A Battery Energy Storage System Assisted EV Charger Based on a Three Port DCDC Converter

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Abstract

In order to achieve a faster charging speed to the electric vehicle by a charger supplied with a limited capacity AC source, a battery energy storage system assisted EV charger based on a non-isolated three-port bidirectional dc-dc converter is proposed in this paper. The converter can work in single input single output, single input dual output, and dual input single output modes. It has the advantages of simple structure and flexible control. The working modes of the charger and the converter is described firstly. Then the working principles of the converter are analyzed and followed by the description of a three layer control system. An experimental prototype was built to test the converter. The experimental results show that the converter can work properly in the proposed modes.

Keywords: EV charger, Bidirectional dc-dc converter, Three-port converter

Nomenclature

Abbreviation

BESS Battery Energy Storage System
EV Electric Vehicle
MOSFET Metal-Oxide-Semiconductor Field-Effect Transistor
IGBT Insulated Gate Bipolar Transistor
SISO Single input single output
SIDO Single input dual output
DISO Dual input single output
SOC State of charge
PWM Pulse width modulation

Symbols

\( P \) Power
\( V \) Voltage
\( I \) Current
\( D \) Duty cycle

Subscript

ref Voltage reference

1. Introduction

In recent years, the number of EVs has been increasing in Beijing, Shenzhen and other cities in China year by year, it has formed a wide range of penetration. It is estimated that by 2050 the number of EVs in China will reach 200 million, and the total charging load will be up to 330 million kilowatts [1]. With the increase of electric vehicles, the demand for charging facilities is also increasing. Therefore, all kinds of charging facilities will penetrate into every node of the distribution network. But for a specific charger, on the one hand, its charging load is intermittent rather than continuous, on the other hand, its existing distribution capacity is likely to be limited. So, it has become a good way to stabilize the load fluctuation by using an energy storage system paralleled to an EV charger. In order to get good operation results, the power conversion device plays an important role.

Multi-port dc-dc converters [2-3] are useful in the applications such as renewable energy power generation, EV charging, power supplies and so on. The research of multi-port converters mainly focuses on three-port converters, which can be divided into two categories: isolated [4-6] and non-isolated [7-10]. Non-isolated topology not only connects all the power and load but also adjusts the flow of energy between the power and load more directly, so as to makes the whole system simpler and more compact. Moreover, fewer power switches than isolated topologies can reduce system losses and achieve higher efficiency and power density.

This paper proposes a Battery Energy Storage System (BESS) assisted Electric Vehicle (EV) charger topology based on a three port DCDC converter. The topology of the proposed charger is shown in Fig.1. When there is no EV connected to the charger, the BESS can be charged by the AC power source. When an EV is connected to the charger, the AC power source and/or the BESS can charge the EV’s battery pack simultaneously or individually. Through the BESS, the peak-shifting and valley-filling operation of the charging
load is realized, thus the fluctuation of the charging load is suppressed and the power impact of the charging load on the power point of the charger is reduced.

The proposed charger uses a symmetric non-isolated three-port bidirectional DCDC converter as shown in Fig.2. The converter adopts a completely symmetrical non-isolated structure which ensures the energy can flow freely among three ports, and it has the advantages of simple structure, flexible control, small volume, and large voltage variation range. Compared with the existing topologies proposed in the literatures of [7-10], this topology can realize more diversified power flow modes and truly adapt to the charging requirements of EVs.

2. Analysis of the charger

2.1 Working modes of the charger

As shown in Fig.2, the three-port bidirectional dc-dc converter has a three half-bridge configuration. In each half bridge, there are three gate controlled power semiconductor devices, such as MOSFETs or IGBTs, anti-paralleled with a freewheeling diode respectively. Taking MOSFETs as the example, the two upper switches in a half bridge are common-drain connected, which can provide the reverse current blocking capability in the bridge. So the inverse connected switches (Qa, Qb, and Qc) are referred as blocking switches. When a port operates as an energy output port, the blocking switch keeps ON state and disables its blocking capability. Under other conditions, the blocking switch can keep OFF state and the current will flow through the anti-parallelled diode or be blocked. Also, the blocking switch can be modulated synchronously with other switches to reduce the power losses of diodes. In order to simplify the working mode analysis, the blocking switches are assumed to be ON or OFF rather than modulated.

