CHAPTER 6

ANALYSIS AND SIMULATION OF BI-DIRECTIONAL Z-SOURCE INVERTER

6.1 INTRODUCTION

Fast growth of solar energy based distributed generation stations makes the contribution of electrical energy storages very important in modern power systems. Energy efficient management is not reachable without energy storage because the power obtained from solar energy sources is very dependent on various factors such as solar irradiation level, temperature etc. In distributed generation stations, battery banks, superconducting magnetic energy storages, hydrogen and synthetic natural gas energy storages, flywheels etc. are considered for the regulation of output electrical power. These types of storages normally require power electronic converter as interface between the DC input and AC output. This converter need to act as the boost converter during DC side to AC side power flow since solar energy sources and storages suffered from low input voltage. On the other hand, the converter is required to work as buck converter during reverse power flow. So the converter must be capable of bidirectional power flow because the need to charge and discharge all types of energy storages.

The Z-source inverter can perform both buck and boost operation and would be utilized for renewable energy power generation applications due to possibility of operation with wide range of the input DC voltage (Yi Huang et al 2006; Miaosen Shen et al 2007). During buck mode of operation of Z-source inverter, the active and zero states are only required in switching
table without any shoot-through states in between. Because of low input voltage and to attain the desired utility voltage, boost feature of the Z-source inverter is required.

In boost mode the shoot-through states are also used along with active and zero states. In shoot-through state, one or more inverter legs are short circuited. The input diode is turned off and Z-network is separated from both DC input and AC output. During this operation, energy is transferred from capacitors $C_{1}$ and $C_{2}$ to inductors $L_{1}$ and $L_{2}$ and significant current flows through one or more short circuited inverter leg. In non shoot-through state, the inverter is in active state or zero state. Between inverter bridge terminals appears sum of the capacitor and inductor voltage, referred to DC link voltage in voltage source inverter. Switching between shoot-through states and non shoot-through states allows boost voltage of inverter bridge over input voltage. From the output terminals of the inverter zero state and shoot-through states are equivalent. So the switching between active states and zero/shoot-through states makes possible AC side voltage generation on pulse width modulation principles.

From the point of view of energy storage system, the use of Z-source inverter is limited to one directional power flow. Due to the presence of the diode in series with the input source, the energy transfer from AC side to the DC side is not allowed. Since the diode plays very important role in DC voltage boost process separating impedance network from input DC source during shoot-through state, it cannot be removed. Only method to change basic topology of Z-source inverter to a new topology with bidirectional capability is replacement of input diode by bidirectional switch, in practice IGBT with a forward diode. Now this modified Z-source inverter named as bidirectional Z-source inverter is able to exchange energy between DC and AC side in both directions without any change in principles of operation (Jacek Rabkowski 2007; Elabbab et al 2010).
6.2 PRINCIPLES OF OPERATION

The topology of the bi-directional Z-source inverter is shown in Figure 6.1. The bi-directional Z-source inverter is able to exchange energy between DC energy storage and AC side in both directions. The bidirectional Z-source inverter acts either as inverter or active rectifier.

![Figure 6.1 Topology of bi-directional Z-source inverter](image)

During the inverter mode, the energy flows from the input DC source to AC side, the additional switch $S_o$ is stay off and the circuit operates as basic version of Z-source inverter. In rectifier mode, the switch $S_o$ plays role of the input diode, separating the impedance network from the input DC source during shoot-through states. The switch $S_o$ is turned on whenever active state or zero state are set in switching pattern of bridge. Now the inductor current will flow from impedance network to DC energy storage. The switching pattern of $S_o$ is calculated as a logical function of $SW1$-$SW6$ gate signals. In inverter mode shoot-through is started by main bridge switches and input diode is turned off, whereas in rectifier mode shoot-through is caused by opening the switch $S_o$ and all six diodes starts conducting.
In one cycle, it has seven possible operating modes (Haiping Xu et al 2008).

**Mode-I**

The inverter is in a shoot-through state when the two switches in any of the three phase legs are turned on at the same time as shown in Figure 6.2, the sum of the voltages across the two capacitors is greater than the DC input voltage \( V_{c_1} + V_{c_2} > V_s \), the diode is in reverse bias condition. So the inductors are getting charged from the capacitors.

The voltages across the inductors are given in Equation (6.1).

\[
V_{l_1} = V_{c_1} \quad \text{and} \quad V_{l_2} = V_{c_2}
\] (6.1)

The current through the inductor rises linearly. Because of the symmetry of the circuit Equation (6.2) is valid.

\[
V_{l_1} = V_{l_2} = V_L, \; V_{c_1} = V_{c_2} = V_C \quad \text{and} \quad i_{l_1} = i_{l_2} = i_L
\] (6.2)

![Figure 6.2 Mode-I operation of bi-directional Z-source inverter](image-url)
Mode-II

The inverter is in the active state which is a non shoot-through state and the inductor current meets the Equation (6.3).

\[ i_L > \frac{1}{2} i_o \]  \hspace{1cm} (6.3)

Since the circuit is symmetric, the capacitor current \( i_{c1} \) and \( i_{c2} \) and the inductor current \( i_{L1} \) and \( i_{L2} \) should be equal to each other respectively.

