Chapter 4

Modeling of Wind Based Generation for Hybrid Power System

4.1 Introduction

Wind power is the conversion of wind energy into useful energy, by windmills for mechanical energy generation for example wind pumps for water pumping and utilizing wind turbine to generate electrical power. This is accomplished by utilizing wind turbines to convert wind energy to mechanical energy. This mechanical energy is converted into electrical energy by an electrical generator which is coupled to the wind turbine. This renewable energy doesn't pollute the air compared to which the conventional power plants rely on combustion of fossil fuels, such as coal or natural gas. This electrical energy is used to supply local loads in stand-alone wind-based generation system. Surplus power is injected into the conventional grid in the grid-tie mode of operation. As the penetration of wind power generation into the grid is increasing day by day, an investigation into the integration of wind energy farms to power grid has become a priority. Power generated by the wind power system is dependent on wind speed. As such study of fluctuations caused by variation in wind speed into the grid has been relevant [184]. This chapter presents the modeling of wind power generation in the proposed hybrid power system shown in Figure 4.1 and its performance is evaluated under different input power level and load variation.

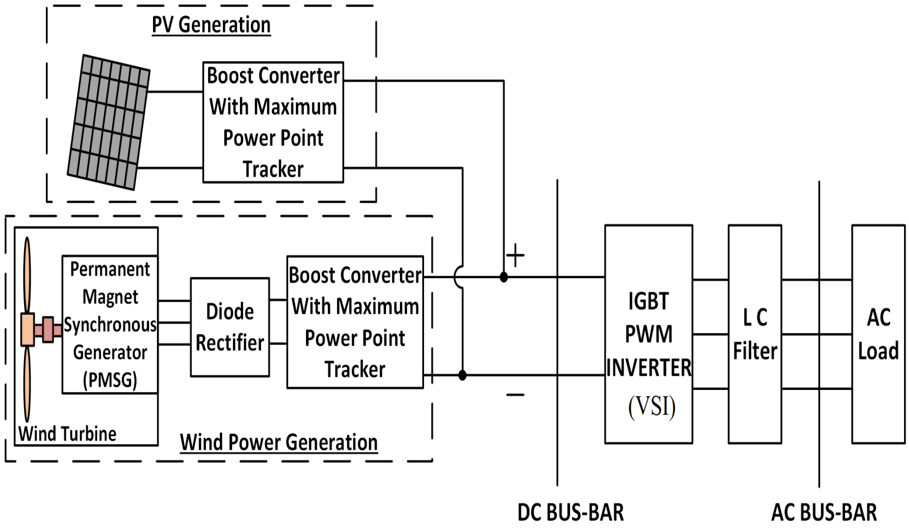

FIGURE 4.1: Block diagram of PV-Wind Hybrid Power System.

4.2 Modeling of Wind-based generation

Wind power has evolved as a viable source of power generation and is economical as compared with the other non-conventional energy sources. It offers a feasible solution to the grid-connected distributed power system. Wind turbine, a rotating device captures the wind energy and converts it into kinetic energy further this kinetic energy is converted into electrical energy by coupled electric power generator [185]. As of 31 January 2017 wind power installation is about 28,871.59 MW [186]. This placed India at this time as the world's fourth-largest producer of wind power (behind 1. China, 2. USA and 3. Germany) as on 31 March 2017. The installed Wind power generation as of 31 March 2016 [187] is tabulated in Table 2.3 and a graphical representation of growth in wind power installation over years in India is shown in Figure 4.2 [188]. Wind power accounts nearly 8.6% of India's total installed power generation capacity and generated 28,604 million Kwh (MU) in the fiscal year 2015-16 which is nearly 2.5% of total electricity generation[188]. The capacity utilization factor is nearly 14% in the fiscal year 2015-16 (15%

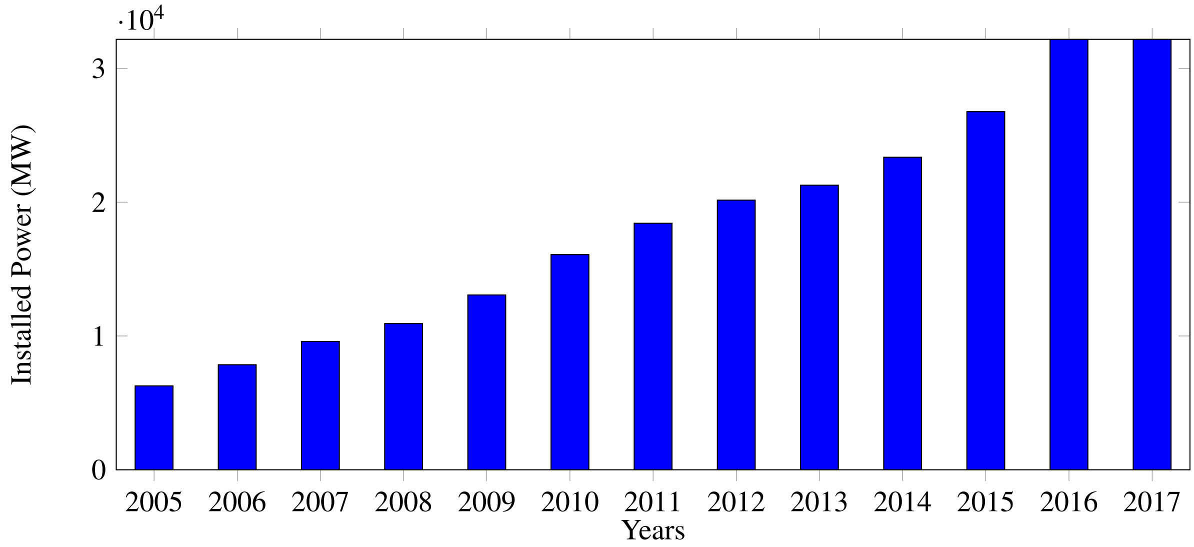

FIGURE 4.2: Growth of Wind Power Installation over years in India

in 2014-15). During the five months duration from May to September 70% of wind power is generated coinciding with Southwest monsoon duration. To install and Harnessing power from wind is not an easy task, the challenges posses by wind power generation will be discussed below.

Challenges of Wind Power Generation: A few challenges faced by wind power generation are highlighted, such as

1. Good wind sites are often located far away from the city where the load demand is heavy. Transmission line should be built to transmit power from the wind farm to the load centers.

2. The wind power generation has very little impact on the environment as compared to conventional power generation. Concern still exists regarding the noise produced by the turbine blades and may cause visual impact to landscapes.

3. Though the wind turbine doesn't harm the wildlife as compared with the conventional generation, turbine blade may damage local wildlife. As in, birds had been killed by flying into spinning turbine blades. Blade strikes have been greatly reduced through technological development or by properly siting wind plants.

4. Lastly, the variability of wind speed is one of the greatest challenge faced by wind power generation,

as the magnitude of the output voltage and frequency directly depend on wind speed. Power electronics controllers are utilized to make the output voltage and frequency independent of wind speed fluctuations. A few measures have been taken to overcome the above-mentioned challenges such as proper selection of a site for wind power generation, the design of wind turbine, sizing of wind generators, power electronic controllers depending on the wind profile of the location. This requires an insight of wind power generation the following section will discuss the basic building blocks of wind power generation.

4.2.1 Basic building blocks of Wind power generation

The basic building blocks of Wind power generation as shown in Figure 4.3 are

- Wind Turbine,
- Gear Box,
- Electrical Power Generator.

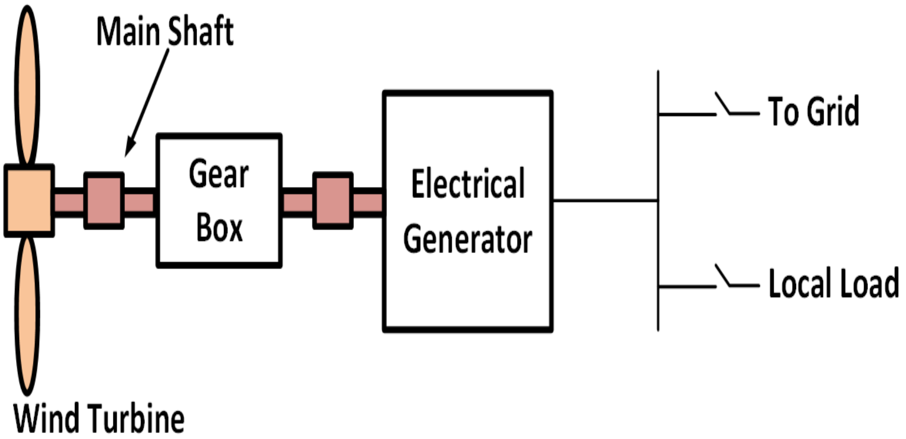

FIGURE 4.3: Schematic of Wind power generation

The wind energy captured by the wind turbine is fed as mechanical input to the electrical generator via the main shaft coupled to the generator through a gearbox. The gearbox keeps the speed of the electrical generator constant under varying wind speed conditions. The gear box in the system limits the efficiency of the system and adds periodic maintenance which increases the operational cost of the system. If the wind profile is promising at the location then the implementation of high capacity direct driven wind power generation is more feasible eliminating the gearbox. In such case the wind power generation can be used as an isolated or grid connected power generation system, feeding local load in an isolated system and feeding the excess power into the grid in grid connected system. Small changes in wind pattern will not affect the output voltage as the large capacity wind turbines have greater inertia which helps it to overcome small changes in the wind speed [189].

