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# Implementation of State-Space-Dqo Model With S-Transformation Based Z-Source Matrix Converter For Wind Energy System

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**ABSTRACT**

This paper is aimed at the solution of Wind Energy System (WES) using Z-Source Matrix (ZSM) converter topology and embedded with State-Space-Direct Quardature (SS-DQO) Pulse Width Modulation (PWM) control. The main objective of this ZSM converter is to maintain the constant frequency and constant load voltage during low wind velocity. In addition to the power loss in the system due to harmonic distortions can be carry out. The overall performance analysis for Total Harmonic Distortion (THD) is obtained using S-transform with dynamic SS-DQO PWM switching techniques. In this proposed work, dynamic SS-DQO is interfaced with the load and dynamic penalization for handling mechanical power, under various wind velocity level. This modification in WES is to maintain the constant system frequency at any desired level. This methodology is implemented for Permanent Magnet Synchronous Generator (PMSG) based 2.5kW WES. The constant V/F control is achieved with the help of comprehensive dynamic model of ZSM converter. To demonstrate its robustness, the proposed method is tested and various models results are represented and discussed.



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## NTRODUCTION

With the rapid change, technological invasions have propelled the development of the entire world to its new heights. These developments have transformed the world into its new dimensions through technological aspects and impact. This is the main reason for the increase in power demand. The rate of world development in geometric ratio catalyses is in the need of extracting power from renewable energy resources. The renewable energy resources were Wind, Geothermal, Solar, Ocean, Biomass and Chemical resources. Out of these, the Wind resources are the one efficient Solution to supply power either directly to a utility grid or to an isolated load. In addition, the other advantages include the long lifetime and low maintenance requirements, reliability, simplicity Nelson DB *et al.* (2006) - R. Ramakumar *et al.* (1999). The wind energy can be harnessed by a Wind Energy Conversion System (WECS), composed of a wind turbine, an electric generator, a power electronic converter and the corresponding control system.

The quality of the produced power is mainly affected by the amplitude of the generator voltage Thiringer.T *et al.* (2004)-Thiringer.T. *et al.* (1996). Conventional converters convert AC to AC with the variable amplitude and the variable-frequency by using a two-stage AC-DC-AC system, which needs bulky dc-link energy storage, such as an electrolytic capacitor. To avoid such a two stage conversion, a Matrix converter was introduced in 1976 and improved version of that by M. Venturini *et al.* (1980). Matrix converter topology provides high degree of controllability, which allows an independent control of amplitude, frequency and phase angle. However, it does not require intermediate energy storage components. A feature of matrix converter is the elimination of bulky dc-link capacitor and it can be realized compactly and prolong its lifetime. Hence the input side and the output side of the converter is directly coupled by power semiconductor switches, the power density of the matrix converter is high and its input power factor can be freely controlled by proper modulation, irrespective of the type of the load Kiwoo Park *et al.* In this paper, ZSM converter topology and its switching methods are introduced. The ZSM converter controls the terminal voltage and frequency of the generator while the wind turbine is operated at

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its maximum power point. This system targets small to medium power wind turbines. Then a comprehensive dynamic model for ZSM converter is developed which is valid for both steady state and transient analyses. The developed model is in DQO reference frame and it is based on the matrix converter input, output voltage and current fundamental components.

### *Configuration of Proposed 2.5kW WES with ZSM Converter:*

A 2.5 kW wind generating system is used for a modeling of a system. A wind generating system contains a wind turbine, direct driven PMSG and the ZSM converter connects the three-phase ac voltage from the PMSG to the three-phase voltage on output side by a 3×3 matrix (or array) of bi-directional switches and impedance source network. In total, ZSM converter needs nine bi-directional switches, each switch is connected between input phase and output phase. A second-order L-C filter is used at the input terminals to filter out the high frequency harmonics of the input currents M. Kazerani *et al.* (1995)-H. Nikkhajoei *et al.* (2006). It satisfies the requirement of providing a sinusoidal voltage on the load side and a sinusoidal current on the source side. Meanwhile, it is possible to adjust the input displacement angle, control the output voltage magnitude, and phase angle by properly operating the switches. SS-DQO model is used for switching ON and OFF the switches. The ZSM converter structure is inherently capable for a four-quadrant operation with the output voltage and input current sinusoidal shaped with low distortion. A brief description and modeling of wind energy system and ZSM converter is mentioned below.

