# Space Vector Modulated Voltage Source Converter for Stand Alone Wind Energy Conversion System

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## Abstract

This paper proposes a voltage and frequency controller for a wind turbine-driven independent asynchronous generator. The proposed controller consists of IGBT (Insulated Gate Bipolar Transistor) based three phase voltage source converter along with battery energy storage system at its DC bus and it inherently adapts to the changes in the rotor speed while maintaining a near constant voltage and frequency at the load terminals. The controller is having bidirectional flow capability of active and reactive powers by which it controls the system voltage and frequency with varying wind speed and load conditions. Among various modulation strategies, Space vector pulse width modulation technique is used in the controller, because it increases the fundamental output voltage. Also they allow reducing commutation losses and the harmonic content of the output voltage, and to obtain higher amplitude modulation indexes. The proposed space vector modulated voltage source converter is modeled and simulated in MATLAB using Simulink and PSB (Power System Block-set) toolboxes.

**Keywords:** Independent Asynchronous Generator, Wind Energy Conversion System, Battery Energy Storage System, Space Vector Pulse Width Modulation.

## 1. Introduction

Differential heating of the earth's surface by the sun causes the movement of large air masses on the surface of the earth, ie., the wind. Wind energy is the one of the most abundantly available forms of renewable energy and has emerged as a viable alternative to conventional non-renewable energy sources. It has proved to be the most promising renewable energy source because of its environment friendliness, sufficient availability, and good conversion efficiency. Electricity derived from wind power provides an alternative to conventional generation that would be used to achieve substantial reduction of fossil fuel use and industrial effluents like carbon dioxide. The wind generation system is the most competitive of all the environmentally clean and safe renewable energy sources. However in wind turbines, variations in speed of the wind and load changes are common phenomena. These variations affect the magnitude of generated voltage and frequency, which in turn influence the magnitude of the machine impedance [10].

Current utilization of renewable energy systems in the form of wind, small hydro and bio-gas have led to the massive use of grid connected and independent asynchronous generator. In grid connected systems the reactive power for setting up magnetic field in machine is drawn from the grid itself. In standalone systems, no external ac power supply is available for setting up the magnetic field in the machine.

Besides being commonly used as drives in the industry, three phase asynchronous generators have earned much attention because of the qualities such as ruggedness, fault tolerance and constructional simplicity and constitute the biggest sector in the present wind power industry [1]. Also induction machine is less prone to sudden torque disturbances as compared with a synchronous machine.

It should be noted that one of the key issues in standalone system is reliability and simplicity in control structure. The space vector pulse width modulation (SVPWM) technique is one of the most popular techniques gained interest recently (Trzynadlowski, 1994). SVPWM technique has been increasingly used in the last decade because it allows reducing commutation loss and the harmonic current of output voltage and results in higher magnitude of fundamental output voltage. It provides voltage utilization of $2/\sqrt{3}$ times of sine PWM and obtains higher amplitude modulation indexes if compared with the conventional sinusoidal PWM technique.

In this paper, a voltage and frequency control schemes is proposed for an independent asynchronous generator with capacitor excitation system. The proposed control scheme presented in this paper optimized cost of the system by requiring reduced number of current sensors and provides a fast response. The proposed voltage and frequency controller is realized using IGBT (Insulated Gate Bipolar Transistor) based voltage source converter (VSC) whose gating signals are provided by SVPWM technique and the performance of the controller is investigated in different wind speed condition for linear load in MATLAB using simulink and PSB toolboxes.

