# Modeling of PMSG based Variable Speed Wind Energy Conversion System

Justin Jose and B. Manju

***Abstract***— *The Permanent Magnet Synchronous Generator (PMSG) based wind turbine with variable speed and variable pitch control is the emerging trend in the growing wind market. The paper describes modeling and simulation of a grid connected wind-driven electricity generation system. The power conversion unit features a wind-turbine, drive train, PMSG, a three phase diode rectifier, closed loop DC-DC boost converter and a DC/AC inverter. Multilevel inerter is employed in DC-AC conversion for power quality improvement. Pitch angle control of wind turbine has been used to reduce output power variation in high rated wind speed areas. Above the rated wind speed pitch angle controller becomes active and limits the power and the speed to their rated values. The grid synchronization is done with voltage control PWM technique. All the components of the wind energy conversion system are developed and implemented in MATLAB/Simulink.*

***Keywords***— *Variable Speed Wind Turbine, AC/DC Converter, Multilevel Inverter, Grid Synchronisation*

## I. INTRODUCTION

IN recent years, the electrical power generation from renewable energy sources, such as wind, is increasingly attracting interest because of environmental problem and shortage of traditional energy source in the near future. Nowadays, the extraction of power from the wind on a large scale became a recognized industry. It holds great potential showing that in the near future will become the undisputed number one choice form of renewable source of energy. The force that pushes this technology is the simple economics and clean energy. As a consequence of rising fossil fuel price and advanced technology, more and more homes and industries have been installing small wind turbines for the purposes of cutting energy bills and carbon dioxide emissions, and are even selling extra electricity back to the national grid. The kinetic energy in the wind is converted into mechanical energy by the turbine by way of shaft and gearbox arrangement because of the different operating speed ranges of the wind turbine rotor and generator. The generator converts this mechanical energy into electrical energy (1).

*Justin Jose, M. Tech, Dept. of Electrical and Electronics Engineering, Government Engineering College, Thrissur, India. E-mail: justinjy003@gmail.com*

*B. Manju, Assistant Professor, Dept. of Electrical and Electronics Engineering, Government Engineering College Thrissur, India. E-mail: manjudeepu@hotmail.com*

However, as wind is an intermittent renewable source, the wind power extracted by a wind turbine is therefore not constant. For this reason, the fluctuation of wind power results in fluctuated power output from wind turbine generator. From the point of view of utilities, due to the fluctuation of generator output, it's not appropriate for the generator to be directly connected to the power grid. In order to achieve the condition that the generator output power is suitable for grid-connection, it is necessary to use a controller to manage the output produced by the wind turbine generator. In order to achieve variable speed operation, a power electronics converter interface is used to connect the generator to the grid(2). Permanent Magnet Synchronous Generator, (PMSG) based wind energy conversion system, is becoming popular nowadays which is based on variable-speed operation. With permanent magnets there is no need for a DC excitation system. With a multipole synchronous generator it is possible to operate at low speeds and without gearbox. Therefore the losses and maintenance of the gearbox are avoided(3).

This paper presents the modeling of a PMSG based wind energy conversion system.The proposed system includes a wind turbine,drive train,PMSG,pitch angle controller,three phase diode bridge rectifier,closed loop DC-DC boost converter,multilevel inverter and the system is grid connected. The system modeling and simulation is performed and discussed to observe the system operation under variable speed.

## II. SYSTEM MODELING AND SIMULATION

The system analysed is a variable speed wind energy conversion system based on a multi-pole PMSG. Due to the low generator speed, the rotor shaft is coupled directly to the generator, which means that no gearbox is needed. The generator is connected to the grid via an *AC/DC/AC* converter, which consists of an uncontrolled diode rectifier, DC-DC boost converter and a multilevel inverter.Fig 1 shows the lay out of the proposed system

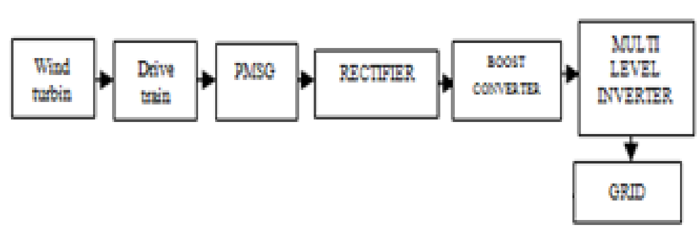


Fig.1. Lay-out of the proposed system

### A. *Wind Turbine*

First element in the proposed system is wind turbine and the main input to wind turbine is the wind speed(4).Present work considers wind speed variation as shown in table 1

Table 1: wind speed

| | | | |
|---|---|---|---|
| TIME (sec) | 0 | 3 | 5 |
| WIND SPEED (m/sec) | 12 | 7 | 12 |

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The power extracted by the wind turbine can be calculated by the given formula:

$$P_W=0.5\rho\pi R^3 V_w^3 C_P(\lambda,\beta) \quad \text{(Eq.1)}$$

Where $P_w$ =extracted power from the wind,ρ= air density,

R = blade radius (in m),$V_w$ = wind velocity (m/s), λ denotes tip speed ratio and β denotes blade pitch angle.