### *A. 2.5 kW Wind Energy Conversion System:*

The functional block diagram of the proposed system is shown in Fig.1. It consists of PMSG, which feeds 3-phase AC power to the ZSM converter. The generator output voltage and frequency varies with respect to different wind velocities. The variable generator output power from the generator is given to ZSM converter for regulated voltage and frequency levels.

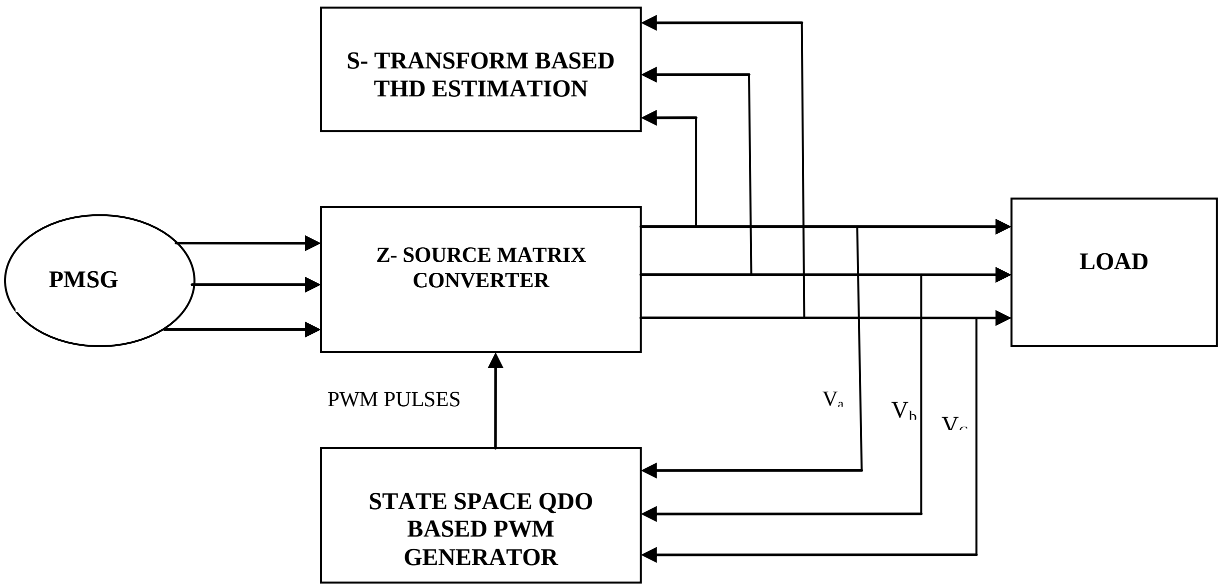


**Fig. 1:** Functional Block diagram of the proposed 2.5kW WES

**Table I:** Technical Data of 2.5kW Wind Farm System

| Title | Parameters | | Value & unit |
|---|---|---|---|
| General | 1. | Cut in wind speed | Approx. 2m/s |
| | 2. | Cut out Wind speed | Approx. 16m/s |
| | 3. | Rated wind speed | 12 m/s |
| Generator | 4. | Rated Power Output | 2.5 KW |
| | 5. | Type | Permanent Magnet |
| | 6. | Voltage | 3 phase 400V |
| | 7. | Revolutions | 145 to 410 rpm |
| | 8. | Frequencies | 50 Hz |
| Rotor | 9. | No. of blades | 3 |
| | 10. | Diameter | 3 m (approximately) |
| | 11. | Material | Fiber glass |
| | 12. | Max. Speed | 410 rpm |

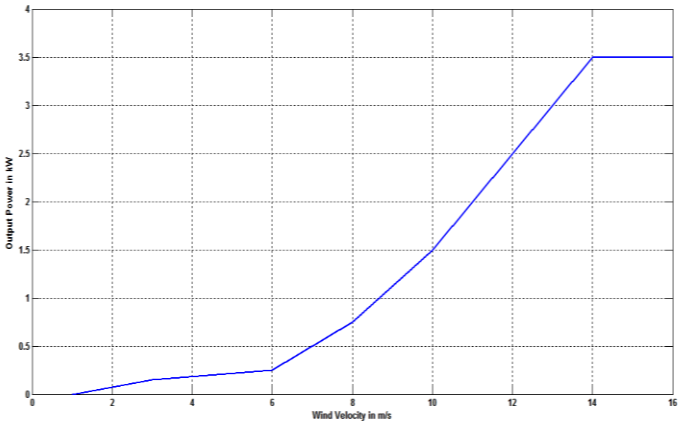


**Fig. 2:** Wind speed vs. Output power curve

different wind velocities. The above data implies to estimate the impedance source network parameters.

