전기자동차용 배터리의 CC/CV 충전을 위한 새로운 듀얼 풀브리지 LLC 공진형 컨버터

부하이남, 최우진
숭실대학교 전기공학부

A Novel Dual Full-Bridge LLC Resonant Converter for CC/CV Charge of the Battery for Electric Vehicles

Hai-Nam Vuand Woojin Choi

Department of Electrical Engineering, Soongsil University

ABSTRACT

This paper introduces a novel dual Full-Bridge LLC(FBLLC)resonant converter forCC/CV Charge of the Battery for Electric Vehicles. One full-bridge LLC resonant converter operates with a fixed-resonant network and the other operates with a variable-resonant network for CC and CV mode operations. The proposed converter can achieve ZVS for all the primary switchesand exhibits a highefficiency characteristics like aconventional single FBLLC resonant converter. In addition, the variable-resonant network helps minimize the switching-frequency variation. The dual structure makes the proposed converter possible to achieve ZVS and nearly ZCS for all the primary switches in CCmode operation. Since the proposed converter can operate at a fixed frequency in CV mode, it can minimize the circulating current and achieve nearly ZCS. A 6.6 kW prototype converter is implemented to verify the validity of proposed converter and the maximum efficiency of 98.3% was achieved.

Index Terms –Dual full bridge LLC resonant converter, CC/CV charge, variable-resonant network and high efficiency.

1. Introduction

Electric vehicles (EVs) and plug-in hybrid EVs (PHEVs) are becoming more popular in order to increasethe energy security, lower the fuel consumption, and reduce the emission. An On-board charger (OBC) with high power density and efficiency is an important technique to proliferate the EVs and PHEVs widely. OBC is normally composed of anac-dc converter followed by a dc-dc converter. The dc-dc converter is used to charge the battery with the dc-link provided by PFC stage. Some dc-dc converter topologies to charge the batteries can be found in[1-3]. One of the popular dc-dc converter topology for the battery charger is the full-bridge LLC(FBLLC) resonant converter [2-3]. The FBLLC resonant converter exhibits a high efficiency characteristics due to its soft switching capability regardless of the load.However, in case of the battery charge application which requires CC and CV mode operations, it becomes more challenging due to the wide range of frequency variation. As well known, once the resonant converter operates out of resonant frequency, itbecomes less efficient. Other disadvantages of the non-resonant operation are high circulating current at lower switching frequency, high turn-off current at high switching frequency and the difficulty in the design optimization.

In this paper a dualFBLLC resonant converter is proposed to provide a solution to the aforementioned problems as shown in *Fig.*1. The full-bridge LLC1 operates with a fixed resonant network, and the FB LL2 operates with avariable-resonant network for CC and CV mode operations.Thedual structure makesit possible to achieve the ZVS for the primary switchesin CC mode by suitably designing the turn-off current of each LLC converter. Therefore, the proposed converter achieve full ZVS range, nearly ZCS for all the primary switches and no circulating current in both CC and CV mode operations. In addition, the proposed converter can achieve a wide range of output voltage variationwitha narrow switching frequency variation.Thanks to the resonant network of LLC2 converter capable of changing itscapacitance valueby the additional MOSFET switch two different resonant operations are possible for CC and CV mode operation, respectively.

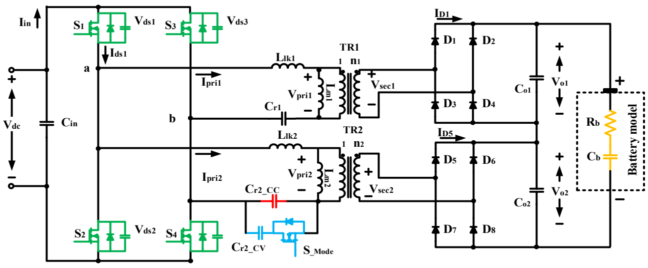


Fig. 1.Proposed dual full-bridge LLC resonant converter

2. Operating principle of the proposed converter

*Fig.*1 shows the circuit diagram of the proposed converter, which is composed of two FBLLC resonant converter.

