CHAPTER 6

SINGLE STAGE POWER CONVERTER FOR DIRECT DRIVE WIND ENERGY CONVERSION SYSTEM

6.1 INTRODUCTION

Matrix converter is mainly used to control the AC output voltage of wind energy conversion system. Also as required the input current and output voltage waveforms are closer to sine wave. Matrix converter is a simple and compact AC-AC converter. Many PWM control methods have been developed and used for matrix converter. The same PWM control methods can be used in Z-Source Matrix Converter. The performance of ZSMC is controlled by using two PWM methods such as carrier based PWM technique and Space Vector PWM technique. Their performance is compared and analyzed based on shoot through placement, switching stress and THD. The simulation model of ZSMC is also analyzed based on generator output voltage and frequency for different values of wind velocity and loading conditions.

6.2 OPERATING MODES OF ZSMC

Figure 6.1 shows the basic configuration of Z-source matrix converter. It consists of a Z-source network and three-phase matrix converter connected between Z-source and load. The matrix converter has nine bidirectional switches, and each bidirectional switch has two IGBTs connected in anti parallel. The readings given in Table 3.1 indicate that the
ZSMC operates in boost mode in the speed range of 55rpm to 116rpm and operates in buck mode during 156 to 200 rpm. According to boost or buck mode the shoot through period and modulation index are adjusted respectively.

The working of Z-source matrix converter is explained by two operating modes (Weizhang Song and Feng et al 2011). They are

1. Shoot through zero state

2. Active state

![Basic Configuration of Z-source Matrix Converter](image)

**Figure 6.1 Basic Configuration of Z-source Matrix Converter**

### 6.2.1 Shoot Through Zero State

In shoot through state the switches $S_1$, $S_2$ and $S_3$ will be in off state. The switches in the same leg (example $S_{Aa}$, $S_{Ba}$ and $S_{Ca}$) will be turned ON for a particular time period, hence short circuit takes place which is called as shoot through period ($T_o$). In this period ($T_o$) a large value of emf induced in
the inductor is transferred to the capacitor. Figure 6.2 shows the equivalent circuit of PMG with Z-source matrix converter in shoot through state mode.

**Figure 6.2 Z-Source Matrix Converter in Shoot Through State**

Assigning of same value for inductors $L_1$, $L_2$ and $L_3$ and that for capacitors $C_1$, $C_2$ and $C_3$, the voltage across inductor and that of and capacitor of Z-source network are given in Equations (6.1) and (6.2) (Kiwoo Park et al 2010).

\[
V_{L1} = V_{L2} = V_{L3} = V_L \tag{6.1}
\]

\[
V_{C1} = V_{C2} = V_{C3} = V_C \tag{6.2}
\]

The equivalent circuit during the shoot-through state can be configured as shown in Figure 6.2. When the shoot-through period $T_0$ accommodated within the switching period $T$, the matrix converter is intentionally short-circuited and switches $S_1$, $S_2$ and $S_3$ are in off condition. From the equivalent circuit, it is obvious that
$V_L = V_C$

The output ZSMC terminal voltages are

$V_{ib} = V_{ic} = V_{ia} = 0 \quad (6.3)$

### 6.2.2 Non Shoot Through State

In non shoot through state (normal operating state) the switches $S_1, S_2$ and $S_3$ will be in ON state. If any one of the switches in each phase is connected between input and output terminals, the capacitor voltages $V_{c1}, V_{c2}$ and $V_{c3}$ directly appear across each phase and get converted into the desired ac voltage and frequency. This active mode is the common operation of traditional matrix converter. Now consider that the Z-source matrix converter is in the non shoot-through state for an interval of $T_1$, within switching period, $T$. The equivalent circuit of the proposed WECS with ZSMC during the non shoot-through state is shown in Figure 6.3.

![Figure 6.3 Z-Source Matrix Converter in Non Shoot Through State](image)
From the equivalent circuit, the line-to-line voltage across the ZS network can be expressed as

\[
\begin{bmatrix}
  v_{ab} \\ v_{bc} \\ v_{ca}
\end{bmatrix} =
\begin{bmatrix}
  v_{C1} \\ v_{C2} \\ v_{C3}
\end{bmatrix} -
\begin{bmatrix}
  v_{L1} \\ v_{L2} \\ v_{L3}
\end{bmatrix},
\begin{bmatrix}
  v_{lab} \\ v_{lbc} \\ v_{ica}
\end{bmatrix} =
\begin{bmatrix}
  v_{C1} \\ v_{C2} \\ v_{C3}
\end{bmatrix} -
\begin{bmatrix}
  v_{L1} \\ v_{L2} \\ v_{L3}
\end{bmatrix}
\]

