A Novel Dual Full-Bridge LLC Resonant Converter for CC and CV Charges of Batteries for Electric Vehicles

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Abstract—This paper introduces a novel concept for implementing constant current (CC) and constant voltage (CV) charges of batteries for electric vehicles using a dual full-bridge LLC (FBLLC) resonant converter, which shares its primary switches. In the proposed concept, the CC and CV charges are implemented using the inherent characteristics of an LLC converter as a current source and a voltage source. One FBLLC resonant converter operates with a fixed-resonant network whereas the other operates with a variable resonant network for the CC and CV charge operations. The proposed converter can achieve zero voltage switching (ZVS) and nearly zero current switching (ZCS) for all of the primary switches in the CC charge operation, and ZVS for all of the primary switches in the CV charge operation, which lead to a high efficiency. In addition, fixed switching frequency operation is possible in both the CC and CV charges thanks to the variable resonant network. A 3.3-kW prototype converter is implemented to verify the feasibility and validity of the proposed converter and a maximum efficiency of 98% was achieved.

Index Terms—CC/CV charge, dual full-bridge LLC (FBLLC) resonant converter, high efficiency, variable resonant network.

I. INTRODUCTION

ELECTRIC vehicles (EVs) and Plug-in hybrid electric vehicles (PHEVs) are becoming more popular in an effort to guarantee energy security and to lower fuel consumption and emissions. On-board chargers (OBCs) with high power density and high power conversion efficiency are crucial for the proliferation of EVs and PHEVs. An OBC is normally composed of an ac–dc converter followed by a dc–dc converter to charge batteries from a dc link. One of the most popular dc–dc converters for battery chargers is the full-bridge LLC (FBLLC) resonant converter. However, the FBLLC resonant converter needs to utilize one of the three control methods, such as frequency modulation, phase-shift modulation, or a modified structure in order to implement constant current (CC) and constant voltage (CV) charges for batteries.

In [1]–[13], frequency modulation methods are used to control the output voltage or output current of an FBLLC resonant converter. The LLC resonant converter with frequency modulation has been researched in many aspects. The research works in [1]–[5] focus on the design of the LLC resonant converter for a wide output voltage range such as the battery charge applications. In [6], it is suggested to use the LLC resonant converter for the distributed power system operating at a high switching frequency due to its zero voltage switching (ZVS) turn-on characteristics. In [7], a design methodology for the LLC resonant converters by using a capacitor-diode clamp is proposed to limit the current in the overload conditions. For the high-power applications, an interleaved LLC resonant converter is suggested to reduce the output voltage ripple [8] and to limit the effects of the component tolerances [9]. Some methods to track the maximum efficiency point of the LLC resonant converter based on the state-of-charge of a battery are introduced in [10] and [11]. In [12] and [13], optimal design of LLC resonant converter is discussed in relation to the dead time, the maximum switching frequency, and the time-weighted average efficiency. However, all of the methods mentioned in [1]–[13] are not able to implement the CC/CV charge of the battery without the wide range of the switching frequency variation. Once the resonant converter operates out of the resonant frequency, it loses its main advantages such as a low switching loss and a low circulating current. As a result, it becomes less efficient. When the switching frequency is higher than the resonant frequency, the primary switches of the FBLLC resonant converter suffer from a high turn-off current. When the switching frequency is lower than the resonant frequency, the circulating current occurs in the primary side. In addition, the wide range of the switching frequency variation causes difficulty in optimizing the magnetic components [14]. Besides, higher conduction losses and a lower power density of the converter are unavoidable when it is not optimized.

In [15]–[19], a phase-shift modulation method is used to increase the efficiency of an FBLLC resonant converter under a light load condition. Compared to the frequency modulation method, phase-shift modulation can reduce the peak-to-peak flux density of the transformer. As a result, the core loss of the transformer can be significantly reduced and a high conversion efficiency can be achieved at a light load. However, the
phase-shift modulation method is not preferred for heavy loads due to its high turn-off currents for the primary switches when compared with the frequency modulation method.

In order to avoid the above-mentioned problems, modified structures of an FBLLC resonant converter are presented in [20]–[21]. These FBLLC resonant converters can transform their structures from full-bridge to half-bridge and vice versa by using additional switches. Hence, it is possible to regulate the output voltage with a minimal operating frequency variation and to optimize the design of the magnetic components. However, these kinds of converters require two additional active switches, which operate with hard switching, to transform their structure and all of the active switches suffer from high turn-off currents leading to a lower efficiency.

In this paper, a novel dual FBLLC resonant converter is proposed to cope with all the aforementioned problems as shown in Fig. 1. The advantages of the proposed converter can be summarized as follows:

1) ZVS and nearly zero current switching (ZCS) for all primary switches in CC charge, and ZVS for all primary switches in CV charge;
2) Only one additional switch to transform the resonant tank and no switching loss associated with it;
3) A fixed-frequency resonant operation in both CC and CV charge and hence lower circulating energy;
4) Perfect soft switching of all the rectifier diodes due to the resonant operation over the entire CC and CV mode charge, hence no reverse recovery problems; and
5) High voltage gain and lower voltage rating of the rectifier diodes due to the series connection of two transformers and two rectifier bridges.

II. PROPOSED DUAL FBLLC RESONANT CONVERTER

It is well known that the LLC resonant converter can operate as a voltage source or as a current source at certain resonant frequencies. The proposed dual FBLLC resonant converter (see Fig. 1) utilizes these inherent characteristics to implement the CC and CV charges. The CC charge can be implemented by operating the upper and lower FBLLC converters as a voltage and current source, respectively. The CV charge can be implemented by operating both of the converters as voltage sources. The basic characteristics of the FBLLC converter are summarized in the Section II-A. The structure and operating principle of the proposed converter are described in Section II-B. Sections II-C and II-D show the methods for implementing the CC and CV charge operations and designing the resonant tanks of the proposed converter, respectively.

