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Comparative analysis of different PWM schemes for Z-Source Matrix Converter

Prof. V.Kandasamy[1], Kavya.G[2]
Department of EEE,Kumaraguru College of Technology,Anna university,Chennai.

Abstract- **Direct Drive Wind Energy Conversion System (DDWECS) requires a compact generator as the widely used induction and synchronous generators are bulky owing to the additional excitation circuit. The ongoing research and development in the area of permanent magnet materials and power electronic devices has identified the required compact Permanent Magnet generator (PMG). The conventional DDWECS requires power electronic conditioner to get the required voltage and frequency. The conventional three stages of power converters such as rectifier, boost chopper and inverter are subject to more switching stress, less voltage boost and require more switching frequency which leads to high switching losses. The main objective of this paper is to overcome the above short comings. A single stage Impedance source matrix converter (ZS-MC based) DDWECS are proposed. Input and output THD, switching stress and efficiency of the conventional and proposed system are compared. A new switching scheme and shoot through placement technique are introduced to improve the performance of ZSMC. The proposed converters are modeled and simulated in MATLAB/SIMULINK software.**
Keywords: Matrix converter, Space Vector Pulse Width Modulation (SVPWM), Permanent Magnet Synchronous Generator (PMSG), Carrier based Pulse Width Modulation (CPWM).

I. INTRODUCTION

In recent years the fixed speed wind energy conversion system due to poor energy capture, stress in mechanical parts and poor power quality has given way to variable speed systems. These systems have reduced mechanical stress and aerodynamic noise. Wind is the safest and most abundant renewable source of energy in nature. Now the wind energy is converted into electrical energy using several techniques. The conventional sources like thermal power stations are facing acute shortage of fuel whereas the nuclear power stations are threatened by natural hazards globally. Under these circumstances, the Wind Energy Conversion System (WECS) can be the major source of power not only to a country like India but also worldwide. In recent years the fixed speed wind energy conversion system due to poor energy capture, stress in mechanical parts and poor power quality has given way to variable speed systems. These systems have reduced mechanical stress and aerodynamic noise. They can be controlled in order to enable the turbine to operate at its maximum power coefficient over a wide range of wind speeds, obtaining a larger energy capture from the wind by quickly responding to the wind fluctuations and load variations[36],[33]. Also the direct drive wind turbine generator makes it possible to achieve maximum energy yield and minimum cost [41],[42]. Historically, the induction generator squirrel cage rotor is a very popular machine because of its low price, mechanical simplicity, robust structure, resistance against disturbance and less vibration [6]. However, the induction generator requires bulky capacitors for its excitation and it needs bi-directional power flow converters [6]. Also at low wind speeds the efficiency and power factor of induction generator are very low. The permanent magnet generator has the advantages of simplicity in construction, very compact in size, no necessity of additional power supply for magnetic field excitation, no need of bi-directional power flow controller and high reliability. Also the PMG has an inherent brushless rotor construction. Hence, PMG is more suitable for Wind Energy Conversion System (WECS)[43].The permanent magnet machines have power to weight ratio, good reliability and high efficiency than other electrically excited machines. Elimination of rotor excitation loss implies that very high efficiency can be achieved. Also recent advances in power electronic semi conductor devices make the PMG more suitable for DDWECS[12].The recent development in power electronic devices and its control strategy over energy efficient Direct Drive Wind Energy Conversion System (DDWECS) has aroused interest in using Permanent Magnet Generator (PMG) in small and medium DDWECS.

Direct Drive Wind Energy Conversion System (DDWECS) requires power converters to obtain the desired voltage and frequency. Figure 1.1 shows the conventional method of WECS consisting of diode rectifier, DC-DC boost chopper and PWM inverter. The continuously varying generated power is fed to the load through the three stages of power conversion to provide desired voltage and frequency by adjusting the duty cycle of the boost chopper. Then the dc voltage is inverted to desired ac voltage and frequency by using PWM inverter [39]. In conventional power conversion system interface circuits have three stages such as rectifier, dc-dc boost chopper and PWM inverter for attaining required voltage and frequency.

