PERFORMANCE ANALYSIS OF Z-SOURCE MATRIX CONVERTER BY IMPLEMENTING DIFFERENT PWM SCHEMES

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ABSTRACT: *This paper clearly explains the problems associated with matrix converters and extends the concept of Z-source to matrix converter. The Z-source converter can achieve buck and boost operation for both frequency and voltage. Comparisons of PWM technique that can be implemented for Z-source matrix converter have been discussed. The simulation and experimental results are given, and it verifies that the Z-source matrix converter can produce high voltage transfer ratio and less THD by suitably implementing the PWM techniques.*

Keywords: *VSMC, ZSMC, CPWM, SVPWM*

I. INTRODUCTION

Matrix converter has drawn the attention of many researchers over the past two decades owing to various advantages such as absence of bulky dc link energy storage devices and absence of electrolytic capacitors over the three-stage ac-dc-dc-ac converters irrespective of the type of load. The input power factor of the matrix converts can be fully controlled by proper modulation. They provide sinusoidal output as well as input [6], [9] and [10]. Figure 1 shows the matrix converter.

The matrix converters are more rugged than the three-stage converters as there is no dc link capacitor. The matrix converter has efficiency higher than the conventional three stage converter and is highly controllable for output voltage and frequency [11] [12] [13]. The individual control of output voltage, input power factor and output power factor are easily achievable [14] [18]. The Z-Source matrix converter can operate on three different operating modes against the two operating modes of conventional matrix converter and as a result the harmonic content of output voltage is reduced considerably. Two types of matrix converters are available

1)VSMC (Voltage Source Matrix Converter)

2)CSMC (Current Source Matrix Converter)

The VSMC is fed by an ac voltage-source. The operating principle of the VSMC is very similar to that of the voltage source inverter. To produce an active voltage to the load, one of three-phase input voltages can be selectively connected to each output terminal. To produce a zero voltage all the load terminals have to be connected to one of the input source terminals. It is that no shoot-through switching states are allowed to the input source side and no open circuit allowed to the output side. The three-phase VSMC has low voltage ratio of 0.866 [1].

The CS-MC is fed from a current source. The CSMC cannot have open-circuit to the input side and short-circuit to the output side. Its output voltage is always greater than the input voltage. The combination of VSMC and CSMC gives the ZSMC. A Z-source converter employs a unique impedance network to couple the main circuit of converter to the power source to achieve boost features. It overcomes the disadvantage of VSMC (low voltage transfer ratio) and CSMC (short circuit on the output side and open circuit on the input side).

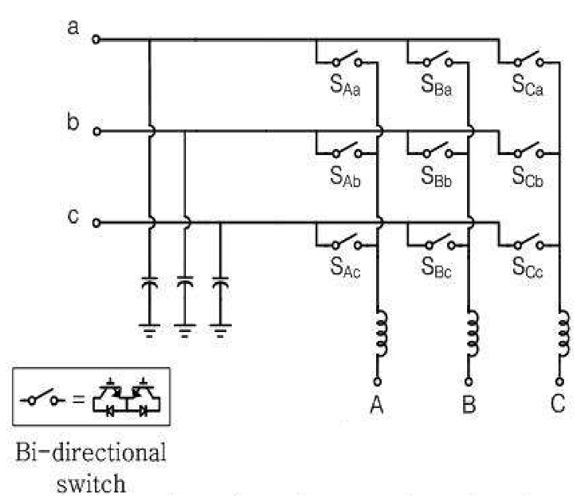


Figure 1. Matrix converter

The performance of the ZSMC is predicted by applying two types of PWM control methods such as Carrier Based Pulse Width Modulation (CPWM) 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 input frequency and loading conditions.

II. PROPOSED Z-SOURCE MATRIX CONVERTER

A novel matrix converter topology applying Z-source network to overcome the theoretical limitation of the voltage transfer ratio of conventional matrix converter is being proposed. A Z-source (or impedance fed) converter employs a unique impedance network to couple the main circuit of converter to the power source to achieve buck and boost features [15][16]. In the case of Z-source inverter for dc-ac power conversion, the theoretical buck-boost factor is 0 to ∞ [17][1].Applying Z-source network to a conventional three-phase matrix converter to utilize its boosting feature, the voltage transfer ratio of unity can be achieved. In addition, a complicated commutation strategy is not necessary because the Z-source matrix converter intentionally uses a short circuit which is strictly forbidden in the conventional matrix converter [16]. Figure 2 shows the proposed Z-source matrix converter.

