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Dynamics and Control of Wind Energy Conversion System with Permanent Magnet Synchronous Generator

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ABSTRACT

Wind Energy is a naturally available omnipotent renewable energy source in all over the world. So for obtaining the quality power from wind, it is necessary to control and dynamics of whole wind energy conversion system. Here this paper presents the modeling and controlling strategy of wind energy conversion system dynamics for particular wind regime.The aim of this paper is to present the complete modeling and simulation of wind turbine driven PermanentMagnet Synchronous Generator (PMSG) which gives ac power to the load. For that, pulse width modulated voltage source converter is connected back to back between the rotor terminals. The PWM converter controls the power flow between the DC bus and the AC side and allows the system to be operated in sub-synchronous and super synchronous mode of operation. The proper rotor excitation is provided by the machine side converter. The complete system is modeled and simulated in the MATLAB-SIMULINK@7.3 environment in such a way that it can be suited for modeling of all types of Permanent Magnet Synchronous Generator configurations. The model makes use of rotor reference frame using dynamic vector approach for machine model.

Keywords: Wind Energy Conversion System, Turbine power,PMSG, Modeling.

1. INTRODUCTION

The capacity of wind energy installations is rapidly growing in all over the world. These wind energy system [1] either standalone or grid connected for different application. With increasing wind power[3] production, it is important, especially for grid owners, to predict the grid interaction of wind turbines in advance. Grid simulation packages, like the Power System Simulator for Engineering (PSS/E), which are commonly used for power system behavior studies,usually require reasonably accurate and low-capacity-demanding models[8] of all power system components. The low-capacity demand is necessary with respect to the high number of components used in the system. Models of the new types of generation units, like wind turbines, have to comply with this requirement. There are various simulation packages, which in principle describe a complete wind turbine. However, the turbine description [6] used in such programs is not viable in grid simulations packages due to its high computational burden. It is necessary, therefore, to simplify such a description to a level acceptable [2] for grid simulation programs, which is the intention of this paper. Approaches to simplify

Aero-dynamic modeling of wind turbines have been presented in [4] and [5]. The main idea in this paper is to give modeling of wind turbine generator set when permanent synchronous generator is used. Having the cubic relation with the power, the wind speed is the most critical data needed to appraise the power potential of a particular site. The wind is never steady at any site. It is affected by the weather system, the local land terrain, and the height above the ground surface. The wind speed varies by the minute, hour, day, season, and year. Therefore, the annual mean speed needs to be averaged over 10 or more years. Such a long term average raises the confined in assessing the energy-capture potential of a site. Here also represent the interaction of turbine blades[11]with the wind speed distribution [7] over the rotor swept area.

The control of wind energy conversion system is very difficult task, here in this paper, the sliding mode control theory has applied to develop the control strategy[9] for wind energy conversion .In this control [10] strategy, the controller worked under two mode of operation. These two mode of operation depends upon the wind regime either sufficient wind or insufficient wind regime.

2. WIND ENERGY CONVERSION SYSTEM

Here the wind energy conversion system consists of a horizontal axis wind turbine coupled to a permanent magnet synchronous generator. An AC-DC

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power electronics interface with diode bridge rectifier and DC-DC converter are used to track and extract maximum power available from wind energy conversion system for a given wind velocity and deliver this power to the load. The concept block diagram of wind energy conversion system is shown in Fig.1

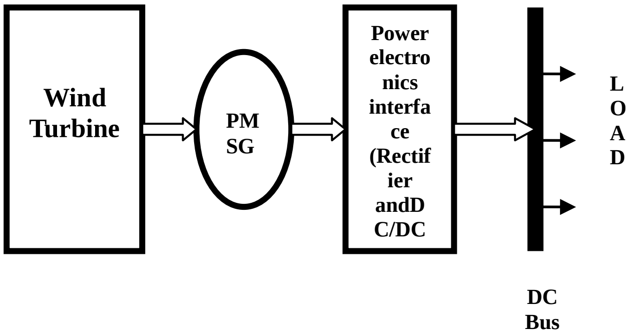

Fig.1. Wind energy conversion system

2.1 AERO DYNAMICS OF WIND TURBINE

A 7.5kW, horizontal-axes, BWC-EXCEL-R/48 type[6] wind electric generator are taken for this hybrid system. The detail specifications of wind turbine are shown in Fig.2.