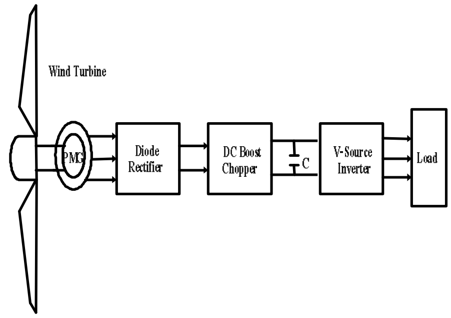

Figure 1.1 Conventional DDWECS with PMG and three stages of power conversion

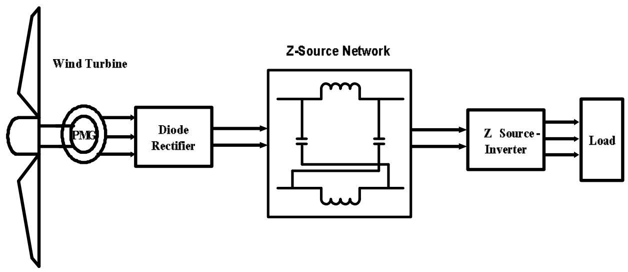

Figure 1.2 Proposed WECS with two stages of power conversion

The newly proposed Z-Source matrix converter overcomes the limitations of PWM-VSI in the traditional DDWECS. It is a single stage buck-boost ac-ac converter and hence its efficiency is improved over the conventional WECS. With this ZSMC the rectifier, boost chopper and PWM Inverter are removed without any change in the objectives. The ZSMC allows short circuit across any phase leg and hence the system reliability is improved. 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. The proposed a novel single phase AC-AC converter topology based on ZS concept [7]. The PWM technique is used to control the proposed single phase ZSMC.

Figure 1.3 shows the proposed DDWECS with single satge ZS-MC. The simulation results match with experimental results. But the output contains rich harmonics and the switching stress becomes more. The voltage gain is also low. The proposed a single phase ZSMC for buck/boost operation of both frequency and voltage [26]. The bucking and boosting of voltage and frequency are clearly proved. However, the placement of shoot through is not mentioned. To overcome the inherent low voltage transfer ratio a novel matrix converter with ZS network is proposed [23].

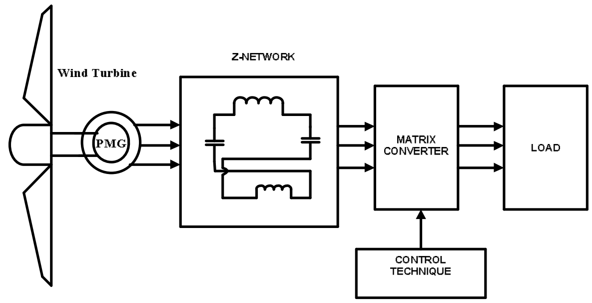

Figure 1.3 Proposed DDWECS with single stage ZS-MC

II. OPERATING MODES OF ZSMC

Figure 2.1 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 2.1 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. They are

1. Shoot through zero state
2. Active state

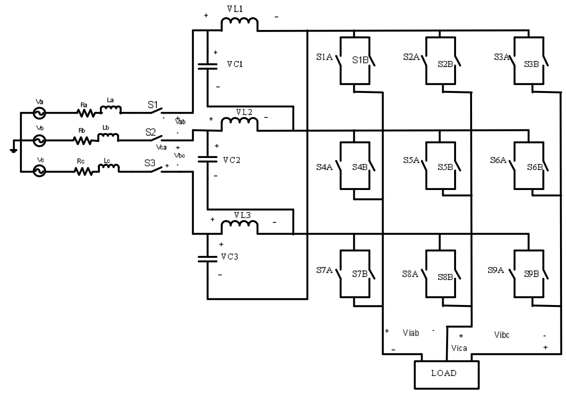

Figure 2.1 Basic configuration of Z-source matrix converter

A. *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 SAa, SBa and SCa) will be turned ON for a particular time period, hence short circuit takes place which is called as 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 2.2 shows the equivalent circuit of PMG with Z-source matrix converter in shoot through state mode.