### *B. ZSM Converter Configuration:*

The system parameters of 2.5KW WES is shown in Table. I... The Fig.2 specifies the manufacturer data of 2.5KW PMSG for various output power with

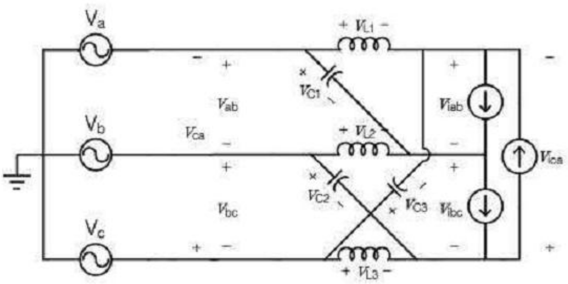

**Fig. 3:** Equivalent circuit of the ZSM converter

The ZSM converter configuration is shown in Fig. 3. From the figure three sets of equal values of inductors ($L_1$, $L_2$, and $L_3$) and capacitors ($C_1$, $C_2$, and $C_3$) are estimated in Eqn. (1).

$$\begin{aligned} V_{L1} &= V_{L2} = V_{L3} = V_L \\ V_{C1} &= V_{C2} = V_{C3} = V_C \end{aligned} \quad (1)$$

Where, $V_L = V_C$

From the equivalent circuit of ZSM converter, initial and final values of inductor currents are estimated through the Eqn.(2).

$$\left.\begin{aligned} \Delta I_{L1} &= (V_{L1}/L)\cdot T_0 = (V_{C1}/L)\cdot T_0 \\ \Delta I_{L2} &= (V_{L2}/L)\cdot T_0 = (V_{C2}/L)\cdot T_0 \,, \\ \Delta I_{L3} &= (V_{L3}/L)\cdot T_0 = (V_{C3}/L)\cdot T_0 \end{aligned}\right\} \quad (2)$$

$$\left.\begin{aligned} \Delta I_{L1}' &= (V_{L1}/L)\cdot T_1 = \{(V_{C3} - V_{ca})/L\}\cdot T_1 \\ \Delta I_{L2}' &= (V_{L2}/L)\cdot T_1 = \{(V_{C1} - V_{ab})/L\}\cdot T_1 \,. \\ \Delta I_{L3}' &= (V_{L3}/L)\cdot T_1 = \{(V_{C2} - V_{bc})/L\}\cdot T_1 \end{aligned}\right\} \quad (3)$$

Where,

$T_0$=shoot through switching period
$T_1$=Non shoot through switching period
The total switching time period is expressed in Eqn. (4) as follows.

$$T = T_0 + T_1 \quad (4)$$

Average output phase voltages of the ZSM network are given in Eqn. (5)

$$\left.\begin{aligned} V_{ia} &= D_u + (V_c - V_{C3})\cdot(1 - D_u) \\ V_{ib} &= D_u + (V_a - V_{C1})\cdot(1 - D_u) \,, \\ V_{ic} &= D_u + (V_b - V_{C2})\cdot(1 - D_u) \end{aligned}\right\} \quad (5)$$

Where, D is duty cycle of the ZSM converter
The output magnitude of voltage (or) current can be controlled by duty cycle. The duty cycle is required to generate PWM signals to the proposed converter. The duty cycle calculation is implemented with the help of SS-DQO model.

### *Generation of PWM pulses using SS-DQO model:*

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Switching method should be selected in proper sequence, such a way that to obtain the output voltages at the desired frequency, magnitude and phase angle. In order to achieve this desired level, a proper choice of the switching pattern brought to be applied to the switches of ZSM converter in a switching period(T), it is expressed in Eqn.(4). A proper switching pattern is obtained by choosing a suitable modulation method. The modulation scheme starts with the selection of switching function for the ZSM converter P.W. Wheeler *et al.* (2002)-A. Alesina *et al.* (1981). The equation (6) and (7) indicates the selection switching pattern.