This will not be the same when the wind profile is not promising. It is not economical to install large capacity wind turbines for the low wind speed locations. As the wind energy will not be sufficient enough to rotate large inertia wind turbine. However when considering direct driven small wind turbines the effect of a change in wind speed affects the performance of the wind turbine. Few techniques like flywheels, power electronic controllers etc. are incorporated into small-scale wind turbines to overcome the fluctuations due to change in wind speed. A feasible implementation of small scale wind power generation with power electronic controller is graphically represented in Figure 4.4.

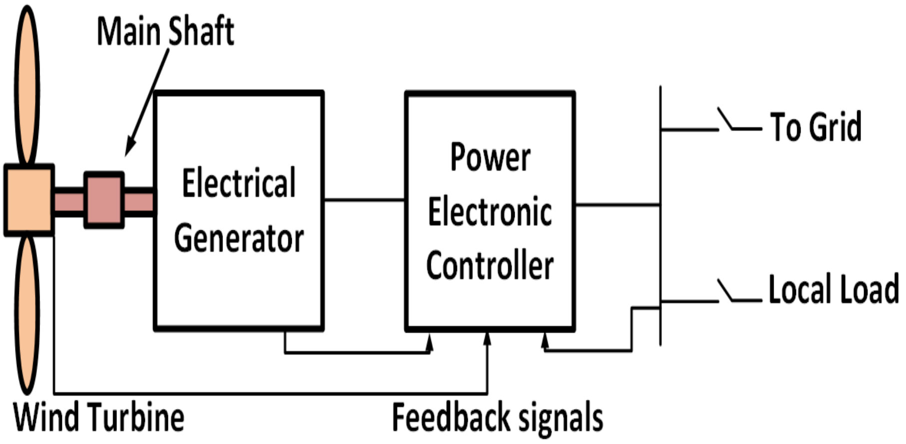

FIGURE 4.4: Schematic of Wind power generation with Power Electronic Controller

The power electronics controller in Figure 4.4 can be either AC-DC-AC, or AC-AC, or AC-DC control depending on the wind profile and type of electrical generator selected. The power electronics controller considers feedback signals from a wind turbine, electrical generator and from load or grid side for controlling the output voltage and frequency of the system at desired level. In order to have an in-depth analysis of small scale direct driven wind power generation mathematical analysis of the system is quite essential. Consequently, the mathematical modeling of a wind turbine is discussed in the following section.

4.3 Modeling of Wind turbine

The first electricity-generating wind turbine was a battery charging machine installed in July 1887 by Scottish academic James Blyth to light his holiday home in Marykirk, Scotland [190]. Later American inventor Charles F Brush built the first automatically operated wind turbine for electricity production in Cleveland, Ohio [190]. The wind turbine are categorized based on the axis of rotation of wind turbine blades are

- Vertical Axis Wind Turbine (VAWT),
- Horizontal Axis Wind Turbine (HWAT).

The detailed mathematical analysis of power conversion from Wind to mechanical power considering general model of wind turbine will be discussed.

4.3.1 Speed and Power relation:

The kinetic energy in air of mass m moving with speed V is given by the following in Joules:

$$KineticEnergy = \frac{1}{3}mV^2 \tag{4.1}$$

The power in moving air is the flow rate of Kinetic energy per second in watts:

$$Power = \frac{1}{2}(massflowpersecond)V^2 \tag{4.2}$$

Then the volumetric wind flow rate across the blades of wind turbine is AV,

The mass flow rate of the air through the blades of wind turbine in Kg/sec is expressed as ρAV, and

The mechanical power coming in the upstream wind is given by the following in watts:

$$P = \frac{1}{2}(\rho AV)V^2 = \frac{1}{2}\rho AV^3 \tag{4.3}$$

where:

P is mechanical power in the moving air (watts),

ρ is air density (Kg/m^3),

A is area of swept by the rotor blades (m^2),

V is the velocity of the upstream wind (m/sec).

The potential of wind sites is computed in terms of the specific wind power expressed in watts per square meter of area swept (A) by the rotating blades. It is also referred as the power density of the site, and is given by the following expression in watts per square meter of the rotor swept area:

$$Specific\ power\ of\ the\ site = \frac{1}{2}\rho V^3 \tag{4.4}$$

This is the power of the upstream wind. It varies linearly with the density of the air sweeping the blades and with the cube of the wind speed. The blades cannot extract all of the upstream wind power, as some power is lost due to downstream air that causes a reduction in speed[191].

4.3.2 Power extracted from the wind:

The actual power extracted by the rotor blades is the difference between the upstream (V) and downstream (V_o)wind powers. Using Equation 4.2, this is given by the following Equation 4.5 in units of watts:

$$P_o = \frac{1}{2}(mass\ flow\ per\ second)\left\{V^2 - V_o^2\right\} \tag{4.5}$$

where:

P_o= mechanical power extracted by the rotor, i.e., the turbine output power,

V= upstream wind velocity at the entrance of the rotor blades,

V_o= downstream wind velocity at the exit of the rotor blades.

Considering the macroscopic view of the airflow around the blades, the air velocity is discontinuous from V to V_o at the "plane" of the rotor blades, with an "average" of $\frac{(V+V_o)}{2}$ [192]. Multiplying the air density by the average velocity, therefore, gives the mass flow rate of air through the rotating blades, given as

$$Massflowrate = \rho A \frac{(V+V_o)}{2} \tag{4.6}$$

The mechanical power extracted by the rotor, which drives the electrical generator, is therefore:

$$P_o = \frac{1}{2}\left[\rho A \frac{V+V_o}{2}\right](V^2 - V_o^2) \tag{4.7}$$

Rearranging the equation and written as Equation 4.8

$$P_o = \frac{1}{2}\rho A V^3 \frac{(1+\frac{V_o}{V})\left[1-(\frac{V_o}{V})^2\right]}{2} \tag{4.8}$$

The power extracted by the blades is customarily expresses as a fraction of the upstream wind power in watts as follows (4.9):

$$P_o = \frac{1}{2}\rho A V^3 C_p \tag{4.9}$$

where

$$C_p = \frac{(1+\frac{V_o}{V})\left[1-(\frac{V_o}{V})^2\right]}{2} \tag{4.10}$$

Comparing Equations 4.3 and 4.9, we can say that C_p is the function of upstream wind power that is extracted by the rotor blades and fed to the electrical generator. The remaining power is dissipated in the downstream wind. C_p is often called as Betz limit after the Germany Physicist Albert Betz who worked it out in 1919. Other names for this quantity are the power co-efficient of the rotor or rotor efficiency. The C_p is not a static value it varies with tip speed ration of the wind turbine [193, 194]. Let λ represents the ratio of wind speed V_o downstream to wind speed V upstream of the turbine and expressed as (4.11).

$$\lambda = \frac{V_o}{V} \tag{4.11}$$

The blade tip speed in meters per second can be calculated from the rotational speed of the turbine and the length of the blades used in the turbine as (4.12).

$$tip\ speed\ ratio = \frac{Angular\ speed\ of\ turbine(\omega) \times R}{wind\ speed} \tag{4.12}$$

where, R is the radius of the turbine and ω is speed measured rad/sec.

Substituting Equation 4.11 in Equation 4.10

$$C_p = \frac{(1+\lambda)(1-\lambda^2)}{2} \tag{4.13}$$

Differentiating C_p with respect to λ and equate to zero to find value of λ that makes C_p a maximum, yielding λ = -1 or $\lambda = \frac{1}{3}$. Now $\lambda = \frac{1}{3}$ makes the value of C_p a maximum. The maximum value is $\frac{16}{27}$. Thus the Betz limit says that no wind turbine can convert more than $\frac{16}{27}$ (59.3%) of the kinetic energy of the wind into mechanical energy turning a rotor, i.e C_{pmax} = 0.59. Wind turbines cannot operate at this maximum limit though. The real world is well below the Betz limit with values of 0.35 to 0.45 common even in best designed wind turbines [195, 196].

