

Performance Evaluation of Three Phase Z-Source Matrix Converter for Wind Energy System Using Various PWM Control Schemes

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Abstract: This proposed research aims to design a Z-Source Matrix converter (ZSM) for wind energy conversion system of 2.5 kW Permanent Magnet Synchronous Generator (PMSG). The main objective of this research is to reduce the power loss during low wind velocity and reduces the Total Harmonic Distortion (THD). The proposed Z-source matrix converter is to reduce the power loss and THD by varying frequencies through various PWM techniques. In proposed research, it also focus on ZSM converter parameters like load frequency, load voltage and THD levels are analyzed for various wind velocities with PWM techniques. In connection to, the proposed research also deals with Sine wave Pulse Width Modulation (SPWM), Space Vector Pulse Width Modulation (SVPWM) and Selective Harmonic Elimination Pulse Width Modulation (SHE PWM) to validate the analysis of ZSM.

Key word: PMSG, PWM, SVPWM, SHE PWM, ZSM

INTRODUCTION

In recent years, the power electronics converters are playing major role in electric energy system, due to this converter, the energy saving is improved lot. In connection with these converter concentrating on other factors like lower cost, smaller size and higher efficiency to meet the required level power demand. This converters are lead to extraction of power from eco-friendly sources such as Wind, Geothermal, Solar, Ocean, Biomass are the efficient Solution to supply power either directly to a utility grid or to an autonomous load. But, the Power Electronic Converter (PEC) is requires some sort of measure and it necessary to suppress the harmonic. The Wind Energy System (WES) is widely used in energy system. The other merits of WES include the long life time and low maintenance requirements, reliability, simplicity (Alesina and Venturini, 1981). The power generated in WES is mainly affected by the amplitude of the generator voltage as explained in Kiwoo Park, Eun-Sil Lee and Kyo-Beum Lee. The use of conventional converters like AD-DC and DC to AC with the variable amplitude, the variable-frequency by using a two-stage AC-DC-AC system which needs bulky dc-link energy storage such as an electrolytic capacitor, etc. In order to avoid this, the matrix converter is developed and implemented for various applications. The matrix converter has several advantages over traditional rectifier-inverter type power frequency converters. The output voltage of matrix

converter contains with minimum amount of higher order harmonics and no sub-harmonics. It has inherent bi-directional energy flow capability; the input power factor can be fully controlled. The various analyzes are carried out against matrix converter performance, the outcome of analyzes; this matrix converter also leads some demerits. The demerits are, it has a maximum input and output voltage transfer ratio limited to 87% for sinusoidal input and output. It requires more semiconductor devices than a conventional AC-AC indirect power frequency converter.

In this proposed research, the above mentioned demerits of matrix converter are eliminated by implementing impedance network at the input side of the matrix converter. There are three PWM schemes for ZSM. The PWM schemes include carrier based PWM, Space Vector PWM (SVPWM) and Selective Harmonics Elimination PWM (SHE PWM) methods. The important performance of a carrier-based PWM modulator is found by its modulation signals. The SPWM signal is generated by comparing a sinusoidal modulating signal with a triangular signal having double edge or a saw tooth signal having single edge carrier signal. The frequency of the carrier is normally kept much higher compared to that of the modulating signal. The SVPWM is the most popular one due to its simplicity both in hardware and software (Dash *et al.*, 2003) and its relatively good performance at low modulation ratio. Generally, carrier-based PWM of multilevel inverter can only select four switching states

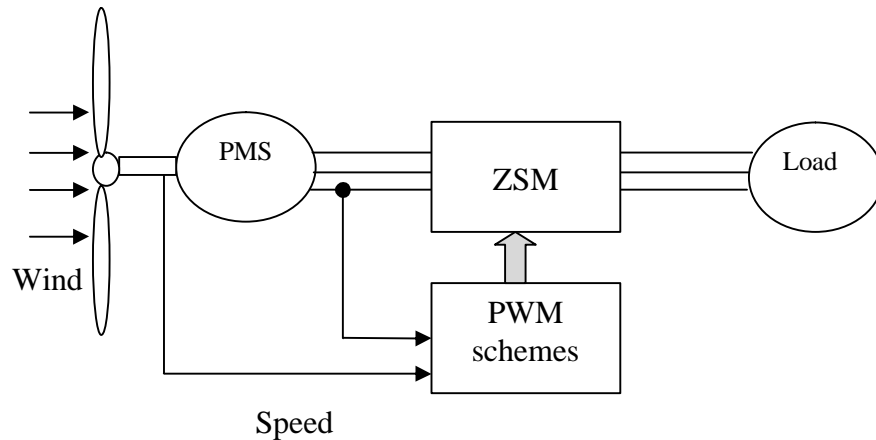


Fig. 1: Block diagram of proposed PMSG ZSM converter

at most but SVPWM can select more. In general, the selection of switching states has more freedom in the SVPWM than the carrier based PWM. Generally, in carrier-based PWM mode the modulated output voltage is smooth and it contains distortion.

Configuration of proposed wind energy system: The WES consists of a small wind turbine and the turbine is coupled with a PMSG. The generator output voltage and frequency varies with respect to different wind velocities. The PMSG is coupled with ZSM converter. The proposed system block diagram is illustrated in Fig. 1. The mechanical output power of the wind turbine is given by cube law:

$$P_w = \frac{1}{2} \rho S \times V_w^3 \times C_p \times \lambda \quad (1)$$

Where:

- ρ = The air density (kg m^{-3})
- S = The surface of the turbine blades (m^2)
- V_w = The average wind velocity in (m sec^{-1})
- C_p = The power coefficient

The tip speed ratio function is given in Eq. 2:

$$\lambda = \frac{\omega_m \times R}{V_w} \quad (2)$$

Where:

- ω_m = The rotor mechanical speed (rad/sec)
- R = The blade radius

The wind turbine output torque T_w is calculated from Eq. 3:

$$T_w = \frac{P_w}{\omega_m} = \left(\frac{1}{2} \rho S R V_w^2 C_p \lambda \right) \quad (3)$$

The mathematical expression (Eq. 3) is used to develop the simulation model in Mat lab environment.

