Bidirectional CLLC Resonant DC-DC Converter with Integrated Magnetic for OBCM Application

Gang Liu1,2, Dan Li1, Jian Qiu Zhang1, and Bo Hu1
1Dept. Electrical Engineering, Fudan University
Shanghai, People’s Republic of China
liugang12@fudan.edu.cn, lidan@fudan.edu.cn, jqzhang01@fudan.edu.cn, bohu@fudan.edu.cn

Min Li Jia2
2 Delta Power Electronics (Shanghai) Co. Ltd,
Shanghai 201209, People’s Republic of China

Abstract—It has been understood the large drawback of a CLLC bidirectional serious resonant converter is using three magnetic components, i.e., the transformer and two resonant inductors. In this paper, an integrated magnetic transformer for simplifying and boosting the electrical vehicle (EV) and plug-in electrical vehicle (PHEV) on board charger module (OBCM) implementation and performance of a bidirectional CLLC resonant converter is proposed. The new integrated magnetic transformer including two primary windings, one secondary winding, bobbin, and a magnetic core, are designed and implemented. With the magnetic integration, the converter with high power density is achieved while the number of its components and cost are reduced. The effectiveness of the proposed integrated magnetic transformer is evaluated with a 3.3kw bidirectional DC/DC converter. The experiential results show that our transformer can operate on the full voltage range of the converter with a high efficiency.

Keywords—Bidirectional DC/DC; CLLC; Magnetic integrated; EV/PHEV;

I. INTRODUCTION

A bidirectional DC/DC converter with high power density and efficiency has been attracted increasing attention in the field of the OBCM for an electrical vehicle or plug-in electrical vehicle (EV/PHEV). Plenty of previous researches work on the isolated bidirectional DC/DC converters [1]. A dual active bridge (DAB) is the most popular topology. Unfortunately, there are some disadvantages in a conventional DAB converter. For example, the modulation strategy of its phase-shift, primary and secondary bridges can only make the soft switching work on a narrow output and loading ranges. To enlarge the soft switching range of a DAB converter, a lot of modified DAB control strategies have been presented in literature [2]-[7]. However, it is rarely possible to meet the requirements of the OBCM voltage range because of its input and output voltage range making the high voltage switches unavailable. Moreover, it also let the body diode recovery and high turn off loss for MOSFET switches become problematic. Thus, most of the DAB circuit applications were based on IGBT switches. As far as the resonant converters are concerned, the conventional series resonant converter (SRC) works on a buck mode, which is also unsuitable for a wide range OBCM application. A new bi-directional SRC with a clamped capacitor was given in [8]. But the topology itself is complex due to the needing of the auxiliary circuits. It is well known that a LLC resonant converter has good performance for DC/DC converting. Unluckily, it can only work on an unidirectional mode. When it is operated in a reverse mode, its gain is limited bellow one.

As a new topology, the CLLC resonant converter has been studied and used in some energy store applications. In [9], a symmetric LLC-type resonant network is proposed for a low-voltage direct current power distribution system and the high efficiency shown can be got. However, its voltage range is not wide so that it is not adopted by a EV/PHEV application. A wide voltage range CLLC topology was given in [10] and used in the uninterrupted power supply system with 400V/48V input/output range. Nevertheless, its transformer ratio is hard designed because of the large difference between the input and output voltages. Different from the above two applications, the bidirectional DC/DC converter used in an EV/PHEV not only requires a wide voltage range, the normal ratio of the input and output voltages is but also needed near to 1. In this paper, a CLLC type bidirectional DC/DC topology to meet the all of the requirements for OBCM applications will be proposed.

To achieve high power density, magnetic design is very important. With the increasing of switching frequency, both magnetic AC loss and winging loss having been known are the main part of the total loss of a converter. Therefore, it is important to optimize its magnetic design. Techniques of the integrated magnetic have been discussed intensively in many applications [11]-[12]. In this paper, an integrated magnetic transformer is also proposed. The value of the magnetizing inductance is derived through the variable length of the gap, whereas the value of the leakage inductance can be obtained by change the number of turns and the space arrangement of the primary and secondary windings. Such a designed integrated transformer will then be used and tested in a prototype. Simulation and experimental results will be used to verify the proposed converter feasibility and effectiveness.

II. ANALYSES OF BIDIRECTIONAL CLLC DC/DC CONVERTER

The proposed bidirectional CLLC DC/DC converter is illustrated in Fig. 1. It has a symmetric structure for its primary and secondary sides. An integrated magnetic transformer is used to achieve the galvanic isolation between its input and
output sides. In Fig. 1 L_m is the magnetizing inductance. \( N \) is the ratio of \( N_p/N_s \). \( L_p \) and \( L_s \) is the leak inductance of primary and secondary windings respectively. \( C_p \) and \( C_s \) are the resonant capacitors that form the resonant tank with \( L_p \) and \( L_s \). According to the power flowing direction, Fig. 2(a) is defined as the equivalent circuit of the charging mode, while Fig. 2(b) denotes as the one of the discharging mode.