## 2. Principle of operation

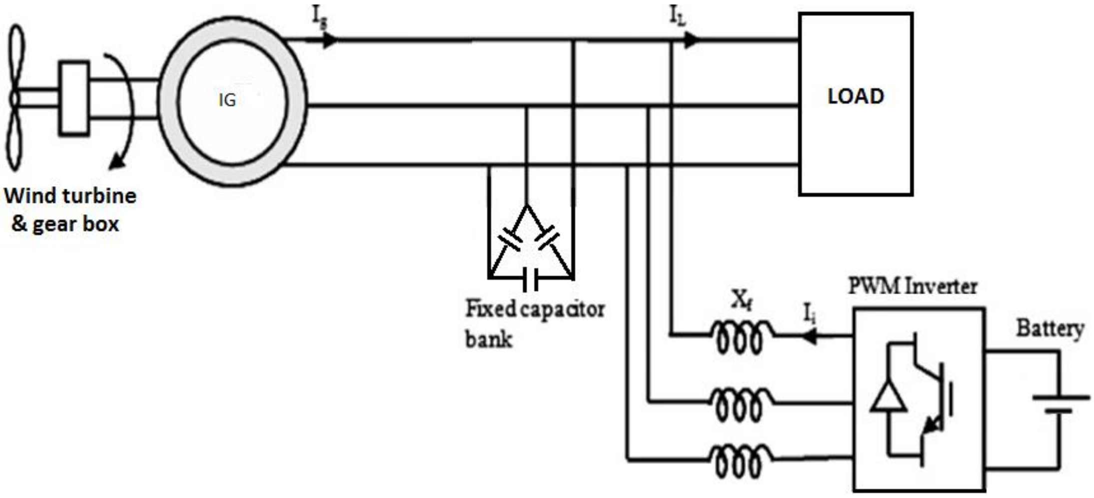

**Fig.1** Schematic diagram of wind turbine driven asynchronous generator

Fig.1 shows a schematic diagram of wind turbine-driven asynchronous generator along with a proposed controller. A squirrel cage induction generator whose excitation is provided from two sources, viz., one fixed capacitor bank and parallel connected three phase voltage source converter with DC bus supported by battery energy storage system. The proposed controller is having bidirectional flow capability of active and reactive powers and thus it controls the frequency and voltage respectively. The basic principle of this operation is that, when there is high wind speed, the generated power is also high and accordingly for frequency regulation, the total generated power should be consumed otherwise difference of electrical power and mechanical power is stored in the revolving components of the generator and in turn it increases the output frequency. Therefore this additional generated power is used to charge the battery to avoid the variation in frequency. Also when there is low speed, there will be deficiency of the generated power. An additional required power is supplied by the battery energy storage system to the non-linear load.

## 3. PWM voltage source inverter

The PWM VSI used here is a three phase VSI with six switches. Each switch (S1, S2, S3, S4, S5 & S6) in the inverter branch is composed of semiconductor devices connected with antiparallel diode. The semiconductor device is a controllable device and diode is for protection..

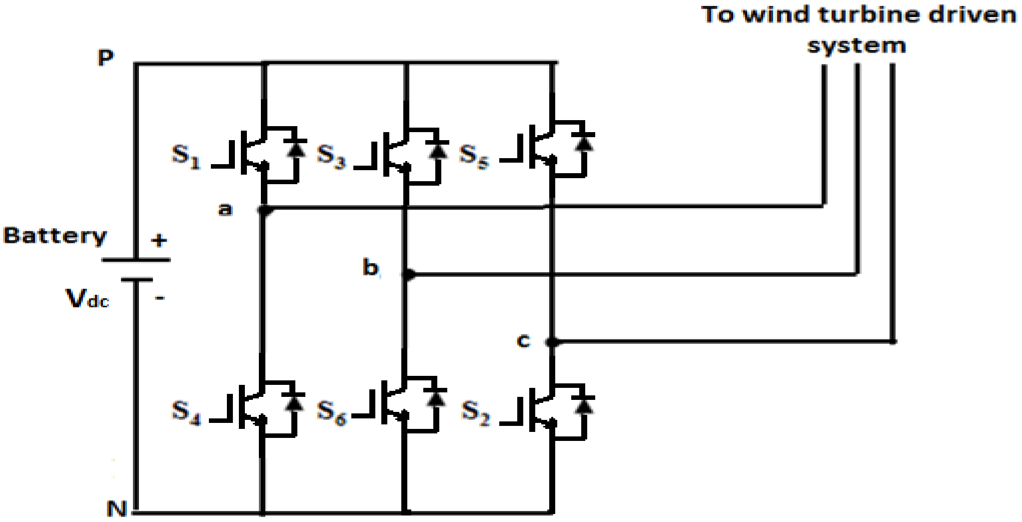

**Fig.2** Three phase voltage source pwm inverter

Phase voltage vectors [$V_{an}$, $V_{bn}$ , $V_{cn}$] represented as

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{1}{3} V_{dc} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{1}$$