Mathematical model of the Permanent Magnet Synchronous Generator (PMSG): A Permanent Magnet Synchronous Generator (PMSG) rated 2.5 kW, 415 V and rated speed 400 rpm is employed in the wind energy system. The output voltage of the generator varies with respect to the wind speed variation. The line to line voltage of an ideal (unloaded and loss-less) PMSG is given as:

$$V_L = K_v \omega_e \text{Sin}(\omega_e t) \quad (4)$$

Where:

- K_v = The voltage constant
- ω_e = The electrical frequency related to the mechanical speed ω_m by the relation

$$\omega_e = \omega_m \left(\frac{N_p}{2} \right) \quad (5)$$

Where, N_p is the number of poles of PMSG. The simulation model, the PMSG, 3 blade and 3-phase wind energy system of 2.5kW is used for the maximum power at wind speed are 12 m sec^{-1} , the cut in and cut out speed are 2 and 12 m sec^{-1} , respectively. The voltage rating is about 440 V when speed of generator nearly 410 rpm. The speed of revolution varies from 145-410 rpm and the operating frequency is 50 Hz

Three phase Z-source matrix converter: The matrix converter (Wheeler *et al.*, 2002) consists of nine bi-directional switches which allow any output phase to be connected to any input phase. The circuit scheme is demonstrated in Fig. 2. The PMSG output connected with the ZSM converter (Kandasamy *et al.*, 2015).

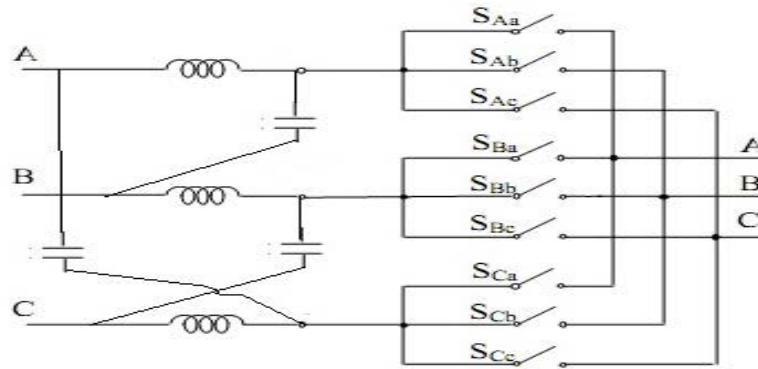


Fig. 2: Circuit diagram of ZSM converter

As consequence of the input-output direct connection, at any instant, the output voltages have to fit within the enveloping curve of the input voltage system. Based on above constraint, the maximum output voltage of matrix converter can generate without entering the over-modulation range is equal to $v_{3/2}$ of the maximum input voltage.

MATERIALS AND METHODS

Two major families of rare earth permanent magnets, SmCo magnets and NdFeB magnets, have been widely used in a variety of applications. Both the magnets NdFeB and SmCo have the main advantage of high power magnetic material properties at small sizes in comparison with traditional ferrites, Alnico and other materials. The desirable qualities of permanent magnet materials are high co-ercivity, high saturation magnetization, high remanence, high energy product and nearly linear in second quadrant of B-H characteristics. The NdFeB magnet is chosen to be the best when compared to SmCo and Alnico magnets. Even though the SmCo magnet consists of higher magnetic properties like that of NdFeB it is very expensive. Among the second quadrant B-H curve of all the magnets Alnico has the highest flux density but it is non-linear. However, NdFeB magnets are linear and it exhibits the highest properties of all magnetic materials at room temperature. The MOSFET power switches are used to fabricate Z-source matrix converter.

PWM control schemes

Sinusoidal PWM: The advancement of solid state devices are the PWM based converter widely used for control of drives. The PWM converters make it possible, to control both the frequency and magnitude of the voltage and current applied to drive motor. The control signal in PWM converter are need to be control the drive, by PWM signals applied to power switches. These

various PWM techniques are commonly used for the control of ac induction, Brushless Direct Current (BLDC) and Switched Reluctance motors. In this regards, the PWM converter powered drives offer better efficiency and higher performance compared to fixed frequency drives. The each carrier signal period at the output of the converter legs is switching between the positive or negative rail of the reference (Nikkhajoie *et al.*, 2006). If the reference signal is greater than the carrier signal, then the active device corresponding to that carrier is switched on and if the reference signal is less than the carrier signal, then the active device corresponding to that carrier is switched off (Nelson *et al.*, 2006). Figure 3 shows the development of carrier-based PWM technique.

The important performance of a carrier-based PWM modulator is found by its modulation signals. The PWM signal is generated by comparing a sinusoidal modulating signal with a triangular signal having double edge or a saw tooth signal having single edge carrier signal (Ray *et al.*, 2012). The frequency of the carrier is normally kept much higher compared, to that of the modulating signal.