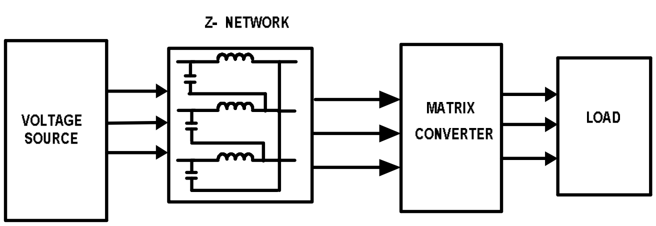


Figure 2. Proposed Z-Source Matrix Converter

III. OPERATING MODES OF ZSMC

Figure 3 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. To operate the Z-source matrix converter in buck or boost mode the modulation index and shoot through are adjusted respectively.

The working of Z-source matrix converter is explained by two operating modes [2].

They are

1. Shoot through zero state
2. Non shoot through state

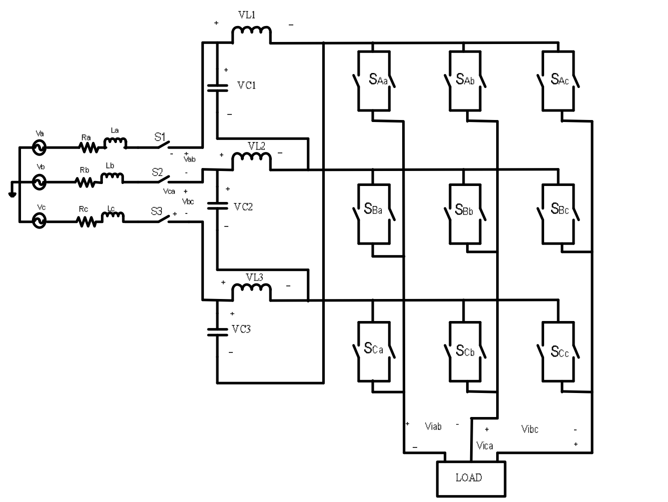


Figure 3. Basic Configuration of Z-source Matrix Converter

1)Shoot Through Zero 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 [3]. By adjusting the shoot through period in the pulses the output voltage and frequency can be stepped up or stepped down to any desired value. The equivalent circuit during the shoot-through state can be configured as shown in Figure 4.

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 shoot through period (T_0). In this period (T_0) a large value of emf induced in the inductor is transferred to the capacitor. Figure 3 shows the equivalent circuit of Z-source matrix converter in shoot through state. Assuming that the inductors L_1, L_2 and L_3 and capacitors C_1, C_2 and C_3 are symmetrical values, the voltage across inductor and capacitor of Z-source network are given in Equations (1) and (2) [4].