Line-line voltage vector $[V_{ab}, V_{bc}, V_{ca}]$ can be calculated as

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \qquad (2)$$

## 4. Space Vector PWM Technique

The concept of voltage space vector is in analogy with the concept of flux space vector as used in three-phase ac machine. The magnitude of the resultant flux due to all phase winding is, however, fixed at 1.5 times the peak magnitude due to individual phase winding. Hence, the resultant voltage space vector will be rotating uniformly at the synchronous speed and will have magnitude equal to 1.5times the peak magnitude of the phase voltage.

Knowing that the inverter cannot produce ideal sinusoidal voltage waveform, a good pwm inverter aims to remove low frequency harmonic components from the output voltage at the cost of increasing high frequency distortion. The high frequency ripple in the output voltage can easily be filtered by a small external filter or by the load inductance itself. In terms of voltage space vectors, the above trade-off between low and high frequency ripples means that the resultant voltage vector will have two components (i) a slowly moving voltage vector of constant magnitude and constant speed superimposed with (ii) a high frequency ripple component whose direction and magnitude changes abruptly.

**Table. 1** switching vectors, phase voltages and output line-line voltages

| Voltage vector | switching vector | | | phase voltage | | | line – line voltage | | |
|---|---|---|---|---|---|---|---|---|---|
| | A | b | C | Van | Vbn | Vcn | Vab | Vbc | Vca |
| V0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| V1 | 1 | 0 | 0 | 2/3 | -1/3 | -1/3 | 1 | 0 | -1 |
| V2 | 1 | 1 | 0 | 1/3 | 1/3 | -2/3 | 0 | 1 | -1 |
| V3 | 0 | 1 | 0 | -1/3 | 2/3 | -1/3 | -1 | 1 | 0 |
| V4 | 0 | 1 | 1 | -2/3 | 1/3 | 1/3 | -1 | 0 | 1 |
| V5 | 0 | 0 | 1 | -1/3 | -1/3 | 2/3 | 0 | -1 | 1 |
| V6 | 1 | 0 | 1 | 1/3 | -2/3 | 1/3 | 1 | -1 | 0 |
| V7 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |

The space vector PWM technique aims to realize this slowly rotating voltage space vector from the state vectors. In voltage source converter, six power transistors (S1 to S6) that shape the output voltage will have eight possible switching combinations. Out of these eight combinations, two combinations wherein all the upper switches or all the lower switches are simultaneously ON result in zero output voltage (V0, V7). These two combinations are referred as null states. The remaining six switching combinations, wherein either two of the upper switches and one of the lower switch conduct or vice versa, are active states results in voltage (V1 to V6). This PWM technique approximates the reference voltage by a combination of these switching patterns (V0 to V7) and should be rotating with fixed magnitude and speed in the voltage plane.

To implement the space vector PWM, the voltage equations in the *abc* reference frame can be transformed into the stationary *dq* reference frame that consists of the horizontal (d) and vertical (q) axes as depicted in Fig.3

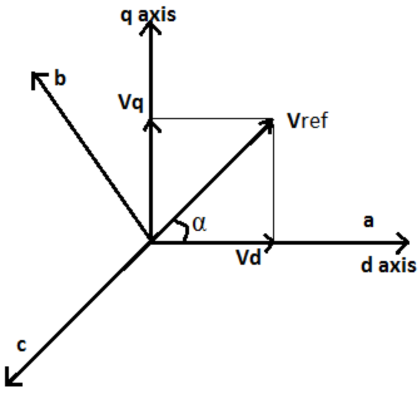

**Fig.3** voltage space vector and its component in (d,q)

$$\therefore \begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \qquad (3)$$

$$\left|\overline{V}_{ref}\right| = \sqrt{V_d{}^2 + V_q{}^2} \qquad (4)$$

$$\alpha = \tan^{-1}\left(\frac{V_q}{V_d}\right) = \omega_s t = 2\pi f_s t \qquad (5)$$