Power co-efficient($C_p$)can be defined

in terms of pitch angle as

$$C_p(\lambda,\theta) = C_1\left(\frac{C_2}{\beta} - C_3 * \theta - C_4 * \theta^x - C_5\right)e^{-\frac{C_6}{\beta}} \quad \text{(Eq.2)}$$

Where $C_1$ to $C_6$ and $x$ are constants and are different for various turbines and β can be defined as

$$\frac{1}{\beta} = \frac{1}{\lambda+.08\theta} - \frac{0.035}{1+\theta^3} \quad \text{(Eq.3)}$$

Where θ is the blade pitch angle in degrees and is defined as the angle between the plane of rotation and blade cross-section

And tip speed ratio λ is

$$\lambda = \frac{\omega_w * R}{V_w} \quad \text{(Eq.4)}$$

where $\omega_w$=angular velocity of generator rotor in rad/sec,

Vw =wind upstream speed of rotor in m/sec, R= rotor radius .

### B. *Drive Train*

Torque output of wind turbine is given to drive train which represents the inertia of wind turbine and generator shaft(5).The simulink model of drive train is developed as shown in Fig.2.The differential equations governing the mechanical dynamics of drive train are

$$2H_t\frac{d\omega_t}{dt} = T_m - T_{sh} \quad \text{(Eq.5)}$$

$$\frac{1}{\omega_{elb}}\frac{d\theta_{tw}}{dt} = \omega_t - \omega_r \quad \text{(Eq.6)}$$

$$2H_g\frac{d\omega_r}{dt} = T_{sh} - T_g. \ (Eq.7)$$

Where $H_t$ and $H_g$ are inertia constants of the turbine and generator,$\theta_{tw}$ is the shaft twist angle, $\omega_t$ is the angular speed of the wind turbine in p.u., $\omega_r$ is the rotor speed of PMSG in p.u.,$T_m$ is the torque input to PMSG.$T_{sh}$ is the torque output of drive train. $\omega_{elb}$ is the electrical base speed and the shaft torque (Tsh) is

$$T_{sh}=K_{sh}\,\theta_{tw}+ D_t.(d\theta_{tw}/dt) \quad \text{(Eq.8)}$$

where $K_{sh}$ is the shaft stiffness,$D_t$ is the damping co-efficient.

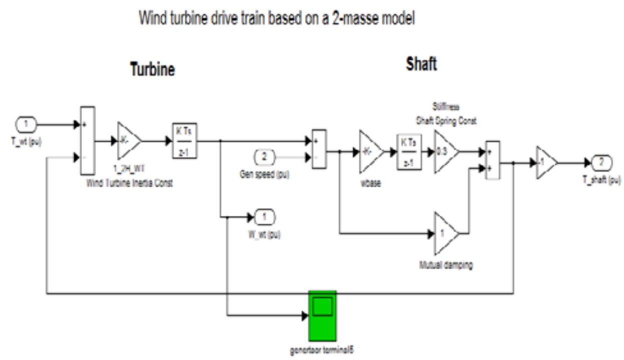


Fig.2.Simulink model of drive train.

### C. *Permanent Magnet Synchronous Generator*

Torque output of drive train is given to PMSG.Parameters used in the modeling of PMSG are as shown in table 2.

Table.2: Parameters of PMSG

| | |
|---|---|
| Number of poles | 10 |
| Rated speed | 153 rad/sec |
| Armature resistance (Rs) | 0.425 ohm |
| Magnetic flux leakage | 0.433 Wb |
| Stator inductance ( Ls) | 8.4 mH |
| Rated torque | 40 Nm |
| Rated power | 6 KW |

### D. *Pitch Angle Controller*

The proposed system also employs a pitch angle controller which is active only at high wind speeds. Simulink model of pitch angle controller is as shown in Fig.3.The pitch angle controller shown will be active only when rotor speed becomes twice the rated value(6).