A. Two Resonant Frequencies of a Single FBLLC Resonant Converter

Fig. 2 shows an equivalent circuit of a single FBLLC resonant converter that was derived by first harmonic approximation, and it has two resonant frequencies [2], [3].

The higher resonant frequency $f_{r1}$ is determined by the resonant components $L_r$ and $C_r$, as in (1). When the FBLLC resonant converter operates at $f_{r1}$, its voltage gain is independent of the load variation since the term associated with the load resistance $R_{ac}$ becomes zero in the denominator as shown in (2).

The lower resonant frequency $f_{r2}$ is determined by the resonant components $L_r$, and $C_r$, plus the magnetizing inductance $L_m$, as shown in (3). When the FBLLC resonant converter operates at $f_{r2}$, its output current is independent of the load variation since the term associated with the load resistance $R_{ac}$ becomes zero in the denominator as shown in (4).

$$f_{r1} = \frac{1}{2\pi \sqrt{L_r C_r}}$$

$$V_o(s) = \frac{n V_{in}}{1 + \frac{L_r s + \frac{1}{L_m}}{C_r} + R_{ac} \left( L_r s + \frac{1}{C_r} \right)}.$$ (2)

$$f_{r2} = \frac{1}{2\pi \sqrt{(L_m + L_r) C_r}}$$

$$I_o(s) = \frac{V_{in}}{n \left( L_r s + \frac{1}{C_r} \right)} \cdot \frac{1}{1 + R_{ac} \left( \frac{L_m s + \frac{1}{C_r}}{L_r s + \frac{1}{C_r}} + 1 \right)}.$$ (4)

B. Structure and Operating Principle of the Proposed Converter

The above-mentioned characteristics of the FBLLC converter can be utilized to implement the CC and CV charges of the OBC of EVs. The proposed converter is composed of two FBLLC converters, which share primary switches as shown in Fig. 1. In the proposed converter, the primary switches always operate with a fixed frequency and a fixed duty cycle of 50%. Whereas the FBLLC1 converter is designed to always work as a voltage source at the higher resonant frequency, and the FBLLC2 converter has a variable structure with an additional switch to...
transform its resonant tank, and hence the resonant frequency, to make it work as a current source for CC charge and as a voltage source for CV charge.

Table I shows three different resonant tanks formed in the proposed dual FBLLC resonant converter, their resonant frequencies, and their usages in implementing the CC and CV charges. The upper converter has a resonant tank composed of $L_{ik1}$, $L_{m1}$, and $C_{r1}$. Only the resonant operation at the higher resonant frequency $f_{r1,L\text{LC}1}$ is used for both the CC and CV charges. The lower converter has two resonant tanks, one composed of $L_{ik2}$, $L_{m2}$, and $C_{r2}$, and the other composed of $L_{ik2}$, $L_{m2}$, and ($C_{r2} + C_{r3}$). In the CC charge, the lower converter operates at the lower resonant frequency $f_{r2,L\text{LC}2}$ so that it can work as a current source. In the CV charge, it operates at the higher resonant frequency $f_{r1,L\text{LC}3}$ so that it can work as a voltage source by turning ON an additional switch $S_{\text{Mode}}$. Here, the resonant network of the FBLLC2 converter is designed to have a lower resonant frequency $f_{r1,L\text{LC}2}$ which is the same as the higher resonant frequency $f_{r1,L\text{LC}1}$ of the upper resonant converter. In the CC charge, both the upper and lower converters work as a voltage source by the resonant operation at $f_{r1,L\text{LC}1}$ and $f_{r2,L\text{LC}3}$, respectively. In this mode, an additional switch is turned ON to transform the resonant tank of the FBLLC2 converter to resonate at $f_{r1,L\text{LC}3}$.

### Table I

<table>
<thead>
<tr>
<th>Resonant tank</th>
<th>Higher and lower resonant frequencies of each resonant tank</th>
<th>CC mode charge</th>
<th>CV mode charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBLLC1 converter</td>
<td>$L_{ik1}, L_{m1}, C_{r1}$</td>
<td>$f_{r1,L\text{LC}1} = \frac{1}{2\pi\sqrt{L_{ik1}C_{r1}}}$</td>
<td>Used</td>
</tr>
<tr>
<td></td>
<td>$f_{r2,L\text{LC}1} = \frac{1}{2\pi\sqrt{L_{ik1}(C_{r1} + C_{r})}}$</td>
<td>Not</td>
<td>Used</td>
</tr>
<tr>
<td>FBLLC2 converter</td>
<td>$L_{ik2}, L_{m2}, C_{r2}$</td>
<td>$f_{r1,L\text{LC}2} = \frac{1}{2\pi\sqrt{L_{ik2}C_{r2}}}$</td>
<td>Used</td>
</tr>
<tr>
<td></td>
<td>$f_{r2,L\text{LC}2} = \frac{1}{2\pi\sqrt{(L_{m2} + L_{ik2})C_{r2}}}$</td>
<td>Not</td>
<td>Used</td>
</tr>
<tr>
<td></td>
<td>$f_{r1,L\text{LC}3} = \frac{1}{2\pi\sqrt{L_{ik2}(C_{r2} + C_{r3})}}$</td>
<td>Not</td>
<td>Used</td>
</tr>
</tbody>
</table>

C. Design Considerations for the CC Mode Operation of the Proposed Converter

As previously mentioned, the CC charge can be implemented by operating the FBLLC1 resonant converter as a voltage source and by operating the FBLLC2 resonant converter as a current source. Hence, the FBLLC1 resonant converter and the FBLLC2 resonant converter need to resonate at $f_{r1,L\text{LC}1}$ and $f_{r2,L\text{LC}2}$, respectively. It should be noted that the FBLLC1 converter must be designed to have a lower output voltage than that of the minimum battery voltage (250 V in this research) in order to operate the entire converter as a current source. The switch $S_{\text{Mode}}$ is turned OFF during the CC charge operation. In this case, the resonant tank of the FBLLC2 resonant converter is composed of $L_{ik2}$, $L_{m2}$, and $C_{r2}$. The equivalent circuit of the proposed converter in the CC charge can be drawn as shown in Fig. 3.