Where $f_s$ is fundamental frequency

This transformation is equivalent to an orthogonal projection of $[a, b, c]^T$ onto the two-dimensional d-q plane. Six non zero vectors (V1 to V6) shape the axes of a hexagonal as depicted in fig. 4, and feed power to the load. The angle between any two adjacent non zero vectors is 60 degrees. Meanwhile, two zero vectors (V0 and V7) are at the origin and apply zero voltage to the load. The objective of space vector PWM technique is to approximate the reference voltage $V_{ref}$ using the eight switching patterns.

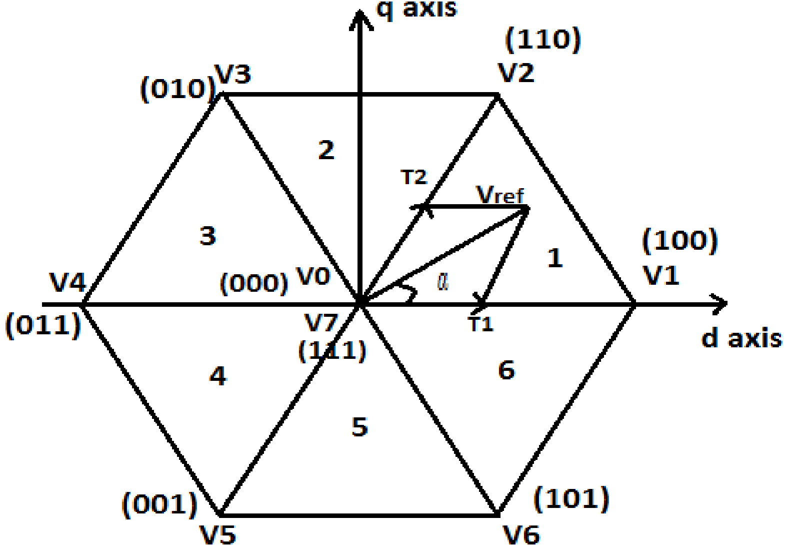

Fig.3 *Basic switching vectors and sectors*

For voltage space vector $V_{ref}$, the inverter may be continuously switched at high frequency between V1 and V2 active states. The resultant vector $V_{ref}$ so realized will occupy the mean angular position of V1 and V2 and the magnitude of the resultant vector can be found to 0.866 times the magnitude of V1 and V2(being vector sum of 0.5V1 and 0.5V2). Further, the magnitude of the resultant voltage vector can be controlled by injecting suitable duration of null state. Hence switching time duration (T1, T2 and T0) at sector 1 can be calculated as

$$T_1 = T_z \cdot a \cdot \frac{\sin(\pi/3-\alpha)}{\sin(\pi/3)} \text{ and}$$

$$T_2 = T_z \cdot a \cdot \frac{\sin(\alpha)}{\sin(\pi/3)}$$

$$\therefore T_0 = T_z - (T_1 + T_2), \quad \left( \text{where,} \quad T_z = \frac{1}{f_s} \quad \text{and} \quad a = \frac{\left|\overline{V}_{ref}\right|}{\frac{2}{3} V_{dc}} \right) <$$

The switching time for each transistor (S1 to S6) can be estimated by space vector PWM switching patterns at each sector. Based on the pattern, the switching time at each sector is summarized in table 2.