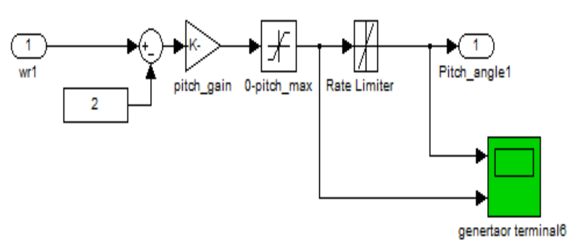


Fig 3.Simulink model of pitch angle controller

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The whole variable speed wind power generation system developed is as shown in fig. 4.

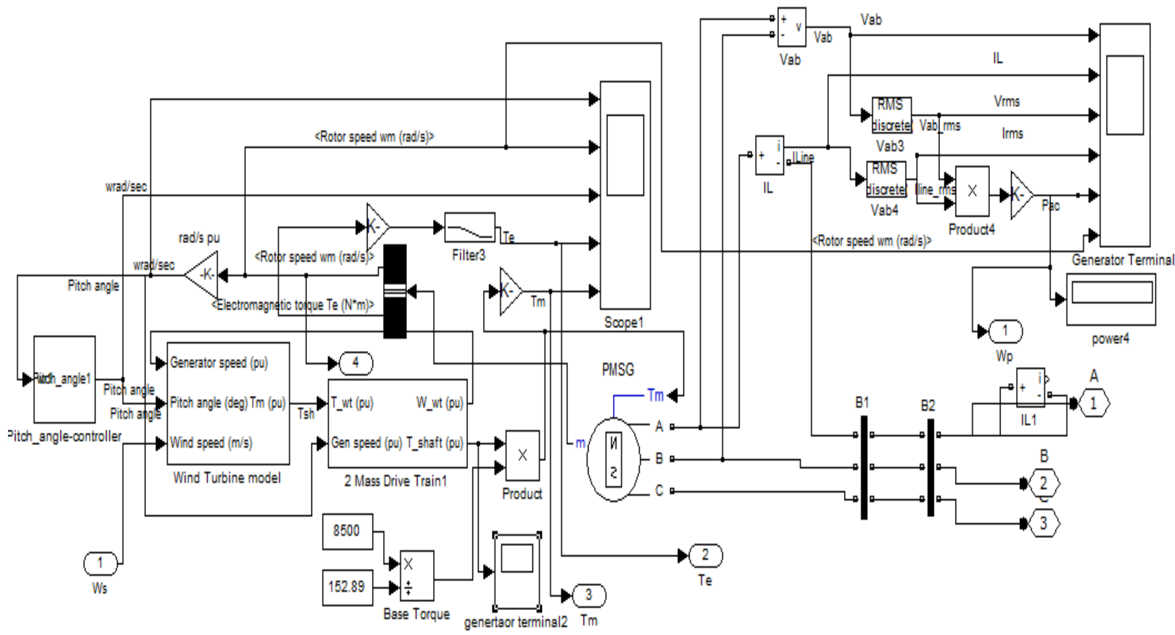


Fig.4: Simulink Model of Variable Speed Wind Power Generaion System

Output of wind power generation system is characterised with varying voltage magnitude and frequency. For the purpose of grid synchronization, output of PMSG interfaced with grid via a power electronic converter which converts AC to DC voltage for control purposes and then invert it to AC using multilvel inverter. Power electronic converter includes

- Three phase diode bridge rectifier.
- Closed loop DC-DC boost converter.
- Multilevel inverter

## *E. Three Phase Diode Bridge Rectifier*

Three phase diode bridge rectifier modeled in simulink is as shown in fig.5

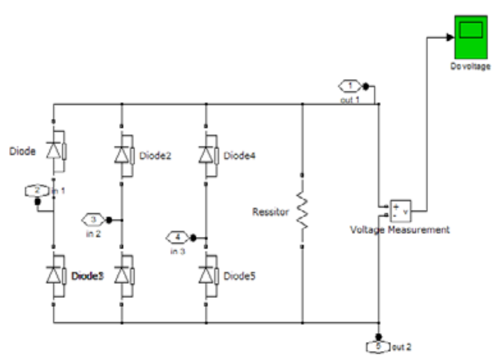


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Fig.5: Simulink model of three phase diode bridge rectifier

The DC output voltage ($V_{dc}$) is calculated as the average of the output voltage waveform over a sub-period from (Π/6) to (Π/2).