**Fig. 1.** Bidirectional CLLC DC/DC converter

### A. CLLC resonant tank analyses

Because of the symmetric structure of the circuit, the leak inductance and resonant capacitor of the primary and secondary sides are related as \( L_p = N^2 \cdot L_s \) and \( C_s = N^2 \cdot C_p \). In this way, its design process can be greatly simplified. i.e., one only need to design the \( C_p \), \( L_p \) and \( L_m \). Similar to the LLC analyses, \( R_o \left( \frac{1}{V_o} \left( \frac{P_s}{\pi} \right) \right) \) is used to equivalently represent the rectified diode and filter capacitor.

\[
\begin{align*}
R_o &= \frac{1}{V_o} \left( \frac{P_s}{\pi} \right) \\
\end{align*}
\]

**Fig. 2.** Resonant tank equal circuit (a) Charging mode (b) Discharging mode

In the charging mode, the resonant and corner frequencies can be calculated as

\[
\begin{align*}
f_{cCh} &= \frac{1}{2\pi \sqrt{L_{Ch} \cdot C_{Ch}}} \\
f_{0Ch} &= \frac{1}{2\pi \sqrt{L_m \cdot C_p}}
\end{align*}
\]

where \( L_{Ch} = L_p + \frac{L_m \cdot N^2 L_s}{L_m + N^2 L_s} \), \( C_{Ch} = \frac{C_p \cdot C_s}{N^2 C_p + C_s} \).

In the discharging mode, the resonant and corner frequencies can be given as

\[
\begin{align*}
f_{cDch} &= \frac{1}{2\pi \sqrt{L_{Dch} \cdot C_{Dch}}} \\
f_{0Dch} &= \frac{1}{2\pi \sqrt{L_m \cdot N^2 \cdot C_s}}
\end{align*}
\]

where,

\[
L_{Dch} = L_s + \frac{1}{N^2} \cdot \frac{L_m \cdot N^2 L_s}{L_m + N^2 L_s}, \quad C_{Dch} = \frac{N^2 C_p \cdot C_s}{N^2 C_p + C_s}
\]

The quality factor of the charging and discharging can be expressed as

\[
Q_{Ch} = \frac{2\pi f_{cCh} L_{Ch}}{R_o}
\]

\[
Q_{Dch} = \frac{2\pi f_{cDch} L_{Dch}}{R_o}
\]

According to Kirchhoff voltage principle and the analyses in [13], the gains of the charging and discharging modes can be expressed as follows.

\[
G_{Ch} = \left| \frac{1}{N} \left[ 1 + \frac{1}{1 + \frac{f_{cDch}}{f_{cCh}}} \right] \right|
\]

\[
G_{Dch} = \left| \frac{1}{N} \left[ 1 + \frac{1}{1 + \frac{f_{cCh}}{f_{cDch}}} \right] \right|
\]

Where, \( A = L_s / L_m \), \( B = N^2 \cdot L_s / L_m \), \( \alpha = 1/(2\pi C_s R_o) \), \( \beta = 1/(2\pi C_p R_o) \).

**B. Gain character of CLLC resonant tank**

Based on (7) and (8), the gain curve of the charging and discharging is depicted as Fig. 3. It can be seen that the voltage gain characteristic is the same as that of the LLC resonant converter. One can also find from the Fig. 3 that the all of the load variation range in both the charging and discharging modes are satisfied. It also shows that the value of the \( L_m \) should be near \( L_p \). If \( L_m >> L_p \), the gain will be not match the bidirectional voltage output. So the gain design is a tread-off process.
III. INTEGRATED MAGNETIC TRANSFORMER DESIGN

The proposed integrated magnetic transformer is illustrated in Fig. 4. Its primary and secondary windings are of a symmetric structure. The core type will be "EE" or "PQ" or others with a symmetric structure. To derive the leak inductance of the integrated transformer, the size has been represented by letters and marked on them. D and E is related with the core size. X and Z represents the half thickness of the primary and secondary windings, respectively. Y is the space between primary and secondary windings.