The air density ρ is another flow input quantity at the rotor system. ρ is a function of both air pressure and temperature. When air pressure increases the value of ρ increases. When air temperature decreases the value of ρ increases. This is in accordance with the equation 4.14

$$P = \rho RT \tag{4.14}$$

where R is the gas constant. Both temperature (T) and pressure (P) decrease with increasing elevation. Hence site location is important as elevation has major effect on power generated as a result of air density variation. At atmospheric pressure, P_{atm} = 14.7 psi, temperature is T = 90° F and density is ρ = 1.225kg/m^3. Temperature and pressure both vary with elevation and the affects the air density is given as follow 4.15.

$$\rho = \rho_o e^{\frac{0.297}{3048} H_m} \tag{4.15}$$

where H_m is site elevation in meters.

The Equtaion 4.15 is simplified as

$$\rho = \rho_o - (1.194 \times 10^{-4} H_m) \tag{4.16}$$

At high elevation the air density corrections can be important.For example, the air density at 2000 m elevation would be 0.986 kg/m^3, 20% lower than the 1.225 kg/m^3 value at sea level. Further the importance of the power co-efficient will be discussed in detail.

4.3.3 Power Coefficient (C_p:)

Equation 4.9 relates the parameters that are required in power production by a wind turbine. The power coefficients C_p is the most important parameter in the case of power regulation. It is a non-linear function whose value is unique to each turbine type and is a function of wind speed that the turbine is operating in. Each turbine manufacturer provides look up tables for C_p for operational purposes. Other than look up tables, model of power coefficient have been developed. The model C_p as a function of the tip speed ratio and the blade pitch angle θ in degrees as 4.17, 4.18 [197–200]

$$C_p(\lambda,\theta) = C_1\left(C_2\frac{1}{\beta} - C_3\beta\theta - C_4\theta^x - C_5\right)e^{-C_6\frac{1}{\beta}} \tag{4.17}$$

or

$$C_p = \frac{1}{2}(\lambda - 0.022\theta^2 - 5.6)e^{-0.17\lambda} \tag{4.18}$$

where the values of the coefficients $C_1 - C_6$ and x in Equation 4.17 depend on turbine type, θ is defined as the angle between the plane of rotation and the blade cross section chord and β is defined by 4.19

$$\frac{1}{\beta} = \frac{1}{\lambda + 0.08\theta} - \frac{0.035}{1+\theta^3} \tag{4.19}$$

The Equation 4.17 is implemented in MATLAB, Simulink and simulated C_p is plotted for the various values of θ = 0°, 5°, 10°, 15°, 20°, 25° and is shown Figure 4.5 below. It is clear that by pitching the turbine blades the value of C_p changes. This factor is good because it controls the power output of the variable speed wind turbine.

Two distinctly different configurations are available for turbine design, the horizontal- axis configuration Figure 4.11 and the vertical-axis configuration Figure 4.7. The horizontal-axis machine has been the standard in Denmark from the beginning of the wind power industry. Therefore, it is often called the Danish wind turbine. The vertical-axis machine has the shape of an eggbeater and is often called the

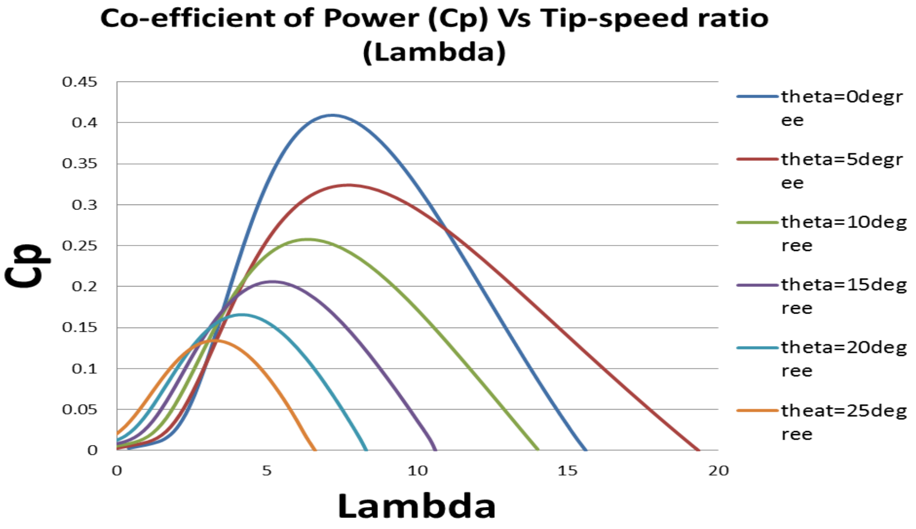

FIGURE 4.5: Simulated Power Coefficient

Darrieus rotor after its inventor. It has been used in the past because of its specific structural advantage. A wind turbine consists of a rotor mounted to a nacelle and a tower with two or more blades mechanically connected to an electric generator. The gearbox in the mechanical assembly transforms slower rotational speeds of the wind turbine to higher rotational speeds on the electric generator. The rotation of the electric generators shaft generates electricity whose output is maintained by a control system. HAWT have the ability to collect the maximum amount of wind energy for the time of day and season and their blades can be adjusted to avoid high wind storm. Wind turbines operate in two modes namely constant or variable speed. Further, the mathematical modeling of VAWT and HAWT will be discussed in detail.

4.3.4 Vertical Axis Wind Turbine (VAWT):

A typical VAWT is shown in Figure 4.6. The VAWT consists of

1. Upper Hub and Lower Hub supporting the Main Rotor Shaft,
2. Rotor Blades,
3. Guy Wire,
4. Gearbox,
5. Generator.

Vertical-axis wind turbines (VAWT) have the main rotor shaft arranged vertically. In this arrangement, the turbine does not face towards the direction of wind speed. This is an advantage on sites where the wind direction is highly variable, for example when integrated into buildings. However, the disadvantages include the low rotational speed with the consequential higher torque and hence higher cost of the Gearbox. The inherently lower power coefficient, the 360-degree rotation of the aerofoil within the wind flow during each cycle causes high dynamic loading on the blade. prior to fabricating a prototype, the following issues have to be investigated such as the pulsating torque generated by rotor designs on the gearbox, and modeling of wind flow accurately and designing the rotor accordingly.

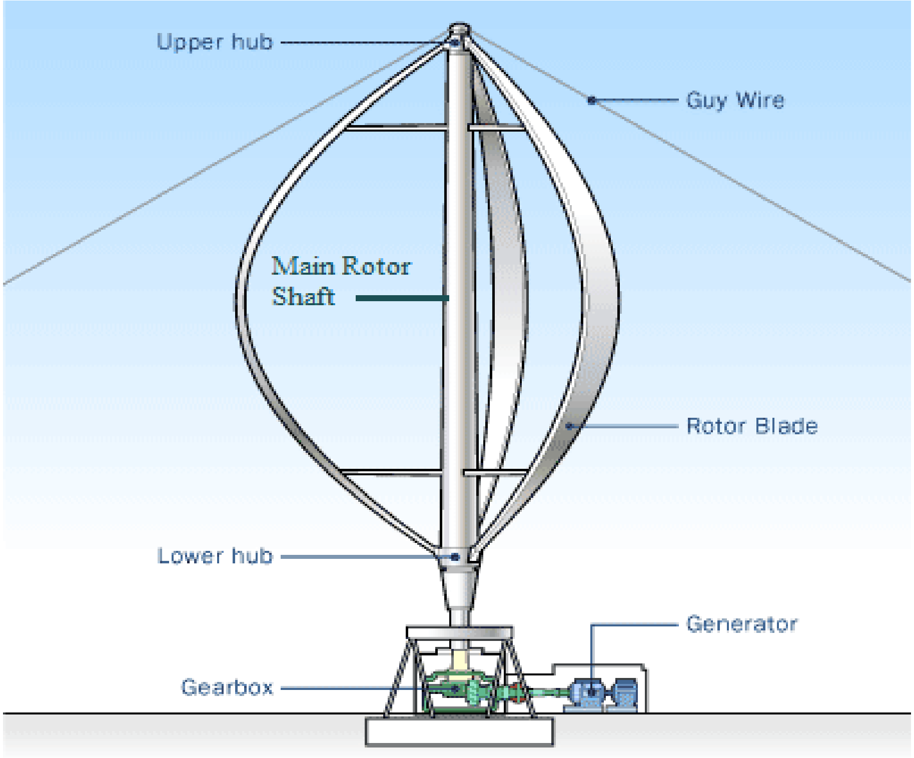

FIGURE 4.6: Vertical Axis Wind Turbine [201]