$$V_{dc} = \frac{1}{\frac{\Pi}{3}} \int_{\Pi/6}^{\Pi/2} v_{dc} d\theta \qquad \text{(Eq.9)}$$

$$= \frac{3\sqrt{2}}{\Pi} V_g \qquad \text{(Eq.10)}$$

$$\frac{V_{dc}}{V_g} = \frac{3\sqrt{2}}{\Pi} \qquad \text{(Eq.11)}$$

And the dc output current can be solved as,

$$I_g = \sqrt{\frac{1}{\Pi} \int_{\Pi/3}^{\Pi} I_{dc}{}^2 d\theta} = \sqrt{\frac{2}{3}} I_{dc} \qquad \text{(Eq.12)}$$

$$\frac{I_g}{I_{dc}} = \sqrt{\frac{2}{3}} \qquad \text{(Eq.13)}$$

Neglecting the power losses in three-phase rectifier, the AC power input is equal to dc power output,

$$3 I_g V_g = I_{dc} V_{dc} \qquad \text{(Eq.14)}$$

Hence, the dc output current can be expressed as,

$$I_{dc} = \frac{3V_g I_g}{V_{dc}} = \frac{\Pi I_g}{\sqrt{2}} \text{ (or) } I_{dc} = \frac{\Pi I_g}{\sqrt{2}} \qquad \text{(Eq.15)}$$

## *F. Closed loop dc-dc boost converter*

Output of three phase diode bridge rectifier is given to a closed loop DC-DC Boost converter in which closed loop is done for a voltage magnitude of 566 V(7).566V is the peak value corresponding to line to line rms value of grid voltage

.i.e. 400 V. Equations governing the operation of DC-DC boost converter can be given as,

$$V_o = \frac{V_g}{\left\{(1-D)\left(1+\frac{R}{(1-D)^2}\right)\right\}} \qquad \text{(Eq.16)}$$

Assuming a lossless circuit,

$$V_g\, I_L = V_o\, I_o \qquad \text{(Eq.17)}$$

$$I_o = (1-D) * \left(1 + \frac{R}{(1-D)^2}\right) \qquad \text{(Eq.18)}$$

Parameters used in the modeling of DC-DC boost converter can be tabulated as shown in table 3.

Table 3: Parameters of Boost converter

| | |
|---|---|
| Input voltage | 500 V |
| Output voltage | 566 V |
| Duty ratio | 11.67 % |
| Switching frequency | 100 KHz |
| Inductor value | 1.945mH |
| Capacitor value | 0.412367 μF |
| Resistance | 566 ohm |

Simulink model of the system in which closed loop DC-DC Boost converter is interfaced with wind power generation is as shown in Fig.6.