(6.4)

From equations (6.3) and (6.4), the average output phase voltages of the Z-source network are:

\[
v_{ia} = 0.5D + (V_c - V_{C3})(1 - D_{om})
\]

\[
v_{ib} = 0.5D + (V_a - V_{C1})(1 - D_{om})
\]

\[
v_{ic} = 0.5D + (V_b - V_{C2})(1 - D_{om})
\]

(6.5)

From the equivalent circuits of ZS-MC the terminal voltage of ZSMC can be expressed as (Kiwoo Park 2011)

\[
v_{oa} = \frac{(V_a + V_b + V_c)D_{om}^2 - (2V_a + V_b)D_{om} + V_a}{1 - 3D_{om}^2 + 3D_{om}}(1 - D_{om})
\]

\[
v_{ob} = \frac{(V_a + V_b + V_c)D_{om}^2 - (2V_b + V_c)D_{om} + V_b}{1 - 3D_{om}^2 + 3D_{om}}(1 - D_{om})
\]

\[
v_{oc} = \frac{(V_a + V_b + V_c)D_{om}^2 - (2V_c + V_a)D_{om} + V_c}{1 - 3D_{om}^2 + 3D_{om}}(1 - D_{om})
\]

(6.6)

Where

\[V_a, V_b, V_c\] are the per phase PMG voltages.
The shoot through duty ratio

\[ D_{om} = \frac{T_b}{T} \]

Suppose that the input three-phase voltage is balanced as

\[ V_a = V_m \cos(\omega t) \]
\[ V_b = V_m \cos(\omega t - 120^\circ) \]
\[ V_c = V_m \cos(\omega t + 120^\circ) \] (6.7)

then the average voltage gain of the Z-source network over one switching period is

\[ G = \frac{|V_{a1b1c1}|}{V_m} = \frac{1 - D_{om}}{\sqrt{1 - 3D_{om} + 3D_{om}^2}} \] (6.8)

\[ D_{om} = 1 - M \] (6.9)

Substituting Equation (6.9) in (6.8)

\[ G = \frac{1 - (1 - M)}{\sqrt{1 - 3(1 - M) + 3(1 - M)^2}} \]

\[ = \frac{M}{\sqrt{1 - 3 + 3M + 3(1 - 2M + M^2)}} \]

\[ = \frac{M}{\sqrt{1 - 3 + 3M + 3 - 6M + 3M^2}} \]

\[ G = \frac{M}{\sqrt{1 - 3M + 3M^2}} \] (6.10)
6.3 SHOOT THROUGH DISTRIBUTION IN Z-SOURCE MATRIX CONVERTER

Figure 6.4 shows the pulse pattern for the Z-source matrix converter with shoot through state. In conventional matrix converter the switches in the same leg cannot be turned on simultaneously, since doing so will cause destruction of the switches but this is possible in ZSMC (Xupeng Fang et al 2010). By adjusting the shoot through period in the pulses the output voltage and frequency can be stepped up or stepped down. The shoot through pulses are applied to the switches in the same leg without disturbing the active state of the matrix converter.

6.4 PWM SCHEMES FOR Z-SOURCE MATRIX CONVERTER

The performance of the ZSMC is predicted by applying two types of PWM control methods such as carrier based pulse width modulation (PWM) and space vector pulse width modulation (SVPWM). The comparison between these two PWM schemes is carried out based on voltage gain, voltage stress and THD for different values of PMG generated voltage and loading conditions.

6.4.1 Carrier Based PWM Scheme

The carrier based PWM technique is used to control the Z-source matrix converter as shown in Figure 6.4. The reference third harmonic wave is compared with the triangular carrier wave to produce the required PWM pulses for active state. A separate shoot through reference signal is used to generate the shoot through pulses. The magnitude of shoot through reference signal is adjusted according to PMG generated voltage. Figure 6.4 (c) shows the shoot through pulse and active pulse generation scheme for CPWM based ZSMC (Baoming et al 2011).
Figure 6.4  Pulse Generation Scheme for CPWM Based ZSMC
(a) $D_{on} = 0.3$  (b) $D_{on} = 0.25$ and (c) $D_{on} = 0.2$

The important expressions for maximum boost control method are

\[
\text{Voltage Gain} \quad G = \frac{M}{2M - 1} \quad (6.11)
\]
Boost Factor \[ B = \frac{1}{1 - 2D_{om}} \]  