Due to its large vertical axis the wind power generator and the gearbox are placed near the ground. This arrangement of VAWT makes improved accessibility for maintenance of VAWT. When a turbine is mounted on a rooftop as shown in Figure 4.8 [203], the building generally redirects wind over the roof and this can double the wind speed at the turbine. If the height of the rooftop mounted turbine tower is approximately 50% of the building height, this is near the optimum for maximum wind energy and

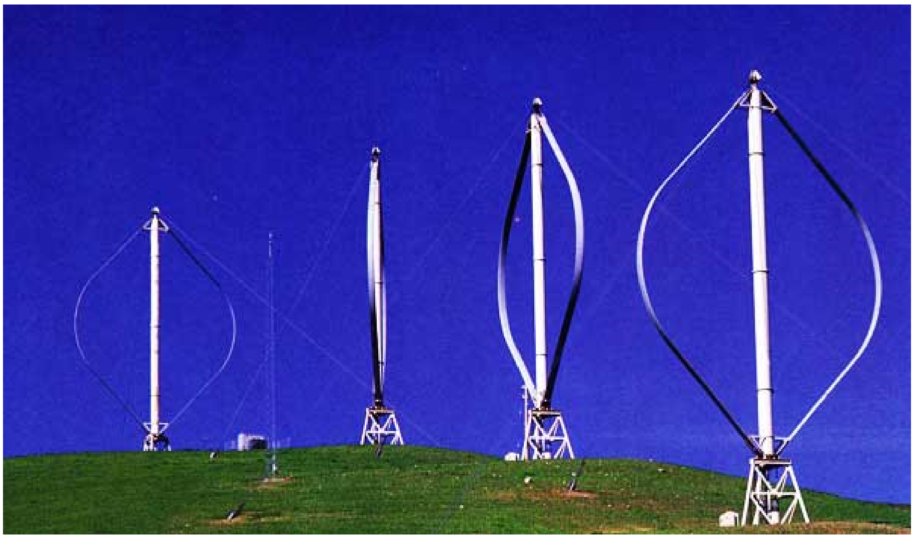

FIGURE 4.7: Vertical Axis Wind Turbine [202]

FIGURE 4.8: Vertical Axis Wind Turbine on buildings [203]

minimum wind turbulence. It should be borne in mind that wind speeds within the man-built environment are generally much lower than at exposed rural sites along with noise being a concern and additionally the existing structure has stress due to the mounted turbine.

Advantages: The advantages of VAWT are

1 The VAWT doesn't require massive structure for installation, as they are mounted directly on the ground with low bearing assembly and generator.

2 Fixed pitch rotor design without yaw mechanism can be achieved and can be built where taller structures are prohibited.

3 The generator of VAWT is placed near the ground level which makes monitoring and maintenance of rotating parts easier.

4 The start-up speed required for VAWT is at low wind speed.

Disadvantages: The dis-advantages of VAWT are

1 VAWT uses GUY wire for mechanical stability which causes downward thrust in wind gusts. From Figure 4.6 it can be observed that the Guy wire arrangement in VAWT. It improves mechanical stability and also causes downward thrust as the cables are connected from the top of the VAWT to ground.

2 With the rotation of blades in vertical axis the stress due to wind loading changes as they rotate. Due to the reversal of wind stress failures of the blade may happen by fatigue.

3 As the rotating mechanical turbine is on top of the electrical generator on the ground maintenance and changing parts of the mechanical structure becomes very difficult if the turbine is not properly designed.

4 Most VAWT have a decreased efficiency, mainly because of the additional drag that they have as their blades rotate into the wind.

The mechanical power output of the wind turbine is given by the Equation 4.9. The relation between the mechanical torque and the mechanical power is given by (4.20)

$$T_m = \frac{P_m}{\omega_m} \tag{4.20}$$

where ω_m = rotor angular speed (rad/s) and is expressed as (4.21)

$$\omega_m = \frac{\lambda V}{R} \tag{4.21}$$

where R is the wind turbine rotor radius in meters (m). Thereby substituting the values of ω_m and P_m in Equation 4.20. we get the Mechanical torque output of the wind turbine as (4.22)

$$T_m = \frac{1}{2} C_t \rho A R V^2 \tag{4.22}$$

where A = $\frac{2}{3}$ × Maximum rotor width at the center × Height of the rotor and C_t is the torque coefficient and is given by (4.23)

$$C_t = \frac{C_p}{\lambda} \tag{4.23}$$

The Simulink implementation of VAWT is shown in Figure 4.9.

4.3.5 Horizontal Axis Wind Turbine (HAWT):

Horizontal-axis wind turbines (HAWT) have their main rotor shaft and electrical generator at the top of a tower and must be pointed into the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor. Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electrical generator. Since a tower produces turbulence behind it, the turbine is usually positioned upwind i.e the turbine is facing in the direction of wind flow and its supporting tower. Turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable

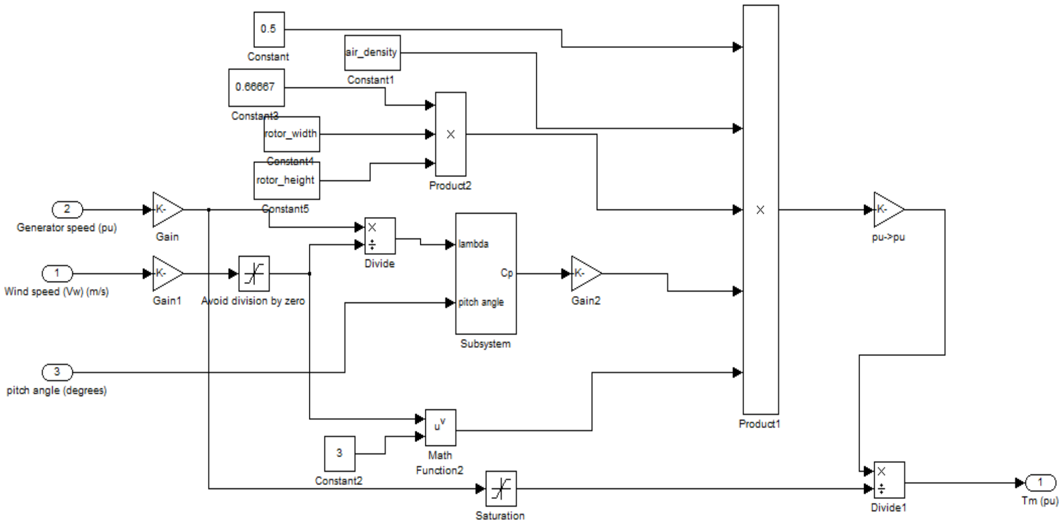

FIGURE 4.9: Simulink implementation of the VAWT

distance in front of the tower and are sometimes tilted forward into the wind by a small amount. Downwind machines (i.e. wind hits the turbine blades from the back) have been built as shown in Figure 4.10, despite the problem of turbulence. No additional mechanism is required for keeping them in line with the wind, and in high wind speed, the blades can be allowed to bend which reduces their swept area and thus their wind resistance. Since cyclical turbulence may lead to fatigue failures, most HAWTs are of upwind design. A typical HAWT is shown in Figure 4.11. The HAWT consists of

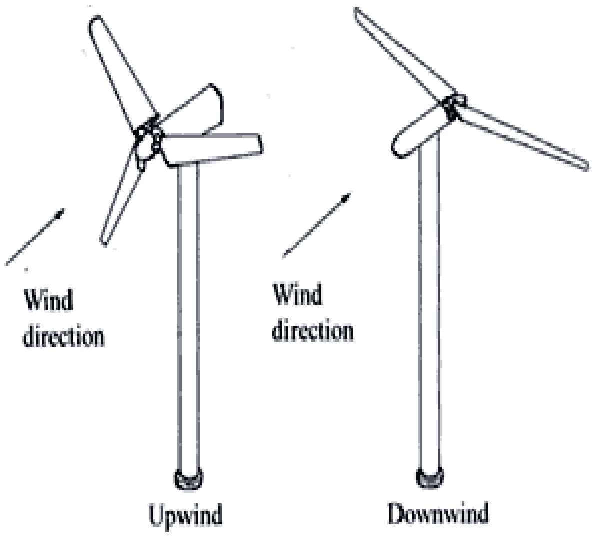

FIGURE 4.10: Upwind and Down Wind turbines [204]