Space vector PWM: The SVPWM is simple in its hardware and software, construction and its relatively good performance at low modulation ratio. But, the SVPWM becomes very difficult to achieve when the levels of the converter increase in manner. Generally, the carrier-based PWM of multilevel inverter can only select four switching states at most but SVPWM can select more. The selection of switching states has more freedom in the space vector PWM than the carrier based PWM. Generally, in carrier-based PWM mode the modulated output voltage is smooth and it contains distortion. This carrier-based PWM technique has advantageous because it consists of large number of levels in inverters. In case of matrix converter which has fixed number of switches space vector Pulse Width Modulation is preferred. The carrier based PWM method with the

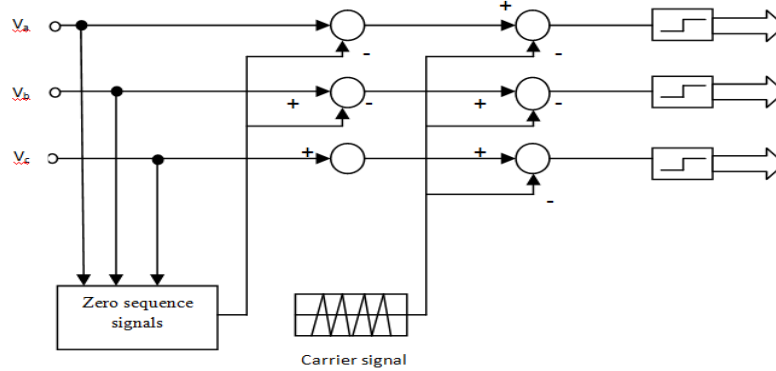


Fig. 3: Development of carrier based PWM Technique

smallest common mode voltage presents a preferable PWM solution for high power and high number level inverters. Then these SVPWM switches should be selected in a proper manner. The matrix converter is a nonlinear controller because it uses nonlinear components.

The SVM strategy, based on space vector representation becomes very popular due to its simplicity. In contrast to sinusoidal PWM, SVM treats the three phase quantities as a single equation known as space vector:

$$V_s = \frac{2}{3} \{V_a(t) + V_b(t)e^{j2\pi/3}\} \tag{6}$$

$$V_s = \frac{2}{3} \{V_a(t) + V_b(t)e^{j2\pi/3} + V_c(t)e^{j2\pi/3}\}$$

where, \$V_a\$, \$V_b\$ and \$V_c\$ are the phase voltages. If \$V_a\$, \$V_b\$ and \$V_c\$ are balanced three phase sinusoidal voltage, then the locus of space vector is circular with a radius equals the amplitude of the phase voltage. The concept of space vector is derived from the rotating field of ac machine which is used for modulating the converter output voltage. In this modulation technique, the three phase quantities can be transformed to their equivalent two phase quantity either in synchronously rotating frame (or) stationary d-q frame. The two phase component, the reference vector magnitude can be found and used for modulating the converter output. The SVM treats the sinusoidal voltage as a constant amplitude vector rotating at constant frequency. This technique approximates the reference voltage \$V\$ by a combination of the eight switching patterns (\$V_{ref}-V_0\$).

Table 1 show the switching patterns and the magnitude of the corresponding output voltage of the switches in the matrix converter. For example, if the reference voltage is located in sector 1, voltage vectors \$V_1\$, \$V_2\$, \$V_0\$ and \$V_7\$ would be selected and applied within a sampling period.

Table 1: Switching patterns to the matrix converter and its output voltage level

a	b	c	\$V_a\$	\$V_b\$	\$V_c\$	\$V_{ab}\$	\$V_{bc}\$	\$V_{ca}\$
0	0	0	0	0	0	0	0	0
1	0	0	2/3	-1/3	-1/3	1	0	-1
1	1	0	1/3	1/3	-2/3	0	1	-1
0	1	0	-1/3	2/3	-1/3	-1	1	0
0	1	1	-2/3	1/3	1/3	-1	0	1
0	0	1	-1/3	-1/3	2/3	0	-1	1
1	0	1	1/3	-2/3	1/3	1	-1	0
1	1	1	0	0	0	0	0	0

Selective harmonic elimination PWM: SHE PWM technique uses many mathematical methods to eliminate specific harmonics such as 5th, 7th, 11th and 13th harmonics. The popular Selective Harmonic Elimination method is also called fundamental switching frequency based on harmonic elimination Theory.

Because, it carries of odd quarter-wave symmetry, the dc component and the even harmonics are equal to zero. Ramakumar and coauthors presented the Fourier series of the three-level SHE PWM as follows:

$$a_n = \frac{4E}{n\pi} \sum_{k=1}^N (-1)^{k+1} \cos(n\alpha_k) \text{ for odd } n \tag{7}$$

The \$N\$ is the number of the switching angles per quarter. The \$\alpha_k\$ is the switching angles which must satisfy the following condition:

$$\alpha_1 < \alpha_2 < \dots < \alpha_N < \frac{\pi}{2} \tag{8}$$

Where:

- \$E\$ = The amplitude of the dc source
- \$n\$ = The harmonic order

The nonlinear equation system of SHE PWM waveform can be written as follows:

$$\left. \begin{aligned}
 \cos(\alpha_1) - \cos(\alpha_2) + \dots \pm \cos(\alpha_N) &= \frac{\pi}{4} M \\
 \cos(3\alpha_1) - \cos(3\alpha_2) + \dots \pm \cos(3\alpha_N) &= \frac{\pi}{4E} h_3 \\
 &\vdots \\
 \cos(5\alpha_1) - \cos(5\alpha_2) + \dots \pm \cos(5\alpha_N) &= \frac{5\pi}{4E} h_5 \\
 \cos(N\alpha_1) - \cos(N\alpha_2) + \dots \pm \cos(N\alpha_N) &= \frac{N\pi}{4E} h_n
 \end{aligned} \right\} (9)$$

Where, M is the modulation index and $M = h_1/E$. From Eq. 9 the cosine terms of are negative with even N and positive with odd N. To control the amplitude of the fundamental component, the modulation index in Eq. 8, M is given. According, to the above nonlinear system, N-1 surplus harmonic can be eliminated from the output waveform by setting Eq. 9 to zero. The lowest odd harmonic components need to be eliminated from a single-phase system. In a three-phase system, the lowest non-triple n harmonic components are eliminated. Generally, all triple n-harmonics in line-to-line voltage will be eliminated by 120 electrical degree phase shift characteristic.

RESULTS AND DISCUSSION

The generalized simulation model the proposed PMSG WES is developed from the mathematical equation from Eq. 1-5. The simulation model data are the PMSG, 3-blades and 3-phase wind energy system of 2.5 kW is considered for configuration. The speed of revolution varies from 145-410 rpm. The operating frequency is assuming 50 Hz.