In this mode, the input current from the dc source is given in Equation (6.4).

\[ i_{in} = i_{L1} + i_{C1} = i_{L1} + (i_{L2} - i_o) = 2i_L - i_o > 0 \]  \hspace{1cm} (6.4)

Now the diode can conduct and the voltage source and capacitor supplies the inverter. The equivalent circuit is shown in Figure 6.3. The capacitors \( C_1 \) and \( C_2 \) are charging.

\[ \text{Figure 6.3 Mode-II operation of bi-directional Z-source inverter} \]
The voltage across the inductor is as,

\[ V_L = V_s - V_C \]  \hspace{0.2cm} (6.5)

This voltage is negative; therefore the current through the inductor decreases linearly.

**Mode-III**

As time increases, the current through the inductor keeps decreasing to a level that no longer the condition given in Equation (6.3) can be met. Now the condition is given in Equation (6.6).

\[ i_L < \frac{1}{2} i_o \]  \hspace{0.2cm} (6.6)

The capacitors \( C_1 \) and \( C_2 \) are discharged to the load (Figure 6.4). The input current \( i_m \) is still satisfying the Equation (6.5).
Mode-IV

The inverter is in one of the two zero states and at the end of mode-III, the current through the inductor reaches zero value, thus a new operation mode appears. In this mode-IV, the inverter is an open circuit to the Z-source network because of \( i_o = 0 \). The current through the inductor maintains zero until the next switching action. The two capacitors \( C_1 \) and \( C_2 \) are charging from the input source. Figure 6.5 shows the equivalent circuit of mode-IV.

![Equivalent circuit of mode-IV](image)

**Figure 6.5 Mode-IV operation of bi-directional Z-source inverter**

Mode-V

The current through the inductor is still decreasing. It becomes reverse current. The switch \( S_o \) is conducting, the input current \( i_{in} \) becomes no longer than zero, and \( i_{in} \) also becomes reverse-flow (Figure 6.6).
Figure 6.6 Mode-V operation of bi-directional Z-source inverter

Mode-VI

The current through the inductor begins to increase at the end of mode-V. The equivalent circuit is shown in Figure 6.7.

Figure 6.7 Mode-VI operation of bi-directional Z-source inverter
The current through the inductor given in Equation (6.7) is in the reverse direction, while the switch $S_o$ is in its on-state.

\[ i_{in} > 0, i_L < 0 \]

\[ i_o = 2i_L - i_{in} \]  \hspace{1cm} (6.7)

The energy from capacitors $C_1$ and $C_2$ is transferred to the input source instead of charging the inductors $L_1$ and $L_2$.

**Mode-VII**

The inverter is in one of the two zero states again. The equivalent circuit of this mode is shown in Figure 6.8. The impedance network is completely isolated from the load. The current through the inductor decreases to zero, and the input current is reverse-flow. Capacitors $C_1$ and $C_2$ are discharged to source. The current through the inductor and period of each operation mode is shown in Figure 6.9.

![Figure 6.8 Mode-VII operation of bi-directional Z-source inverter](image)
6.3 PWM TECHNIQUES FOR BI-DIRECTIONAL Z-SOURCE INVERTER

PWM techniques used in the basic Z-source inverters are very similar to voltage source inverter. They are either carrier based type or space vector type, developed according to applications. The additional thing in the switching pattern of the Z-source inverters is that dead-time is not required. To obtain the voltage boost, the voltage source inverter switching table is modified by inserting the shoot-through states. In the simple control method, every phase leg transition is utilized to make shoot-through states. In place of dead-time an overlapping of switching signals of upper and lower switch is done.

The bi-directional Z-source inverter can operate with any of the PWM strategies useable for basic Z-source inverter. Since the additional switch $S_o$ is operating with impedance network, it is required to develop the switching pattern for $S_o$. With the above bi-directional Z-source inverter operation modes analysis, it is concluded that the switch $S_o$ has to operate in off-state during inverter operation in the shoot-through states. The switch $S_o$ operates in on-state during the inverter in its non-shoot-through states. That is to say, the switching pattern of $S_o$ is complement with the shoot-through
signal. Jacek Rabkowski et al 2008 suggested two PWM schemes, Maximum Constant Boost Control (MCBC) and Minimum Switching Number (MSN) to control the bi-directional Z-source inverter. It is observed from their work that the output voltage waveforms are the same in both PWM methods, but MSN PWM gives better THD of output current. The value of estimated THD of output current is given in the range of 6% to 7%. In this work, space vector based PWM techniques suitable for bi-directional Z-source inverter are proposed to minimize the output THD.