- Tower,

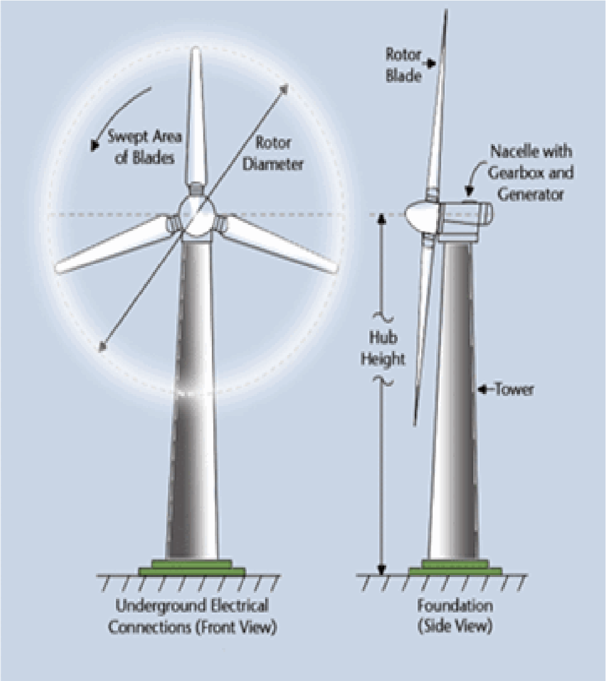

FIGURE 4.11: Horizontal Axis Wind Turbine [204]

- Rotor Blades,
- Nacelle with gearbox and Electrical generator.

Advantages: The advantages of HAWT are

1 HAWT collects maximum amount of wind energy by adjustable blade pitch control,

2 As the wind turbine is placed on taller towers facilitates access to the stronger winds at high altitudes,

3 HAWT has high efficiency as the blades moves perpendicular to wind and receives power through 360° rotation,

4 The wind loading on the turbine is consistent as the face of HAWT is facing the wind at a consistent angle. This results in a reduction of vibration and audible noise.

Disadvantages: The disadvantages of HAWT are

1 The taller tower and the wind turbine assembly occupies large area,

2 Transportation and installation of long wind turbine blades is costlier and difficult,

3 A heavy base tower is required to support heavy blades, gearbox and the generator,

4 In order to minimize fatigue loads due to wake turbulence, wind turbines have usually positioned a distance of 5 rotor diameter away from each other.

The power output of the wind turbine is given by the Equation 4.9

The area of swept (A) of HAWT is given as (4.24)

$$A = \frac{\pi}{4} D^2 \tag{4.24}$$

where D is the diameter of the rotor. The Simulink implementation of the HAWT is shown in Figure 4.12.

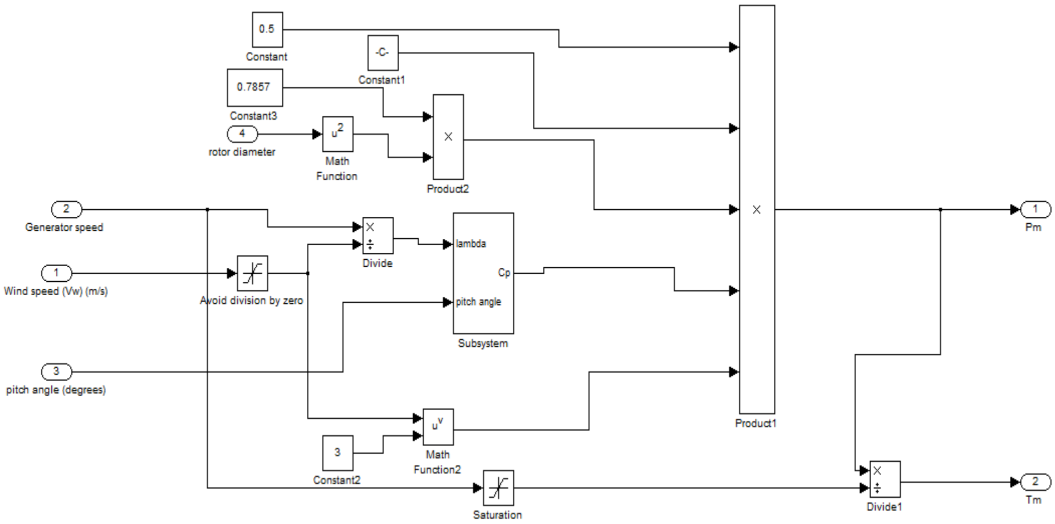

FIGURE 4.12: Simulink implementation of the HAWT

Key findings:

1 The mathematical modeling of the wind turbine has studied for both HAWT & VAWT,

2 The Simulink implementation of both the wind turbine are studied,

3 The main difference in the modeling of HAWT & VAWT is the area of swept of the turbine (A). The HAWT blade have larger diameter as compared with the VAWT,

4 The HAWT are used for high-speed generation and the VAWT are preferred for low-speed generations because of the physical structure,

5 As the diameter of the rotor of HAWT increases i.e. area of swept (A) the power generating capability of the turbine increases. In the VAWT the rotor diameter and the length of the rotor have to be increased in order to increase the generation capability. By increasing the length of the rotor the VAWT will have the gravity problem. The HAWT are much balanced and are well supported by the structural design where the generator, gearbox, the turbine are enclosed in a capsule-like structure.

6 On observation HAWT has more advantages as compared to VAWT. HAWT is selected for the study whose parameters are tabulated in Table 4.1

TABLE 4.1: Wind turbine parameters

Parameter	Symbol	Value
Wind turbine rotor radius	R (m)	1.25
Length of blade	L (m)	2.5
Area of swept	A (m^2)	6.25
Air density	ρ (Kg / m^2)	1.225
Pitch angle	v (degree)	0

In this subsection the relevant models of wind turbine are established. From which the HAWT is selected for further study in wind based generation system. After wind turbine the next building block in wind power generation as shown in Figure 4.4 is Electrical Generator. Further the modeling of Electrical generator will be discussed.

4.4 Electrical Generator:

The wind turbine is coupled to the electrical generator to convert the mechanical power extracted from the wind into electrical power. The general schematic of wind power generator is shown in Figure 4.3. Wind power has evolved as a viable source of power generation and is economical as compared with the other non-conventional energy sources. It offers a feasible solution to the distributed power system. A wind turbine, a rotating device captures the wind energy and converts it into kinetic energy and by coupling electric power generator to wind turbine the kinetic energy can be converted into electrical power [205]. The different electrical generators are

- Induction Generator or Asynchronous Generator,
- Wound Rotor Synchronous Generator (WRSG),
- Doubly-Fed Induction Generator (DFIG),
- Permanent Magnet Synchronous Generator (PMSG),
- High-Voltage Generator (HVG),
- Switch Reluctance Generator (SRG).

If the wind profile is promising at the location then the implementation of high capacity direct driven wind power generation is more feasible eliminating the gearbox. In such case the wind power generation can be used as an isolated or grid connected power generation system, feeding local load in an isolated system and feeding the excess power into the grid in grid connected system [206].

This will be not the same when the wind profile is not promising. It is not economical to install large capacity wind turbines for the low wind speed locations. For such locations variable speed small wind turbines with Permanent Magnet Synchronous Generator (PMSG) can be utilized to extract maximum power from the conditions. Wind power generation using Induction generator, doubly fed induction generators, Permanent Magnet Synchronous Generator (PMSG), etc. and with various control methods and different ways of extracting power from the wind under different conditions have been proposed by various researchers [207–209].

The large capacity wind turbines have greater inertia which helps it to overcome small changes in the wind speed. Small changes in wind pattern will not affect the output voltage. However when considering small wind turbines the effect of a change in wind speed affects the output performance of the wind turbine. Few techniques like gearbox, flywheels etc. are incorporated into small wind turbines to overcome the fluctuations due to change in wind speed. However, the gearbox adds weight and maintenance due to which the overall system efficiency decreases. In order to overcome these drawbacks direct driven PMSG machines has emerged as the best alternative. PMSG based wind power generation has the advantage of permanent magnets for magnetic flux production eliminating additional supply for excitation and can be used for power generation at low wind speed [210, 211]. The schematic of wind power generation is as shown in Figure 4.13. The mathematical modeling of PMSG will be discussed in the following subsection.