The higher resonant frequency of the FBLLC1 resonant converter $f_{r1,L\text{LC}1}$ and the lower resonant frequency of the FBLLC1 resonant converter $f_{r2,L\text{LC}2}$ can be calculated, respectively, by the following equations:

$$f_{r1,L\text{LC}1} = \frac{1}{2\pi\sqrt{L_{ik1}C_{r1}}} \quad (5)$$

$$f_{r2,L\text{LC}2} = \frac{1}{2\pi\sqrt{(L_{m2} + L_{ik2})C_{r2}}} \quad (6)$$

Since the two converters share the primary switches, the resonant tank of two converters need to be designed to have the same resonant frequency, as shown in the following equation:

$$f_{r1,L\text{LC}1} = f_{r2,L\text{LC}2} \quad (7)$$

Fig. 4 shows the voltage gain curves for the FBLLC1 resonant converter and the output current curves for the FBLLC2 resonant converter.
converter under different load conditions. As shown in Fig. 4, the FBLLC1 converter and the FBLLC2 converter both resonate at a switching frequency $f_s$, thereby operating the FBLLC1 resonant converter as a constant voltage source and the FBLLC2 resonant converter as a constant current source, respectively.

As shown in Fig. 3, the output of the FBLLC1 resonant converter is represented by a constant voltage source $V_{o1}$, which can be calculated by

$$V_{o1} = n_1 V_{in} \quad (8)$$

where $n_1$ is the turns ratio of the transformer $TR_1$ of the FBLLC1 resonant converter. The output of the FBLLC2 resonant converter can be represented by a constant current source $I_{o2}$, which is calculated by

$$I_{o2} = \frac{V_{in}}{n_2 \omega_s L_{ik2} - \frac{1}{\omega_s C_{r2}}} \quad (9)$$

In the CC charge, the output of the proposed converter is composed of a voltage source and a current source connected in series. The output current of the FBLLC2 converter is the same as the charge current of the battery in the CC charge as shown in the following equation:

$$I_o = I_{o2} \quad (10)$$

Therefore, the output power of the FBLLC1 resonant converter and FBLLC2 resonant converter can be represented by

$$P_{FBLLC1} = V_{o1} I_o, \quad P_{FBLLC2} = (V_o - V_{o1}) I_o \quad (11)$$

**D. Design Considerations for the CV Mode Operation of the Proposed Converter**

In order to implement the CV charge of the proposed converter, both converters work as voltage sources. Since the resonant tank of the FBLLC2 used for the CC charge is designed to satisfy (7), the higher resonant frequency of it $f_{1,LLC2} = \frac{1}{2\pi \sqrt{L_{ik2} C_{r2}}} \quad$ cannot be the same as the higher resonant frequency of the FBLLC1 resonant converter $f_{1,LLC1}$. Hence, the switch $S_{Mode}$ is turned on to transform the resonant tank in this mode. Since the resonant capacitor $C_{r2}$ and $C_{r3}$ are connected in parallel, the total capacitance increases to $C_{r2} + C_{r3}$ as shown in Fig. 5. Hence, in this mode, the resonant frequency of the FBLLC2 resonant converter can be expressed by

$$f_{1,LLC3} = \frac{1}{2\pi \sqrt{L_{ik2} (C_{r2} + C_{r3})}} \quad (12)$$

Since both the converters have to resonate at the same switching frequency in the CV charge operation, the higher resonant frequency of the FBLLC2 resonant converter $f_{1,LLC3}$ needs to be designed to have the same resonant frequency as the higher resonant frequency of the FBLLC1 resonant converter $f_{1,LLC1}$ as shown in the following equation:

$$f_{1,LLC3} = f_{1,LLC1} \quad (13)$$

Fig. 6 shows the voltage gain curves for the FBLLC1 resonant converter and the FBLLC2 resonant converter under different load conditions. As shown in Fig. 6, the FBLLC1 converter and the FBLLC2 converter both resonate at a switching frequency $f_s$, thereby operating both of them as constant voltage sources. The output of the FBLLC2 resonant converter can be represented by a constant voltage source $V_{o2}$ which is calculated by

$$V_{o2} = n_2 V_{in} \quad (14)$$

where $n_2$ is the turns ratio of the transformer $TR_2$ of the FBLLC2 resonant converter. In this CV charge, the output of the proposed converter is composed of two voltage sources connected in series and the output voltage can be represented by

$$V_o = V_{o1} + V_{o2} = V_{in} \left(n_1 + n_2\right) \quad (15)$$

**E. Charge Sequence of the Proposed Converter**

The specification of the proposed converter is shown in Table II, and the CC/CV charge profile of the EV battery and its equivalent impedance during the charge are shown in Fig. 7. The battery pack is composed of 100 Li-ion battery cells and
### TABLE II
**Resonant Specification of the Proposed Converter**

<table>
<thead>
<tr>
<th>Parameter Designator</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>$V_{in}$</td>
</tr>
<tr>
<td>Output voltage (battery voltage)</td>
<td>$V_o$</td>
</tr>
<tr>
<td>Power rating</td>
<td>$P_o$</td>
</tr>
<tr>
<td>CC charge current</td>
<td>$I_c$</td>
</tr>
<tr>
<td>CV charge voltage</td>
<td>$V_{cc}$</td>
</tr>
<tr>
<td>Resonant frequency</td>
<td>$f_r$</td>
</tr>
</tbody>
</table>

The voltage of it varies from 250 to 420 V. The charge starts with CC mode charge with a constant current of 7.8 A. The CC mode charge is finished when the voltage of the battery pack reaches its maximum voltage (420 V). After then, the proposed converter switches its charge mode to CV mode charge by turning ON the switch $S_{mode}$. The CV mode is ended when the charge current is decreased to 0.78 A (0.1 C).