(6.12)

The capacitor voltage amplitude

\[ V_{c} = \frac{D_{om}}{1 - 2D_{om}} V_{im} \]  

(6.13)

The line to line voltage across inverter bridge

\[ V_{ab}' = \frac{1}{1 - 2D_{0}} V_{ab} \]  

(6.14)

The phase voltage on the output side of ZSMC is given as

\[ V_{ab} = V_{\text{ab}}' = \frac{V_{ab}}{\sqrt{3}} B M \]  

(6.15)

where

\[ \frac{V_{ab}}{\sqrt{3}} \]  

Input phase voltage

6.4.2 Space Vector Pulse Width Modulation Scheme for ZSMC

The space vector based pulse width modulation (SVPWM) technique is a well known method in the control of DC/AC converters. The SVPWM offers a number of useful features, especially in realistic implementation, such as:

- Voltages and currents can be represented in two-dimension reference frames instead of three-dimensional abc frames.
- Reduction in the number of switchings in each cycle is achieved.
- Better output waveforms as compared to conventional methods
- Controllable input power factor is possible regardless of the load power factor.
- SVPWM is a digital modulation technique which is easy to implement with digital controller.

SVPWM can be applied to MC in the same way as it is applied to DC/AC converter (Jayamala and Kalaiarasi 2009, Casadei et al 2002). The shoot through state is inserted besides the active and zero state of conventional SVPWM technique. The width of the shoot through placement is varied according to the variations of input voltage magnitude and frequency. The shoot through placement in SVPWM pulses for ZSMC is shown in Figure 6.5.

![Figure 6.5](image-url)
Figure 6.6  Shoot Through Placement in SVPWM Based ZSMC for (a) Sector I and (b) Sector II

The shoot through period in PWM signals is indicated as dashed lines. The voltage switching stress across the power switches is directly proportional to the shoot through period and hence its width period should be minimized.

The width of the shoot through period of ZSMC is varied according to the PMG generated voltage and wind velocity as shown in Figures 6.7. It is known that the shoot through period is minimum at higher wind velocities.
Figure 6.7 Distribution of Shoot through Pulses in SVPWM of ZSMC
(a) $D_{on} = 0.3$ (b) $D_{on} = 0.25$ and (c) $D_{on} = 0.2$
6.5 RESULTS AND DISCUSSION

Figure 6.8 shows the simulated waveforms of ZSMC for a PMG generated voltage of 166V, 12.5 Hz at turbine speed of 97 rpm as shown in Figure 6.8 (b) and 6.8 (a) respectively. To obtain the desired voltage and frequency, the shoot through period is increased according to input voltage and frequency. The ZSMC output voltage is 415V with frequency of 50Hz and the corresponding value of shoot through duty ratio is 0.25 as shown in Figure 6.9 (d). The shoot through duty ratios are 0.3 and 0.4 for the wind velocity of 4m/s and 3m/s respectively to obtain the desired voltage and frequency.

![Figure 6.8](image)

(a)

(b)

Figure 6.8 Simulated Results of CPWM Based ZSMC for (a) Wind Turbine Speed and (b) PMG Generated Voltage

Similarly the performance of ZSMC is predicted by applying SVPWM scheme. The SVPWM pulse width is varied according to PMG generated voltage. Figure 6.10 shows the ZSMC terminal voltage, capacitor
voltage and inductor current of SVPWM based ZSMC for a generated voltage of 166V, 12.5Hz and at a speed of 97rpm. From Figures 6.9 and 6.10 it is observed that the SVPWM scheme has larger ripples in its inductor current and its capacitor voltage than the SVPWM scheme. But the voltage gain is greater than the CPWM scheme. The voltage increase of SVPWM based ZSMC is around 8V which is greater than the CPWM based ZSMC.
Figure 6.9  Simulated Results of CPWM Based ZSMC for (a) Inductor Current (b) Capacitor Voltage (c) AC Link Voltage (d) Line Voltage and (e) ZSMC Phase Voltage

Figure 6.10  Simulated Results of SVPWM Based ZSMC for (a) Inductor Current (b) Capacitor Voltage (c) AC Link Voltage (d) Line Voltage and (e) Phase Voltage
The simulation also aims to verify the performance of the proposed WECS for different loading conditions. The percentage input current and output voltage total harmonic distortion for different loading conditions are given in Table 6.1.