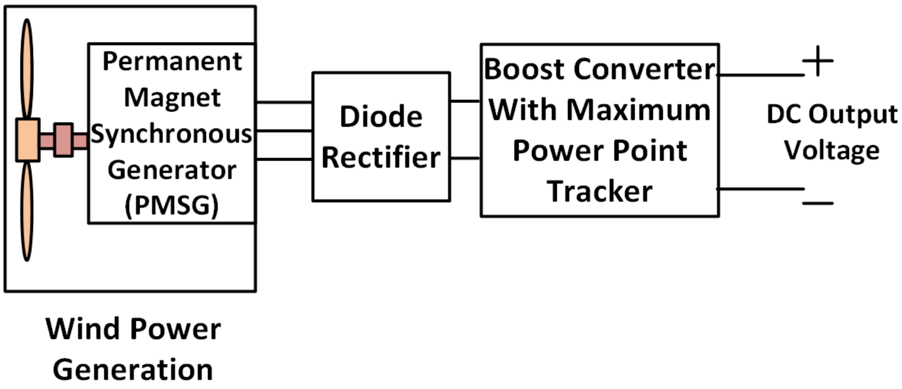

FIGURE 4.13: Schematic diagram of wind power generation system

4.4.1 Mathematical Modeling of PMSG:

The Park's transformation is a mathematical transformation which aims to simplify the analysis of synchronous machinery models, and was first introduced by R. H. Park in 1929. In the three-phase PMSG, the phase quantities which include stator voltages, stator currents, and flux linkages, are time varying quantities. By applying Park's transformation, which is in essence the projection of the phase quantities onto a rotating two axes reference frame, the AC quantities are transformed to DC quantities which are independent of time. The abc to dq0 transformation can be expressed in matrix form (4.25) [212, 213]

$$\begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} cos(\theta_r) & cos(\theta_r - \frac{2\pi}{3}) & cos(\theta_r + \frac{2\pi}{3}) \\ -sin(\theta_r) & -sin(\theta_r - \frac{2\pi}{3}) & -sin(\theta_r + \frac{2\pi}{3}) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \cdot \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \tag{4.25}$$

The inverse park's transformation is given by (4.26)

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} cos(\theta_r) & -sin(\theta_r & \frac{\sqrt{2}}{2} \\ cos(\theta_r - \frac{2\pi}{3}) & -sin(\theta_r - \frac{2\pi}{3}) & \frac{\sqrt{2}}{2} \\ cos(\theta_r + \frac{2\pi}{3}) & -sin(\theta_r + \frac{2\pi}{3}) & \frac{\sqrt{2}}{2} \end{bmatrix} \cdot \begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix} \tag{4.26}$$

where u can be Voltage (V), Current (I) or Flux (λ)

The dynamic equation based modeling of PMSG in dq reference frame is given by (4.27), (4.28)

$$\frac{di_d}{dt} = \frac{1}{L_d}(-R_s i_d + \omega_e L_q i_q + V_d) \tag{4.27}$$

$$\frac{di_q}{dt} = \frac{1}{L_q}(-R_s i_q - \omega_e[L_d i_d + \lambda_o] + V_q) \tag{4.28}$$

where

R_s - Stator Resistance (Ω),

L_d, L_q - Inductance of the generator on d and q axis (H),

λ_o - magnetic flux of permanent magnet (wb),

i_d,i_q - d and q axis currents (A),

V_d, V_q - Voltage across the load on d and q axis (V),

ω_e - Speed of generator (rad/s) = P.ω_m

Assuming the inductance of generator on d, q-axis as (4.29)

$$L_d = L_q = L \tag{4.29}$$

substituting (4.29) in (4.27), (4.28)

$$\frac{di_d}{dt} = -\frac{R_s i_d}{L} + \omega_e i_q + \frac{V_d}{L} \tag{4.30}$$

$$\frac{di_q}{dt} = -\frac{R_s i_q}{L} + \omega_e (i_d + \frac{\lambda_o}{L}) + \frac{V_q}{L} \tag{4.31}$$

The q-axis counter electric potential and the d-axis counter electric potential and the equivalent circuit for both d and q axis derived from (4.30), (4.31) are shown in Figure 4.14, and Figure 4.15. The electric

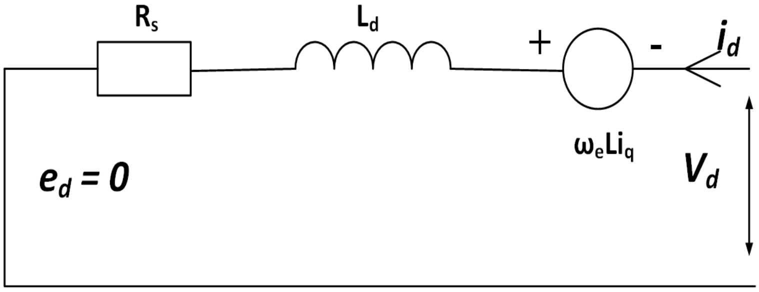

FIGURE 4.14: The equivalent circuit of d-axis

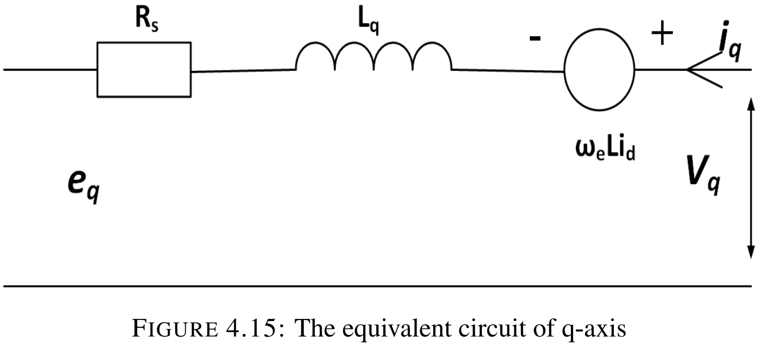

FIGURE 4.15: The equivalent circuit of q-axis

torque produced by the PMSG is given by (4.32)

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\lambda_o i_q - \lambda_q i_d) \tag{4.32}$$

where P is the number of pole pairs.

Re-writing the (4.32) as (4.33)

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\lambda_o i_q + (L_d - L_q) i_q i_d) \tag{4.33}$$

As both d and q- axis inductances are equal, hence the electromagnetic torque (4.33) can be expressed in terms of i_q as (4.34):

$$T_e = 1.5 P i_q \lambda_o \tag{4.34}$$

The PMSG is modeled in the MATLAB, Simulink using Equations 4.25 - 4.34 and shown in Figure 4.16 and the necessary parameters of the PMSG are tabulated in Table 4.2. The output voltage from the PMSG is not a constant value as its variation depends on the variation in wind speed. In order to maintain constant output voltage across the load the variable output voltage from the PMSG is rectified using diode bridge rectifier and the rectified voltage is steped up to the required level and maintained constant using a boost converter. The modeling of boost converter will be discussed in detail.

TABLE 4.2: Parameters of PMSG

Parameter	Symbol	Value
Power output	W (kW)	3
Stator Resistance	R_s (Ω)	2.875
Inductance on d-axis	L_d (H)	0.0085
Inductance on q-axis	L_q (H)	0.0085
Magnetic flux	λ_o (wb)	0.175
Pole Pairs	P	12
Moment of inertia	J (Kg m^2)	0.0008