Fig.2. 7.5kW BWC Excel R/48 wind turbine[11]

Type: 7.5kW, BWC XL-R/48, 3 Blade Upwind
Rotor Diameter: 2.5 m (8.2 ft.)

Start-up Wind Speed: 3 m/s (6.7 mph)
Cut-in Wind Speed: 2.5 m/s (5.6 mph)
Rated Wind Speed: 11 m/s (24.6 mph)
Rated Power: 7.5 kW
Maximum Power: ~ 7,800 kW
Cut-Out Wind Speed: None
Furling Wind Speed: 13 m/s (29 mph)
Max. Design Wind Speed: 54 m/s (120 mph)

Blade Pitch Control: None, Fixed Pitch
Over speed Protection: Auto Furl
Gearbox: None, Direct Drive
Temperature Range: -40 to +60 Deg. C (-40 to +140 Deg. F)
Generator: Permanent Magnet Synchronous Generator

Output Form: 24 VDC Nominal

The wind power generation from the turbine could predict from the wind power equation discussed here as under. The wind Turbine is characterizes by non- dimensional performance as a function of tip speed ratio. The output of mechanical power captured from wind by a wind turbine is given here as under.

$$P_t = \frac{-(C_p \lambda \rho A V^3)}{2}$$

In addition, Torque developed by wind turbine is express as

$$T_t = \frac{P_t}{\omega_m}$$

Where, P_t=Output power;

T_t =torque developed by wind turbine,

C_p =Power co-efficient,

λ=Tip speed ratio ρ=Air density in Kg/m3;

A=Frontal area of wind turbine;

V=wind speed

Where

$$\lambda = \omega_m \frac{R}{v}$$

Where

v is the turbine rotor speed in “rad/s”,

R is the radius of the turbine blade in “m”, and

ω_m is the wind speed in “m/s”

2.2. WIND TURBINE CHARACTERISTICS

Power output of wind turbine generator set at

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a specific site depends on wind speed at hub height and speed characteristics of the turbine. Wind speed at hub height can be calculated by using power-law equation.

$V_z = V_i \, (Z/Z_i)^x$

Where V_z and V_i are the wind speed at.

Z and Z_i are hub and reference height respectively and x is power law exponent.

The Fig.3 and Fig. 4 shows the typical wind turbine characteristics and pdf distribution of wind speed respectively. Power output P_w (kW/m^2) from wind turbine generator can be calculated as follows:

$$
\begin{aligned}
P_w &= 0, && V<V_{ci} \\
P_w &= aV^3 - bP_x, && V_{ci}<V<V_r \\
P_w &= P_r && V_x<V<V_{co} \\
P_w &= 0, && V>V_{co}
\end{aligned}
$$

Where $a = \frac{P_r}{V_r^3 - V_{ci}^3}$, b = $\frac{V_{ci}^3}{V_r^3 - V_{ci}^3}$,

P_x is the rated power,

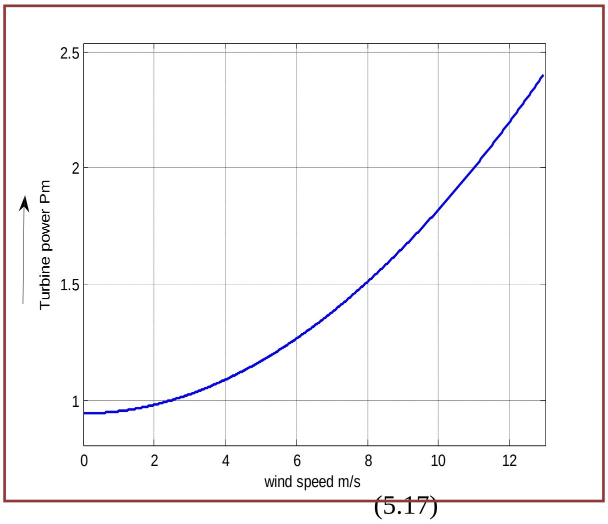
V_{ci}, V_{co}, and V_r are the cut in, cut-out and rated speed of the wind turbine.