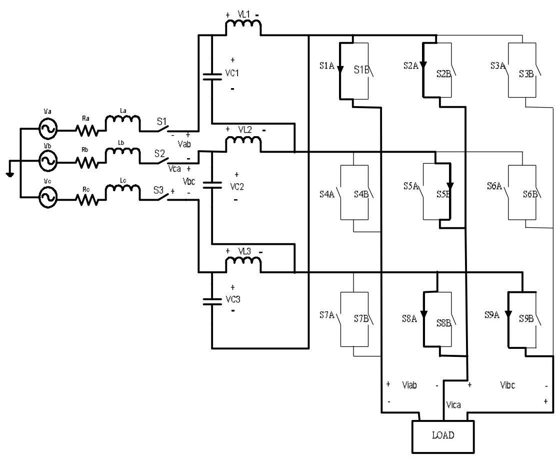

Figure 2.2. Z-source matrix converter in shoot through state

Assigning of same value for inductors L1, L2 and L3 and that for capacitors C1, C2 and C3, the voltage across inductor and that of and capacitor of Z-source network are given in Equations (2.1) and (2.2) [23].

$$V_{L1} = V_{L2} = V_{L3} = V_L \quad (2.1)$$

$$V_{C1} = V_{C2} = V_{C3} = V_C \quad (2.2)$$

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The equivalent circuit during the shoot-through state can be configured as shown in Figure 2.2. When the shoot-through period 0 T accommodated within the switching period T, the matrix converter is intentionally short-circuited and switches 1 S , 2 S and 3 S are in off condition. From the equivalent circuit, it is obvious that

$V_L=V_C$

The output ZSMC terminal voltages are

$V_{iab} = V_{ibc} = V_{ica} = 0$ (2.3)

B. Non Shoot Through State

In non shoot through state (normal operating state) the switches S1,S2 and S3 will be in ON state. If any one of the switches in each phase is connected between input and output terminals, the capacitor voltages Vc1, Vc2 and Vc3 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 2.3.

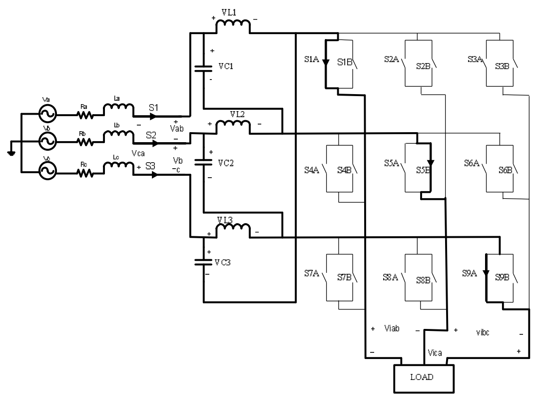

Figure 2.3. Z-source matrix converter in non shoot through state

From the equivalent circuit, the line-to-line voltage across the ZS network can be expressed as

$$\begin{bmatrix} v_{ab} \\ v_{bc} \\ v_{ca} \end{bmatrix} = \begin{bmatrix} v_{C1} \\ v_{C2} \\ v_{C3} \end{bmatrix} - \begin{bmatrix} v_{L1} \\ v_{L2} \\ v_{L3} \end{bmatrix}, \begin{bmatrix} v_{iab} \\ v_{ibc} \\ v_{ica} \end{bmatrix} = \begin{bmatrix} v_{C1} \\ v_{C2} \\ v_{C3} \end{bmatrix} - \begin{bmatrix} v_{L1} \\ v_{L2} \\ v_{L3} \end{bmatrix} \quad (2.4)$$