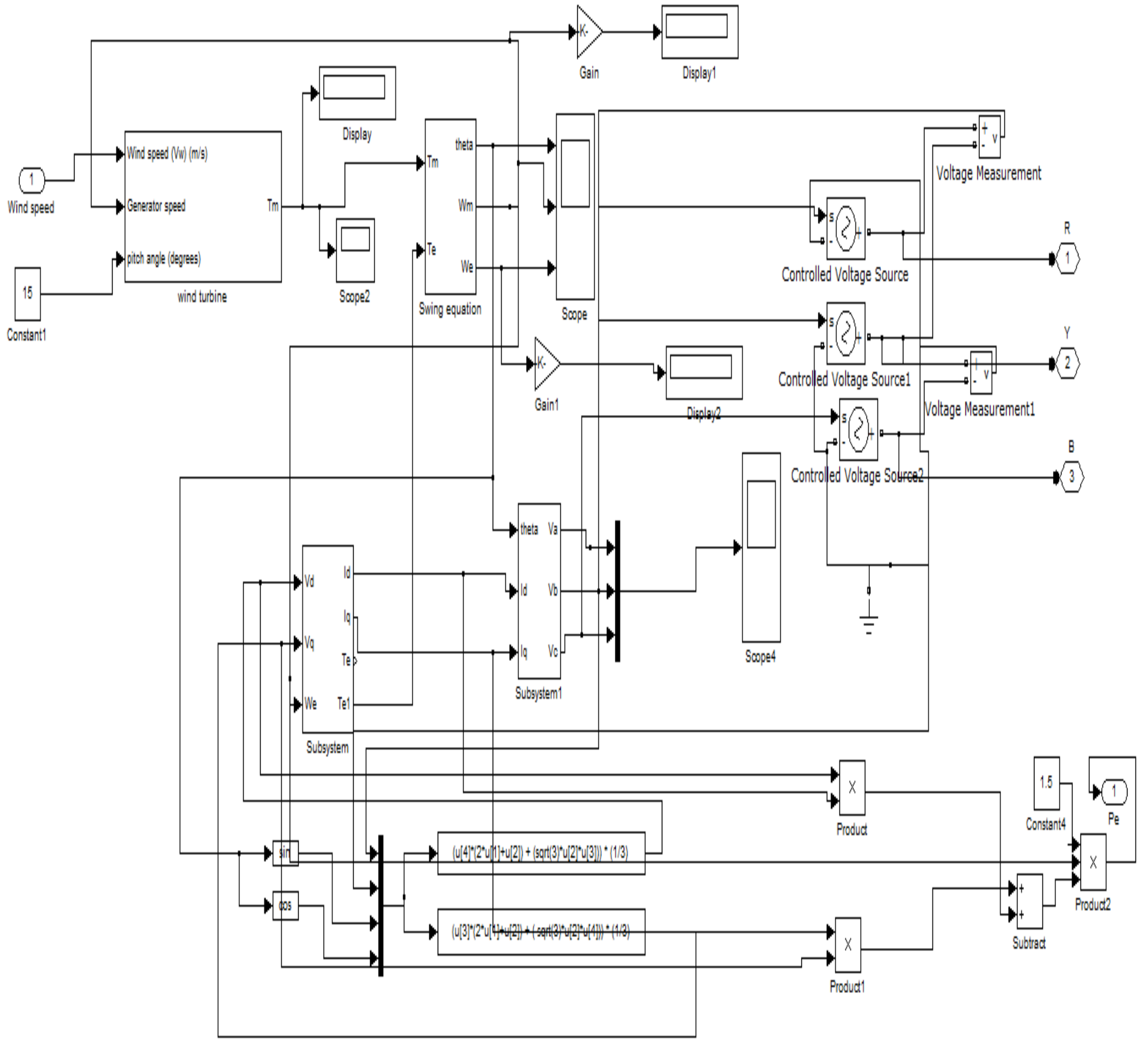

FIGURE 4.16: Equation based implementation of PMSG in Simulink

4.4.2 Boost Converter:

This variable dc voltage is given as input to the MPPT (Maximum Power Point Tracking) controlled boost converter as shown in Figure 4.17 in order to maintain the desired output voltage for the smooth operation. The voltage and current samples from the output of diode rectifier and angular speed of the wind turbine are given as the input to the MPPT control logic. The mathematical modeling of the boost converter is similar to modeling of boost converter discussed in Subsection 3.4.4.

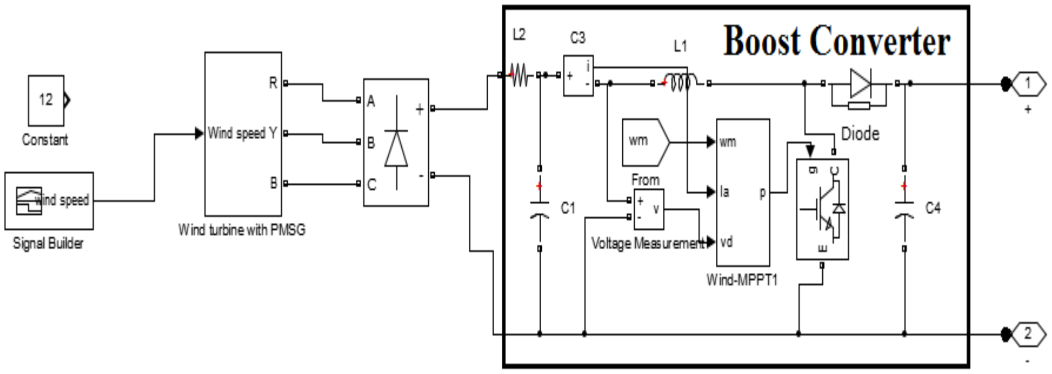

FIGURE 4.17: Boost converter in wind power generation system

4.4.3 Maximum Power Point Tracking Algorithm

Wind energy, being abundant in nature, the consistency of wind speed is a major challenge for wind power generation. The power output of the wind power generation directly relies on the accurate tracking of peak power by MPPT controller. From the literature [214–226] the different MPP control techniques investigated are using Fuzzy logic, ANN, HCS, and different optimizing techniques. The MPPT algorithm are classified into three main control methods,

- Tip Speed Ratio (TSR) control,
- Power Signal Feedback (PSF) control, and
- Hill climb Search (HCS) control.

4.4.3.1 Tip Speed Ratio (TSR) control

The TSR control methodology regulates the rotational speed of the generator to maintain the TSR to an optimum value at which power extracted is maximum. This method requires both the wind speed and the turbine speed to be measured in addition to the knowledge of optimum TSR of the turbine to operate the system at maximum power point to extract maximum power. The block diagram representation of TSR control is shown in Figure 4.18.

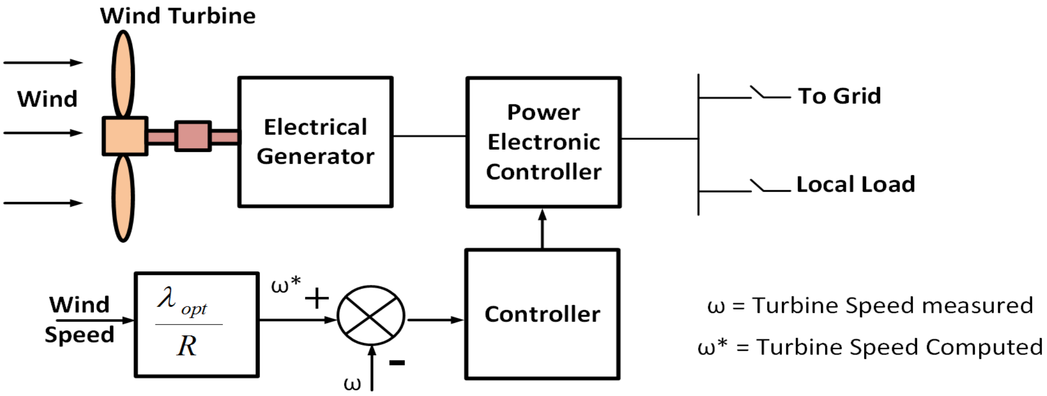

FIGURE 4.18: Tip Speed Ratio control of Wind Power generation

4.4.3.2 PSF control Implementation

Implementation of PSF control requires knowledge of the wind turbine maximum power curve, and track this curve through its control mechanism. The maximum power curve can be obtained by simulating or off-line experimental on an individual wind turbine. In this technique, reference power is generated either using a measured or simulated maximum power curve or using the mechanical power equation of the wind turbine where wind speed or the rotor speed is used as the input. The block diagram representation of PSF control technique is shown in Figure 4.19.

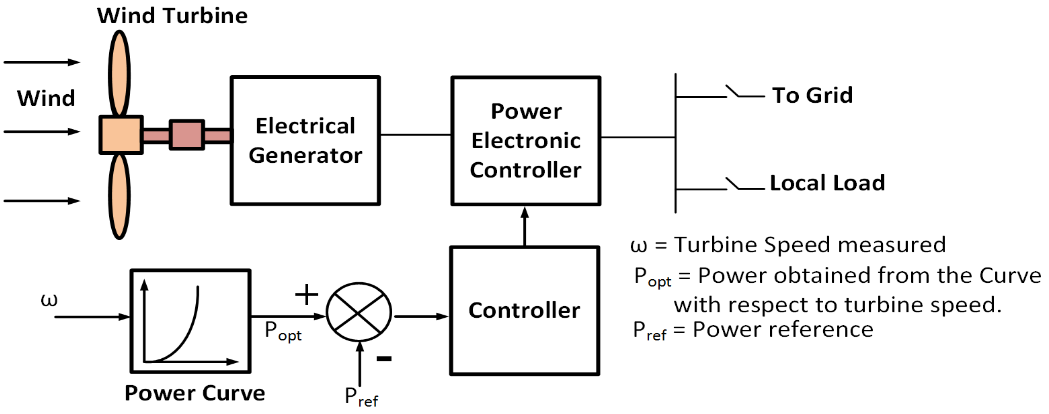

FIGURE 4.19: Power Signal Feedback control of Wind Power generation

4.4.3.3 HCS control Implementation

The HCS control algorithm continuously searches for the peak power of the wind turbine. The tracking algorithm depends on the location of the operating point in the power characteristics and relation between the change in power to speed. which is utilized to compute the desired optimum signal to extract maximum power from the wind generation system. The graphical representation of HCS algorithm is shown in Figure 4.20.