**Table. 2** Switching time calculation at each sector

| SECTOR | Upper Switches (S1, S3, S5) | Lower Switches (S4, S6, S2) |
|---|---|---|
| 1 | S1 = T1 + T2 + T0/2<br>S3 = T2 + T0/2<br>S5 = T0/2 | S4 = T0/2<br>S6 = T1 + T0/2<br>S2 = T1 + T2 + T0/2 |
| 2 | S1 = T1 + T0/2<br>S3 = T1 + T2 + T0/2<br>S5 = T0/2 | S4 = T2 + T0/2<br>S6 = T0/2<br>S2 = T1 + T2 + T0/2 |
| 3 | S1 = T0/2<br>S3 = T1 + T2 + T0/2<br>S5 = T2 + T0/2 | S4 = T1 + T2 + T0/2<br>S6 = T0/2<br>S2 = T1 + T0/2 |
| 4 | S1 = T0/2<br>S3 = T1 + T0/2<br>S5 = T1 + T2 + T0/2 | S4 = T1 + T2 + T0/2<br>S6 = T2 + T0/2<br>S2 = T0/2 |
| 5 | S1 = T2 + T0/2<br>S3 = T0/2<br>S5 = T1 + T2 + T0/2 | S4 = T1 + T0/2<br>S6 = T1 + T2 + T0/2<br>S2 = T0/2 |
| 6 | S1 = T1 + T2 + T0/2<br>S3 = T0/2<br>S5 = T1 + T0/2 | S4 = T0/2<br>S6 = T1 + T2 + T0/2<br>S2 = T2 + T0/2 |