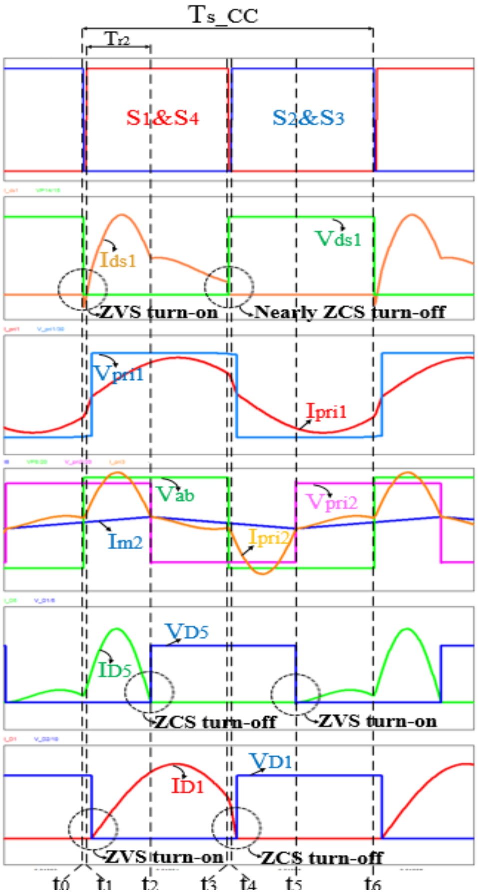


Fig. 2. Key waveforms of the proposed converter

In the primary side, four switches $S_1 \sim S_4$ are shared for two converters.$Fig.2$shows the key waveforms in CC mode operation of the proposed converter.

Mode $1(t_0 - t_1)$: At $t = t_0$, switches S_2 and $S_3$are turned off with nearly ZCS. The primary current of FBLLC1 converter $i_{pri1}(t)$ goes through the primary transformer of FBLLC2converter. This current also discharges the output capacitances of switches $S_1$and S_4 to create ZVS condition.

Mode $2(t_1 - t_2)$: The switches S_1 and S_4 are turned on with ZVS which was already achieved in mode 1at $t = t_1$. In this mode, the power is transferred to the battery through both the FBLLC1 converter and the FBLLC2 converters.

Mode $3(t_2 - t_3)$: The resonance between L_{lk2} and $C_{c2_CC}$is finished at $t = t_2$. Therefore, the voltage and current of the transformer TR_2 start to change from the positive value to the negative value. In the secondary side of FBLLC2 converter, diodes D_5, and D_8 are turned off with ZCS, meanwhileD_6, and D_7 are turned on with ZVS.

Mode $4(t_3 - t_4)$:, The switches S_1 and $S_4$are turned off with nearly ZCS at $t = t_3$. The primary current of the transformer TR_1discharges the output capacitances of the switches S_2 and S_3 to maintain the ZVS condition until they are turned on.

Mode $5(t_4 - t_5)$: The switches S_2 and S_3 are turned on with ZVS which was already achieved in mode 4at $t = t_4$. The power is transferredthrough two paths, FBLLC1 with TR_1, $D_2$and D_3 and FBLLC2 with TR_2, $D_6$and D_7.

Mode $6(t_5 - t_6)$: At $t = t_5$, this moment is the end of resonance withL_{lk2} and C_{c2_CC}. The voltage and current of the transformer TR_2start to change from the negative value to the positive value. In the secondary side of FBLLC2 , diodes D_6, and D_7 are turned off with ZCS meanwhileD_5, and D_8 start to conduct under ZVS condition.

3. Design of the proposed converter

A. *ZVS condition in CV mode.*

For CV mode, the sum of magnetizing current I_{m1} and I_{m2} is used to discharge the output capacitances of the primary switches. The magnetizing current and the inductive energy stored in the magnetizing inductances can be represented by (1)~(3).

$$I_{m1,pk} = \frac{V_{dc}T_s}{2L_{m1}} \tag{1}$$

$$I_{m2,pk} = \frac{V_{dc}T_s}{2L_{m2}} \tag{2}$$

$$E_L = \frac{1}{2}L_{m1}I_{m1,pk}^2 + \frac{1}{2}L_{m2}I_{m2,pk}^2 \tag{3}$$

B. *A small increase in switching frequency to store enough inductive energy for ZVS condition in CC mode*

The primary current to discharge the output capacitance of primary switches in CC mode is the sum of $I_{pri1}$and I_{pri2}. In order to store enoughenergy for ZVS it is required to increase the value of I_{pri1}. It can be achieved by decreasing the magnetizing inductance, however it will also increase the circulating current thereby increasing the turn-off loss of the switches.Hence, it is selected to increasethe switching frequency little bit to increase I_{pri1} rather than increasing the magnetizing current in I_{pri1}.