A. Integrated transformer leak inductance calculation

According to the distribution principle of the electromagnetic field, all electric field intensity of X, Y, and Z regions can be expressed as follows:

\[ E_X = \int_x \frac{1}{2} u_0 \cdot H_x(x)^2 \cdot A_x \, dx \]  \hspace{1cm} (9)
\[ E_Y = \frac{1}{2} u_0 \cdot H_y^2 \cdot Y \cdot A_e \]  \hspace{1cm} (10)
\[ E_Z = \int_z \frac{1}{2} u_0 \cdot H_z(z)^2 \cdot A_e \, dz \]  \hspace{1cm} (11)

Where \( H_x(x) = H \cdot x/X \), \( H_y = H \), \( H_z(z) = H - H \cdot z/Z \), \( H = I \cdot N_p/2 \cdot G \), \( G = (D - E)/2 \), \( A_e = \pi(D^2 - E^2)/4 \), \( N_p \) is the primary winding turns.

\[ E = 2(E_X + E_Y + E_Z) \]  \hspace{1cm} (12)

According to the Faraday's law of induction:

\[ E = \frac{1}{2} \cdot L_k \cdot I^2 \]  \hspace{1cm} (13)

Combining (12) and (13), the leak inductance \( L_k \) can be expressed as:

\[ L_k = \frac{N_p^2}{2G^2} \cdot A_e \cdot u_0 \cdot \frac{X + Y + Z}{3} \]  \hspace{1cm} (14)

From (14), it can be found that the value of leak inductance depends on \( X \), \( Y \), \( Z \), and \( N_p \) after the core size is determined. The value of \( L_k \) is all of the leak inductance which includes both the primary and secondary sides. While the integrated transformer is designed, the winding loss and the core loss are also two important components. Thus the parameter determination process also needs to be traded off.

B. Leak inductance character

Fig. 5 shows that the leak inductance is increase with the \( N_p \) and \( Y \) increase, so the resonant inductance can be easy determined.
IV. SIMULATION RESULTS

TABLE I. Resonant parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cp</td>
<td>50nF</td>
</tr>
<tr>
<td>Lp</td>
<td>30uH</td>
</tr>
<tr>
<td>Lm</td>
<td>50uH</td>
</tr>
<tr>
<td>Ls</td>
<td>20uH</td>
</tr>
<tr>
<td>Cs</td>
<td>70nF</td>
</tr>
<tr>
<td>N</td>
<td>34:28</td>
</tr>
</tbody>
</table>

In order to verify the proposed CLLC resonant converter, a simulation circuit of the charging and discharging modes were built. The transformer parameters is derived following the analytical processing as given in section III. The parameters obtained are shown in Table I.

A. Simulation of charging mode

B. Simulation of discharging mode

The simulation circuits of the charging and discharging modes are shown in Figs. 5 and 6 respectively. For the charging mode simulation, the results is given in Fig.6 (a) when battery voltage is 270V. Fig. 6 (b) is the results when battery voltage is 430V. It can be seen that the primary MOS is ZVS-ON and secondary diodes is ZCS-OFF, so the switching loss is very low. For the discharging mode, the simulation results is shown in Fig.8, one can see that the same switching characters as the charging mode are achieved.

V. EXPERIMENT RESULTS

A prototyped 3.3kw bidirectional CLLC converter with integrated magnetic transformer was built and tested. Fig. 9(a) shows the proposed integrated transformer and Table II gives the designed sizes. The structure in Fig. 9 has a good thermal radiating characteristic because the air can flowing through the region of Y. Such a characteristic is very important for the transformer cooling design.
Table II. The integrated transformer

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>44mm</td>
</tr>
<tr>
<td>E</td>
<td>20mm</td>
</tr>
<tr>
<td>X</td>
<td>8mm</td>
</tr>
<tr>
<td>Y</td>
<td>6.5mm</td>
</tr>
<tr>
<td>Z</td>
<td>7mm</td>
</tr>
</tbody>
</table>

The experiment prototype is shown in Fig. 9(b). The main specifications of the integrated transformer are given in Table III.

Table III. main specification

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus voltage</td>
<td>380-400Vdc</td>
</tr>
<tr>
<td>(Normal:390Vdc)</td>
<td></td>
</tr>
<tr>
<td>Battery voltage</td>
<td>270-430Vdc</td>
</tr>
<tr>
<td>(Normal:330Vdc)</td>
<td></td>
</tr>
<tr>
<td>Devices S1~s8</td>
<td>IPW65R080CFD</td>
</tr>
<tr>
<td>DSP</td>
<td>Ti F28035PAGQ</td>
</tr>
</tbody>
</table>

The experimental waveforms of the charging mode are shown in Fig. 10, which is tested with the 390Vbus-270Vbat and 390Vbus-430Vbat respectively. It can be seen from Fig. 10 that the switching is ZVS-ON and the OFF loss is not worse than as expected one. All of the results show that the converter can operate with a high efficiency in its whole output range.
reduce the magnetic volume and keep high efficiency, its thermal radiating performance can but also be improved.

ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation of China by Grant 61171127

REFERENCES