Here, the output voltage of the FBLLC1 converter is designed to take a half of the maximum battery voltage (210 V), which is less than the minimum battery voltage (250 V). Therefore, in the CC mode the charge current depends solely on the output current of the FBLLC2 resonant converter. The FBLLC1 converter must be designed to have a lower output voltage than that of the minimum battery voltage (250 V) in order to operate the entire converter as a current source. Otherwise constant current mode cannot be implemented since the FBLLC1 becomes active due to its higher voltage than that of the battery.

#### F. Power Distribution in FBLLC1 Resonant Converter and FBLLC2 Resonant Converter

Since the output of two FBLLC resonant converters is connected in series, the output power of each FBLLC resonant converter is proportional to its output voltages in both CC and CV mode operations. The power distribution in two converters during CC and CV mode operations is shown in Fig. 8.

During the CC mode charge operation, the output power of FBLLC1 is 1638 W (50% of the total output power) and the output power of FBLLC2 increases gradually from 312 W (19% of the total output power) to 1638 W (50% of the total output power). In the CV mode operation, the output powers of FBLLC1 and FBLLC2 are equal when their output voltages have the same values. Since the maximum output powers of both resonant converters are the same, the components with same ratings can be used for each converter, which is advantageous.

### III. MODES OF OPERATION OF THE PROPOSED DUAL FBLLC RESONANT CONVERTER

In this section, the modes of operation of the proposed converter in the CC and CV charges are detailed. Some of the circuit parameters are predefined as follows. The angular switching frequency and the switching period are expressed by (16) and (17), respectively

$$\omega_s = 2\pi f_s$$  
$$T_s = \frac{1}{f_s}$$  

#### A. CC Charge Operation

The switch $S_{mode}$ is always turned off during the CC charge operation. There are four operating modes in a half switching cycle of the proposed converter in the CC charge operation. The key waveforms for each of the operating modes are illustrated in Fig. 9.

**Mode 1** ($t_0$–$t_1$): Switches $S_2$ and $S_3$ are turned ON with ZVS at $t_0$. The primary current of the FBLLC resonant converter $i_{pri}$ discharges the output capacitance of the switches $S_1$ and $S_4$. After the voltage of the switches $S_1$ and $S_4$ drops to zero, the body diodes of these switches conduct and achieves zero-voltage switching conditions. The slope of the magnetizing current $i_{m1}(t)$ can be expressed by

$$\frac{di_{m1}(t)}{dt} = \frac{V_{in}}{L_{m1}}.$$  

**Mode 2** ($t_1$–$t_2$): The switches $S_1$ and $S_4$ are turned on with ZVS at $t_1$. The primary current of the FBLLC1 resonant converter, which is composed of $L_{b1}$ and $C_{r1}$, starts to resonate and the primary current $i_{pri1}(t)$ can be expressed by

$$i_{pri1}(t) = \frac{4V_{in}}{\pi} \frac{1}{Z_{in1}(j\omega_S)} \sin(\omega_S(t - t_1) - \theta_{pri1})$$

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where $Z_{m1}(j\omega_s)$ is the input impedance of the FBLLC1 resonant converter at the angular switching frequency $\omega_s$ and $\theta_{pri1}$ is the phase angle of the primary current $i_{pri1}$ with respect to that of the fundamental component of the voltage $v_{ab}$.

At the same time, the resonant tank of the FBLLC2 resonant converter, which is composed of $L_{m2}$, $L_{k2}$, and $C_{r2}$, starts to resonate and the primary current $i_{pri2}$ can be expressed by (20). Since the FBLLC2 resonant converter operates at the lower resonant frequency $f_{r2,\text{LLC2}}$, its primary current can be expressed by the Fourier series in (20)

$$i_{pri2}(t) = \sum_{N=1,3,5,...}^{\infty} \frac{4V_{in}}{N\pi|Z_{m2}(jN\omega_s)|} \sin(N\omega_s(t-t_1))$$

$$- \theta_{pri2,n}$$

(20)

where $Z_{m2}(jN\omega_s)$ is the input impedance of the FBLLC2 resonant converter at the angular switching frequency $N\omega_s$, and $\theta_{pri2,n}$ is the phase angle of the $N$th component of the primary current $i_{pri2}$ with respect to that of the $N$th component of the voltage $v_{ab}$.

Therefore, the summation of the above two primary currents expressed by (19) and (20) is the same as the primary switch current $i_{d1}$ as shown in Fig. 7.

**Mode 3 ($t_2$–$t_3$):** At $t_2$, the magnitude of the primary current $i_{pri2}(t_2)$ is equal to that of the magnetizing current of the transformer $TR_2$ in the FBLLC2 resonant converter. The power transfer through it ends and the rectifier diode $D_2$ achieves ZCS turn-off. In this mode, the primary currents $i_{pri1}$ and $i_{pri2}$ can be expressed by (19) and (20), respectively. The magnetizing current $i_{m2}(t)$ can be expressed by

$$i_{m2}(t) = i_{m2}(t_2) - \frac{V_o}{n_2L_{m2}}(t - t_2).$$

(21)

**Mode 4 ($t_3$–$t_4$):** At $t_3$, the switches $S_1$ and $S_4$ are turned off with nearly ZCS, and the rectifier diode $D_1$ achieves ZCS turn-off. As mentioned in Mode 2, since the switch current is a summation of the two primary currents of the FBLLC resonant converters, some design rules should be applied to design the transformer $TR_1$ of the FBLLC1 resonant converter to achieve nearly ZCS turn-off of the primary switches. This is described in detail in the following section. Since the operation of the proposed converter during the second half of the switching cycle is symmetric to that during the first half of the switching cycle, it is omitted here.