$$V_{L1} = V_{L2} = V_{L3} = V_L \quad (1)$$

$$V_{C1} = V_{C2} = V_{C3} = V_C \quad (2)$$

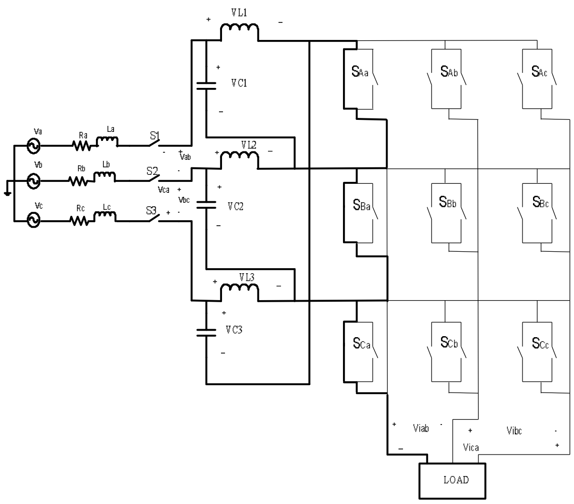


Figure 4. Z-Source Matrix Converter in Shoot Through State

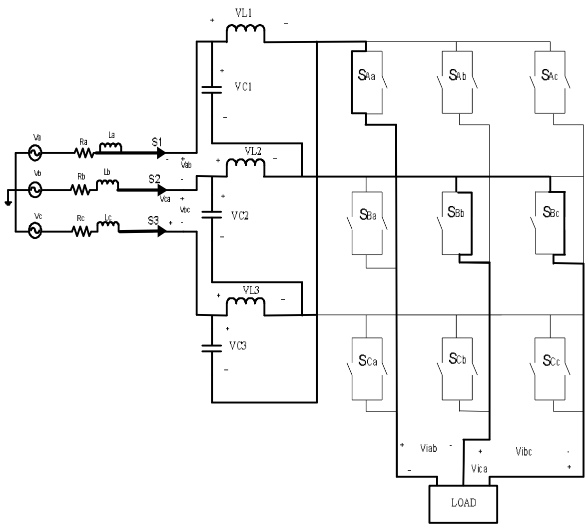


Figure 5. Z-Source Matrix Converter in Non Shoot Through State

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

$$V_L = V_C \qquad V_{iab} = V_{ibc} = V_{ica} = 0 \tag{3}$$

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. 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 as shown in Figure 5.

From the equivalent circuit, the line-to-line voltages on either side of the Z-source network can be expressed as

$$\begin{bmatrix} v_{ab} \\ v_{bc} \\ v_{ca} \end{bmatrix} = \begin{bmatrix} v_{C1} \\ v_{C2} \\ v_{C3} \end{bmatrix} - \begin{bmatrix} v_{L1} \\ v_{L2} \\ v_{L3} \end{bmatrix}, \begin{bmatrix} v_{iab} \\ v_{ibc} \\ v_{ica} \end{bmatrix} = \begin{bmatrix} v_{C1} \\ v_{C2} \\ v_{C3} \end{bmatrix} - \begin{bmatrix} v_{L1} \\ v_{L2} \\ v_{L3} \end{bmatrix} \tag{4}$$

The theoretical equation of the voltage transfer ratio is derived considering the current in each inductor. During the shoot-through state, the inductor current can be expressed as

$$I_{L1} = \frac{1}{L}\int_0^{T_0} V_{L1}dt + I_{L10}$$
$$I_{L2} = \frac{1}{L}\int_0^{T_0} V_{L2}dt + I_{L20}$$
$$I_{L3} = \frac{1}{L}\int_0^{T_0} V_{L3}dt + I_{L30} \tag{5}$$

where I_{L10}, I_{L20} and I_{L30} are the initial currents in each inductor. During non shoot through period the inductor currents are expressed as

$$I_{L1}' = \frac{1}{L}\int_{T_0}^{T_0+T_1} V_{L1}dt + I_{L10}'$$
$$I_{L2}' = \frac{1}{L}\int_{T_0}^{T_0+T_1} V_{L2}dt + I_{L20}'$$
$$I_{L3}' = \frac{1}{L}\int_{T_0}^{T_0+T_1} V_{L3}dt + I_{L30}' \tag{6}$$

where I_{L10}', I_{L20}' and I_{L30}' are the initial currents in each inductor.

Assuming that the inductances and capacitances are large enough and using Equations (3) and (4), the changes of currents during shoot through and non shoot through periods can be calculated from Equations (5) and (6). The changes in current during shoot through period are:

$$\Delta I_{L1}=\left(\frac{V_{L1}}{L}\right).T_0=\left(\frac{V_{C1}}{L}\right).T_0$$

$$\Delta I_{L2}=\left(\frac{V_{L2}}{L}\right).T_0=\left(\frac{V_{C2}}{L}\right).T_0$$

$$\Delta I_{L3}=\left(\frac{V_{L3}}{L}\right).T_0=\left(\frac{V_{C3}}{L}\right).T_0 \quad (7)$$

The changes in currents during non shoot through period are:

$$\Delta I_{L1}^{'}=\left(\frac{V_{L1}}{L}\right).T_1=\left\{\frac{\left(V_{C3}-V_{ca}\right)}{L}\right\}.T_1$$

$$\Delta I_{L2}^{'}=\left(\frac{V_{L2}}{L}\right).T_1=\left\{\frac{\left(V_{C1}-V_{ab}\right)}{L}\right\}.T_1$$

$$\Delta I_{L3}^{'}=\left(\frac{V_{L3}}{L}\right).T_1=\left\{\frac{\left(V_{C2}-V_{bc}\right)}{L}\right\}.T_1 \quad (8)$$

In steady state the average voltage across the inductors over one switching period ($T=T_0+T_1$) is zero. In other words, the changes of currents over one switching period should be zero. Therefore,

$$\Delta I_{L1}+\Delta I_{L1}^{'}=0$$

$$\Delta I_{L2}+\Delta I_{L2}^{'}=0$$

$$DI_{L3}+DI_{L3}^{'}=0 \quad (9)$$

The average voltages of each capacitor (V_{c1}, V_{c2} and V_{c3}) can be obtained from Equation (9).