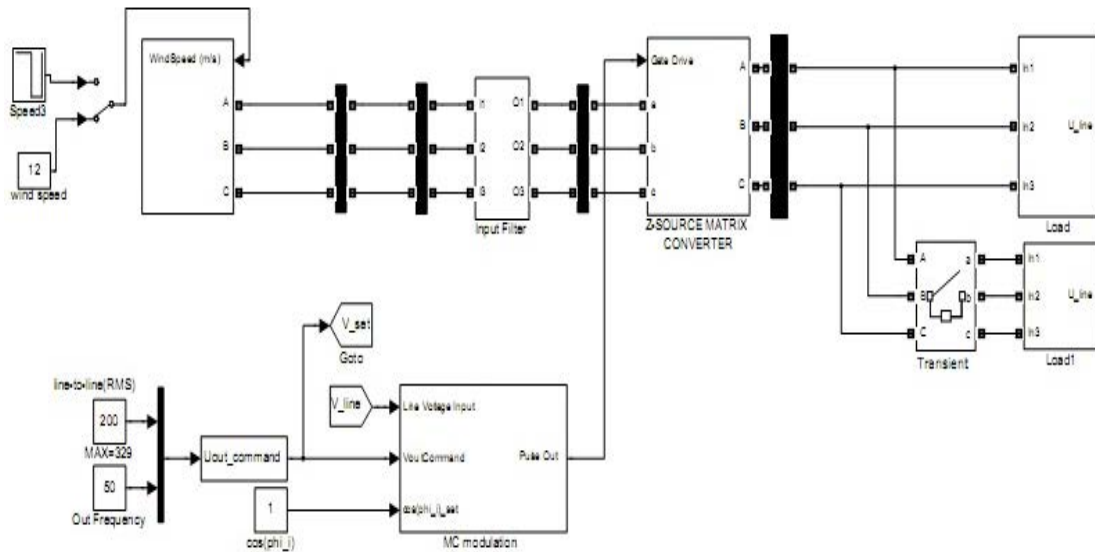


Fig. 4: The simulation model of the proposed Z-source matrix converter

In existing system consists of AC-DC and DC-AC converters for regulating the output power at required level. In this proposed system, the output of generator is connected to the AC-AC voltage controller called matrix converter with impedance network.

This circuit is known as Z-source Matrix Converter (ZSM) which is used in proposed PMSG WES model (Fig. 4). This proposed converter is not only regulating the output power and also maintaining the power quality. In order to ensure that the simulation studies validating the results with various PWM techniques like PWM, SVPWM, SHE-PWM. The results are illustrated as follows

PMSG WES with PWM converter: The simulation results are been considered out for steady state and during fault conditions under various wind velocities.

Figure 5 demonstrates the speed of wind generator at various wind velocities like 3, 6 and 12 m sec. the corresponding power output of the generator at full load condition is given in Fig. 5. Figure 6 also detailed power output at various wind velocities under steady state conditions.

PWM technique: The pulse width Modulation (PWM) is introduced for analyzing the performance of the ZMC. The simulation results for various wind velocities are obtains and its listed in Table 2. The wave forms are demonstrated at the wind velocity level of 12 m sec⁻¹, the wind speed is normal for all operating conditions.

The voltage magnitude and frequency maintained at nominal level during fault condition. It because of ZSM converter, the voltage magnitude is maintained 412.9 V even, if the fault occurs. The ZSM converter focused to play major role is maintain

