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A High Frequency Isolated Current-fed Bidirectional DC/AC Converter for Grid-tied Energy Storage System

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Abstract—In applications of modern power distribution with distributed energy resources, grid-tied energy storage systems (ESS) will be increasingly incorporated. Energy storage devices (ESD) such as lithium-ion battery or super-capacitor cells however have low DC terminal voltages. It is essential to develop a bidirectional DC/AC converter to interface ESS based on low voltage cells to the higher voltage grid without using high number of cells in series. In this paper a bidirectional current-fed converter with high frequency transformer isolation is proposed. In this proposed topology, a current source inverter (CSI) is used to interface to the grid. A DC/DC converter with High frequency (HF) transformer is used to feed the current to CSI. Low voltage and high voltage side of DC/DC converter can be either Push-Pull or Full-Bridge. The proposed topology has the advantage of reduced component count and simple control strategy. Simulation and hardware results have shown that the proposed circuit can work in charging and discharging of the ESS and the control strategy is effective.

Keywords—DC/DC, DC/AC, Current Source Inverter, High Frequency Link.

I. INTRODUCTION

Grid-tied energy storage system (ESS) is increasingly used in many power distribution applications such as uninterruptable power supplies (UPS) and solar photovoltaic power generation for buildings. Electrochemical battery which has acceptable power and energy density and super-capacitor which has high power density are commonly considered for the energy storage devices (ESD) inside the grid-tied ESS [1-3]. However terminal voltage of a single cell of either battery or super-capacitor is very low. There are basically two ways to interface the low terminal voltage ESD cells to the grid. One is to connect many cells in series to achieve a sufficiently high DC link voltage for a voltage source inverter (VSI) to interface the ESS to the grid. Due to varying chemical characteristics and aging effects, maintaining the many series-connected cells in balance is a major issue. For active balancing, auxiliary power electronic circuits known as cell equalizers [4, 5] are required to balance the series-connected cells. This will add to system complexity and cost.

Another way is to interface a low voltage ESS comprising only a few cells in series, to the high voltage AC grid by a converter with high-frequency (HF) transformer. As shown in Fig. 1, a bidirectional DC/DC converter with HF transformer such as dual active bridge (DAB) [6-9] converts the low voltage to a high-voltage DC link. A cascaded connected VSI allows bidirectional energy transfer between the grid and the DC link. This two-stage topology requires bulky DC capacitors and complex control strategy.

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Fig. 1 Interfacing ESDs to grid with Bidirectional DC/DC cascaded by VSI

Fig. 2 Voltage-fed high frequency AC link

In this paper a novel bidirectional DC/AC converter with high frequency transformer isolation is proposed. The proposed topology has a current source inverter (CSI) to interface the grid. A DC/DC converter with either Push-Pull or Full-Bridge in low and high voltage side is used to feed the current to CSI. Contrary to conventional topology, current instead of voltage is fed from the low voltage to high voltage side. As the CSI works in boost mode, reduced transformer winding is required for the HF transformer. The proposed circuit also has a simple control strategy and a continuous ESS charging and discharging current. Section 2 will explain the operation of the
proposed topology. Control strategy will be introduced in section 3. In section 4 and 5, simulation and hardware results will be presented to verify the proposed circuit.

II. PROPOSED TOPOLOGY AND MODULATION METHOD

A. Proposed Topology

As shown in Fig. 3 (a), the proposed topology does not require bidirectional switch or bulky DC link capacitors. DC/DC part can be configured as Full-Bridge or Push-Pull as shown in Fig. 3 (b), (c), (d). The following of this paper will use Full-Bridge in low voltage side and Push-Pull in high voltage side to demonstrate the working principles and modulation of the proposed topology. ESD is connected to the primary winding of a HF transformer by a full-bridge. The two secondary windings of the HF transformer are connected to the inductor \( L_s \) by \( T_{21}, D_{21} \) and \( T_{22}, D_{22} \) respectively. A CSI connects \( L_s \) to the AC grid. \( G_{TII} \) is the gate signals of \( h \) (U[1,4]). \( G_{TI1} \) to \( G_{TI4} \) have a fix duty cycle of 0.5 without considering dead time. \( G_{TII} (GT_{12}), G_{TI2} (GT_{12}) \) are the same and \( G_{TI1} (GT_{13}), G_{TI2} (GT_{13}) \) are complementary. Phase shift of \( GT_{11} \) to \( GT_{12} \) is fixed at \( \pi \). \( GT_{21} \) and \( GT_{22} \) are also complementary. CSI can regulate inductor current \( i_{Ls} \). CSI with \( L_s \) can be modeled as a current source. Modulation of CSI and the coordination with DC/DC will be described in the next subsection. Based on the power flow of ESD, the circuit has two operation modes: charging and discharging. Operation mode can be controlled by the phase shift of low voltage side switches and high voltage side switches of DC/DC part. This can be explained as follows. Assume that all the switches are ideal except for their body diodes. The dead time for voltage type converter and the shoot-through state for current type inverter are neglected.