From equations (3) and (4), average output phase voltages of the Z-source network are:

$$V_{ia}=0.D_{om}+\left(V_c-V_{C3}\right).(1-D_{om})$$

$$V_{ib}=0.D_{om}+\left(V_a-V_{C1}\right).(1-D_{om})$$

$$V_{ic}=0.D_{om}+\left(V_b-V_{C2}\right).(1-D_{om}) \quad (10)$$

$$D_{om}=\frac{T_0}{T}$$

Where

D_{om}= shoot through duty ratio

Substituting capacitor voltages derived from Equations (9) in (10), it can be written as

$$V_{ia}=\frac{\left(V_a+V_b+V_c\right)D_{om}^2-\left(2V_a+V_b\right)D_{om}+V_a}{1-3D_{om}+3D_{om}^2}.(1-D_{om}) \quad (11)$$

Suppose that the input three-phase voltage is balanced as

$$V_a=V_m\cos\left(\omega t\right)$$

$$V_b=V_m\cos\left(\omega t-120^o\right)$$

$$V_c=V_m\cos\left(\omega t+120^o\right) \quad (12)$$

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

$$G=\frac{\left|V_{ia,ib.ic}\right|}{V_m}=\frac{1-D_{om}}{\sqrt{1-3D_{om}+3D_{om}^2}} \quad (13)$$

$$D_{om}=1-M \quad (14)$$

Substituting equation (14) in (13)

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

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

$$=\frac{M}{\sqrt{1-3+3M+3-6M+3M^2)}}$$

$$G=\frac{M}{\sqrt{1-3M+3M^2}} \quad (15)$$

III. PWM SCHEMES FOR PROPOSED Z-SOURCE MARTRIX CONVERTER

A) Carrier Based PWM Scheme

The carrier based PWM technique is used to control the Z-source matrix converter as shown in Figure 6. The reference sine wave is compared with the triangular carrier wave to produce the required PWM pulses with the combination of logical circuits. In this control scheme for a half cycle the switch corresponding to the positive half cycle in each leg is kept switched ON completely and the switch corresponding to the negative half cycle is turned ON and OFF alternately to control the shoot through duty ratio. This is repeated alternately for every half cycle in each leg [5].

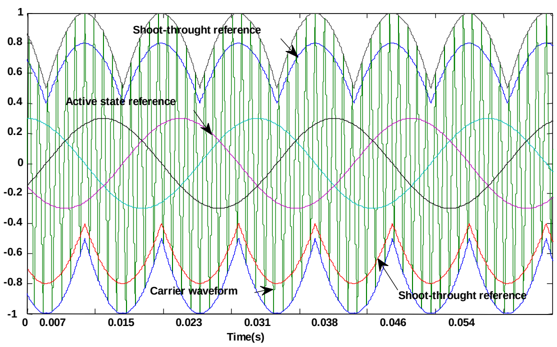


Figure 6. Pulse generation scheme for CPWM based ZSMC

B) SVPWM 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 [6]:

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

SVPWM can be applied to MC in the same way as it is applied to DC/AC converter [7] and [8]. The shoot through state is inserted besides the active and zero state.

The width of the shoot through placement is varied according to the required input voltage magnitude and frequency. The shoot through placement in SVPWM pulses for ZSMC is shown in Figure 7.