4. Experimental results

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

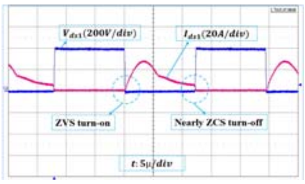
TABLE 1.SPECIFICATION OF THE PROPOSED CONVERTER

Parameter	Designator	Value
DC-link Voltage	V_{DC}	$380 - 420\ [V]$
Battery Voltage Range	$V_{Bat,min} - V_{Bat,max}$	$250 - 420\ [V]$
Power Rating	P_o	$6.6[kW]$
Switching Frequency	f_s	$45[kHz]$

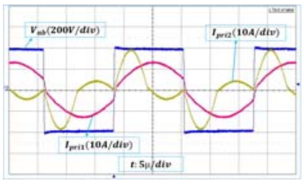
$Fig.3-5$show the CC mode waveforms of the proposed converter.$Fig.3$ shows the current and voltage waveforms of switch S_1. Both ZVS turn-on and nearly ZCS turn-off are achieved for the switch S_1.The waveforms of S_2, S_3, and$S_4$are similar to the waveform of S_1. The waveforms of two transformersareshownin $Fig.4$. The measured waveforms of diode$D_1$are shown in $Fig.5$, the diode achieves both ZVS turn-on and ZCS turn-off.

$Fig.6-7$show the CV mode waveforms of the proposed converter. $Fig.6$ shows the current and voltage waveforms of switch S_1 at light load condition. The waveforms of switch $S_1$are shown in $Fig.7$,both ZVS and nearly ZCS are achieved for this switch regardless of load.

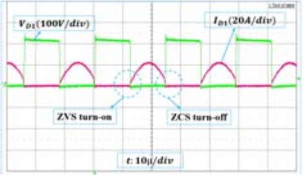
The efficiency of proposed converter including CC mode and CV mode is shown in $Fig.8$ with constant current 15.8A and constant voltage 420V. The maximum efficiency of 98.3% was achieved during the CV mode operation.



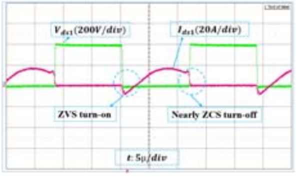
$Fig.3$. The waveform of S_1



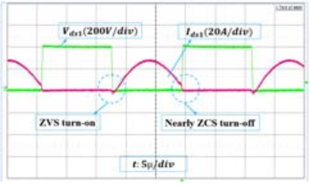
$Fig.4$. The waveform of transformer



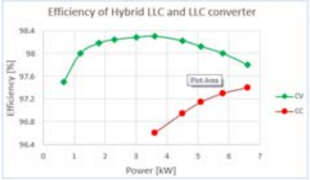
$Fig.5$. The waveform of D_1



$Fig.6$. The waveform of S_1



$Fig.7$. The waveform of S_1



$Fig.8$. The efficiency plot

5. Conclusion

This paper has introduced a novel dual full-bridge LLC resonant converter. The dual structure helps compensate current between the two converters for achieving ZVS condition in both CC and CV mode. The resonant network of the second FBLLC converter can be varied for CC mode and CV mode to minimize the switching frequency variation.A high efficiency is achieved over the wide range of the battery voltage and power.The proposed converter is suitable for battery charge applications for electric vehicles.

References

[1] B. McDonald and F. Wang, “LLC performance enhancements with frequency and phase shift modulation control,” in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, Mar. 2014, pp. 2036–2040.

[2] R. Beiranvand, B. Rashidian, M. R. Zolghadri, S. M. H. Alavi, "Using LLC Resonant Converter for Designing Wide-Range Voltage Source," *Industrial Electronics, IEEE Transactions on,* vol. 58, pp. 1746-1756, 2011.

[3] F. Musavi, M. Craciun, D. S. Gautam, W. Eberle, W. G. Dunford, “An LLC Resonant DC-DC Converter for Wide Output Voltage Range Battery Charging Applications,” *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5437–5445, Dec. 2013.