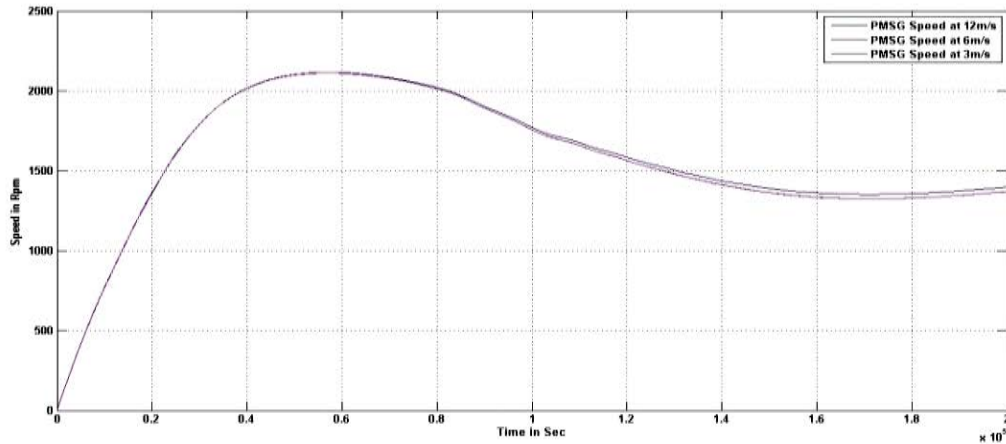


Fig. 5: Speed of PMSG with various wind velocities

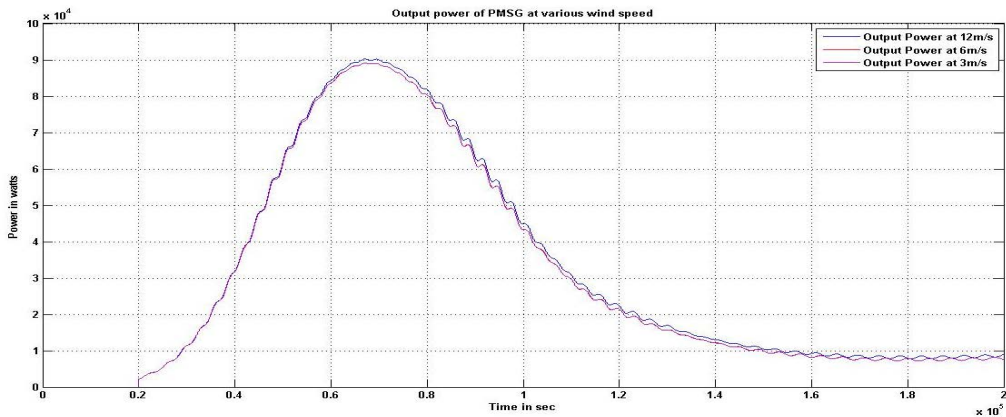


Fig. 6: Power output at full load condition

Table 2: Proposed PMSG system parameters

Title (parameters)	Value and unit
General	
Cut in wind speed	Approx. 2 m sec ⁻¹
Cut out wind speed	Approx. 16 m sec ⁻¹
Rated wind speed	12 m sec ⁻¹
Generator	
Rated power output	2.5 KW
Type	Permanent magnet
Voltage	3 phase 400 V
Revolutions	145-410 rpm
Frequencies	50 Hz
Rotor	
No. of blades	3
Diameter	3 m (approximately)
Max. speed	410 rpm

the voltage magnitude when the current drastically increases twice as that nominal load value. The voltage wave form during fault is given in Fig. 7. The current analyze during fault condition is illustrated in Fig. 8. The FFT (Fast Fourier Transform) technique is used for

analyzing Total Harmonic Distortion (THD) content of the ZSM. The THD is maintained 2.92% for PWM technique. The THD spectrum is given in Fig. 9.

SVPWM technique: In normal PWM technique, the two analog signal and carrier signal directly utilized for generating switching pulses. But the converter output contains some harmonic content. In SVPWM technique; the harmonic content eliminated by protecting the exact voltage reference and its angle through the mathematical calculation (Venturini, 1980). Figure 10 shows the ZSM terminal voltage waveforms the voltage magnitude is 413.4 V for modulation index of 0.66, shoot through duty ratio of 0.3 and wind velocity of 12 m sec⁻¹ with SVPWM technique. Figure 11 shows the response of ZSM current waveform when sudden removal of loads.

The THD spectrum is reduced to 1.4% as compared with PWM technique. The harmonic content nearly 50%

