ABSTRACT

This paper introduces a novel dual Full-Bridge LLC (FBLLC) resonant converter for CC/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 switches and exhibits a high-efficiency characteristic like a conventional 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 CC mode 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 the 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 increase the 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 an ac-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 characteristic 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, it becomes 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 dual FBLLC 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 a variable-resonant network for CC and CV mode operations. The dual structure makes it possible to achieve the ZVS for the primary switches in CC mode by suitably designing the turn-off current of each LLC converter. Therefore, the proposed converter achieves 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 variation with a narrow switching frequency variation. Thanks to the resonant network of LLC2 converter capable of changing its capacitance value by 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 converters.
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 $i_{pr1}(t)$ goes through the primary transformer of FBLLC2 converter. This current also discharges the output capacitances of switches $S_1$ and $S_2$ to create ZVS condition.

Mode 2 ($t_1 - t_2$): The switches $S_1$ and $S_3$ 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 $L_{th2}$ and $C_{2,CC}$ is finished at $t = t_2$. Therefore, the voltage and current of the transformer $TR_1$ start to change from the positive value to the negative value. In the secondary side of FBLLC2 converter, diodes $D_2$ and $D_3$ are turned off with ZCS, meanwhile $D_5$ 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 $TR_1$ discharges 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 transferred through two paths, FBLLC1 with $TR_1$, $D_2$ and $D_3$ and FBLLC2 with $TR_2$, $D_5$ and $D_7$.

Mode 6 ($t_5 - t_6$): At $t = t_5$, this moment is the end of resonance with $L_{th2}$ and $C_{2,CC}$. The voltage and current of the transformer $TR_2$ start 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 meanwhile $D_5$, and $D_6$ 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).

$$I_{m1, pk} = \frac{V_{dc} T_2}{2 L_{m1}}$$

$$I_{m2, pk} = \frac{V_{dc} T_2}{2 L_{m2}}$$

$$E_L = \frac{1}{2} I_{m1} t_{m1, pk} + \frac{1}{2} I_{m2} t_{m2, pk}$$

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 $I_{pr1}$ and $I_{pr2}$. In order to store enough energy for ZVS it is required to increase the value of $I_{pr1}$. 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 increase the switching frequency little bit to increase $I_{pr1}$ rather than increasing the magnetizing current in $I_{pr1}$.

4. Experimental results

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Designator</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-link Voltage</td>
<td>$V_{dc}$</td>
<td>380–420 [V]</td>
</tr>
<tr>
<td>Battery Voltage</td>
<td>$V_{bat,min} - V_{bat,max}$</td>
<td>250–420 [V]</td>
</tr>
<tr>
<td>Power Rating</td>
<td>$P_{in}$</td>
<td>6.6 [kW]</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>$f_s$</td>
<td>45 [kHz]</td>
</tr>
</tbody>
</table>

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 transformers are shown in 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 $S_2$ 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.

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 networks 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