Bidirectional DC-DC Converter with Full-bridge / Push-pull circuit for Automobile Electric Power Systems

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Abstract—In recent years, energy storage systems assisted by super capacitor have been widely researched and developed to progress power systems for the electronic vehicles. In this paper, a full-bridge/push-pull circuit-based bidirectional DC-DC converter and its control methods are proposed. From the results of detailed experimental demonstration, the proposed system is able to perform adequate charge and discharge operation between low-voltage high-current super capacitor side and high-voltage low-current side with drive train and main battery. Furthermore, conduction losses and voltage/current surge are drastically reduced by ZVS operation with loss-less snubber capacitor in high voltage side as well as the synchronous rectification in low-voltage high-current super capacitor side.

Keywords—Bidirectional DC-DC converter, super capacitor, synchronous rectifier, high frequency power conversion, automobile electric power system

I. INTRODUCTION

With the increasing needs for electric power in future automobiles such as electric vehicles (EVs), hybrid EVs and Fuel-Cell EVs, supercapacitor (S.C.) based energy storage systems are required for charge/discharge assistance of the main battery array. For these applications, bi-directional DC-DC converters to transfer the electric energy between low voltage S.C. based energy storage system and the high voltage drive train including three phase inverter-motor system and the main battery, are required as shown in Fig.1. Generally, electric power conversion with a high step-up/down ratio can be efficiently performed only in topologies with a high frequency transformer. For the low voltage and high current side, the synchronous rectifier has been widely adopted to reduce the rectification conduction losses \(^1\).

In this paper, a high frequency transformer linked full-bridge/push-pull circuit based bidirectional DC-DC converter is proposed for automobile electric power system. The presented concept with charge and discharge operation between low voltage high current S.C. side and high voltage low current main battery side, is simulated and demonstrated by the experimental proto-type system. Furthermore, synchronous rectification (S.R.) is considered to reduce conduction losses and voltage/current surge caused by diode recovery characteristics as well as soft switching operation accomplished with lossless snubber capacitor.

II. PROPOSED CIRCUIT TOPOLOGY

A proposed circuit configuration of a bidirectional DC-DC converter is shown in Fig.2. In this figure, \(V_b\) and S.C. represent the main battery bank high voltage source and the supercapacitor. The high voltage power train system is replaced to resistance \(R_1\). The full-bridge circuit (\(S_1/D_1\) to \(D_4/S_4\)) in high voltage side and the push-pull circuit (\(S_5/D_5\) and \(S_6/D_6\)) in the low voltage side are connected with the high frequency transformer \(T\). In case of the charge mode in S.C., full-bridge circuit operates as a high frequency inverter. On the contrary, push-pull circuit operates as a high frequency inverter in S.C. discharge mode. \(C_{r1}\) and \(C_{r2}\) are additional loss less capacitor for zero voltage switching (ZVS) commutation.

A. S.C. charge mode (PWM and phase shift PWM)

In this paper, two types of PWM scheme for S.C. charge
with the blanking dead time interval $t_d$. This interval $t_d$ is needed to obtain the ZVS commutation of the switches $S_1$ and $S_2$ at the turn-on instant. The output current $I_o$ of the proposed DC-DC converter is regulated by lagging the gate pulse of the switch $S_2$ ($S_3$) with respect to the gate pulse of the switch $S_1$ ($S_2$) and varying by this way an interval $t_{on}$ ($t_{on} = DT/2$) as PS-PWM control with the constant switching frequency $f = 1/(T/2)$.

$$D_c = \frac{T_{oph}}{T/2}$$  \hspace{1cm} (3).

Fig.5 represent the synchronous rectification control circuit. Reference voltage $E_s$ is considerably adjusted because of the practical conditions such as the device operation delay from the gate signal.

B. S.C. discharge mode

The operation waveforms in S.C. discharge mode are shown in Fig.6. The push-pull switches ($S_5$ and $S_6$) are operated with overlapping interval. S.C. discharge current $I_{sc}$ is controlled by overlapping interval. At this interval, $I_{sc}$ is stored to $L_{DC}$, after that, stored current flows to the battery side. This means that discharging duty ratio $D_{discharge}$ should be larger than 0.5.

$$D_{discharge} = \frac{T_2}{T}$$  \hspace{1cm} (4).

In discharge mode, full-bridge circuit acts as a full-bridge diode rectifier.

C. Circuit design

First of all, rate of the handling storage energy in S.C. is defined as 75% of the maximum capacity. This rate corresponds the minimum voltage of the S.C. is a half of the maximum voltage $V_{C_{\text{max}}}$. And then, the turn ratio of high frequency transformer $N_T$ can be determined based upon eq.(5).

$$N_T = \frac{N_p}{N_S} = \frac{V_b}{V_{C_{\text{max}}}}$$  \hspace{1cm} (5).

The supercapacitor cell used in this system is PSLF-1350, Power System Co., and the specification in four series of cells is described in TABLE I. The total design specifications and circuit parameters of the proposed bidirectional DC-DC converter are shown in TABLE II.
### TABLE I.
**CHARACTERISTICS OF THE SPERCAPACITOR**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitance</td>
<td>340 F</td>
</tr>
<tr>
<td>Maximum Voltage</td>
<td>10.8 V</td>
</tr>
<tr>
<td>Continuous Charge-Discharge Current</td>
<td>60 A</td>
</tr>
<tr>
<td>Maximum ESR</td>
<td>1.5 mΩ</td>
</tr>
<tr>
<td>Energy Density</td>
<td>6.5 Wh/kg</td>
</tr>
<tr>
<td>Power Density (cell)</td>
<td>5.5 kW/kg</td>
</tr>
</tbody>
</table>

(four series of 1350 F cells)