Actual mechanical power available from wind turbine is given by:

$$P_m = P_w A_w \eta$$

Where A_w is the total swept area,

η is efficiency of wind turbine generator and corresponding converters.



(5.17)

Fig.3. Wind turbine characteristics

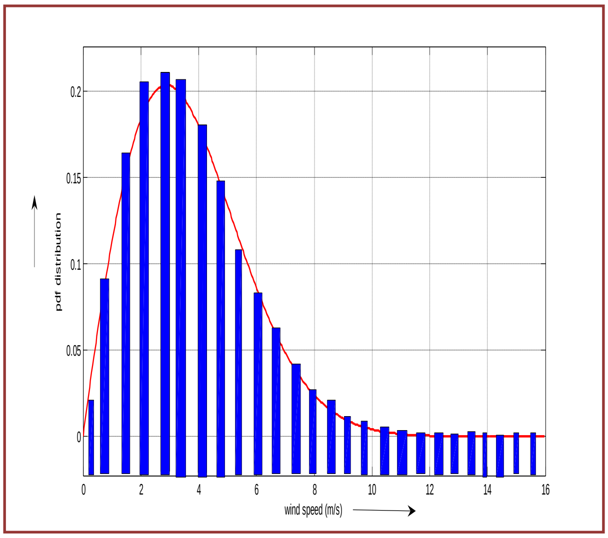


Fig.4. frequency distribution of wind speed

2.3. PERMANENT MAGNET SYNCHRONOUS GENERATOR (PMSG)

A 3.5 KW, 24pole, 450 rpm rated speed, permanent magnet generator (PMG) is employed in the WECS. The generator output voltage varies according to the wind speed variation. Hence the 3 phase output of the PMG is rectified with a full wave diode bridge rectifier, filtered to remove significant ripple voltage components, and fed to two consecutive dc-dc buck boost converters. For an ideal PMG, the line to line voltage is given as

$$VL = K_V \omega_e \sin\omega_e t \;\; [V]$$

Where

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$K_v$is the voltage constant and $\omega_e$is the electrical frequency related to the mechanical speed $\omega_m$by

$$\omega_e = \omega_m * (\frac{n_p}{2})\ [rad/s] \qquad (1)$$

where$n_p$is the number of poles of the PMG.

Neglecting commutation delays, the dc rectifier voltage $V_d$is given as

$$V_d = \left(\frac{3\sqrt{2}}{\pi}\right) * V_{Lrms} - \left(\frac{3\omega_e L_s}{\pi}\right) I_d\ [V] \qquad (2)$$

Where

$V_{Lrms}$is the rms value of the PMG output voltage,

$I_d$is the rectifier output current

$L_s$is the stator inductance. Neglecting the generator and rectifier losses, the PMSG output rectified electrical power P_{dc}, is equal to the mechanical power input to it is given here.

$$P_{dc} = \frac{V_d}{d} \qquad (3)$$

The current in Permanent manete synchronous generator (PMSG) dynamic model in a rotor reference frame is given by the following equations [4] and the Matlab/Simulink simulation model is shown in Fig. 5

$$i_q = -\frac{R_s}{L} i_q - \omega_e i_d + \frac{\omega_e \varphi_m}{L} - \frac{\pi v_b i_q u_x}{3\sqrt{3} L \sqrt{i_q^2 + i_d^2}} \qquad (4)$$

$$i_d = -\frac{R_s}{L} i_d + \omega_e i_q - \frac{\pi v_b i_d u_x}{3\sqrt{3} L \sqrt{i_q^2 + i_d^2}} \qquad (5)$$

$$\omega_e = \frac{P}{2J}\left(T_t - \frac{3}{2}\frac{P}{2}\phi_{sr} i_q\right) \qquad (6)$$

whereiq and id are respectively, the quadratic current and the direct current; L and R_s are the per phase inductance and resistance of the stator windings ; P is the PMSG number of poles; J is the inertia of the rotating parts; $\Phi_m$is the flux linked by the stator windings; and$u_X$is the control signal.