**B. CV Charge Operation**

The switch $S_{Mode}$ is turned on during the CV charge operation. In this operation, both the FBLLC1 and FBLLC2 converters operate at their higher resonant frequencies. The operating principle in CV charge operation is the same as the conventional FBLLC resonant converter and it can be found in [2]. In this mode, if the converter operates at the frequency higher than 31 kHz, the converter operates in inductive region and the ZVS condition for all of the primary switches can be guaranteed regardless of the load variation.

**IV. DESIGN PROCEDURE FOR RESONANT NETWORKS**

In this section the design procedure for the resonant tanks is detailed. In order to implement the CC and CV charges with fixed-frequency operation, the resonant tanks need to be designed carefully by the following procedure.

**Step 1 (Design of magnetizing inductance $L_{m2}$):** In CC charge operation, the FBLLC2 resonant converter operates at its lower resonant frequency $f_{r2,\text{LLC2}}$. Therefore, as shown in Fig. 3 and (6), the impedance of the resonant tank in FBLLC2 becomes zero at the angular switching frequency $\omega_s$ and (22) can be derived

$$|\omega_sL_{m2}| = \left|\frac{\omega_sL_{k2} - \frac{1}{\omega_sC_{r2}}}{\omega_s}\right|. $$

(22)

By using (9), (10), (14), and (22), the magnetizing inductance $L_{m2}$ of FBLLC2 converter can be calculated by

$$L_{m2} = \frac{V_{in}}{n_2\omega_s I_o}.$$  

(23)

**Step 2 (Design of leakage inductance $L_{k2}$):** In the FBLLC2 resonant converter, the rms value of the primary current $i_{pri2}$
depends on the leakage inductance $L_{lk2}$. The rms value of the primary current $i_{pri2}$ can be calculated from (20) by the following equation:

$$I_{pri2,RMS} = \sqrt{\frac{4V_{in}}{\sum_{N=1,3,5,...}^{\infty} 2N\pi |Z_{in2}(jN\omega_s)|}}. \quad (24)$$

It can be seen from (24) that the magnitude of $I_{pri2,RMS}$ depends on the values of $|Z_{in2}(jN\omega_s)|$. The input impedance of the FBLLC2 resonant converter at the angular switching frequency $N\omega_s$ can be expressed by

$$Z_{in2}(jN\omega_s) = \frac{1}{jN\omega_sC_{r2}} + jN\omega_sL_{lk2} + \frac{jN\omega_sL_{m2}R_{ac2}}{jN\omega_sL_{m2} + R_{ac2}}. \quad (25)$$

where $R_{ac2} = \frac{n_2^2}{8\pi^2}R_{0}\frac{V_{in}}{V_{ac}+V_{ac}}$. Since $C_{r2}$ can be calculated by $1/(\omega^2(L_{m2} + L_{lk2}))$ at the lower resonant frequency, the input impedance $Z_{in2}(jN\omega_s)$ can be expressed by

$$Z_{in2}(jN\omega_s) = \frac{1}{jN\omega_s\frac{1}{L_{m2}+L_{lk2}}} + jN\omega_sL_{lk2} + \frac{jN\omega_sL_{m2}R_{ac2}}{jN\omega_sL_{m2} + R_{ac2}}. \quad (26)$$

Equation (26) shows that the input impedance $Z_{in2}(jN\omega_s)$ depends on $L_{lk2}$ and $L_{m2}$ once the load impedance is designated. Since $L_{m2}$ is already decided in step 1, the rms value of the primary current $I_{pri2,RMS}$ only depends on the value of $L_{lk2}$.

Fig. 10 illustrates the relationship between the leakage inductance $L_{lk2}$ and the rms current value of the primary current $i_{pri2}$ of the FBLLC2 resonant converter under a certain operating condition ($V_{DC} = 400$ V, $V_o = 250$ V, $P_r = 1.95$ kW, $I_o = 7.8$ A, and $f_s = 50$ kHz). As shown in Fig. 10, the rms values of the primary current $i_{pri2}$ is inversely proportional to the value of $L_{lk2}$. Therefore, the magnetizing inductance $L_{lk2}$ should be designed to be as large as possible in order to minimize the rms values of the primary current $i_{pri2,RMS}$, which results in lower conduction losses of the primary switches. A leakage inductance value larger than 120 $\mu$H is suitable to keep the rms value of the primary current $i_{pri2}$ less than 5.5 A.

Step 3 (Design of resonant capacitor $C_{r2}$): The resonant capacitor $C_{r2}$ can be calculated from (6) as

$$C_{r2} = \frac{1}{\omega^2(L_{m2} + L_{lk2})}. \quad (27)$$

Step 4 (Design of resonant capacitor $C_{r3}$): The resonant capacitor $C_{r3}$ can be calculated from (12) as

$$C_{r3} = \frac{1}{\omega^2L_{lk2}} - C_{r2}. \quad (28)$$

Step 5 (Design of leakage inductance $L_{lk1}$): There are no specific requirements for the design of the leakage inductance $L_{lk1}$ since the FBLLC1 converter always operates at its higher resonant frequency and only the magnetizing current contributes to the discharge of the output capacitors of the primary switches. However, it is better to minimize this since the voltage stress applied to the resonant capacitor $C_{r1}$ is increased when the value of the leakage inductance $L_{lk1}$ is large.