Sector 1

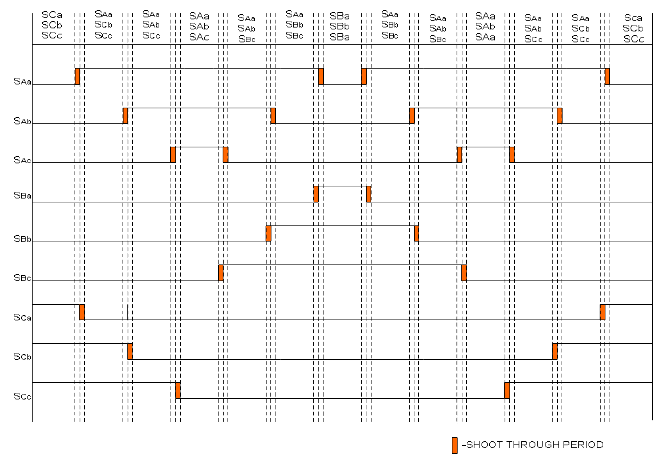
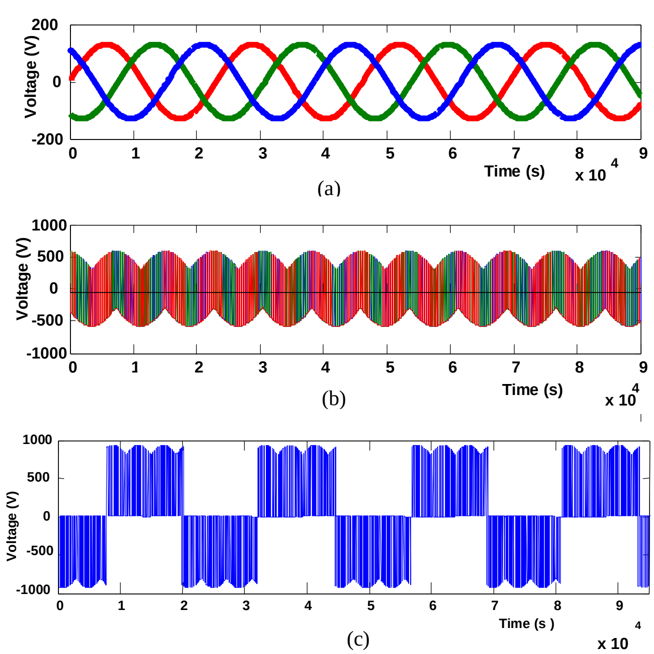


Figure 7. Shoot Through Placement in SVPWM based ZSMC

IV. RESULTS AND DISCUSSION

Figure shows the ZSMC terminal voltage, capacitor voltage and inductor current of CPWM based ZSMC for a input voltage of 166V, 12.5 Hz. To obtain the desired voltage and frequency, the shoot through period is added 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 0.448 as shown in Figure 8 (f).



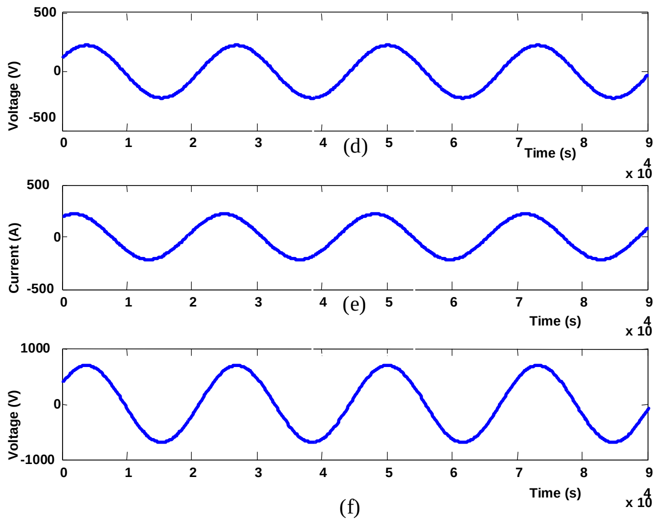
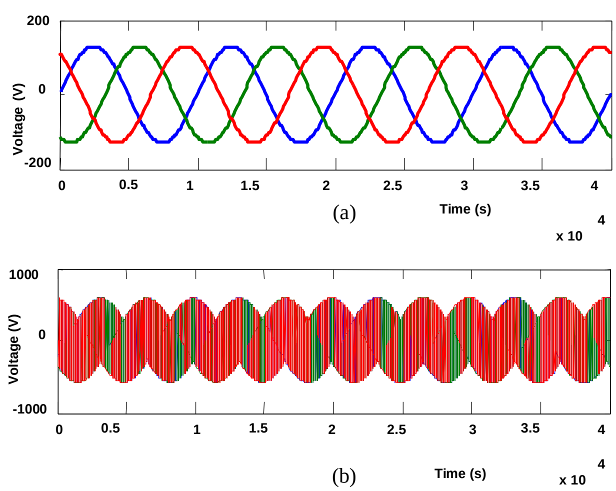


Figure 8. Simulated Results of CPWM Based ZSMC for(a)Input Voltage (b) ZSMC Phase Voltage (c) Line Voltage (d) Capacitor Voltage (e) Inductor Current (f) AC Link Voltage

Similarly the performance of ZSMC is predicted by applying SVPWM scheme. The SVPWM pulse width is varied according voltage available. Figure 8 shows the ZSMC terminal voltage, capacitor voltage and inductor current of SVPWM based ZSMC for a input voltage of 166V, 12.5Hz. From Figure 8 and 9 the carrier based PWM scheme has larger ripples in its inductor current and its capacitor voltage than the SVPWM scheme. But the voltage gain is greater than the SVPWM scheme. The voltage gain of SVPWM based ZSMC is around 8V which is greater than the CPWM based ZSMC.