The voltage V_S is externally imposed by the DC/DC converter as a function of the duty cycle, and is described by:

$$V_S = \frac{\pi v_b}{3\sqrt{3}} u_X \qquad (7)$$

If we assume an ideal static conversion, the current at the output of the DC/DC converter could be determined as shown in the following equation.

$$i_w = \frac{\pi}{2\sqrt{3}} \sqrt{\left(i_q^2 + i_d^2 u_x\right)} \qquad (8)$$

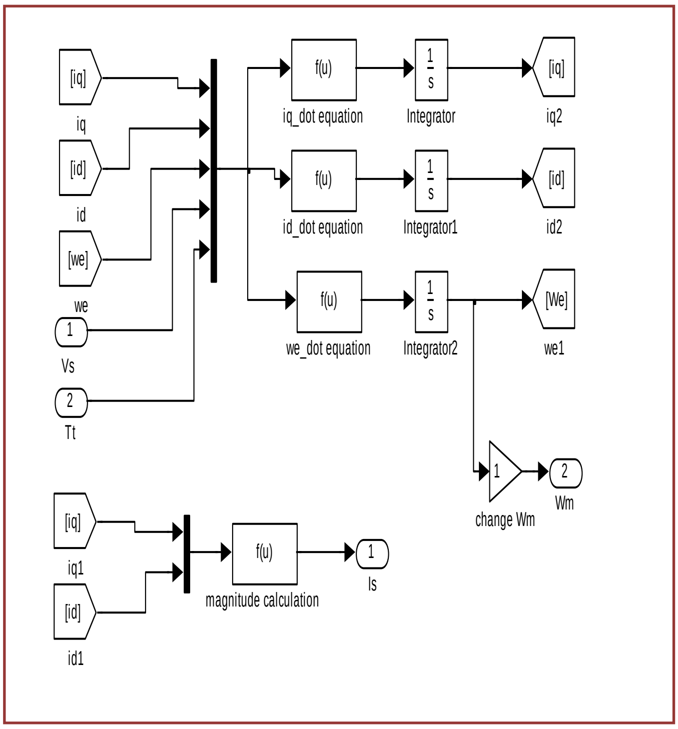

Fig.5.Simulink model of PMSG.

3. SIMULINK MODEL OF WECS-

The complete wind energy conversion system is modeled in Matlab-Simulink environment. The complete Simulink model of WECS is shown in Fig.5. This simulation model develops on the bases

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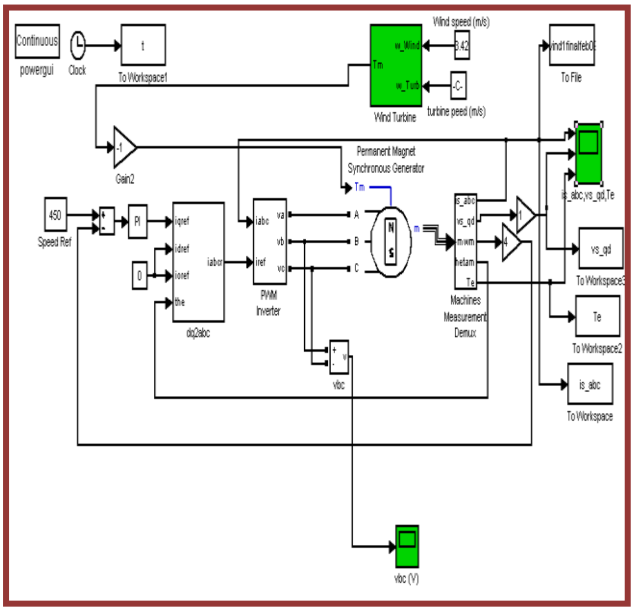

Fig.6. Simulink model of wind energy conversion system

of wind energy conversion system. This system is the combination of wind turbine, permanent magnet synchronous generator and Inverter.