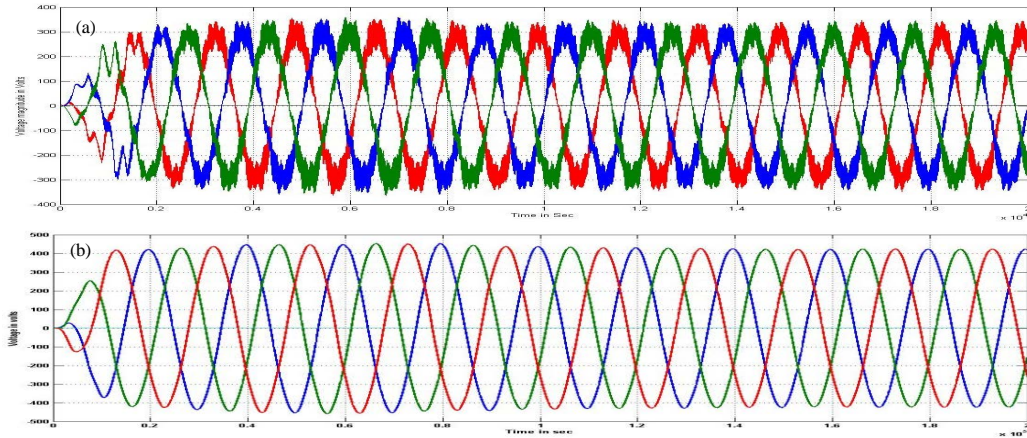


Fig. 7: ZSM output wave form (a) without filter (b) with filter

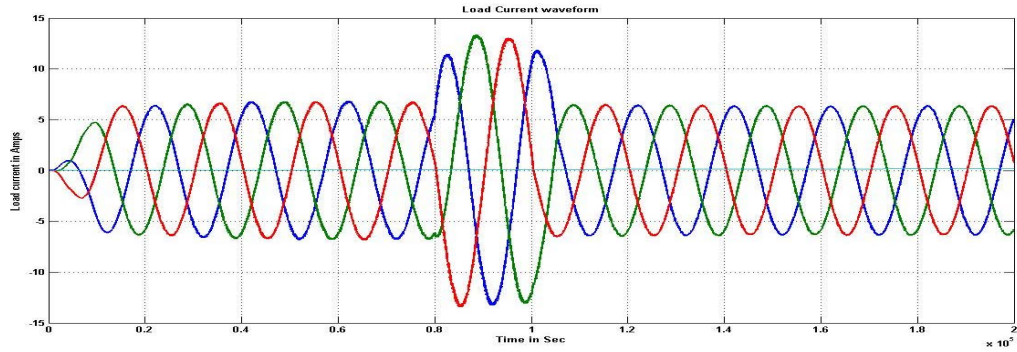


Fig. 8: Current wave form during fault

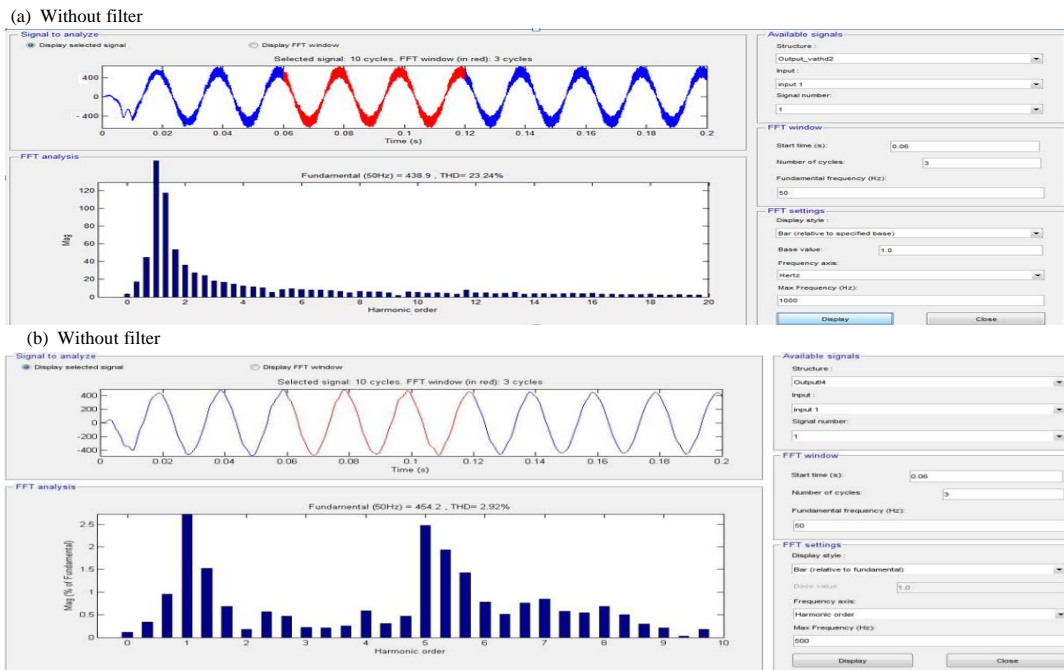


Fig. 9: THD spectrum Wave form for PWM

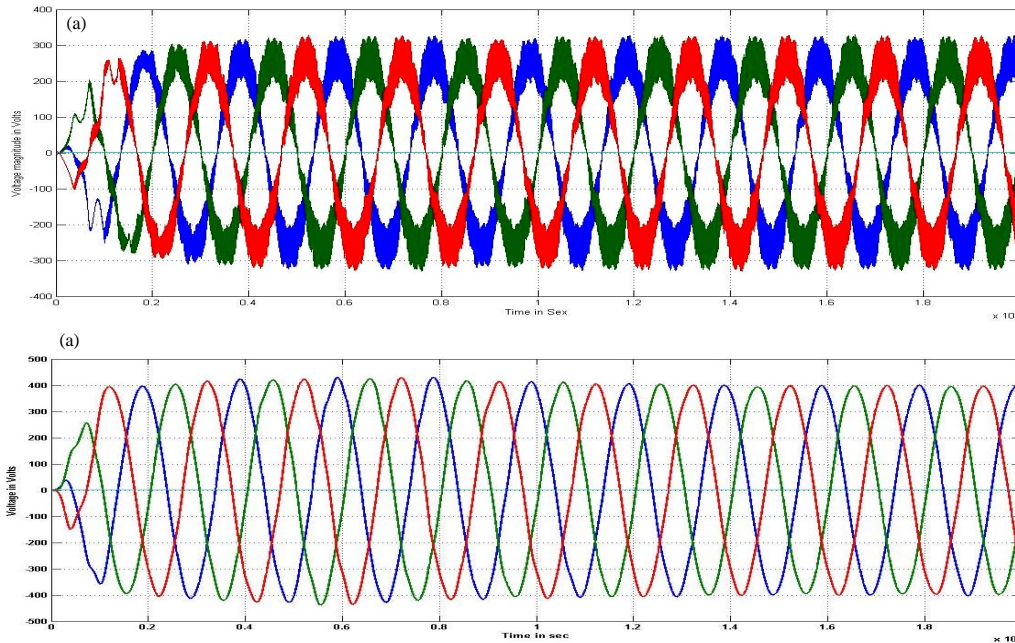


Fig. 10: ZSM output voltage wave form: a) without Filter; b) with filter

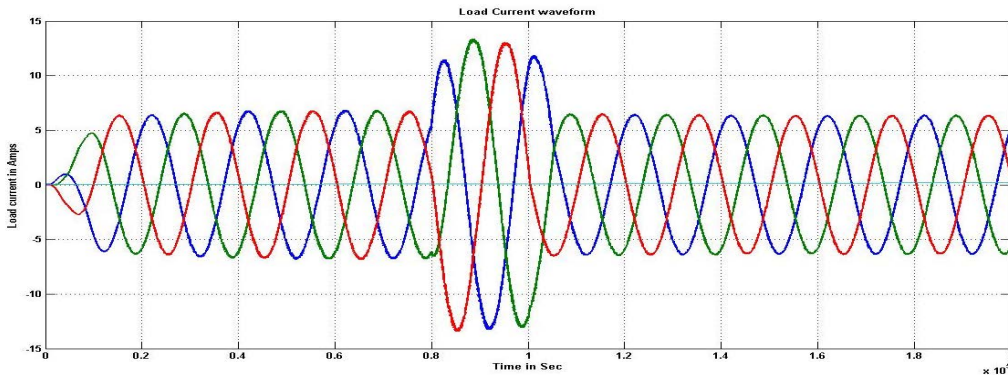


Fig. 11: Current wave form of ZSM when sudden removal of load

reduced by using SVPWM technique. But, the voltage magnitude is not in the desired level. The harmonic content 1.4% is obtained due to the 3rd, 5th, 7th and 9th order harmonics. In the 1.4% harmonic content the 0.9% is connected with 3rd and 5th harmonics, the 0.3% is due to all other odd and even order harmonics. The THD spectrum is given in Fig. 12. In order to reduce the above mentioned 3rd, 5th, 7th and 9th order harmonics the SHE-PWM technique is introduced (Venturini and Alesina, 1980).

SHE-PWM technique: The implementation steps of SHE-PWM taken from Eq. 6-9. Figure 13 is detailed above voltage wave form of ZSM converter with connection of SHE-PWM technique. In addition to the SHE-PWM

technique voltage magnitude is very much improved, even in the fault conditions. The voltage magnitude range is 440.9 V for the same fault conditions as discussed in PWM and SVPWM techniques. The current wave form during fault conditions with addition of SHE-PWM technique is detailed in Fig. 14.