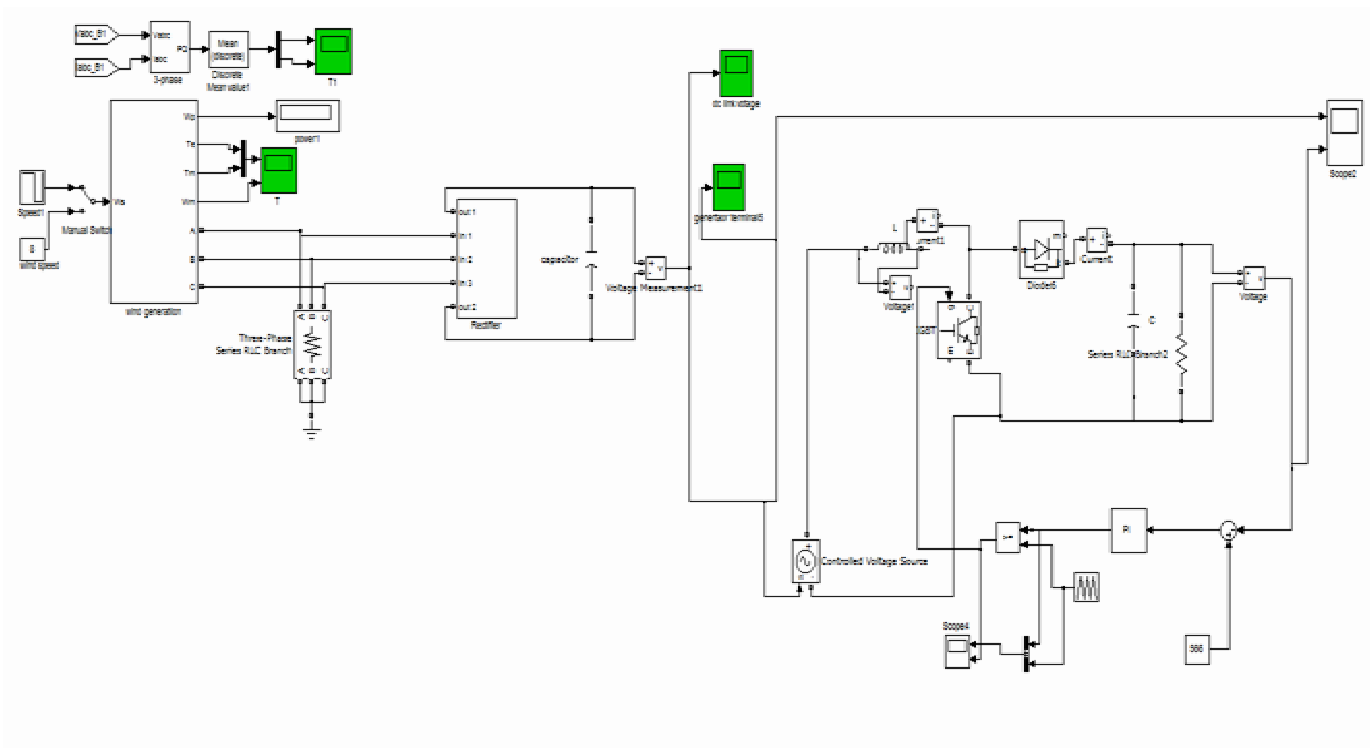


Fig .6: Closed loop Boost converter interfaced with wind system

## G. *Multilevel Inverter*

Output of DC-DC Boost converter is given to three phase inverter. Multilevel inverter topology is employed for power quality improvement (8).Three level and Five level multilevel inverter topolgies are discussed**.** Simulink models of multilevel inverters with separate dc sources are as shown in fig 7 and fig.8.