The permanent magnet synchronous generator is coupled to the wind turbine. The minimum wind speed is set to minimum 3.42 m/s at hub height 25 meter.

SimulationResults-

Upon examining the simulation results of wind energy conversion system at measured wind speed level, it is seen that this model is acceptable to use in producing a realistic wind profile for an input to a wind turbine - generator system. These simulation results gives the responses of wind energy conversion system when wind turbine is used with permanent magnet synchronous generator are shown in Fig..6. The torque climbs to nearly 30 N/m when the generator starts and stabilizes rapidly. The nominal torque is applied at t = 0.5 second by wind turbine when wind speed is constant at 3.42m/s. The three phase output current i_a, i_b, $i_c$are shown in Fig. 7 and the inverter voltage is 300V.

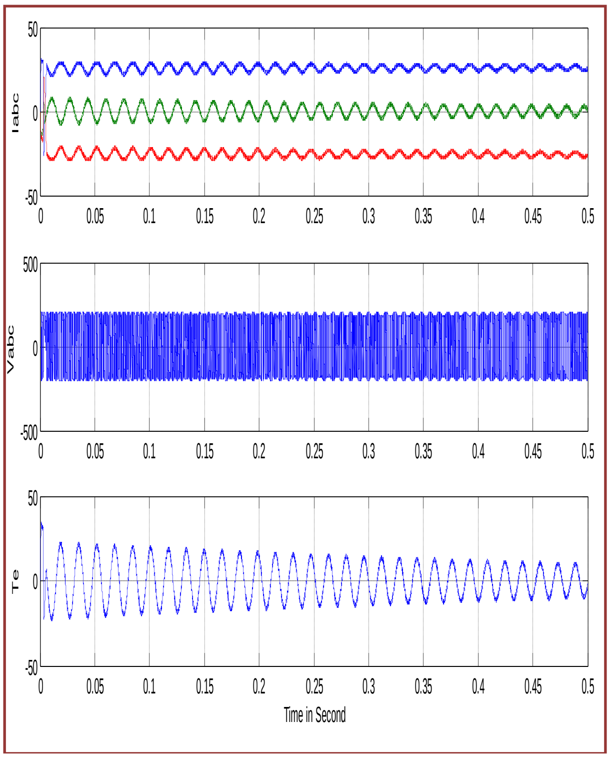

Fig.7. The output current, voltages and torque

4. CONTROLLER FOR WIND ENERGY SYSTEM-

The wind Energy system acts under supervisor control commands whichever supplying the total load or tracking the operation point of maximum power conversion. This subsystem is turned on in all modes of operation because is designated as the principal energy source. The impulse for this design choice was that it was taken from the perspective of applications in geographical areas with affluent wind regimes.
The main objective is to control the power produced by the wind subsystem into the DC bus to satisfy the total demand (the load and the battery charge requirements I_{bref}). In this case, the control is just used to reject the unwanted internal forces that draw the system apart from the sliding surface.

4.1.MODES OF OPERATION

For this energy conversion system, there are two modes of operation as described in section. The first occurs when the wind subsystem could generate enough power to satisfy the total power demand.

$$P_{wref1} = Vb(i_L + i_{bref}) \quad (7)$$

The second mode of operation occurs when the maximum energy captured from the wind is not

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enough to satisfy the total demand. For this case, we make as a power reference the optimum power extracted by the turbine minus losses

$$P_{w\,ref2} = P_{w\,opt} - P_{losses} \quad (8)$$

$$P_{w\,ref2} = K_{opt}\varpi_m^{\,3} - \frac{3}{2}(i_q^{\,2} + i_d^{\,2})r_s \quad (9)$$