Energy can be transferred through the inductors between the ports. Because the circuit topology is completely symmetrical, Port 1, 2, and 3 can be used as input or output ports arbitrarily, but there should be at least one input port and one output port. The amount of energy and its transmission direction can be changed according to the operating state of the switches and their duty cycle. If the power flowing into the port is assumed to be positive, then the power of three ports can be described as Eq. (1) without considering the power losses in the converter.

\[ P_1 + P_2 + P_3 = 0 \]  

(1)

So, the converter can have three working modes according to the power flow directions: (1) Single input single output (SISO) mode, (2) Single input dual output (SIDO) mode, and (3) Dual input single output (DISO) mode. For the charger, according to the dc-dc converter working modes, there are five possible working modes as shown in Fig.3. However, mode (e) may seldom appear since the limited AC source power. Depending on the BESS capacity, EV charging capacity, and
charger’s usage rate, several modes may combine a whole procedure. For example, mode (a), (c), (b) may combine a whole procedure to ensure that an EV can be charged from empty to full charge.

2.2 Working principle of the converter

Assuming that all the devices are ideal and the inductors are all the same, the working principle of the converter is described according to its working modes.

2.2.1 SISO mode

Referring to Fig.1, Fig.2 and Fig.3 (a), Port 1 works as input and Port 2 works as output with Port 3 is shut down by keeping Qc OFF. In this mode, the converter is equivalent to a cascade bidirectional step-up and step-down converter [8], where the inductance value is equivalent to 2/3 of a single inductor.

2.2.2 SIDO mode and DISO mode

Referring to Fig.1, Fig.2 and Fig.3 (e), Port 1 works as input and Port 2 and Port 3 works as output when Qa keeps OFF and Qb and Qc keep ON. Q11, Q22, and Q32 can totally have eight switching mode combinations, as shown in Table 1 and the simplified equivalent circuit diagram for the eight modes is shown in Fig. 4.

Table 1 Switching state combinations of Q11, Q22, and Q32.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Q11</th>
<th>Q22</th>
<th>Q32</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>On</td>
<td>On</td>
<td>On</td>
</tr>
<tr>
<td>2</td>
<td>On</td>
<td>On</td>
<td>Off</td>
</tr>
<tr>
<td>3</td>
<td>On</td>
<td>Off</td>
<td>On</td>
</tr>
<tr>
<td>4</td>
<td>On</td>
<td>Off</td>
<td>Off</td>
</tr>
<tr>
<td>5</td>
<td>Off</td>
<td>On</td>
<td>On</td>
</tr>
<tr>
<td>6</td>
<td>Off</td>
<td>On</td>
<td>Off</td>
</tr>
<tr>
<td>7</td>
<td>Off</td>
<td>Off</td>
<td>On</td>
</tr>
<tr>
<td>8</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
</tr>
</tbody>
</table>

If the main waveforms are same as Fig.5, the switching modes of 1, 2, 6, and 8 are included in one switching period, with the duty cycle of Q11, Q22, and Q32 are denoted by \( D_{11} \), \( D_{22} \), and \( D_{32} \) respectively.

Then, according to the volt-second balance principle, the voltages of Port 2 and Port 3 can be described by Eq. (2).

\[
\begin{align*}
V_2 &= f(D_{11}, D_{32}) = V_1 \frac{D_{11}}{1 - D_{22}} \\
V_3 &= f(D_{11}, D_{32}) = V_1 \frac{D_{11}}{1 - D_{32}}
\end{align*}
\] (2)

Referring to Fig.1, Fig.2 and Fig.3 (c), the voltage of Port 3 in DISO mode can be drawn by Eq. (3).

