전기자동차 온보드 충전기를 위한 새로운 하이브리드 LLC 공진 컨버터

타리안다오, 이동춘
영남대학교 전기공학과

A novel hybrid LLC converter topology of on-board battery chargers for electric vehicles

Le Anh Dao Ta and Dong-Choon Lee
Department of Electrical Engineering, Yeungnam University

ABSTRACT

This paper proposes a novel hybrid converter topology suitable for electric vehicle on-board battery chargers, which is a combination of the full-bridge (FB) and half-bridge (HB) LLC circuits. A full load controllability under wide output voltage range can be achieved with a small resonant inductance, which increases the efficiency and lowers the size and cost. Simulation results are shown to evaluate the dynamic performance of the proposed converter.

1. Introduction

The LLC resonant converter has been an excellent candidate for the dc-dc converter stage in on-board battery chargers (OBCs) of electric vehicles due to isolation, high efficiency and high power density. The frequency modulation scheme is commonly used in LLC resonant converters to respond to the change in output power demand and voltage gain. The EV traction battery voltage variation is wide, typically from 250V to 400V, which requires wide frequency variations. This leads to an increase in the transformer and driving losses and problems in designing the controllers and electromagnetic interference filters. For the LLC converter design, a low ratio of $k_L=L_m/L_r$ is adopted to reduce the frequency variation [1]. A large resonant inductor is employed in the designs for wide voltage range, with a tradeoff of size and weight. Designs with lower magnetizing inductance L_m have a narrower frequency range, but high conduction loss.

In the proposed converter, the operation of HB LLC converter and FB is combined. The converter operates as two paralleled HB LLC converters under high output voltage and high load and as a FB converter when the output voltage and load power are low. The advantages of the LLC converter such as zero voltage switching (ZVS) turn-on of the switches and zero current switching (ZCS) turn-off of the secondary diodes are kept while the output voltage is regulated within a low switching frequency range and with a reduced-size of components. Analysis comparison using calculation and simulation results are presented to explain the superiority of the proposed converter.

2. Proposed Converter

2.1 Operating principles

Fig. 1 shows the proposed converter topology, which consists of two switching legs whose switching point is connected to the primary side of two transformers. The common point of the transformers is connected to a resonant branch L_r and C_r. A voltage-doubler rectifier configuration is adopted on the secondary side.

2.1.1 Paralleled HB LLC mode (mode 1)

Under operating mode 1, S_1 and S_3 are turned on simultaneously for $T_s/2$, complimentarily to S_2 and S_4. The resonant branch is shared by the two switching legs. Therefore, the converter operation is equivalent to two HB LLC resonant converters connected in parallel. The output voltage can be compensated by regulating the switching frequency. The equivalent circuit is shown in Fig. 2.

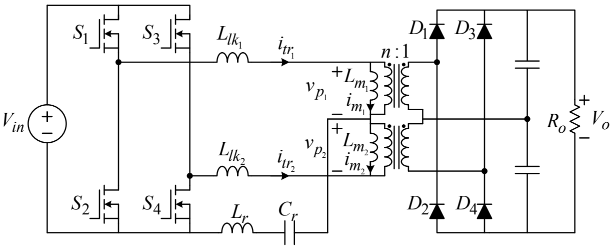


Fig. 1. Proposed topology.

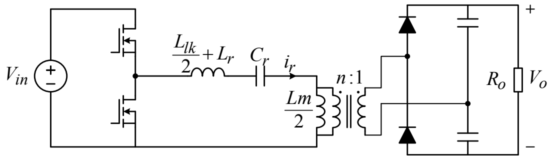


Fig. 2. Equivalent circuit in HB LLC mode.

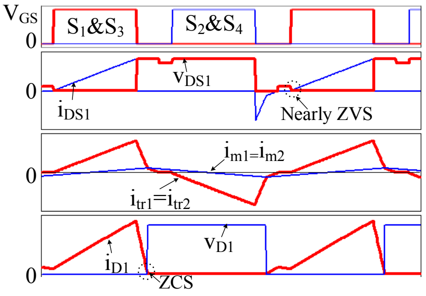


Fig. 3. Operation waveforms of the duty cycle FB mode.