Where

$$K_{opt} = \frac{Ct(\lambda opt)\rho A R^3}{2\lambda opt^2}$$

λ_{opt} is the tip speed ratio that maximizes the power extracted to the wind. The boundary between the operation modes of the wind energy system is given by the angular shaft speed of the boundary point, and is obtained by equating the mechanical power references of both modes of operation (Equation 7 and 8), that is:

$$P_{w\,ref1} + \frac{3}{2}(i_q^{\,2} + i_d^{\,2})r_s = K_{opt}\varpi_m^{\,3}sw^3 \quad (9)$$

Therefore the following function for the delimiting electrical angular speed:

$$\varpi_{mSW} = \sqrt[3]{\frac{P_{w\,ref1} + \frac{3}{2}(i_q^{\,2} + i_d^{\,2})r_s}{K_{opt}}} \quad (10)$$

Figure 8 shows the operation points of both sliding surfaces. The decision to work in one mode of operation or the other can be taken by comparing the measured speed with the boundary speed ϖ_{mSW} as follow:

$\varpi m \geq \varpi mSW \Rightarrow$ First mode of operation

$\varpi m \leq \varpi mSW \Rightarrow$ Second mode of operation

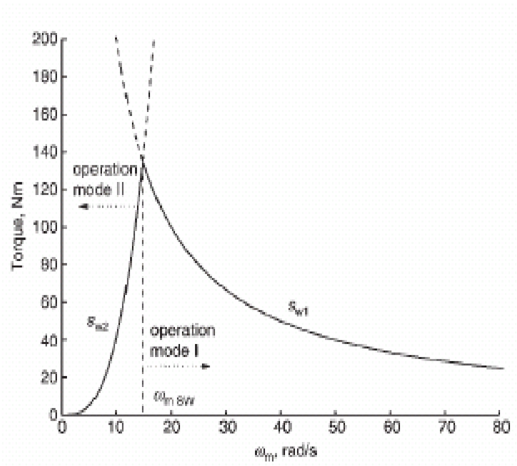

Fig. 8. Operation Points of both sliding surfaces

a) Sufficient Wind Regime

On this mode of operation, the main objective of the wind subsystem is to regulate the power produced by the wind turbine following $P_{w\,ref1}$. To accomplish this objective, the sliding surface h_1 was written in terms of currents on the battery bank.

$$h_1 = P_{wref1} - P_w = V_b(I_{bref} + i_L - i_w) \quad (11)$$

The switched control signal produces an unwanted deviation in Te, and a high ripple on the current of the DC/DC converter. To avoid this problem, we added an integrator to the input ux, channel turning ux into a new state variable and the integrator input signal *w* becomes the new input to the system. In consequence, the algebraic dependence between the input of the system and the sliding surface is broken.

b) Insufficient Wind Regime

On this mode, the system is not able to operate on the sliding surface h1, and it is necessary to incorporate a secondary sliding surface h2 whose main objective is to extract the maximum power available from the wind turbine.

$$h_2 = P_w - P_{wref2} \quad (12)$$

And the switching input signal is given by

$$w = \begin{cases} w_2^{+} > 0\,if & h2 \geq 0 \\ w_2^{-} < 0\,if & h2 \leq 0 \end{cases} \quad (13)$$

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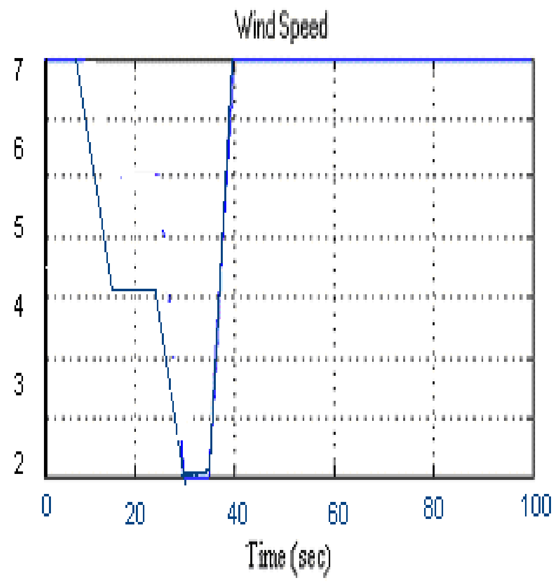