Step 6 (Design of resonant capacitor $C_{r1}$): The resonant capacitor $C_{r1}$ can be calculated using (29) after determining the leakage inductance $L_{lk1}$ in the previous step

$$C_{r1} = \frac{1}{\omega^2L_{lk1}}. \quad (29)$$

Step 7 (Design of magnetizing inductance $L_{m1}$): In the CC charge operation of the proposed converter, the FBLLC1 and FBLLC2 converters operate in the ZVS and ZCS regions, respectively. In order to ensure the soft switching at both the turn-on and turn-off of the switches, the proposed converter, which is a combination of two FBLLC converters, should operate in the ZVS region over the entire load range during the CC charge. In this section, the magnetizing inductance $L_{m1}$ is designed to ensure ZVS and nearly ZCS for all of the primary switches over the entire load of the CC charge.

The ZVS for all of the primary switches can be achieved by designing the inductive energy $E_L$ stored in the primary side to have a higher value than the capacitive energy $E_C$ stored in the output capacitances of the primary switches by the following equation:

$$E_L \geq E_C. \quad (30)$$

The total inductive energy $E_L$ stored in the primary side at the switching moment can be calculated by

$$E_L = \frac{1}{2}L_{m1}i^2_{m1}(t_3) + \frac{1}{2}L_{lk1}i^2_{pri1}(t_3) - \frac{1}{2}L_{m2}i^2_{m2}(t_3) - \frac{1}{2}L_{lk2}i^2_{pri2}(t_3). \quad (31)$$

where $i_{m1}(t_3) = \frac{V_{in}}{4V_{in}^{2}}$, $i_{pri1}(t_3) = i_{m1}(t_3)$, $i_{pri2}(t_3) = \sum_{N=1,3,5,...}^{\infty} \frac{N\pi}{2N\pi Z_{in2}(jN\omega_s)} \sin(\theta_{pri2,N})$, $i_{m2}(t_3) = \frac{V_{ac}}{n_2 L_{m2}}$. 

Authorized licensed use limited to: Soongsil University. Downloaded on April 30,2020 at 02:22:08 UTC from IEEE Xplore. Restrictions apply.
The capacitive energy stored in the output capacitors of one pair of primary switches $E_C$ can be calculated by

$$E_C = 2 \times \frac{1}{2} C_{oss} V_{in}^2.$$  \hspace{1cm} (32)

By using (30)–(32), the magnetizing inductance $L_{m1}$ can be calculated by

$$L_{m1} = \frac{(2C_{oss} V_{in}^2 + L_{m2}^2 i_{m2}^2 (t_3) + L_{lk2} i (t_3)) (\frac{4T_s}{V_{in}})^2}{L_m^2 - L_{m1} - L_{lk1} \leq 0}. \hspace{1cm} (33)$$

Since all of the resonant network parameters for the FBLLC2 and FBLLC1 converters have been decided through step 1 to step 6, the inductive energy $E_L$ only depends on the magnetizing inductance $L_{m1}$. In order to make the turn-off currents of the primary switches as small as possible, the magnetizing inductance $L_{m1}$ needs to be as large as possible in order to achieve a nearly ZCS condition. Therefore, the magnetizing inductance $L_{m1}$ can be calculated from (33) as (34) as shown at the bottom of this page.

In order to verify the full soft-switching condition during the CC mode operation, the input impedance $Z_{in}$ of the proposed converter needs to be drawn by using

$$Z_{in} (s) = \frac{Z_{in1} (s) Z_{in2} (s)}{Z_{in1} (s) + Z_{in2} (s)}. \hspace{1cm} (35)$$

The input impedance of the FBLLC1 resonant converter $Z_{in1} (s)$ and the input impedance of the FBLLC2 resonant converter $Z_{in2} (s)$ can be calculated by using (36) and (37), respectively

$$Z_{in1} (s) = sL_{lk1} + \frac{1}{sC_{r1}} + \frac{sL_{m1} R_{ac1}}{sL_{m1} + R_{ac1}} \hspace{1cm} (36)$$

$$Z_{in2} (s) = sL_{lk2} + \frac{1}{sC_{r2}} + \frac{sL_{m2} R_{ac2}}{sL_{m2} + R_{ac2}} \hspace{1cm} (37)$$

where $R_{ac1}$ and $R_{ac2}$ are the reflected load resistance of the FBLLC1 converter and FBLLC2 converter, respectively, and it can be expressed by (38) and (39), respectively

$$R_{ac1} = 8 \frac{8}{\pi^2} R_0 \frac{V_{o1}}{V_{o1} + V_{o2}} \hspace{1cm} (38)$$

$$R_{ac2} = 8 \frac{8}{\pi^2} R_0 \frac{V_{o2}}{V_{o1} + V_{o2}}. \hspace{1cm} (39)$$

Fig. 11 shows the input impedance $Z_{in}$ of the proposed converter with varying battery impedance during the CC mode operation drawn with the specification in Table II and the circuit parameters in Table II. As shown in Fig. 11, at the switching frequency, the phase of input impedance $Z_{in}$ always lies in between $3^\circ$–$8^\circ$ over the wide range of battery impedance variation. Therefore, the proposed converter can achieve ZVS and nearly ZCS for all of the primary switches during the CC mode operation.

### V. Impact of the Tolerances in Resonant Components and Closed-Loop Control Scheme of the Proposed Converter

#### A. Impact of the Tolerances in Resonant Components

One important factor needed to be considered in implementing the proposed converter is the tolerances of resonant components, which can affect the output current gain and output voltage gain of the converter. In the design procedure shown in Section IV, the leakage inductance and the magnetizing inductance of the transformer are measured after the transformer is actually implemented. Then, the values of the resonant capacitors ($C_{r1}$, $C_{r2}$, and $C_{r3}$) are calculated again depending
TABLE III

<table>
<thead>
<tr>
<th>Variation in the resonant frequencies [%]</th>
<th>$C_{r1}$</th>
<th>$C_{r2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{r1}^{\text{res}}$</td>
<td>97.6%</td>
<td>102.6%</td>
</tr>
<tr>
<td>$f_{r2}^{\text{res}}$</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$f_{r1}^{\text{res}} / f_{r}$</td>
<td>+5%</td>
<td>X</td>
</tr>
<tr>
<td>$f_{r2}^{\text{res}} / f_{r}$</td>
<td>-5%</td>
<td>X</td>
</tr>
</tbody>
</table>

Fig. 12. Change of output current according to the variation of resonant frequencies.