From equations (2.3) and (2.4), the average output phase voltages of the Z-source network are:

$$V_{ia} = 0.D_u + (V_c - V_{C3}).(1 - D_u)$$

$$V_{ib} = 0.D_u + (V_a - V_{C1}).(1 - D_u)$$

$$V_{ic} = 0.D_u + (V_b - V_{C2}).(1 - D_u) \quad (2.5)$$

$$D_u = \frac{T_0}{T}$$

where

D_u= shoot through duty ratio

From the equivalent circuits of ZS-MC the terminal voltage of ZSMC can be expressed as [22].

$$V_{ia} = \frac{(V_a + V_b + V_c) D_u^2 - (2V_a + V_b) D_u + V_a}{1 - 3D_u + 3D_u^2} . (1 - D_u)$$

$$V_{ia} = \frac{(V_a + V_b + V_c) D_u^2 - (2V_b + V_c) D_u + V_b}{1 - 3D_u + 3D_u^2} . (1 - D_u)$$

$$V_{ia} = \frac{(V_a + V_b + V_c) D_u^2 - (2V_c + V_a) D_u + V_c}{1 - 3D_u + 3D_u^2} . (1 - D_u) \quad (2.6)$$

Where

V_a, V_b, V_c are the per phase PMG voltages.

The shoot through duty ratio

Suppose that the input three-phase voltage is balanced as

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

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

$$V_c = V_m \cos(\omega t + 120^o) \quad (2.7)$$

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

$$G = \frac{|V_{ia,ib.ic}|}{V_m} = \frac{1 - D_u}{\sqrt{1 - 3D_u + 3D_u^2}} \quad (2.8)$$

$D_u = 1\text{-}M$ (2.9)

Substituting Equation (2.9) in (2.8)

$G = M/\sqrt{1\text{-}3M+3M^2}$ (2.10)

C. Shoot Through Distribution In Z-Source Matrix Converter

Figure 2.4 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[56] (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.

III. 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.

A. Carrier Based PWM Scheme

The carrier based PWM technique is used to control the Z-source matrix converter as shown in Figure 2.4. 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.

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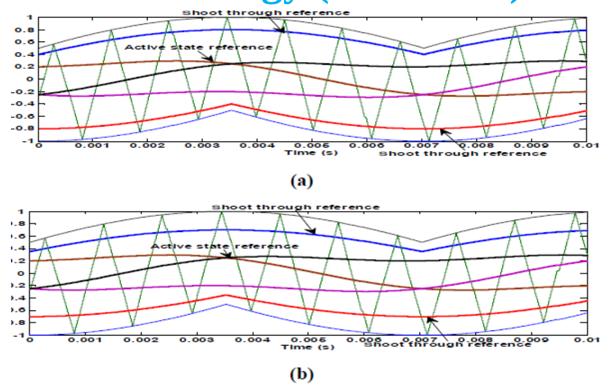


Figure 2.4 Pulse Generation Scheme for CPWM based ZSMC (a) D_{om}=0.3 and (b) D_{om} =0.25

The important expressions for maximum boost control method are

Voltage Gain $G = \frac{M}{2M-1}$

Boost Factor $B = \frac{1}{1-2D_u}$

The capacitor voltage amplitude

$$V_c = \frac{D_u}{1-2D_u} V_{im}$$

The line to line voltage across inverter bridge

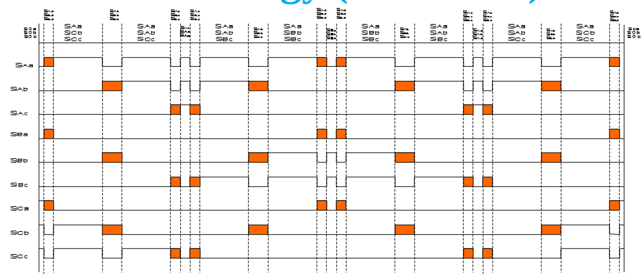
$V_{ab} = 1/(1-2D_0)\, V_{ab}$

The phase voltage on the output side of ZSMC is given as $V_{a'b'} = BM\, V_{ab} / \sqrt{3}$