The application of SHE-PWM technique is introduced in ZSM converter and outcome of this scheme is reduces the THD level of 0.7%. In connection with, harmonic content of 0.7% is obtained by eliminating 3rd, 5th, 7th and 9th order harmonics. Figure 15 shown the THD waveform of ZSM with and without filter.

Validity analysis: In the proposed system, the 2.5 kW PMSG system has been analyzed for various desired

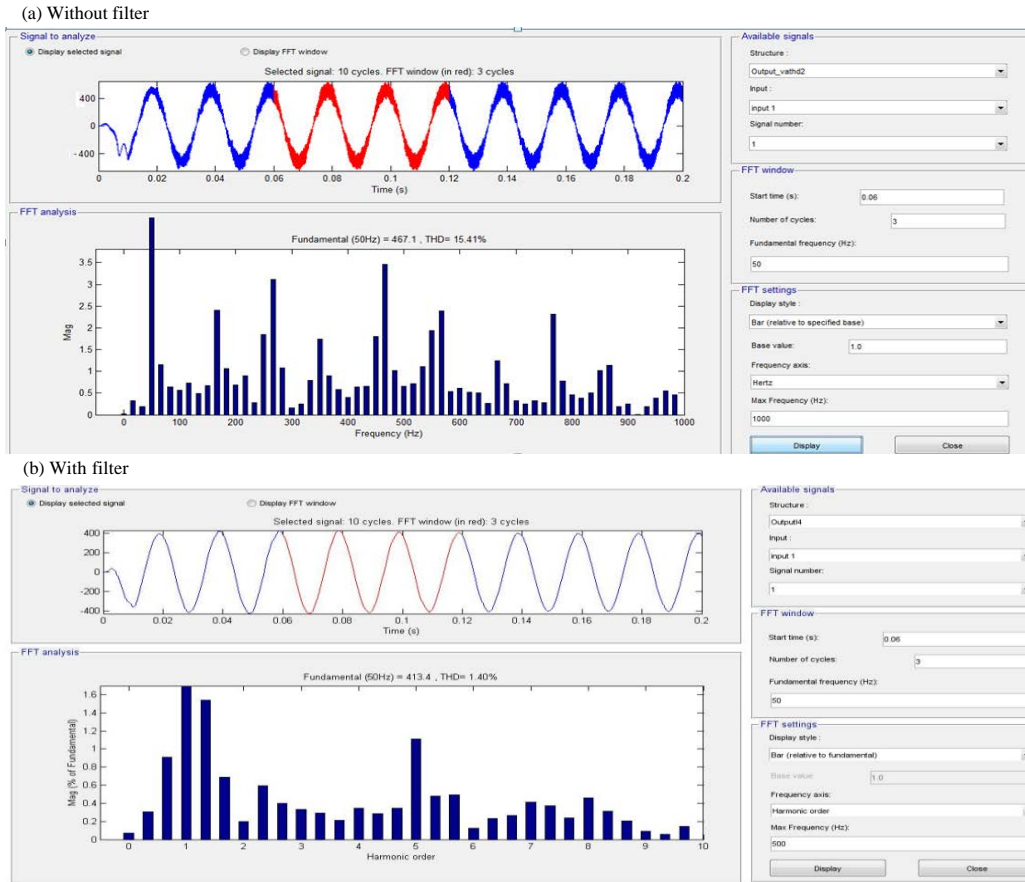


Fig. 12: THD spectrum with SVPWM

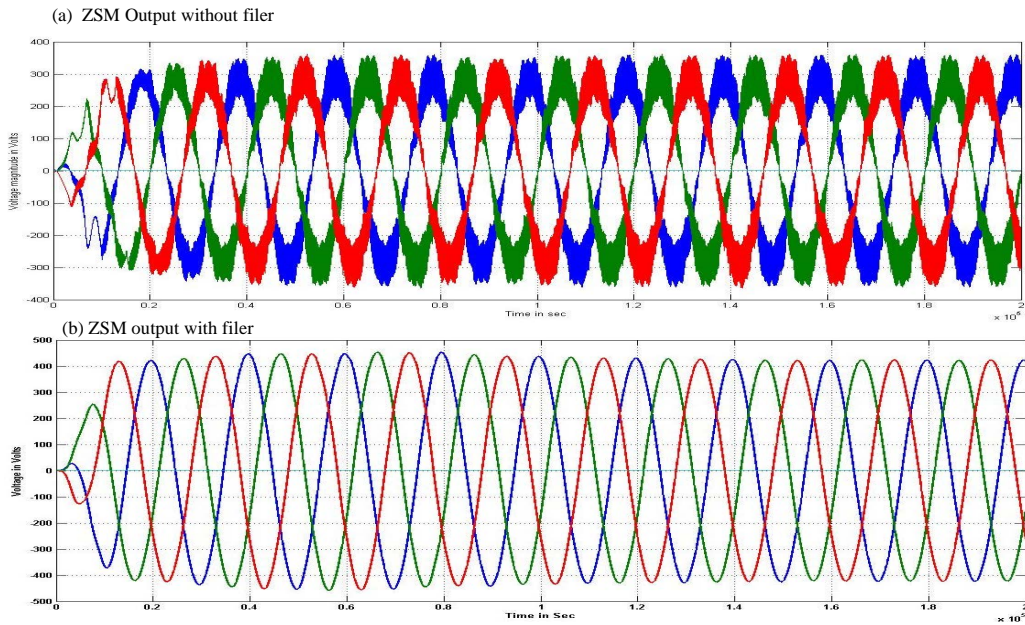


Fig. 13: Voltage wave form during fault condition with SHE-PWM

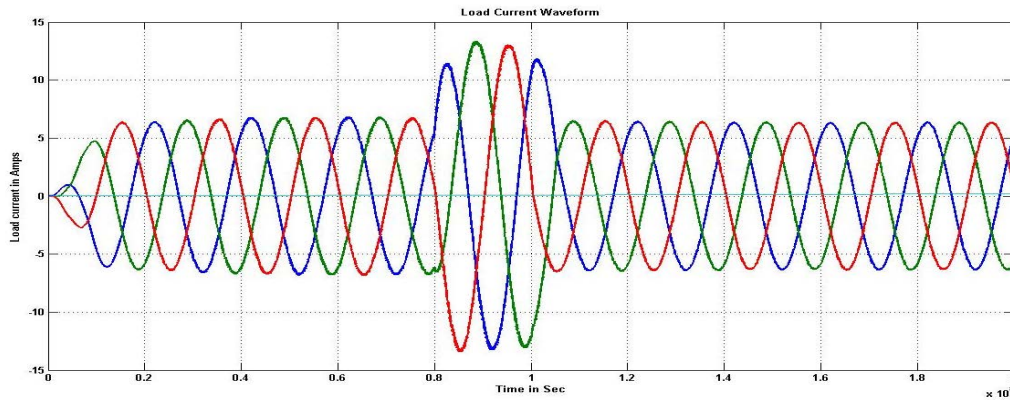


Fig. 14: Current wave form during fault conditions

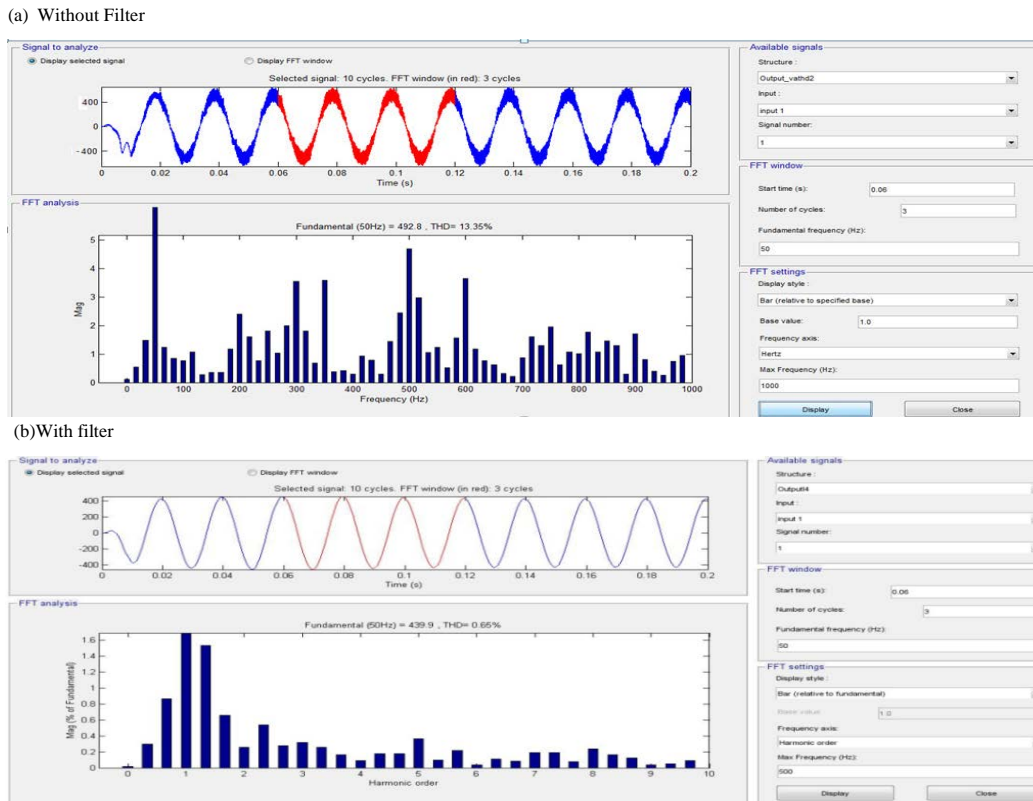


Fig. 15: THD spectrum Wave form for SHE-PWM

operating conditions. The results have been evaluated for various wind velocities and various PWM techniques. The various wind velocities such as 3, 6 and 12 m sec⁻¹ against PWM, SVPWM and SHE-PWM techniques. The comparison results of various PWM techniques for ZSM converter is tabulated in Table 3.

From the results, it is observed that in PWM technique does not eliminate the harmonic content because the switching pattern directly obtained from the comparison of two analog signals. In the SVPWM