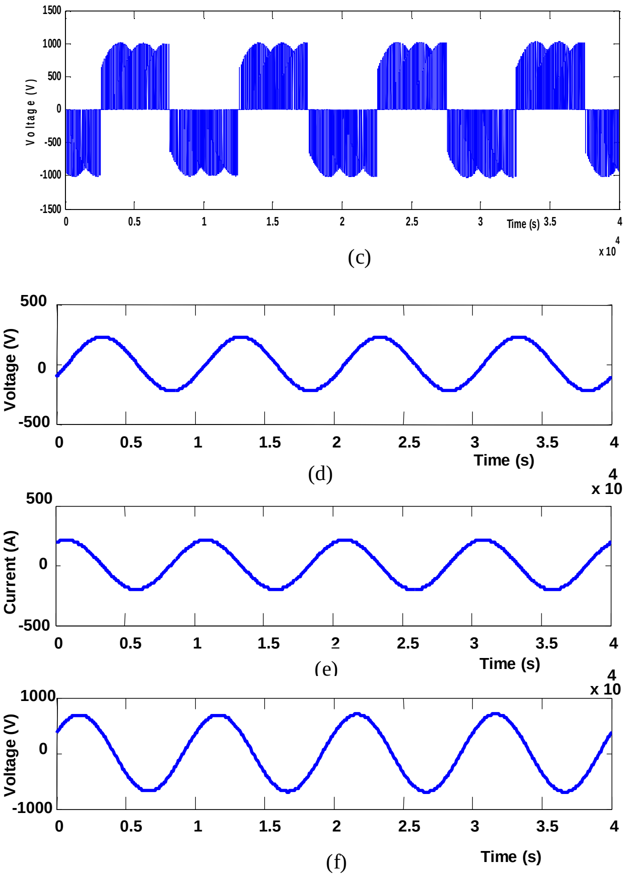
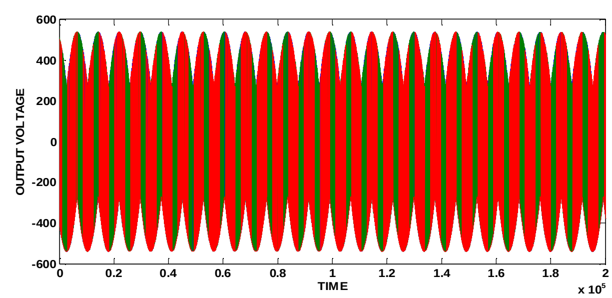
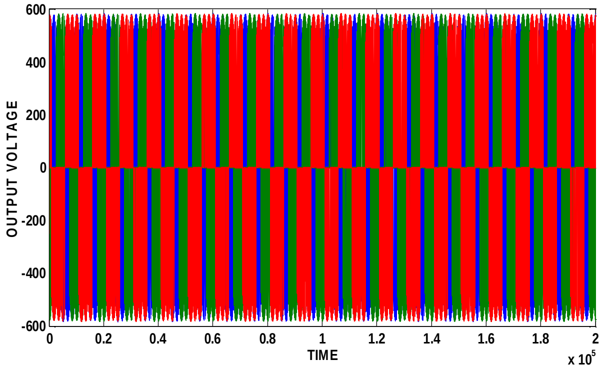


Figure 9 Simulated Results of SVPWM Based ZSMC for(a)Input Voltage (b) ZSMC Phase Voltage (c) Line Voltage (d) Capacitor Voltage (e) Inductor Current (f) AC Link Voltage

The Z-source matrix converter is controlled by PWM controller along with voltage feedback to obtain the desired voltage and frequency. Figure 10 shows the magnitude of the voltage of the Z-source matrix converter. The output voltage is almost sinusoidal and hence it contains lower value of THD.