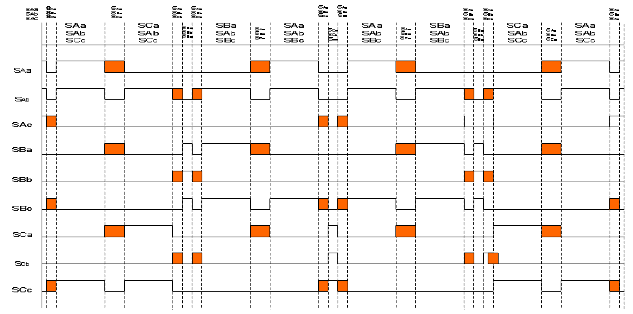
B. Space Vector Pulse Width Modulation Scheme for ZSMC

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 fram, reduction in the number of switching 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 and 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. 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 3.2.



(a)



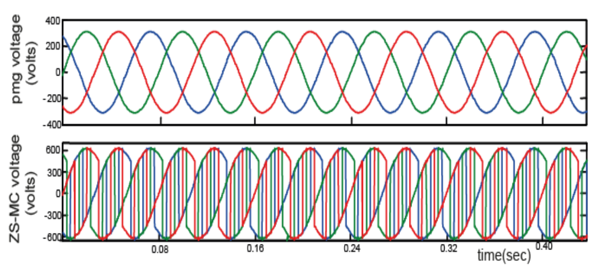
(b)

Figure 3.2 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.

IV. RESULTS AND DISCUSSION

Figure 4.1 shows the simulated waveforms of ZS-MC for different values of wind velocity. To obtain the desired voltage and frequency, the shoot through period is added according to input voltage and frequency. The PMG generated voltage is 128V with a frequency of 12.5Hz at wind velocity of 6m/s. The ZS-MC output voltage is 415V with frequency of 50Hz and the corresponding value of shoot through duty ratio is 0.448 as shown in Figure 4.1(a). The shoot through duty ratio are 0.394 and 0.42 for the wind velocity of 8m/s and 10 m/s respectively to obtain the desired voltage and frequency.
Figure 4.2 shows the wind turbine speed in rpm for different wind velocities. The turbine speed is 53 rpm at 6m/s and reaches the maximum speed of 107 rpm at 12m/s. Figure 6.9 shows the PMG generated voltage for different wind velocities. The generated voltage is a maximum of 400V at 12m/s and a minimum value of 170V at 6m/s. The frequency of the generated voltage is at its rated value of 25Hz at 10m/s and 12.5Hz at 6m/s. When the matrix converter is fed without closed loop controller the frequency and amplitude of matrix converter output vary may vary.



(a)

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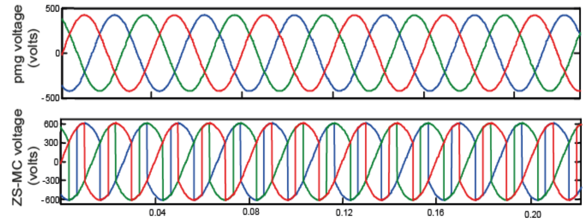

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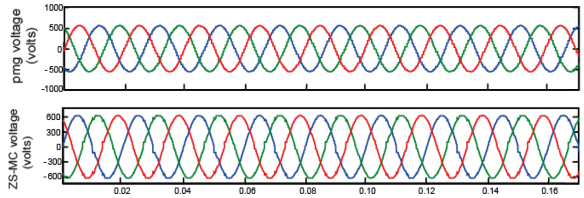
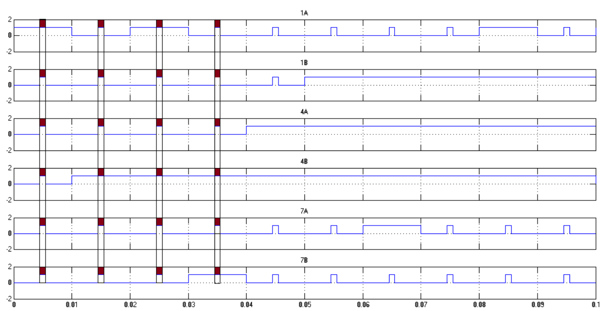