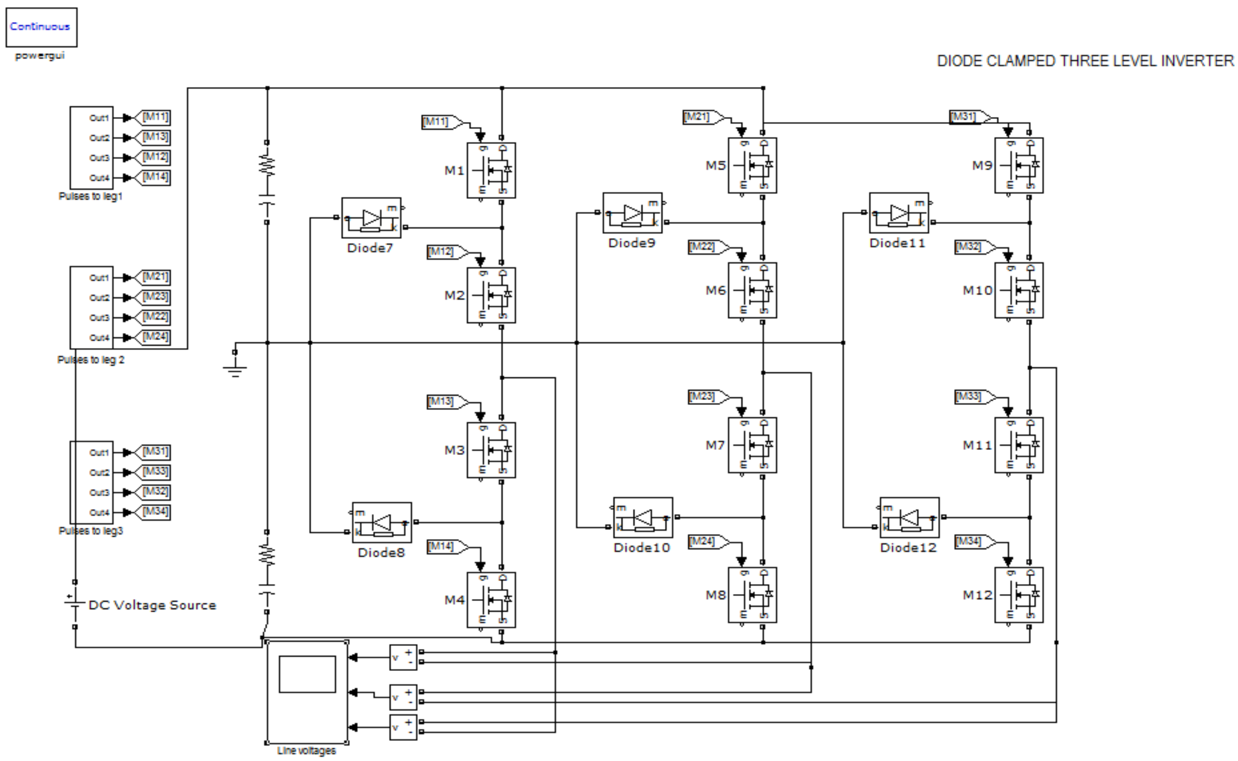


Fig.7: Three phase Three level multilevel inverter

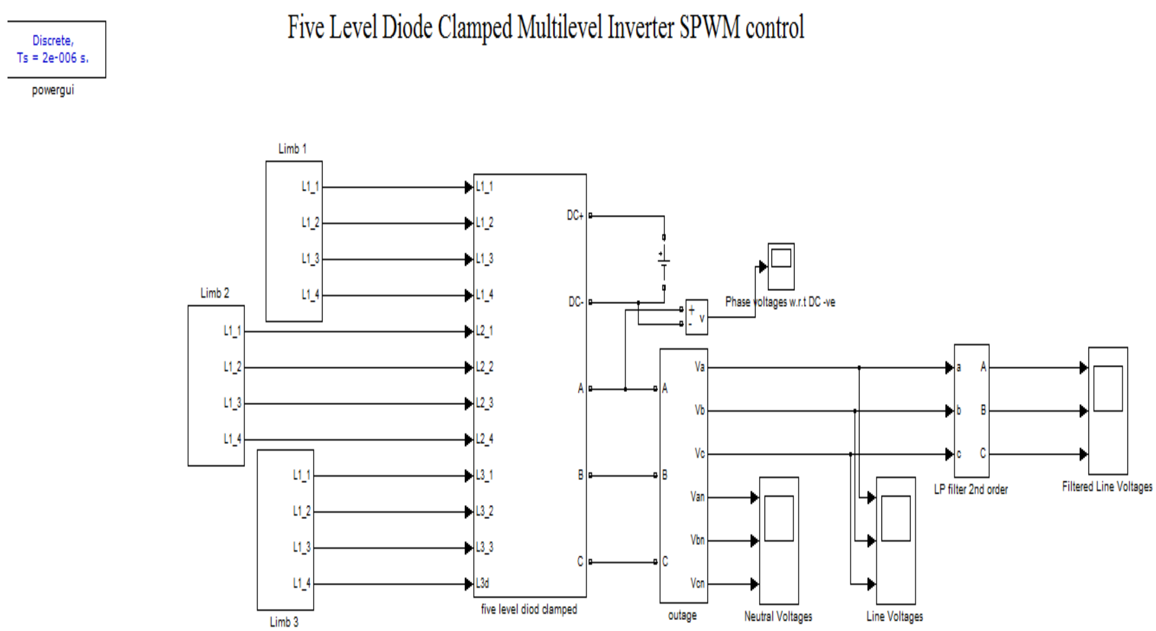


Fig.8: Fivelevel Multilevel Inverter

FFT analysis is done in the output voltage obatined in the case of three level and five level multilevel inverter when connected to wind system.Total Harmonic Distortion(THD) obtained in the both topologies of mutilevel inverter can be tabulated as follows.

Table.4.THD in multilevel inverter topologies

| Inverter topology | THD |
|---|---|
| Three-level multilevel inverter | 35.02% |
| Five-level multilevel inverter | 17.10% |

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Since THD obtained is less in the case of five level multilevel inverter,it is used for furher procedure in wind system.

*H. Grid Synchronisation*

In the proposed system for grid synchronisation voltage control PWM technique is adopted. In this Technique the transistors are controlled by using bipolar width modulation switching such that the inverter's voltage follows the grid voltage(9).

The inverter voltage is compared to a reference signal and the error is fed back through a proportional controller. The output of the controller is scaled and added to a feed forward loop with the final output of the new PWM duty given

$$D=(0.5+\frac{V_{ref}}{V_{dc}}) + \frac{K_v(V_{ref}-V_{inv})}{2\,V_{dc}} \quad \text{(Eq.19)}$$

Same as in a classic scenario the duty cycle is compared to a triangular wave to generate a switching signal to control the transistors gate.

## III. Simulation Results

Power co-efficient Cp varies with tip speed ratio λ of wind turbine is as shown in figure.

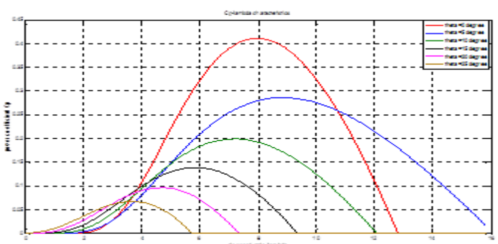

Fig. 9: Cp- λ characteristics of wind turbine

From the characteristics shown above, information obtained can be tabulated as shown in table 6.