Table 6.1  Input and Output THD of Proposed and Conventional WECS for Different Loading Conditions

<table>
<thead>
<tr>
<th>Load power (kW)</th>
<th>Input current THD (%)</th>
<th>Output voltage THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CPWM</td>
<td>MSVPWM</td>
</tr>
<tr>
<td>0.15</td>
<td>4.5</td>
<td>3.5</td>
</tr>
<tr>
<td>0.5</td>
<td>5.1</td>
<td>4.5</td>
</tr>
<tr>
<td>0.75</td>
<td>5.9</td>
<td>5.6</td>
</tr>
<tr>
<td>1</td>
<td>6.89</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Figures 6.11 and 6.12 show the simulated and experimental input current harmonics spectra of CPWM based ZSMC and SVPWM based ZSMC. The corresponding output voltage harmonic spectra as shown in Figure 6.13 and 6.14 for a load of 1kW. Figure 6.15 (a) and (b) shows the variation of input current THD and output voltage THD of CPWM and SVPWM based Z-source matrix converter. The percentage THD of CPWM scheme is almost 0.6% greater than SVPWM scheme. This issue leads to lower input power factor and hence the conduction loss in the switches is slightly increased. The output voltage THD of CPWM scheme is almost 4.5% greater than SVPWM scheme as shown in Figure 6.15(b).

From Figure 6.16, the voltage stress to the power switches of CPWM based ZSMC is around 55V greater than the SVPWM based ZSMC in all operating points are noted down. The switching current stress in the power switches are depends on the current ripples in Z-source inductor. Figure 6.17
shows the variation of switching current stress with the variation of shoot through period in both CPWM and SVPWM schemes. The current stress in SVPWM based ZSMC is 0.2 amps greater than the CPWM based ZSMC.

Figure 6.11 Simulation Results for Input Current THD of (a) CPWM Based ZSMC and (b) SVPWM Based ZSMC
Figure 6.12  Experimental Results for Input Current THD of (a) CPWM Based ZSMC and (b) SVPWM Based ZSMC
Figure 6.13 Simulation Results for Output Voltage THD of (a) CPWM Based ZSMC and (b) SVPWM Based ZSMC
Figure 6.14 Experimental Results for Output Voltage THD of
(a) CPWM Based ZSMC and (b) SVPWM Based ZSMC
Figure 6.15  Percentage THD at Different Loading Conditions (a) Input Current THD and (b) Output Voltage THD
Figure 6.16  Voltage Stress Across the Switches Under Different Loading Conditions

Figure 6.17  Current Stress Across the Switches with Shoot Through Duty Ratio

6.6  EXPERIMENTAL SETUP

A prototype Z-Source Matrix Converter rated 1200V, 3kVA is fabricated to validate the simulation results. The photographic view of
The experimental setup is shown in Figure 6.18. The nine PWM signals with shoot through period are generated using VHDL with Spartan-6 FPGA controller. The carrier based PWM scheme with shoot through period is shown in Figure 6.19. The shoot through period is 0.3 for the input voltage of 132V. The experimental pulse pattern of ZSMC is for duty ratio of 0.3 and modulation index 0.7. The corresponding ZSMC terminal voltage is shown in Figure 6.20. Figure 6.21 shows the experimental current waveforms of ZSMC for a load of 0.25kW. From the Figures 6.19, 6.20 and 6.21 it is evident that the experimental readings very well coincide with simulation readings. Also it is very challenging to implement the SVPWM technique for ZSMC. From implementing the SVPWM technique itself it is understood that the placement of shoot-through period is very difficult. The ZSMC requires lot of complicated algorithms for intermediate frequency conversion especially for intermediate frequency like 13Hz, 24Hz but it is very simple for voltage transfer control.

Figure 6.18 Prototype Experimental Setup of Z-Source Matrix Converter
Figure 6.19 Experimental Pulse Pattern of CPWM Based ZSMC for $D_{0m} = 0.3$ and $M = 0.7$

Figure 6.20 Experimental Line and Phase Voltage Waveforms
(a) SVPWM Based ZSMC and (b) CPWM Based ZSMC
6.7 SUMMARY

The Z-source matrix converter is analyzed for different values of input voltage and frequency. It is observed that it can be implemented by using different switching strategies and voltage boost up can be achieved by adjusting the shoot through duty ratio from 0.4 to 0.2. The comparison is made between the two different PWM schemes based on placement of shoot through period, voltage gain, THD and switching stress. The voltage increase in SVPWM is 6% higher than the CPWM scheme. But the shoot through placement is quite easy and switching voltage stress is 55% less than the space vector schemes. In this thesis the carrier PWM scheme is considered for further investigations on ZSMC based DDWECS, and discussed in chapter 8.