(c)

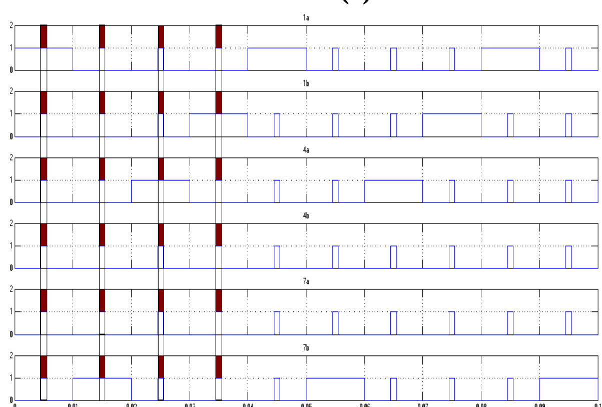
Figure 4.1 Simulated results of PMG generated voltage and ZS-MC for wind velocity of a) 6m/s b)8m/s c) 10m/s

The Z-source matrix converter is controlled by PWM controller along with voltage feedback to obtain the desired voltage and frequency. Figure 4.3 shows the magnitude of the voltage of the matrix converter voltage with controller. For all values of voltage and frequency shown in Table 6.1 the output voltage is converted into fixed value of 415V at 50Hz. The output voltage is almost sinusoidal and hence it contains lower value of THD..

Figure 4.4 shows the pulse pattern for ZS-MC for different values of PMG generated voltage and frequency. The carrier based PWM scheme is used to analyze the performance of ZS-MC. The shoot through width is adjusted according to PMG generated voltage and frequency.



(a)



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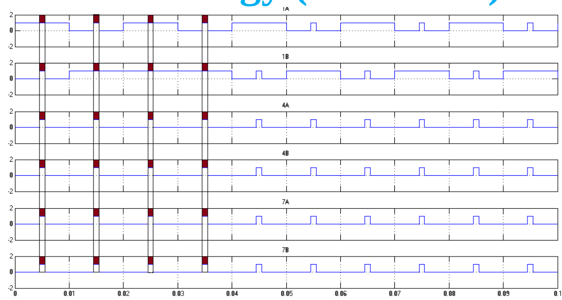

(c)

Figure 4.2 Pulse pattern for ZS-MC for the input frequency of (a) 12.5Hz (b) 25Hz and (c) 50Hz.

The simulation also aims to verify the performance of the proposed WECS for different loading conditions. The results of load current for RL load can be seen in Figure 4.3(c).

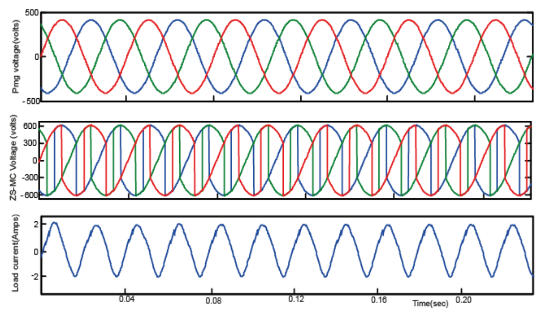

Figure 4.3 simulation for a load 1 kW (a) PMG generated voltage (b) ZS-MC Output voltage (c) load current

Table 3.1 Simulation readings of proposed WECS under different wind velocity

Wind Velocity (m/s)	Speed (rpm)	PMG rms voltage (Volts)	Frequency of the PMG generated voltage (Hz)
3	28	82	7
6	54	129	12.5
8	71	171	21
10	89	216	25
12	107	258	32