$$S_{ij}(t) = \begin{cases} 1, S_{ij} \text{ is Closed}, i = A, B, C \\ 0, S_{ij} \text{ is Opened}, j = a, b, c \end{cases} \quad (6)$$

$$S_{ia} + S_{ib} + S_{ic} = 1, \quad i = A, B, C \quad (7)$$

To find a proper modulation strategy for ZSM converter, it starts with considering a set of input, output voltage and current, based on matrix converter circuit of Fig.1, as follows:

$$\overline{V_{abc}} = \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \qquad \overline{V_{ABC}} = \begin{bmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \end{bmatrix} \qquad \overline{i_{ABC}} = \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \qquad \overline{i_{abc}} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (8)$$

Where, $V_{abc}$ and $V_{ABC}$ are the Input and output voltage vectors of Matrix converter, $i_{abc}$ and $i_{ABC}$ input and output current vectors.

Based on the switching function given by equation (6), the instantaneous switching function of matrix converter follows M. Kazerani *et al.* (1995)-S. M. Barakati *et al.* (2006).

$$S=\begin{bmatrix} S_{Aa} & \cdots & S_{Ac} \\ S_{Ba} & \ddots & S_{Bc} \\ S_{Ca} & \cdots & S_{Cc} \end{bmatrix} \quad (9)$$

The input and output side voltage and current are related by the following equations:

$$V_{ABC} = S * V_{abc} \text{ , } i_{abc} = S^T * i_{ABC} \quad (10)$$

Where, $\mathbf{S}^{\mathbf{T}}$ is the transpose of ***S***. The elements of *S* should be chosen properly to obtain the desired fundamental components of output voltage and input current.

$$d_{ij}(t) = \frac{t_{ij}}{T_{seq}}, \text{ i= A, B, C and j= a, b, c} \quad (11)$$

Where, $t_{ij}$ is ON period of the switch ij in a switching sequence time.

To obtain a duty cycle D using SS-DQO model, it is desired to develop an equation for the input frequency frame and then transfer them to the output frequency frame. The transformation matrix D is given by:

$$D = a*D_1 + (1-a) D_2. \quad (12)$$

$D_1$ and $D_2$ satisfy the duty cycle restriction, given by Eqn. (12), it provides controllability of input displacement power factor.

In this model, the ZSM converter control variables ($\omega_o$, $q$, $a$, and $\alpha_o$) such as input and output source powers are chosen as the input and output variables, respectively. Also the model is valid for a balanced system without zero-sequence.

***S-Transformation for THD Analysis:***

For the study of evolving transient signals, the measurements must be made accurately in the frequency domain. This being the criterion, S-transform can be applied for detection and analysis of such time varying signals as it has accurate localization characteristics in the frequency domain.

The S-Transform is denoted as modified Wavelet transform and it is only an extension of the ideas behind the wavelet transforms with the main advancement being the usage of a variable window. S-Transform can be derived for Continuous Time signal. So S-Transform is defined as a Phase corrected Wavelet transform Fengzhan Zhao *et al.* (2007). The function S-transform is defined as equ. (13).

$$S(\tau, f) = \int_{-\infty}^{\infty} h(t) \frac{|f|}{\sqrt{2\pi}} e^{\frac{-t^2 f^2}{2}} e^{-j2\pi f t} \, dt \quad (13)$$

The ST also can be written as operations on the Fourier spectrum H (f) of h (t)

$$S(\tau, f) = \int_{-\infty}^{\infty} H(\alpha + f) e^{-\frac{2\pi^2 \alpha^2}{f^2}} e^{j2\pi\alpha\tau} d\alpha \quad f \neq 0 \quad (14)$$

The ST localizes the phase spectrum as well as the amplitude spectrum. The harmonic distortion is included in each frequency ranges can be detected by using approximation and detail coefficients, which is measured from sub-band harmonics in terms of RMS value as in (15).

$$RMS = \sqrt{\left(\frac{1}{N_j} \sum_n CDj(n)^\wedge 2\right)} \quad (15)$$

$$THD = \frac{\sqrt{\left(\frac{1}{Nj}\sum CDj\,(n)^{\wedge}2\right)}}{\sqrt{\left(\frac{1}{N5}\sum CA5\,(n)^{\wedge}2\right)}}\ X\ 100 \qquad (16)$$

Where Nj is the number of detail coefficients at scale -j. The total harmonic distortion (THD) is calculated by including each sub-band contribution as in (16).