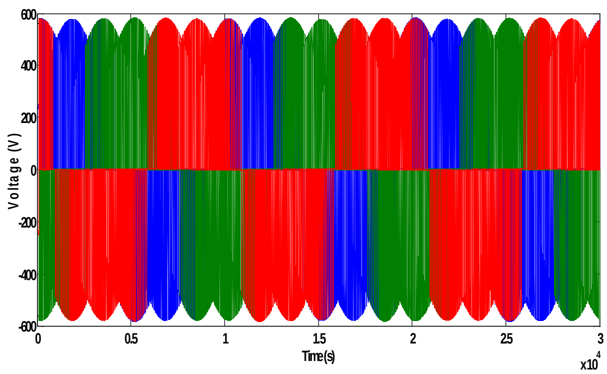
(a)



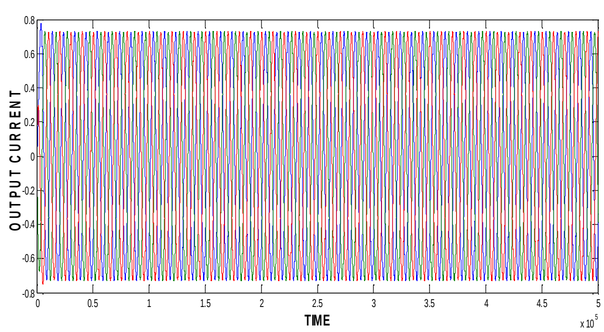
(b)

Figure 10. ZS-Matrix Converter Terminal Voltage (a) CPWM Based ZSMC (b) SVPWM Based ZSMC

The simulation also aims to verify the performance of the proposed WECS for different loading conditions. The results of load current for RL load of 1kW can be seen in Figure 11(b). The percentage input and output total harmonic distortion for different loading conditions are given in table 1



(a)



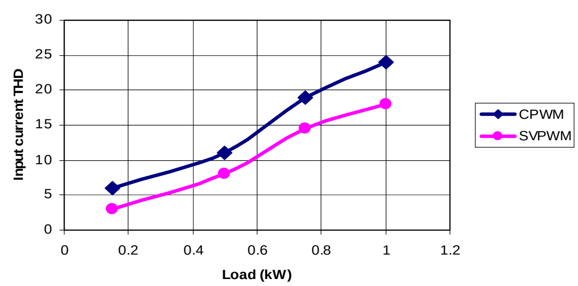
(b)

Figure 11 SVPWM Based Output of ZSMC (a)Output Voltage (b)Output Current

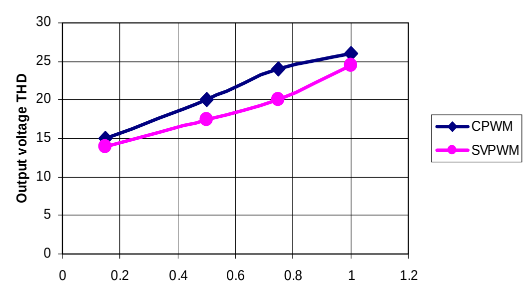
Table 1. Input and output THD of proposed and conventional WECS for different loading conditions

Load power (kW)	Input current THD (%)		Output voltage THD (%)	
	CPWM	MSVPWM	CPWM	MSVPWM
0.15	6	3	15	14
0.5	11	8	20	17.5
0.75	19	14.5	24	20
1	24	18	26	24.5

Figure 10(a) and (b) shows the variation of input current THD and output current THD of CPWM and SVPWM based Z-source matrix converter. The percentage THD of CPWM scheme is almost 3% 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 2% greater than SVPWM scheme as shown in Figure 12.



(a)



(b)

Figure 12. (%)THD for Various Value of Wind Velocity(a) Input Current THD (b)Output Voltage THD

It is seen from the Figure 13, that the voltage stress to the power switches of CPWM based ZSMC is around 340V greater than the SVPWM based ZSMC in all operating points as shown in Figure 13.