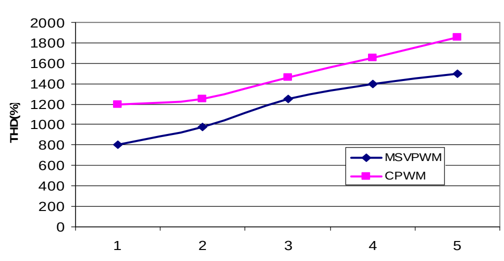

Figure 4.4 Switching voltage stress for various value of wind velocity

V. CONCLUSION

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

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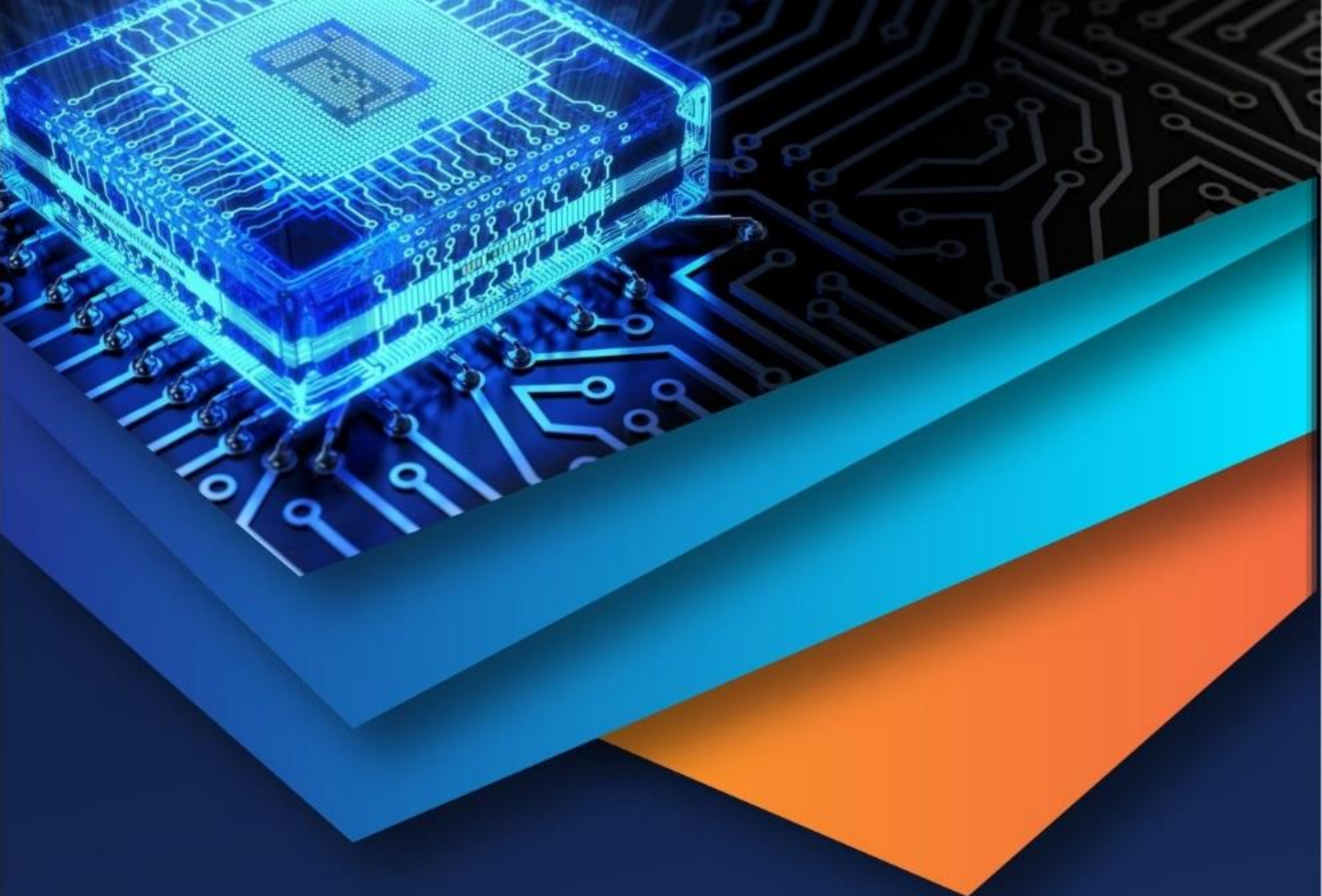

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