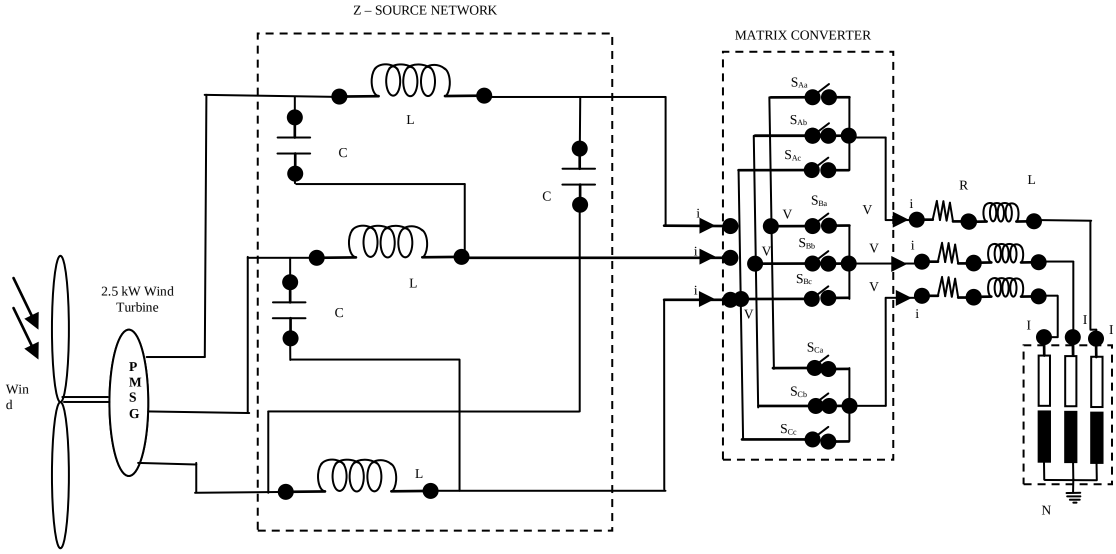


**Fig. 4:** Proposed system model of WES

## RESULTS AND DISCUSSION

The proposed system model is shown in Fig.4. Investigation is carried out for different load conditions, to estimate THD level without ZSM converter. Further the THD analysis is carried out for SS-DQO model with ZSM converter. The SS-DQO Model with ST-THD model has been developed for ZSM converter and its components in 2.5 KW WES. The time phase system and its line represented by lumped parameters the wind system is modeled as a PMSG. The machine electrical system is represented in the DQO frame with ZSM converter topology. The excitation model of machine is also included in the same model. The control system of the converter is represented in the DQO model and control methodology in instantaneous real / reactive power control with the specification of ‘D’ and ‘Q’. The simulation model also enriches the measurement of the line voltage and RMS value, including current estimation, rotor speed tracking and instantaneous real and reactive power measurement also. The rotor speed measurement is synchronized with voltage and current control in addition to the real and reactive power control.

Several analyses are carried out for different load current for validate the results. In addition to, the real and reactive power control is also carried out to evaluate the SS-DQO PWM model. The results based on steady state control in addition with SS-DQO control implementation is shown in Fig.5. The wind turbine system results shows that, system can be controlled to provide better regulation, stable in voltage and connection with reactive power requirement of the sensitive load. The %THD of the proposed system with various wind velocities are shown in table. II. Also the table III shows the %THD of S-transform based system results with ZSM converter and without ZSM converter for various load conditions.