Table 5: Power co-efficient Cp obtained for various thetas

| Theta | Cp |
|---|---|
| 0 | 0.42 |
| 5 | 0.28 |
| 10 | 0.19 |
| 15 | 0.13 |
| 20 | 0.09 |
| 25 | 0.07 |

From table 6,it is clear that value of Cp is maximum for theta=0.i.e. power output from wind turbine is maximum for a blade pitch angle equal to zero.

Power-speed characteristics of wind turbine for varoius wind speeds can be plotted as shown in fig.10.

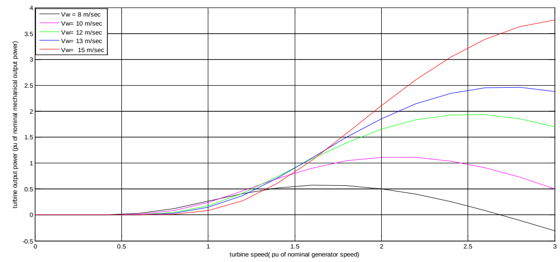

Fig.10.Power-speed characteristics of wind turbine

Here for different values of wind speed,power output of wind turbine is plotted as a function of rotor speed of generator.

Under normal conditions pitch angle remains zero as the wind turbine output power is maximum at zero value of pitch angle .When the rotor speed increases drastically with input wind speed ,pitch angle controller will become active.i.e.pitch angle will increase as shown in Fig.11.

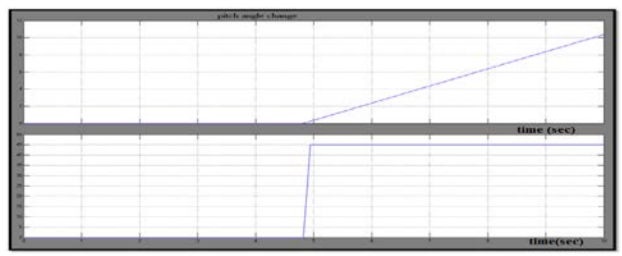


Fig.11.Pitch angle change

Pitch angle change is very slow as shown in figure and the maximum value of pitch angle is chosen as $45^0$

RMS value of output voltage and output current,rotor speed,active and reactive component of output power shows variations with variations in input wind speed as shown in Fig.12-14.

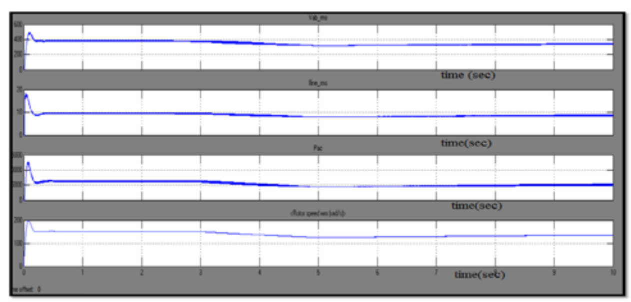


Fig .12.Voltage and current RMS output,active power output and rotor speed in rad/sec.

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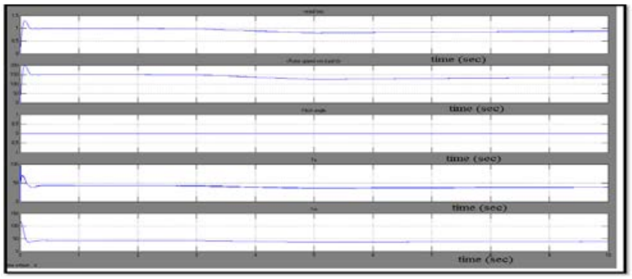


Fig 13.Rotor speed in p.u. and in rad/sec,pitch gle,mechanical torque input and electrical torque output(Te)

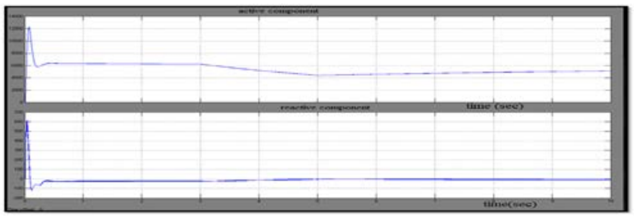


Fig.14.Active and reactive component of output power

Output voltage of three phase diode bridge rectifier is as shown in Fig.15.