### 6.3.1 Modified Space Vector PWM-1

The space vector PWM (SVPWM) is the widely used PWM technique in PWM inverters because of lower current harmonics and a higher modulation index. The SVPWM is suitable to control the Z-source inverter. The principle of modified SVPWM (MSVPWM) for Z-source inverters is explained in chapter 4. Unlike the traditional SVPWM, the MSVPWM has an additional shoot-through time \( T_o \) for boosting the dc link voltage of the inverter beside time active state intervals \( T_1, T_2 \) and zero state interval \( T_z \). The zero voltage period should be diminished for generating a shoot-through time, and the active states \( T_1 \) and \( T_2 \) are unchanged. So, the shoot-through time does not affect the PWM control of the inverter, and it is limited to the zero state time \( T_z \).

A novel modified space vector PWM technique with four shoot-through states in one switching period is proposed to control the output voltage of bi-directional Z-source inverter. This PWM method only alters the top switch of minimum switching control signal and the bottom switch of maximum switching control signal. The switching pattern of modified control signals for sector-I is shown in Figure 6.10.
The effectiveness of the proposed MSVPWM-1 technique is verified by simulating the bi-directional Z-source inverter supplying RLE load in MatLab/Simulink with the following specifications: Z-source network parameters \( L_1 = L_2 = 3 \text{mH} \), \( C_1 = C_2 = 1000 \mu \text{F} \), switching frequency 10 kHz. The input DC voltage is obtained from a generic battery with voltage varying between 80V and 100V (fully discharged to fully charged). On the AC side, a three-phase capacitor bank of 2.5 \( \mu \text{F} \) per phase is connected between the load inductor and AC source. This capacitor bank is used as a harmonic filter to reduce the harmonic distortion of inverter output voltage and current. During the inverting mode, the current flow is only from the battery to the load. So the input switch \( S_n \) never conducts during this operation. Hence the operation of the bi-directional Z-source inverter is similar to the basic Z-source inverter. Figure 6.11 shows the waveforms of output line voltage, load current and DC link voltage obtained from the simulation with a boost factor of 1.6 during the inverter mode of working. Figure 6.12 shows the similar waveforms obtained during the rectifier mode of operation.

![Switching pattern of MSVPWM-1 in sector-I](image)

**Figure 6.10 Switching pattern of MSVPWM-1 in sector-I**
Figure 6.11 Simulation results of MSVPWM-1 during inverter mode

Figure 6.12 Simulation results of MSVPWM-1 during rectifier mode
6.3.2 Modified Space Vector PWM-2

Even though the results obtained from the MSVPWM-1 are encouraging, the eight transitions in single sampling period force the input switch \( S_o \) to operate with increased switching frequency. This increases the switching loss and rating of switch. Despite the switching loss analysis in not a goal of this work, a different pattern of space vector PWM (MSVPWM-2) is proposed to limit the number of transitions. This pattern also uses four shoot-through intervals in a switching cycle, but the zero state duration at the middle section is fully replaced by the shoot-through states. The MSVPWM-2 pattern is shown in Figure 6.13 for sector-I. However, the maximum shoot-through time interval has to reduce to \( T_o \). So the voltage gain achieved by this method is lesser than that of MSVPWM-1. But the number of switching transitions for the input switch \( S_o \) is reduced to six. This definitely reduces the switching loss in the system. The simulation circuit of bi-directional Z-source inverter with this MSVPWM-2 technique is developed. The inverter mode results are shown in Figure 6.14 and the rectifier mode results are shown in Figure 6.15.

![Figure 6.13 Switching pattern of MSVPWM-2 in sector-I](image-url)
Figure 6.14 Simulation results of MSVPWM-2 during inverter mode

Figure 6.15 Simulation results of MSVPWM-2 during rectifier mode
Based on the simulation studies, output voltage THD and output current THD of bi-directional Z-source inverter for various PWM techniques are compared and the results are given in Table 6.1. From the study, both of the proposed PWM techniques are producing better results on quality of output waveforms compared to the methods suggested in literature. Among all the methods considered, the proposed MSVPWM-1 owns little THD on both output voltage and current. But the switching rate of the input switch is high, which increases the switching loss. In MSVPWM-2, the switching rate of the input switch is comparatively low, but the output THD is quite high.

<table>
<thead>
<tr>
<th>PWM</th>
<th>% THD of Output Voltage</th>
<th>% THD of Output Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCBC</td>
<td>7.13</td>
<td>6.50</td>
</tr>
<tr>
<td>MSN</td>
<td>4.22</td>
<td>3.12</td>
</tr>
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<td>MSVPWM-2</td>
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<td>1.87</td>
</tr>
</tbody>
</table>

6.4 SUMMARY

The basic Z-source inverter can be used for bi-directional power flow with a little modification in its topology, so that it can be applied for variable-voltage DC energy storage connected to an AC network. The PWM techniques developed in the literature show main drawbacks on the quality of the output voltage and current waveforms. Two new modified space vector PWM techniques have been proposed in this research work to improve the harmonic profile of the output waveforms. Simulation studies of bi-directional Z-source inverter with the two proposed PWM techniques and their comparison with the other PWM techniques have been presented in this chapter.