Fig. 13. Variation in the output voltage gain of the proposed converter according to the variation in the resonant frequencies.

Fig. 14. Closed-loop control scheme of the proposed converter.

on the leakage inductances and the magnetizing inductances of the transformers, and the actual resonant capacitors are selected by using the inductance values and the switching frequency as shown in (27)–(29). Therefore, the resonant frequencies $f_{r1,LXC1}$, $f_{r2,LXC1}$, and $f_{r1,LXC1}$ are only affected by the tolerance of the resonant capacitors. The following analysis shows as to how much the tolerance of the resonant capacitors affects the variation in the output current and output voltage gains. If the resonant capacitors have $\pm 5\%$ tolerance in their values (typical value of J-type), the resulting variation in the resonant frequencies can be calculated as shown in Table III.

When the value of resonant frequency varies from 97.6% (48.8 kHz) to 102.6% (51.3 kHz), the output current gain in CC mode operation is varied from 95% (7.4 A) to 105% (8.2 A), as shown in Fig. 12.

Similarly, when the value of resonant frequency varies from 97.6% (48.8 kHz) to 102.6% (51.3 kHz), the output voltage gain in CV mode operation is varied from 102% (428.4 V) to 98% (411.6 V), as shown in Fig. 13.

As shown in Figs. 12 and 13, the proposed converter still exhibits desired characteristics even though the resonant capacitors have a small deviation in their values. In the CC mode operation, it is important to keep the current constant and the switching frequency needs to be adjusted to find out the exact resonant frequency for the FBLLC2 converter. In this case, the output voltage of the FBLLC1 may not be exactly 210 V but it is not important as long as the output voltage of FBLLC1 is lower than that of the battery. In the CV mode operation, switching frequency needs to be adjusted to keep the output voltage (420 V) constant and the output voltage of each converter may not be exactly 210 V. In this case, a closed-loop control is essential to adjust the switching frequency in order to obtain the suitable current and voltage gains.

B. Closed-Loop Control Scheme of the Proposed Converter

Once the resonant tanks are designed suitably according to the design procedure presented in the Section IV, the CC and CV mode charge can be simply implemented with a fixed switching frequency and guaranteed the full soft-switching condition. However, it is only possible under the assumption that the input voltage is always constant and there is no tolerance of resonant components. Hence, the operation of the proposed converter deviates from the perfect resonant condition slightly because the input voltage varies in a range of $\pm 5\%$.

A closed-loop control is necessary to implement the CC and CV mode charge operation properly. Therefore, a simple PI control scheme is adopted as shown in Fig. 14. The controller is composed of a PI controller, a mode transfer switch, and a limiter. An anti-wind-up scheme is adopted to reduce the overshoot and transient time caused by the limiter operation.
When the battery voltage is lower than the maximum charge voltage, 420 V in this research, the current controller is activated to charge the battery with a constant current. Once the voltage of the battery reaches its maximum charge voltage (420 V), the controller automatically switches its mode to the CV mode by turning ON the switch $S_{\text{Mode}}$ and by activating the voltage controller.

In order to design the PI controllers, open-loop transfer functions for CC mode and CV mode are obtained by using the ac sweep function in PSIM software as shown in Figs. 15 and 16, respectively. Based on the obtained bode plots, PI controllers for the CC mode and the CV mode have been designed as shown in (40) and (41), respectively. The $K_p$ value and $K_i$ value of the current controller for CC mode operation is 0.02 and 2, respectively. The $K_p$ value and $K_i$ value of the voltage controller for CV mode operation is 0.04 and 12, respectively.

$$G_{cc}(s) = 0.02 + \frac{2}{s} \quad (40)$$

$$G_{cv}(s) = 0.04 + \frac{12}{s} \quad (41)$$

VI. EXPERIMENTAL RESULTS

A 3.3-kW prototype battery charger has been implemented to validate the performance of the proposed dual FBLLC resonant converter. The design parameters are shown in Table IV.

### Table IV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching frequency ($f_s$)</td>
<td>50 kHz</td>
</tr>
<tr>
<td>Primary switches ($S_1$–$S_4$)</td>
<td>IPW65R041CFD</td>
</tr>
<tr>
<td>Turns ratio of TR$_1$ (1:n$_1$)</td>
<td>1:0.55</td>
</tr>
<tr>
<td>Leakage inductance of TR$<em>1$ ($L</em>{k1}$)</td>
<td>13.2 μH</td>
</tr>
<tr>
<td>Magnetizing inductance of TR$<em>1$ ($L</em>{m1}$)</td>
<td>345 μH</td>
</tr>
<tr>
<td>Resonant capacitor of FBLLC1 ($C_{r1}$)</td>
<td>730 nF</td>
</tr>
<tr>
<td>Core size of TR$_1$</td>
<td>PQ50/50</td>
</tr>
<tr>
<td>Turn ratio of TR$_2$ (1:n$_2$)</td>
<td>1:0.55</td>
</tr>
<tr>
<td>Leakage inductance of TR$<em>2$ ($L</em>{k2}$)</td>
<td>128 μH</td>
</tr>
<tr>
<td>Magnetizing inductance of TR$<em>2$ ($L</em>{m2}$)</td>
<td>272 μH</td>
</tr>
<tr>
<td>Resonant capacitor of FBLLC2 ($C_{r2}$)</td>
<td>25 nF</td>
</tr>
<tr>
<td>Resonant capacitor of FBLLC2 ($C_{r3}$)</td>
<td>54 nF</td>
</tr>
<tr>
<td>Core size of TR$_2$</td>
<td>PQ50/50</td>
</tr>
<tr>
<td>Rectifier diodes ($D_1$–$D_8$)</td>
<td>HFA50PA60C</td>
</tr>
</tbody>
</table>

A. CC Mode Operation

Figs. 17–21 shows the key waveforms of the proposed converter at each part during the CC mode operation. ($V_{DC} = 400$ V, $V_o = 250$ V, $P_o = 1.95$ kW, $I_o = 7.8$ A, and $f_s = 50$ kHz).