Figure 9 Wind Speed

Figure 10shows that the power reference of the wind turbine to follow the first generation mode,

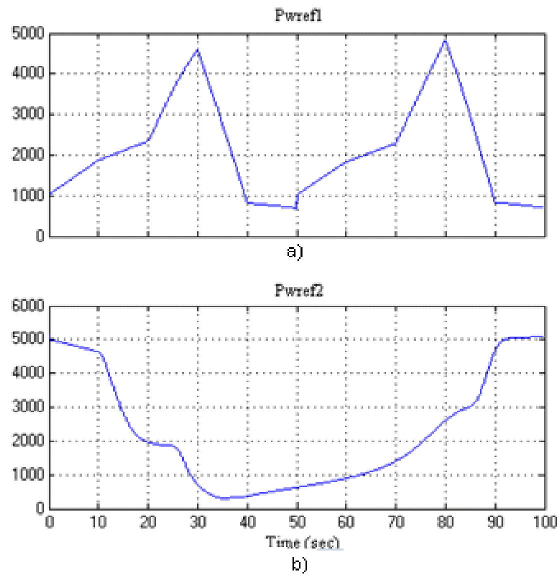

Figure 10 Power Reference of wind subsystem. a) Mode 1 b) Mode 2

4.2. Simulation Results

In order to test the operation of wind subsystem, two scenarios were simulated and evaluated. Over the first 25 seconds, there is a sufficient wind for the wind turbine to work well (the minimum wind speed recommended for this turbine is 4 m/s), between 30 and 38 seconds the wind speed was reduced to simulate insufficient wind power mode (See Figure 9). For all scenarios, the load is a variable current source.

5. CONCLUSIONS

The wind energy is unpredictable and naturally available in all over the world. So for obtaining the quality power from wind, it is necessary to study the dynamics of whole wind energy conversion system for particular site. Here this paper has presented the modeling and controlling strategy of wind energy conversion system for particular wind regime. The modeling of the wind energy conversion system is play an important role to analyze the unpredictable behavior of the wind system to be installed in particular site. Here in this paper author presented the modeling of different wind energy conversion system components i.e. turbine, permanent synchronous generator, inverter. The behavior and characteristics of different system components has analyzed by using MATLAB-SIMULINK software, under different weather condition. After acquiring the wind energy from turbine generator set, the main problem is to controlling and quality power feed to the load. The sliding mode control theory has been applied to develop the control strategy for wind energy conversion .In this control strategy, the controller worked under two mode of operation. These two mode of operation depends upon the wind regime either sufficient wind or insufficient wind regime. Over all wind energy conversion system with permanent synchronous generators modeling and controlling has analyzed in this paper.

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AUTHOR PROFILE

Dr. PragyaNema obtained her B.E. (Electrical Engineering) degree from Govt. engineering college, Sagar, in 1995.M.Tech. (Heavy Electrical Enginnering)from Maulana Azad College of Technology, Bhopal in 2001 and Ph.D. in Energy System from Maulana Azad National Institute of Technology, Bhopal in 2010.her research interest in power system, hybrid energy system, solar and wind energy. She is actively involved in various research work in the field of renewable energy.She has published 27 research papers in different national and international journals andconferences. She is expert in the field of renewable energy, integrated renewable energy system, and power system. Currently she is working as a professor and Head of the Department in Electrical Engineering Department at Lakhmi Narayan College of Technology, Indore, MadhyaPradesh.

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Table -1

Average Wind Speed (m/s) at height of 25m													
BhopalCity Lat 23.59 degree Lon77.21degree	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
Average data for last 10-years	3.04	3.33	3.35	3.79	4.44	4.63	4.17	3.49	3.15	2.47	2.46	2.75	3.42