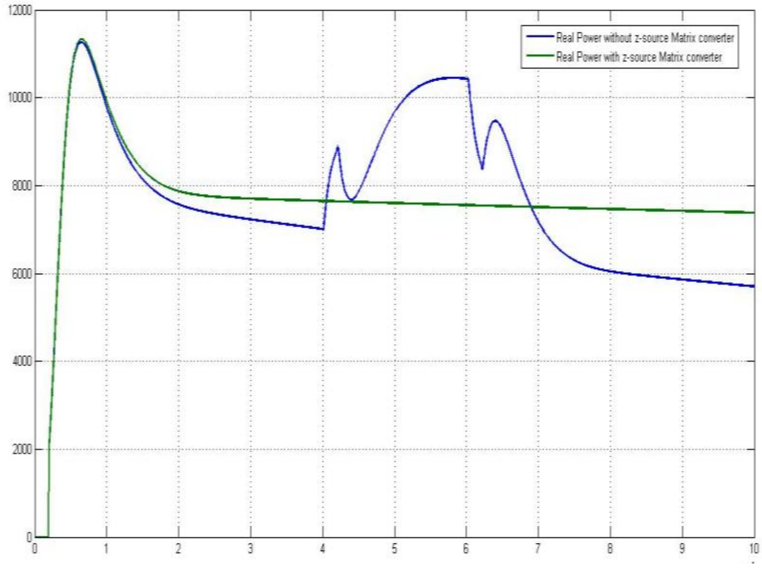


**Fig. 5:** Comparison of Real power magnitude with and without Z source matrix converter at wind velocity 12m/s with 50 % load variation

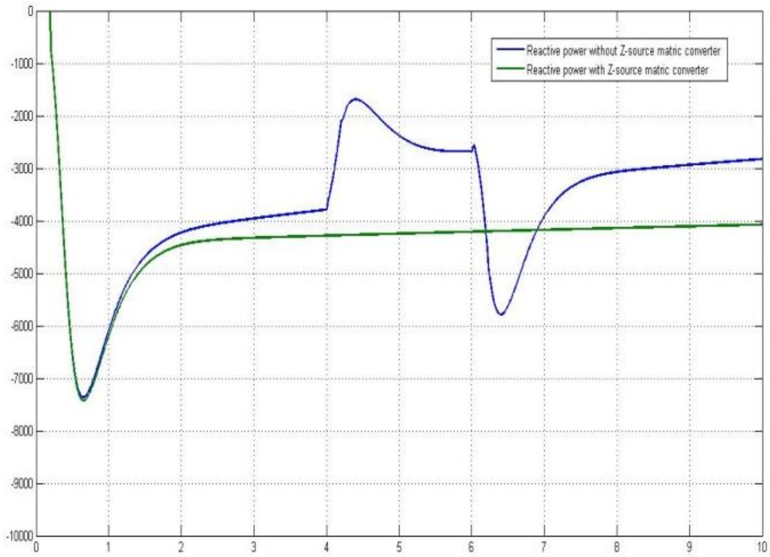


**Fig. 6:** Comparison of Reactive power magnitude with and without Z source matrix converter at wind velocity 12m/s with 50 % load variation

**Table II:** 2.5kW WES Parameter analysis

| Wind Speed (m/s) | Rotor Speed (Rpm) | Power Developed (kW) | THD% Using ST with ZSM |
|---|---|---|---|
| 3 | 145 | 0.25 | 15.1 |
| 6 | 200 | 1.20 | 15.2 |
| 12 | 400 | 2.50 | 15.2 |

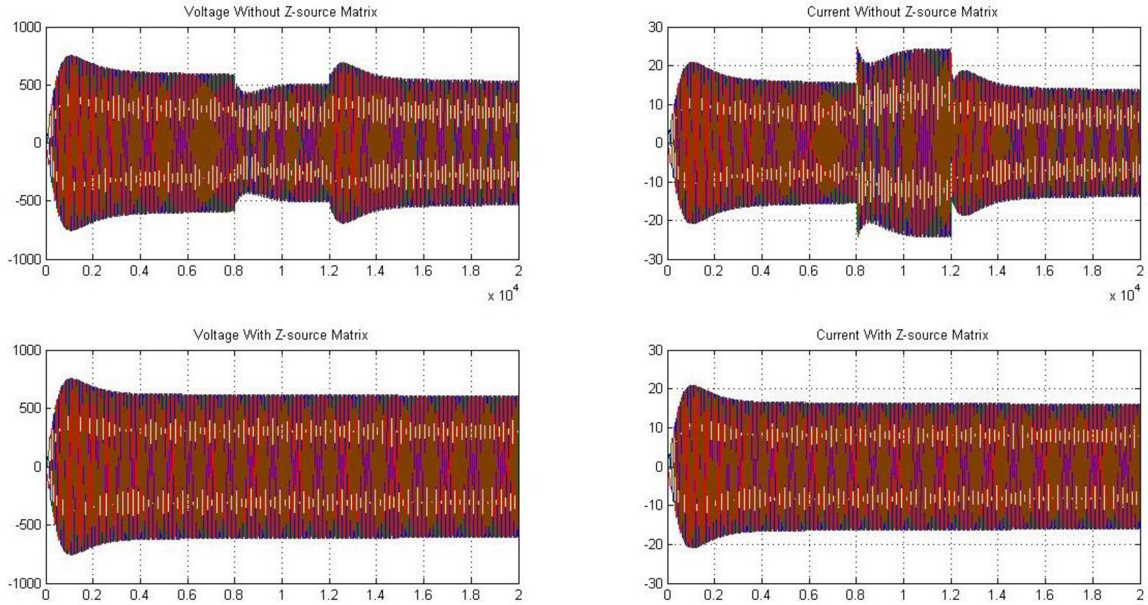


**Fig. 7:** Comparison of voltage and current waveforms with and without Z source matrix converter at wind velocity 12m/s with 50 % load variation