### TABLE II.
**CIRCUIT CONFIGURATIONS**

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Source Voltage</td>
<td>Vb</td>
<td>50 V</td>
</tr>
<tr>
<td>Inductor</td>
<td>Ldc</td>
<td>60 µH</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>Fs</td>
<td>60 kHz</td>
</tr>
<tr>
<td>Trans. Winding Turn Ratio</td>
<td>Np:Ns:Ns</td>
<td>5:1:1</td>
</tr>
<tr>
<td>Additional lossless snubber capacitor</td>
<td>Crx</td>
<td>4.7 nF</td>
</tr>
<tr>
<td>On-resistance of MOSFET</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Infineon, BUZ 341)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>35 mΩ</td>
</tr>
</tbody>
</table>

### III. PERFORMANCE ANALYSIS

#### A. Steady state experimental results with PWM control

To verify the steady state performances of the proposed bidirectional DC-DC converter, a small scale lab. model is built and tested. In the experimental set-up, trench-gated IGBT 2 in 1 modules (CM100DUS-12F: Mitsubishi electric Co. Ltd.) are used for full-bridge stage. At the same time, two paralleled MOS-FETs (BUZ341: Infineon Co. Ltd.) in each arm are applied for the push-pull stage.

Figure 7 shows the operating waveforms in S.C. charge mode without S.R. and without lossless snubber capacitor for ZVS at full-bridge stage. The S.C. charge current $I_{sc} (= I_L)$ is well regulated by full-bridge side operation. As shown in these waveforms, recovery current surge at the rectifier diodes $D_5$ and $D_6$ cause measurable voltage spikes at S.C. voltage ($V_c$), however, these diode recovery characteristics oriented spikes can be easily reduced by synchronous rectification, as follows in the next chapter.

Figure 8 illustrates the operating waveforms in S.C. discharge mode. Significant current surges are observed in the push-pull current waveforms. These surges are caused by hard switching operation of MOS-FETs ($S_5$ and $S_6$). From the other experimental results in our research, these current surges are able to damp by adding the RCDi snubber to the MOS-FET in push-pull circuit.

#### B. Current surge suppression with Synchronous rectification

Figure 9 depicts the magnified current surge waveform of rectifying diode $D_5$ without S.R., observed in Fig.7. This current surge is caused by the recovery characteristics of rectifying diodes in opposite side ($D_6$). These recovery-oriented surges can be effectively suppressed by S.R. shown in Fig.4. Figure 8 represents the effectively suppressed current waveform with S.R..
In addition, S.R. is an effective approach to reduce the device conduction losses generated in rectifying devices at large current push-pull stage. The measured conduction losses in the MOS-FET rectifier are shown in Fig. 9. From the measured results, it can be seen that the suppressed conduction loss in each rectifying arm at the push-pull stage reached to 9.8W at $I_{SC} = 30$A.

C. Parasitic oscillation caused by lossless snubber capacitor and suppression technique

In case of S.C. charge mode, proposed DC-DC converter can achieve ZVS/ZCS turn on and ZVS turn off commutation by adding the loss less snubber capacitor $C_{rx}$ ($x=1$ or 2) in parallel with $S_2$ and $S_4$ as shown in Fig.2. $C_{rx}$ are set to 4.7nF, the leakage inductance of the high frequency transformer $T$ is 10uH.

However, parasitic oscillation in dead time periods appears to voltage waveforms in both S.C. charge/discharge mode as shown in Fig. 12 and Fig.13. These oscillations are caused by $C_{rx}$ and the leakage inductance, because no current flows to $S_2$ and $S_4$ in these periods. They are able to be suppressed by introducing synchronous rectification in S.C. discharge mode and phase shift PWM in S.C. charge mode, as follows.

Figure14 shows the operating waveforms in S.C. charge mode (without S.R. in push-pull side) by introducing phase shift PWM control represented in Fig. 4. As shown in these waveforms, oscillation appeared in case of PWM control can be perfectly suppressed by phase shift PWM control. As shown in these waveforms, recovery currents in the rectifier
diode $D_6$ in push-pull stage caused measurable current spikes observed in $S1$ current ($i_{s1}$) waveform via high frequency transformer $T$. However, introducing S.R. in push-pull stage can easily reduce these rectifier-oriented current spikes as mentioned above.

Furthermore, significant oscillations in S.C. discharge mode are observed in the full-bridge side $S_1$ voltage waveform as shown in Fig.13. These oscillations can be suppressed by introducing S.R. in full-bridge side as well as push-pull side. Figure 15 shows suppressed experimental waveforms by introducing S.R. in full-bridge side.

In this case, circulating current is generated at marked area in Fig.15. This circulating current flows $S_1$ to $S_3$ or $S_2$ to $S_4$, and this means newly conduction loss is generated. Figure 16 shows the measured conduction losses generated by circulating current in full-bridge side. As shown in this chart, percentage of conduction losses is 0.3% at the maximum. It is not too much to say that newly generated conduction losses are negligible small compared to the improved efficiency by introducing soft switching operation.

In this paper, a full-bridge/push-pull stage-based bidirectional DC-DC converter for automobile electric power systems and its control schemes are proposed. From the experimental point of view, the proposed system is able to perform adequate charge and discharge operation between low-voltage high-current push-pull stage and high-voltage low-current full-bridge stage. Furthermore, conduction losses and voltage/current surges at S.C. charge mode are drastically reduced by synchronous rectification in push-pull stage. The parasitic oscillation caused by loss less snubber capacitor introduced for soft switching commutation is drastically suppressed by phase shift PWM control and synchronous rectification in full-bridge stage.

In future, further investigations in both S.C. charge/discharge operations, such as total performance evaluation and power conversion efficiency analysis are required.

**REFERENCES**


