery chargers, DC-DC converters for fuel cells and hybrid electric vehicles, and soft switching techniques.

Dai-Duong Tran received the B.Sc. degree from the Hanoi University of Science and Technology, Hanoi, Vietnam, in 2011, and the M.Sc. degree from Soongsil University, Seoul, Republic of Korea, in 2016, both in electrical engineering. Since January 2017, he has been a PhD candidate with the Power Electronics and Electrical Machines (PEEM) team in MOBI group, Vrije Universiteit Brussel, Belgium. He was a researcher with Viettel Research and Development Institute, Hanoi, from 2012 to 2014. His research interests include the Integrated Energy Manage-ment Strategies for (hybrid) electric vehicles (EVs), high-efficiency On-board Battery Chargers and power electronics interface for powertrain system of EVs.

Van-Tuan Doan was born in Hai Phong, Vietnam, in 1985. He received his B.S. and M.S. degrees in electrical engineering from Vietnam Maritime University, Vietnam, in 2008 and 2012, respectively. He is currently pursuing his Ph.D. degree in electrical engin-eering at Soongsil University, Republic of Korea. His research interests include DC-DC converters, power factor regulator converters, inverters, and soft-switching techniques for pulse-width modulation converters.

Ki-Young Kim was born in Pohang, Republic of Korea, in 1990. He received his B.S. degree in electrical engineering from Korea National Railroad University, Republic of Korea, in 2014. He is pursuing his M.S. degree at Soongsil University, Republic of Korea. His research interests include DC-DC converters and optimal sizing of the standalone photo-voltaic power generation system.

Woojin Choi was born in Seoul, Republic of Korea, in 1967. He received his B.S. and M.S. degrees in electrical engineering from Soongsil University, Republic of Korea, in 1990 and 1995, respectively. He received his Ph.D. degree in electrical engineering from Texas A&M University, USA, in 2004. He worked with Daewoo Heavy Industries as a research engineer from 1995 to 1998. In 2005, he joined the School of Electrical Engineering at Soongsil University. His research interests include modeling and control of electrochemical energy sources (e.g., fuel cells, batteries, and supercapacitors), power-conditioning technologies in renewable energy systems, and DC-DC converters for fuel cells and hybrid electric vehicles. Dr. Choi is an associate editor of IEEE Transactions on Industry Applications and a publication editor of the Journal of Power Electronics of the Korean Institute of Power Electronics.