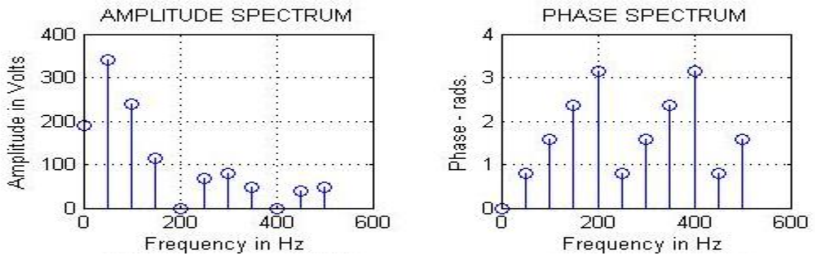


**Fig. 8:** Harmonic Spectrum under Z-source matrix converter when wind velocity is 12m/s

**Table III:** Percentage THD of with and without ZSMC

| Load level | Wind Configuration | THD% |
|---|---|---|
| 50% of Rated load | Without Z-source Matrix Converter | 40.22 |
| | With Z-source Matrix Converter | 15.28 |
| 75% of Rated Load | Without Z-source Matrix Converter | 40.28 |
| | With Z-source Matrix Converter | 15.22 |
| 100% of Rated Load | Without Z-source Matrix Converter | 32.21 |
| | With Z-source Matrix Converter | 15.28 |

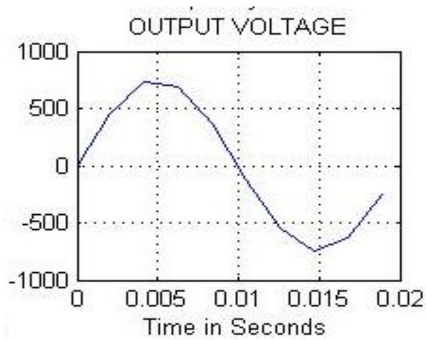


**Fig. 9:** the RMS value of output voltage values

The sensitive load voltage maintain within + or – 1%. The integration voltage control and p-q control is necessary in the case of distributed generation because high penetration is happen during grid connections. The voltage control ensured that no circulating routine current in the sources. The simulation requires the voltage $V_s$ other parameters control, so that in this proposed work the S-transformation evidence is extended by providing power quality. In the control components of the dqo control by matrix converter, the Q component current adjusts the reactive power injection. Even though there is the reactive power injection in the level during load variation, the voltage is controlled within + or – 1%. The fig.7.clearly indicates the output voltage and current maintains in nominal level throughout the control and switching schemes provided by ZSM converter.

Fig.6. Shows, the voltage maintaining at the corresponding level, because of reactive power control and by way excessive real power generated. The proposed system comprised with control scheme provided by ZSM converter and S-transform operation. The action of control scheme, adjusts the system to balance the real power to the rise of power demand according to the dynamic load response. The dynamic model enriches the voltage quality even after the changes in load demand. The voltage quality is maintained through the analysis and viewed in Fig 7. The harmonic spectrum of proposed ZSM converter for odd and even order at a 12m/sec wind velocity is shown in fig.8.

### *Conclusion:*

An investigative study has been carried out to bring out the impact of the Z-source matrix converter analysis on Wind Energy System for different values of input voltage and different input frequencies. A new design approach for SS-dqo model and S-Transform analysis was developed for estimation of THD. It is observed that the frequency conversion can be obtained by using different switching strategies and voltage boost up can be achieved by adjusting duty ratio through PWM schemes. The validation analysis is carried for two different schemes with and without ZSM schems. The generic complexity and comparison of results with state-of-the-art simulation works prove the potential of Z-source matrix converter and this topology is more efficient in wind energy conversion system.

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