Discharging Mode: In discharging mode, ESD is being discharged and energy is transferred from ESD to AC grid. Phase shift of \( T_{11} \) and \( T_{21} \) is controlled to 0 as shown in Fig. 4 (a). In this mode, the circuit has two operation stages:

Stage 1: As shown in Fig. 4 (b), \( T_{11} \) and \( T_{13} \) are turned on. \( V_{dc} \) is connected to \( TR_1 \). The primary winding of the HF transformer is connected to the AC grid. Phase shift of \( T_{11} \) and \( T_{21} \) is 0. \( T_{21} \) is turned on while \( T_{22} \) is being blocked. \( TR_2 \) is connected to the current source \( I_s \). Energy is being released from ESD.

Stage 2: \( T_{11} \) and \( T_{13} \) are turned off while \( T_{12} \) and \( T_{24} \) are turned on. \( -V_{dc} \) is connected to \( TR_1 \). Energy is transferred from ESD to the grid.

Charging Mode: In Charging mode phase shift of \( T_{11} \) and \( T_{21} \) is controlled to be \( \pi \). Gate signals are shown in Fig. 4 (d) and circuit operations stages are shown in Fig. 4 (e), (f). Stages of charging mode are described as follows:

Stage 3: \( T_{11} \) and \( T_{13} \) are turned on, \( V_{dc} \) is connected to \( TR_1 \). \( V_1 \) equals to \( V_{dc} \). \( T_{22} \) is turned on while \( T_{21} \) is turned off. So \( V_3 \) equals to \( V_1 \) and ESD is charging by \( I_s \).
Stage 4: $T_{12}$ and $T_{14}$ are turned on while $T_{13}$ and $T_{15}$ are turned off. $-V_{dc}$ is connected to $TR_1$ and $V_I$ equals to $-V_{dc}$. $T_{23}$ is turned off and $T_{21}$ is turned on. So $V_I$ equals to $-V_{dc}$ and ESD is charging by $I_L$.

**B. Modulation Method**

Space Vector Modulation (SVM) will be applied for controlling CSI. The hexagon of space vector definition is shown in Fig. 5. Switch group notation is ignored. E.g. $S_{35}$ means $T_{35}$ and $T_{36}$ are turned on and group notation “3” is ignored.

![Hexagon of CSI Space Vector](image)

**Stage 4:**

To ensure the volt-second balance for DC/DC side, DC modulation should be aligned with CSI modulation. Modulation for DC/DC and CSI in discharging mode is shown in Fig. 6.

![Modulation and Waveforms in Discharging Mode](image)

**III. Control Strategy**

**Stage 4:**

As shown in Fig. 8, ESD current can be controlled by $i_{Ls}$, which is controlled by the CSI. Control and modulation of CSI is well stated in [12,13]. CSVM is the current source vector.
generator that will generate the gate signals for the CSI switches. Charging and discharging is decided by the sign of the \(i_{dc}\) reference. Gate signals of \(GT_{11}\) and \(GT_{13}\) are square wave with 0.5 duty cycle. When \(i_{dc\text{ref}}\) is greater than 0, system works in discharging mode. \(GT_{21}\) and \(GT_{11}\) are in phase. When \(i_{dc\text{ref}}\) is negative, system is working in charging mode. \(GT_{11}\) will be shifted by \(\pi\) to get \(GT_{21}\). This control strategy is easy to implement.

IV. SIMULATION RESULTS

System parameters used for simulation are summarized in Table I. A DC voltage source is used to simulate ESD.

<table>
<thead>
<tr>
<th>(V_{dc})</th>
<th>15V</th>
</tr>
</thead>
<tbody>
<tr>
<td>(TR_1:TR_2:TR_3)</td>
<td>3:20:20</td>
</tr>
<tr>
<td>(L_s)</td>
<td>10mH</td>
</tr>
<tr>
<td>(L_{ab,c})</td>
<td>1mH</td>
</tr>
<tr>
<td>(C_{ab,c})</td>
<td>100(\mu)F</td>
</tr>
<tr>
<td>(f_c)</td>
<td>10kHz</td>
</tr>
<tr>
<td>(V_{abc\text{rms}})</td>
<td>115.5V</td>
</tr>
<tr>
<td>(i_{dc\text{ref}})</td>
<td>66.7A</td>
</tr>
</tbody>
</table>