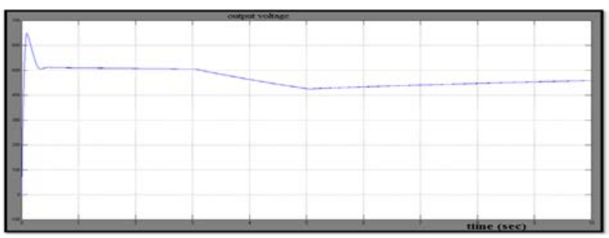


Fig.15.Output voltage of three phase bridge rectifier

Output and input voltage of closed loop converter interfaced with wind system is as shown in Fig.16.

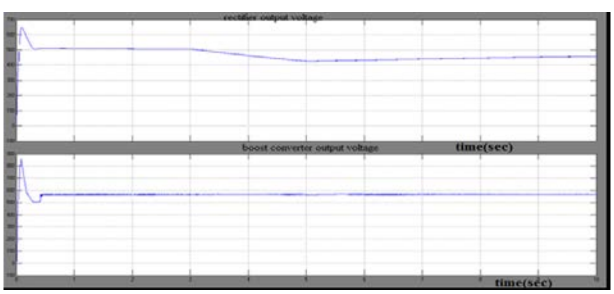


Fig.16.Output voltage of the closed loop Boost converter interfaced with wind system

Fig.17. shows output line voltages of three phase three level multilevel inverter.

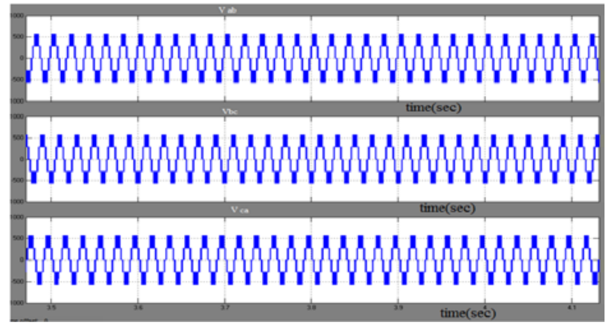


Fig.17.Output line voltages of three level multilevel inverter when connected to wind system

Output line voltages obtained in the case of five level multilevel inverter interfaced with wind power generation is as shown in Fig 18.

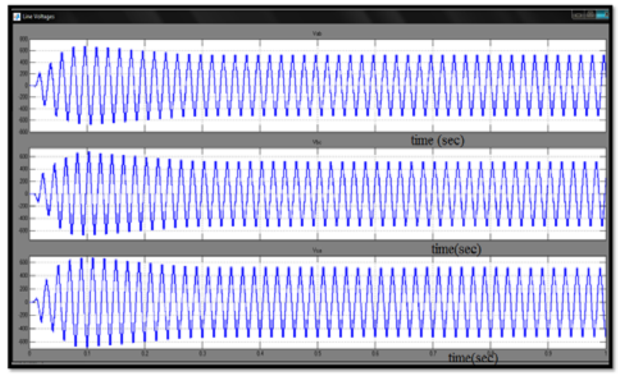


Fig.18.Output line voltages of five level multilevel inverter when connected to wind system.

The output voltage and current delivered to grid is as shown in Fig.19.From the figure it is clear that output voltage and current delivered shows an unity power factor.

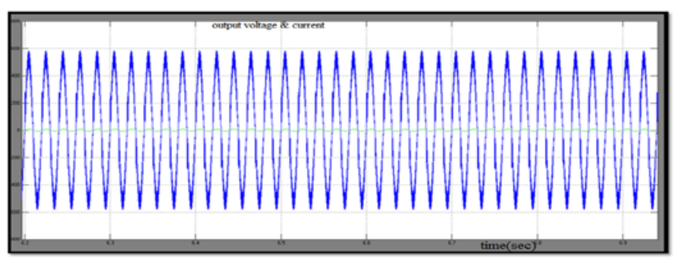


Fig.19.Output voltage and current delivered.

FFT analysis shows a THD of 12.10% in the filtered inverter output which is delivered to grid.

## IV. Conclusion

A grid connected variable-speed wind energy conversion system using a permanent magnet synchronous generator has been developed .The developed simulink model consists of a wind power generation system, power converter and the system is grid connected. Wind power generation system includes a wind turbine, drive train and PMSG. Power converter includes a three phase diode bridge rectifier, DC-DC boost converter and a multilevel inverter and the inverter control using voltage control PWM technique. The model has

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been implemented in MATLAB/Simulink in order to validate it.

In future, the model will be extended to the various types of the MPPT algorithms together with different types of converters such as Buck converter, Boost converter, Buck-Boost converter, SEPIC converter. Also THD in the output delivered to grid will be reduced to less than 5% using selective harmonic elimination technique.

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