2.1.2 Duty cycle FB mode (mode 2)

In operating mode 2, S_1 and S_4 are turned on simultaneously with the duty cycle D. The gating signals of S_2 and S_3 are shifted by the phase of 180° from those of S_1 and S_4. The output voltage can be controlled by modulating the duty cycle D of the switches. The operating waveforms are shown in Fig. 3.

Stage 1 [t_0, t_1]: At t_0, the voltage on the switch is $1/2(V_{in}-nV_o)$. S_1 and S_3 are turned on with nearly ZVS. The transformer currents increase with the slope $1/2L_{lk}(V_{in}-nV_o)$ and power is transferred to the load through D_1 and D_4.

Stage 2 [t_1, t_2]: At t_1, S_1 and S_3 are switched off. The transformer currents decrease with the slope $-1/2L_{lk}(V_{in}+nV_o)$ and power is transferred to the load through D_1 and D_4. At t_2, the diode current reaches 0 and turns off with ZVS.

Stage 3 [t_2, t_3]: For $i_{tr1}<i_{m1}$, the reflected current is negative. D_2 and D_4 begin to conduct and v_{p1} is clamped to $-nV_o/2$.

Stage 4 [t_3, t_4]: At t_3, $i_{tr}=0$. The energy stored in L_m is transferred to the load, clamping V_{DS2} and V_{DS3} to $1/2(V_{in}-nV_o)$ for a near ZVS turn-on.

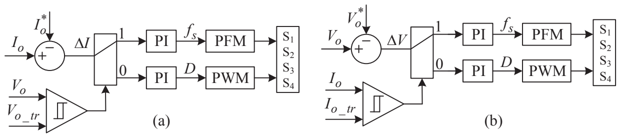
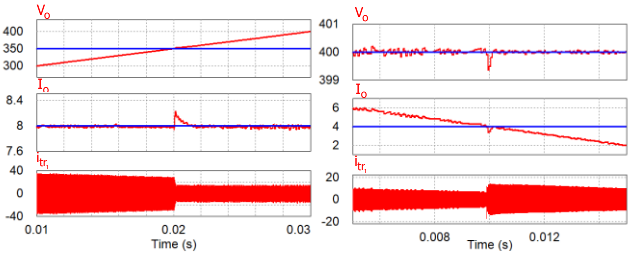


Fig. 4. Control block diagram in (a) CC mode (b) CV mode

Table I. Specifications of the EV charger

Parameters	Values	Parameters	Values
Input DC voltage (V_{in})	400V	Switching frequency (f_s)	200-250kHz
Output DC voltage (V_{out})	250-400V	Resonant frequency (f_r)	200kHz



(a) (b)

Fig. 5. Waveforms in transition in (a) CC mode (b) CV mode

2.2 Control strategy

The control block diagram for the proposed converter is shown in Fig. 4. In constant current (CC) mode, the output voltage is sensed and compared to a voltage threshold reference V_{o_tr} through a hysteresis comparator. For V_o>V_{o_tr}, the output of the comparator is 1, operating mode 1 with the pulse frequency modulation (PFM) scheme is selected to regulate the output current. For V_o<V_{o_tr}, the output of the comparator is 0, operating mode 2 with the pulse width modulation (PWM) scheme is adopted. The control scheme in constant voltage (CV) mode is similar to that of the CC mode, with the reference output current compared to the sensed one to select the mode.

3. Simulation Results

The waveforms in transition between operation mode 1 and 2 in CC and CV charging modes are shown in Fig. 5 to evaluate the dynamic performance of the converter. In CC mode, the charging current is 8A and the battery voltage gradually increases to 400V. When the output voltage reaches the reference threshold, a transition takes place from mode 2 to mode 1. It can be seen that the current is tightly regulated and the transition is smooth with an overshoot of 2.5%. In CV mode, the output voltage is well regulated at 400V with the decreasing charging current. When the current reaches the threshold, a transition from mode 1 to mode 2 occurs with a voltage undershoot of 0.2%.