## 5. Results and discussions:

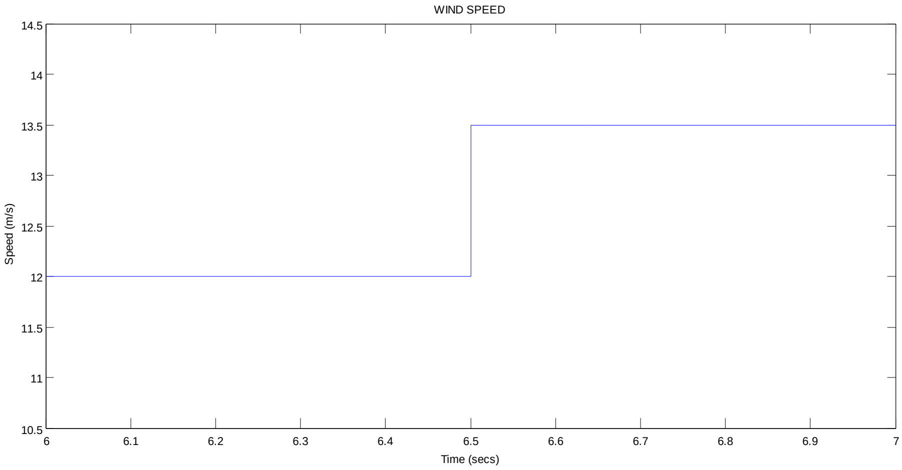

**Fig. 4** Wind speed variation

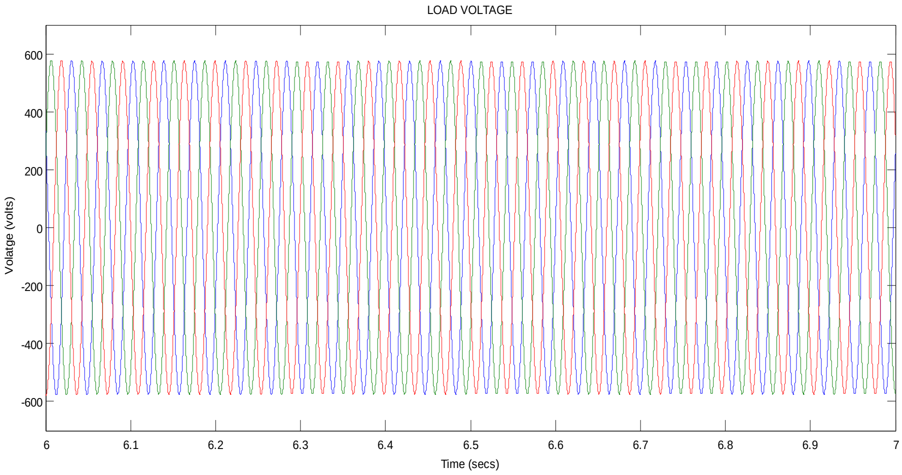

**Fig. 5** Load Voltage

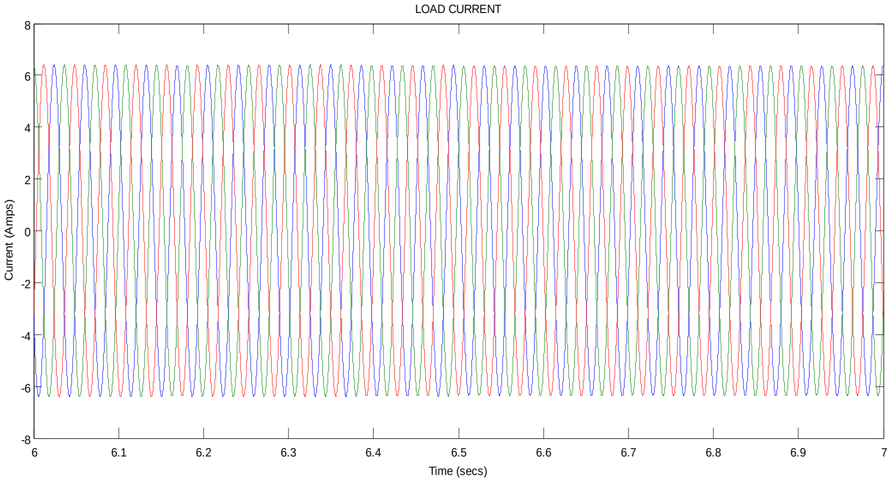

**Fig.6** Load Current

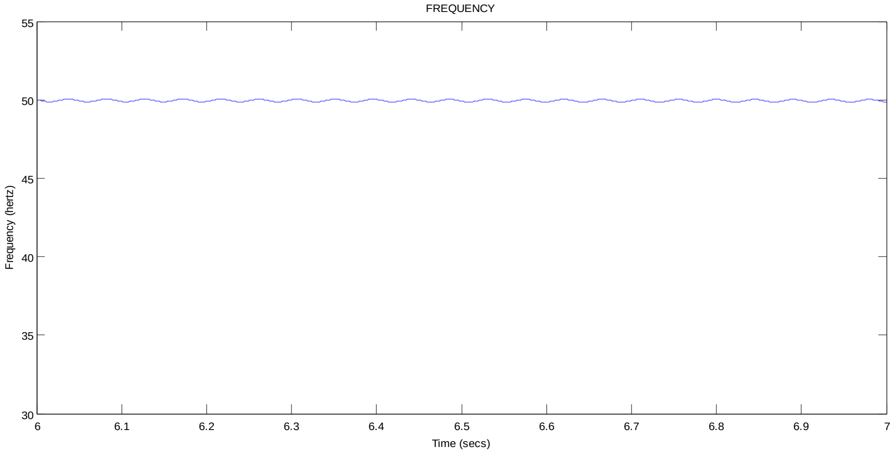

**Fig. 7** Frequency

The performance of the proposed controller for a stand alone wind energy conversion system under varying wind speeds are shown in Figs 4-7.At 6 secs, the wind speed is 12m/s, it is observed that due to insufficient power generation at low wind speed an additional power is supplied by the battery to regulate the frequency. At 6.5 secs, the wind speed is increased from 12m/s to 13.5m/s, an output power is increased so that at particular load now the power supplied by the battery energy storage system is reduced because now demand is met by the generator itself and having the availability of enough wind power.

## 5. Conclusion:

A standalone wind energy conversion system based on asynchronous generator has been modeled and simulated in the MATLAB using the Simulink and PSB tool boxes. The proposed controller with space vector PWM technique is used to regulate the voltage and frequency under varying wind speeds. The space vector PWM technique reduces the commutation loss and increases the magnitude of fundamental output voltage. The performance of the system has been demonstrated under different wind speed variation (dynamic conditions). It has been observed that the controller results in satisfactory operation under different dynamic conditions along with voltage and frequency control. Moreover, the controller has a capability of harmonic elimination and load balancing.

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