technique, the mathematical functions are used to estimate the voltage magnitude and voltage angle for PWM generation. Even if, the SVPWM does not have functional capability to eliminate the order of harmonics.

Hence, the SHE-PWM technique is best choice for estimating the harmonic content and also maintaining the voltage profile at the desired level. The frequency also maintained desired operating level by the application of SHE-PWM technique.

Table 3: Comparison of ZSM in 2.5 kW PMSG system

Wind velocities (m sec ⁻¹)	Without filter			With filter			
	PWM techniques	Voltage magnitude (V)	Frequency (Hz)	THD (%)	Voltage magnitude (V)	Frequency (Hz)	THD (%)
12	PWM	238.9	50	23.24	412.9	49.0	2.92
	SVPWM	267.1	50	15.41	413.4	49.7	1.40
	SHE-PWM	292.8	50	13.3	439.9	49.9	0.65

CONCLUSION

This proposed research deals various PWM techniques and the analyzes of various performance of Z-source matrix converter for control the voltage and harmonic profile under various desired operating conditions are carried out. The performance analyze of ZSM converter is accompanying with, 2.5 kW permanent magnet synchronous generator for wind energy conversion system. The proposed ZSM converter scheme with SHE-PWM technique results have confirmed better in voltage and harmonic profile under desired operating conditions. The obtained results are validated with other PWM techniques.

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