4. Comparison of Topologies

In order to prove the advantages of the proposed topology, it is compared with the conventional FB LLC, dual HB LLC and the improved LLC topology in [2]. The converter parameters are designed to satisfy the EV charger specifications in Table. I. The component values are shown in Table. II.

In the proposed converter, the LLC mode is employed only in high gain and high power conditions. Therefore, the resonant inductance and its flux swing are small, which lead to smaller core size. The number of resonant capacitors is fewer than those of in [2] and dual HB LLC, and the capacitor peak voltage is lower than that of in FB LLC. The total volume is about 8% larger than FB LLC, but 24% smaller than [2] and dual HB LLC. The total weight is lower more than 24% compared with the other topologies.

Table II. Topology comparison

Component	Value	Proposed	FB LLC	[2]	Dual HB LLC
Switches	I_{rms} (A)	4x6.85	4x16	I_{S1}=I_{S2}=8.7 I_{S3}=I_{S4}=4.5	4x10
Diode	I_{AV} (A)	4x4	2x8	4x4	4x4
Resonant capacitor	C (F)	63n	32n	C_1=C_2=14n	C_1=C_2=42n
	V_{peak} (V)	510	810	V_{C1}=510 V_{C2}=690	V_{C1}=V_{C2}=575
Resonant inductor	L_r(H)	8u	20u	L_1=L_2=45u	L_1=L_2=15u
	Core	PQ35/35	PQ40/40	2*PQ40/40	2*PQ35/35
Transformer	L_m (H)	2x250u	15u	2x250u	2x15u
	Turns	14:15	20:11	24:17 16:11	14:30
	Core	2*PQ40/40	PQ50/50	PQ50/50 PQ35/35	2*PQ40/40
Total	Volume (cm^3)	155.4	144.1	204.4	204.8
	Weight (g)	291	410	383	385

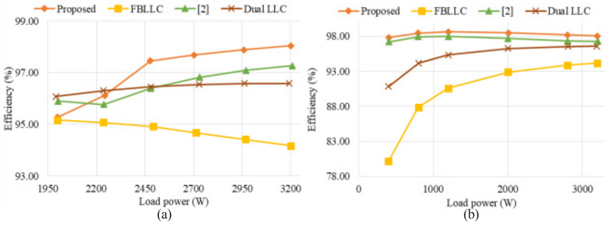


Fig. 6. Efficiency comparison in (a) CC mode, (b) CV mode.

The efficiencies of the four topologies during CC and CV charging stages are compared in Fig. 6. During the CC charging stage, the battery voltage is increased from 250V to 400V, where the current is kept as 8A. In the CV stage, the output voltage is kept as 400V while the current is decreased from 8A to 1A.

In CC mode, the proposed converter works at mode 2 when the load power is less than 2400W. Under low output voltage, the duty of switches are low, which increases the rms current. The efficiency is therefore slightly lower than dual HB LLC. However, when the converter operates with mode 1, the efficiency is the highest, with a peak of 98% at full load.

In CV mode, the proposed converter has the highest efficiency over the whole load range with a flat frequency curve.

5. Conclusions

This paper has proposed the new hybrid converter used for EV OBCs. The comparison evaluation has shown that the proposed converter can achieve higher frequency than other topologies for P_o>2400W in CC mode and in the entire load range in CV mode. In additions, the total volume of the main components is low and the total weight is the lowest among the topologies, which makes the proposed topology a good candidate for dc-dc converter of OCBs.

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References

[1] R. Beiranvand et al., “Using LLC resonant converter for designing wide-range voltage source,” *IEEE Trans. Ind. Electron.*, vol. 58, no. 5, pp. 1746–1756, 2011.

[2] W. Sun, Y. Xing, H. Wu, and J. Ding, “Modified high-efficiency LLC converters with two split resonant branches for wide input-voltage range applications,” *IEEE Trans. Power Electron.*, vol. 33, no. 9, pp. 7867–7879, 2018.