Fig. 17 shows the voltage and current waveforms of the primary switch $S_1$. They clearly show that the ZVS turn-on and
Fig. 18. Primary side waveforms of TR1 and TR2.

Fig. 19. Secondary side waveforms of the transformers TR1 and TR2.

Fig. 20. Waveforms of the diodes D1 and D5.

Fig. 21. Output current and output voltage in CC mode operation.

Fig. 22. Efficiency plots in CC mode operation of the proposed converter and conventional FBLLC resonant converter.

Fig. 23. Waveforms of the switch S1 at light load condition (VDC = 400 V, V0 = 420 V, P0 = 660 W, and f = 50 kHz).

nearly ZCS turn-off of the primary switches are achieved in the CC charge operation.

Primary and secondary side waveforms of the transformer TR1 and TR2 are shown in Figs. 18 and 19, respectively. The rms value of the primary current i_{pri RMS} is 5 A as shown in Fig. 18, and the leakage inductance of the transformer TR2 (L_{lk2}) is 128 μH as shown in Table IV. It can be seen that the rms value of the primary current i_{pri RMS} is successfully limited by the design in step 2 in Section IV. Fig. 20 shows that the rectifier diodes D1 and D5 achieve ZCS turn-off and no reverse recovery. Fig. 21 shows the output current and voltage waveforms of the proposed converter. An efficiency plot of the proposed converter in the CC charge operation is shown in Fig. 22.

This plot shows that a maximum efficiency of 98% was achieved. It also shows that the proposed converter has a higher efficiency when compared to the conventional FBLLC converter due its superior soft-switching performance.

B. CV Mode Operation

Figs. 23 and 24 show the waveforms of the primary switch S1 in the CV charge operation under light and heavy load...
Fig. 24. Waveforms of the switch $S_1$ at heavy load condition ($V_{DC} = 400\,V$, $V_o = 420\,V$, $P_o = 3.3\,kW$, and $f_s = 50\,kHz$).

Fig. 25. Primary side waveforms of the transformers $TR_1$ and $TR_2$.

Fig. 26. Waveforms of the diodes $D_1$ and $D_5$.

conditions, respectively. Under both conditions, the switch $S_1$ achieves ZVS turn-on, but the turn-off current is relatively large.

Fig. 25 shows waveforms of the primary sides of the transformers in both the FBLLC1 and FBLLC2 converters of the proposed converter during the CV charge operation. It is shown that both the resonant converters operate under perfect resonant conditions. The waveforms of the rectifier diodes $D_1$ and $D_5$ are shown in Fig. 26. Both the rectifier diodes achieve ZCS turn-off. As a result, there is no reverse recovery loss. Fig. 27 shows the

output current and output voltage waveforms of the proposed converter. It should be noted that the loss at the switch $S_{Mode}$ is negligible since there is only a small conduction loss (0.8 W in this case) and no switching loss during the CV mode operation.

An efficiency plot of the proposed converter in the CV charge operation is shown in Fig. 28. It shows that a maximum of 97% efficiency was achieved. It also shows that the proposed converter exhibits a slightly higher efficiency when compared to the conventional FBLLC converter.

C. Comparison of the Proposed Converter With Other Topologies

In order to prove the superiority of the proposed converter, a comparison has been made between the proposed converter and the other conventional LLC resonant converters. Table V provides a comprehensive comparison of the proposed converter with other topologies in relation to the component counts, the complexity of control, and the soft-switching characteristics.

A loss comparison between the proposed converter and the conventional FBLLC resonant converter designed with same specification is given in Fig. 29. The losses of the conventional FBLLC converter and the proposed converter are calculated at the end of CC mode charge ($V_{DC} = 400\,V$, $V_o = 420\,V$, $P_o = 3.3\,kW$ and $I_o = 7.8\,A$). As shown in Table V and Fig. 29, the proposed converter has many advantages in terms of losses though the component count of the proposed converter is larger than those of the other topologies.
This paper introduced a novel dual FBLLC resonant converter suitable for implementing the CC and CV charge of the batteries. By designing the two resonant converters to resonate at lower and higher resonant frequencies, respectively, it is possible to obtain the advantages of each operation, which results in ZVS and nearly ZCS of the primary switches in the CC charge operation. The CV charge is implemented by operating both the converters at the higher resonant frequency by transforming the resonant tank of the FBLLC2 resonant converter. The converter operates with no switching losses at the primary switches and no switching frequency variation over the entire charge process. Its high efficiency over a wide range of output power makes it suitable for battery charge applications, such as electric vehicles and energy storage systems.

### VII. Conclusion

This paper introduced a novel dual FBLLC resonant converter suitable for implementing the CC and CV charge of the batteries. By designing the two resonant converters to resonate at lower and higher resonant frequencies, respectively, it is possible to obtain the advantages of each operation, which results in ZVS and nearly ZCS of the primary switches in the CC charge operation. The CV charge is implemented by operating both the converters at the higher resonant frequency by transforming the resonant tank of the FBLLC2 resonant converter. The converter operates with no switching losses at the primary switches and no switching frequency variation over the entire charge process. Its high efficiency over a wide range of output power makes it suitable for battery charge applications, such as electric vehicles and energy storage systems.

### References


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