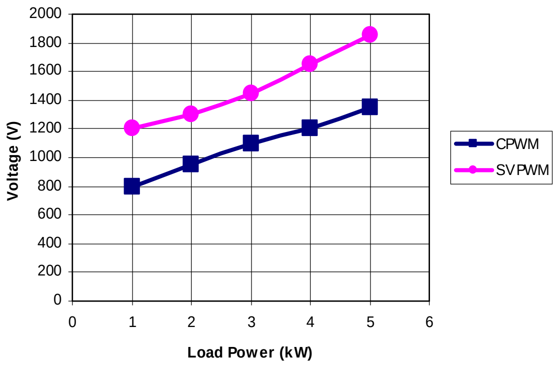


Figure 13. Switching Voltage Stress for Various Value of Wind Velocity

V. EXPERIMENTAL RESULTS

A prototype ZSMC rated 1200V, 3kVA is fabricated to validate the simulation results. The nine PWM signals with shoot through period are generated using VHDL with Spartan-6 FPGA controller. The shoot through period is adjusted according to input voltage variations as shown in Figure 14.

The shoot through period is higher the value of 0.3 for the input voltage of 82V. The experimental pulse pattern of ZSMC for duty ratio equal to 0.3 and modulation index of 0.7 is shown in Figure 14. The corresponding ZSMC terminal voltage is shown in Figure 15. From the Figures, it is evident that the experimental readings very well coincide with simulation readings.

It is very tough to implement the SVPWM technique for ZSMC. From the carrier based PWM technique itself it is understood that the placement of shoot-through period is very difficult.

The ZSMC requires lot of complicated algorithm for individual frequency conversion but it is very co-operative for voltage transfer or control but frequency conversion especially for intermediate frequency like 13Hz, 24Hz.

Hence it requires further investigation. In this section, the analysis made for the hardware implementation is based on carrier PWM scheme only.

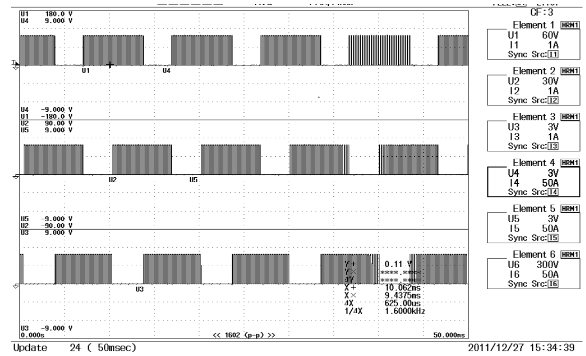
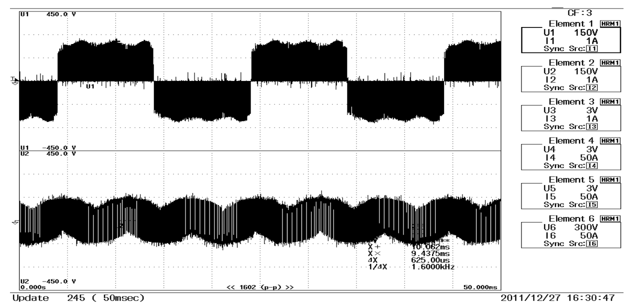
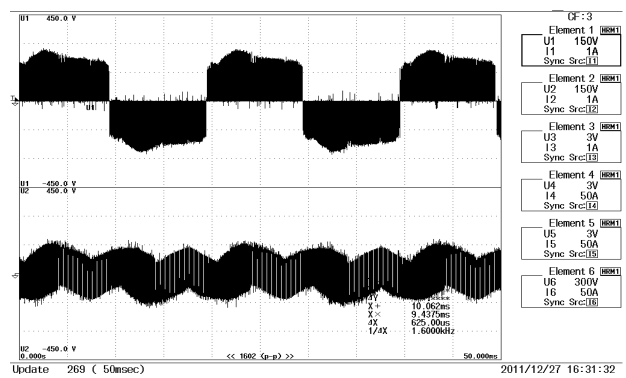


Figure 14. Experimental Pulse Pattern of CPWM based ZSMC for D_{0m}=0.3 and m=0.7



(a)



(b)

Figure 15. Experimental Line and Phase Voltage Waveforms for CPWM Based ZSMC (a)D_{0m}=0.2 and (b)D_{0m}=0.3

VI. CONCLUSION

The Z-source matrix converter is analyzed for different values of input voltage and frequency. It is observed that the frequency conversion can be obtained by using different switching strategies and voltage boost up can be achieved by adjusting the shoot through duty ratio. The comparison is made between the two different PWM schemes based on plcement of shoot through, voltage gain, THD and switching stress.

The voltage gain is higher in carrier based PWM schemes whereas it is lower in the space vector PWM scheme. But the shoot through placement is quite easy and switching stress is also very low in space vector schemes.

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