As shown in Fig. 9, the proposed circuit is working in discharging mode. In Fig. 9(a), when \(T_2\) and \(T_4\) are turned on, \(V_{dc}\) is applied at \(TR_1\). \(V_2\) and \(V_3\) equals to \(-V_{dc}\). \(T_5\) is off and \(T_6\) is on, so \(i_{TR_2}\) is 0 and \(i_{TR_3}\) equals to \(i_{L_s}\). Energy is transferred from ESD through \(T_2\), \(T_4\) and \(T_6\) to the grid. After half switching cycle \(T_1\) and \(T_3\) will be turned on, energy will be discharged from ESD through \(T_1\), \(T_3\) and \(T_5\) to the grid. Fig. 9(b), (c) shows the grid voltage and current. Fig. 9(d) shows the ESD discharging current. Fig. 10 shows the circuit operation in charging mode. In Fig. 10(a), contrary to discharging mode, when \(T_2\) and \(T_4\) are turned on, \(T_5\) is on and \(T_6\) is off. Energy is transferred from the grid to ESD through \(T_5\), \(T_2\) and \(T_4\). Voltage and current are shown in Fig. 10(b) and (c). ESD charging current is shown in Fig. 10(d). The simulation results show that the circuit can work in both charging and discharging mode properly and validates the theoretically analysis.
V. HARDWARE EXPERIMENTAL RESULTS

A hardware prototype shown as Fig. 11 has been built to verify the proposed topology and modulation method. DC/DC side of this prototype is based on full-bridge and full-bridge which is shown in Fig. 3(b).

System parameters used for discharge mode is summarized in Table II.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{dc}$</td>
<td>50V</td>
</tr>
<tr>
<td>$TR_1:TR_2$</td>
<td>1:3</td>
</tr>
<tr>
<td>$L_a$</td>
<td>0.5mH</td>
</tr>
<tr>
<td>$L_{a,c}$</td>
<td>0.3mH</td>
</tr>
<tr>
<td>$C_{a,c}$</td>
<td>20μF</td>
</tr>
<tr>
<td>$f_i$</td>
<td>20kHz</td>
</tr>
<tr>
<td>$V_{ac, rms}$</td>
<td>100V</td>
</tr>
<tr>
<td>$i_{ac, ref}$</td>
<td>2.5A</td>
</tr>
</tbody>
</table>

Key waveforms of discharge mode are shown in Fig. 12.

Fig. 10 Modulation and Key Waveforms in Discharging Mode

Fig. 11 Hardware Prototype with Full-Bridge and Full-Bridge Configuration

In discharge mode, energy is transferred from DC side to AC side. In this mode, ESD will be discharged and release energy to AC grid. As shown in Fig. 12 (a), $V_f$ is the voltage of primary side of the high frequency transformer, $V_{link}$ is the virtual DC link voltage as shown in Fig. 3(a). $V_{link}$ is not a constant voltage as the case of VSI and is decided by input AC voltage and modulation method. After applied modulation method shown as Fig. 6, a balanced primary side voltage is
applied. In Fig. 12 (b), input AC voltage and current are shown. There is a small phase difference between the voltage and current. So power factor is not unit. This phase difference is due to the LC filter and power factor can be compensated to unit which will be done in the future.

Key waveforms of charge mode are shown in Fig. 13. DC voltage is changed to 35V, other parameters are the same as discharge mode.

![Waveforms in Discharge Mode](image)

(a) Low voltage side transformer and link voltage, inductor current

(b) Input AC voltage and current with link voltage

In charge mode, energy is transferred from AC side to DC side. In this mode, ESD will be charged by AC grid. As shown in Fig. 13(a), $V_{\text{link}}$ is reversed and inductor current is not reversed. A square wave is got at the low voltage side and is rectified to charge $V_{\text{dc}}$. As shown in Fig. 13 (b), AC voltage and current has a phase difference close to $\pi$ and is charging $V_{\text{dc}}$.

### VI. CONCLUSION

In this paper a current-fed bidirectional DC/AC converter with HF transformer isolation is proposed to interface low voltage ESDs such as batteries and super-capacitors to AC grid. The proposed topology is comprised of a CSI, a DC/DC converter with a HF transformer. DC/DC converter for low voltage side and high voltage side can be either push-pull or full-bridge. Current instead of voltage is fed from the high voltage side to the low voltage. CSI is used to regulate the inductor current that will be fed to the low voltage side. CSI works in boost mode and reduced low voltage side transformer winding is required. The proposed circuit has the advantage of simple control strategy and fewer components. Simulation results have proven that the proposed circuit worked properly in both charging and discharging modes and the control strategy is effective. It can thus avoid the balancing issues associated with ESS which relies on high number of cells in series.

### REFERENCES