\[
V_3 = V_1 \frac{D_{11}}{1 - D_{32}} = V_1 \frac{D_{11}}{1 - D_{32}}
\] (3)

2.3 Control strategy of the converter

The control system of the proposed charger has a three-layer structure as shown in Fig.6. The top layer fulfills the AC source and BESS power management function, which will give the converter control instructions to the middle layer according to the state and parameters of AC source and BESS, for example, maxim supply power, SOC of BESS and so on. The middle layer runs a working mode selection decision algorithm based on the converter control instructions. And then, the middle layer will output the port voltage references to the bottom layer, which is a closed-loop control and dual-carrier PWM modulation unit to trigger the switching devices properly [11].

Figure 4 Equivalent circuit of eight switching modes in SIDO mode

Figure 5 Main waveforms in SIDO mode
2.4 Experimental results of the converter

An experimental prototype of 1kW was built to test the converter topology. The experimental waveforms in different working mode are shown in Fig.7~9 and the stable results are shown in Table 2~4 respectively.

### Table 2 Stable results in SISO mode

<table>
<thead>
<tr>
<th>$V_{ref2}$</th>
<th>$V_2$</th>
<th>$I_L1$</th>
<th>$I_L2$</th>
<th>$I_L3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>60.1</td>
<td>3.3</td>
<td>1.69</td>
<td>-1.64</td>
</tr>
<tr>
<td>80</td>
<td>80.7</td>
<td>4.85</td>
<td>2.5</td>
<td>-2.39</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>7.6</td>
<td>3.86</td>
<td>-3.74</td>
</tr>
</tbody>
</table>

### Table 3 Stable results in SIDO mode

<table>
<thead>
<tr>
<th>$V_{ref2}$</th>
<th>$V_2$</th>
<th>$V_3$</th>
<th>$I_L1$</th>
<th>$I_L2$</th>
<th>$I_L3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>40/60</td>
<td>40.6/60.3</td>
<td>2.44</td>
<td>2.81</td>
<td>0.64</td>
<td></td>
</tr>
<tr>
<td>60/90</td>
<td>60.1/90.2</td>
<td>3.61</td>
<td>4.33</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>90/100</td>
<td>90.6/100</td>
<td>4.83</td>
<td>4.83</td>
<td>0.25</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4 Stable results in DISO mode

<table>
<thead>
<tr>
<th>$V_{ref3}$</th>
<th>$I_{ref3}$</th>
<th>$V_2$</th>
<th>$I_L1$</th>
<th>$I_L2$</th>
<th>$I_L3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>2</td>
<td>40.8</td>
<td>0.04</td>
<td>2.81</td>
<td>0.64</td>
</tr>
<tr>
<td>70</td>
<td>3</td>
<td>70.5</td>
<td>0.03</td>
<td>4.33</td>
<td>0.95</td>
</tr>
<tr>
<td>100</td>
<td>6</td>
<td>100</td>
<td>-0.28</td>
<td>4.83</td>
<td>0.25</td>
</tr>
</tbody>
</table>
In addition, in order to verify the power regulation ability of the converter, the current references are changed to regulate the current of the port with higher voltage, that is, to change its input power to realize the power distribution between the two input ports. The stable results are shown in Table 5.

| Table 5 Stable results in DISO mode |
| Vref/V | Iref/A | V3/V | l1/A | l2/A | l3/A |
| 100    | 2      | 100  | -2.85| 5.24 | 9.06 |
| 100    | 7      | 100  | 0.34 | 7.37 | 7.94 |
| 100    | 13     | 100  | 4.55 | 9.15 | 5.61 |

3. Conclusions

The proposed three-port DC-DC converter is based on the half-bridge buck-boost unit and introduces a switch in reverse series in each half-bridge, which ensures the converter to have power blocking capability. The experiment results in different modes show that the converter can work in three modes properly, which can be used to form the BESS assisted EV charger. So, the charger can be used in applications where power supply is insufficient. By using this type of charge, the EV charging load fluctuation is suppressed effectively and the EV can be charged quickly with a higher efficiency.

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Reference