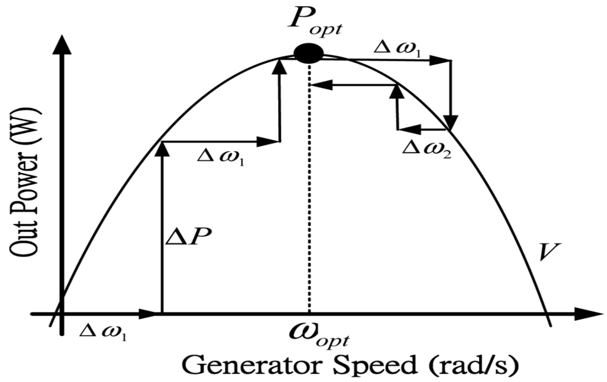

FIGURE 4.20: MPP tracking using HCS algorithm

Selection of MPPT algorithm:

1. The TSR control technique is accurate, highly efficient and robust. But, the technique requires an accurate anemometer for wind speed measurement. which makes this control technique complex, costlier for wind energy generation especially for small scale generation.

2. The main drawback of PSF control technique is the reference characteristics for the control are obtained from simulation or experimental test. The actual characteristics of the wind power generation may vary from the test conditions.

3. The HCS control technique implementation can overcome the problems associated with the other two techniques and provide optimum tracking of the MPP. The HCS algorithm is selected for the further study. The HCS algorithm is selected based on easy implementation, robust and accuracy [227].

4.4.3.4 Hill Climb Search Control algorithm:

The HCS algorithm is widely used for MPP tracking in wind power generation. A typical power output versus generator speed characteristics is shown in Figure 4.20. The inputs to the MPPT are the voltage and current samples sensed at the output of the electrical generator and speed of the wind turbine as one of the control parameters. Using these input the control logic which computes the duty cycle of the power electronic switch in the boost converter is controlled. Thus the MPP of the wind generation is continuously tracked by the MPPT control logic and the output of wind power system is boosted up to the desired value.

The Simulink implementation of HCS MPPT algorithm is shown in Figure 4.21.

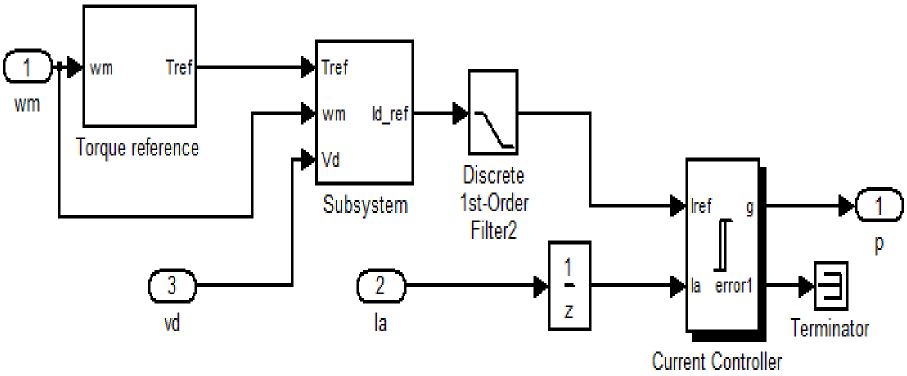

FIGURE 4.21: Simulink implementation of HCS MPPT algorithm

4.5 Simulation results:

The Simulink model of PMSG based wind power generation system has been implemented and the Simulink model is simulated with a resistive load of 2.7KW at 220V. The MPPT controller action for the wind power system developed is investigated for four different conditions,

1. Constant Wind Speed and Constant resistive load,
2. Constant Wind speed and Varying resistive load,

3. Varying Wind Speed and Constant resistive load, and
4. Varying wind speed and Varying resistive load.

The constant wind speed considered is 12 m/s as it represents standard test parameter or base wind speed. The varying wind speed is real-time data of wind measured at BITS-Pilani, Hyderabad campus.

4.5.1 Case i: Constant wind speed and constant resistive load:-

Considering the wind speed is constant at 12 m/s and simulating the system to feed a DC load of 2.7 KW at 220V. The wind pattern as shown in Figure 4.22 and the respective load voltage, current, and power are graphically represented in Figure 4.23.

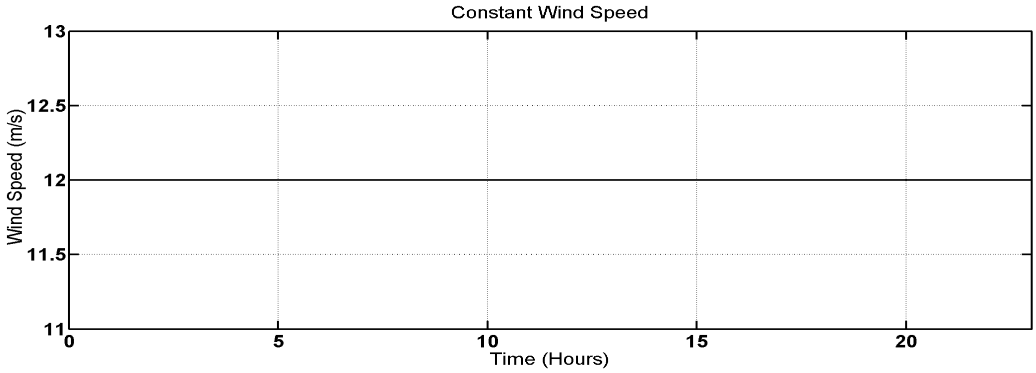

FIGURE 4.22: Wind speed

Figure 4.23 shows the simulated results of wind power system for a constant wind speed of 12 m/s as shown in Figure 4.22. It can be analyzed that the output voltage of the wind power system is boosted up to the desired voltage level of 220V by boost converter and is maintained constant. The required load current of 12.3A is supplied by the wind power generator and load power of 2.7KW is maintained constant at desired level.

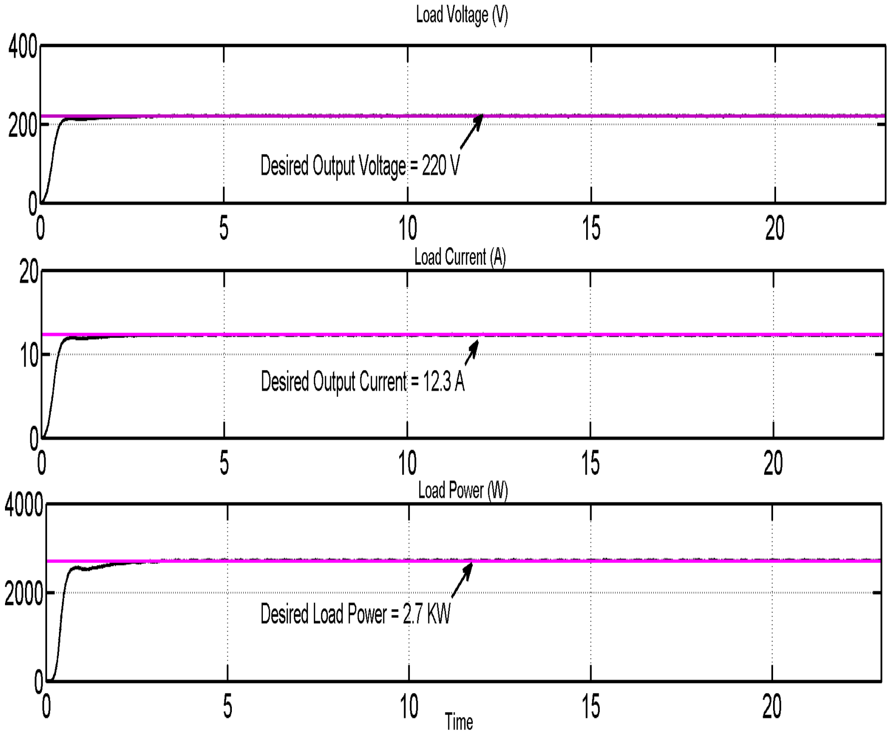

FIGURE 4.23: Simulated Load Voltage, Current, and Power

4.5.2 Case ii: Constant wind speed and variable resistive load:-

The performance of the MPPT algorithm is investigated under varying load condition keeping the wind speed constant. The simulation results of the wind power system are graphically represented in the Figure 4.24.

From the Figure 4.24 it can be comprehended that the load voltage remained constant at 220 V with the change in load condition. The load on the system is increased in steps from 1000W, 1500W, 2000W and 2700W. At the instance of the load change, we can observe that the output voltage is brought to the required value without any steady state error. The desired controller action is to maintain load voltage at desired value of 220 V after load changes but the control brings back the output voltage to 224 V slightly higher than desired value of 220 V after a change in load. However, the load perturbation is affecting the voltage profile of the system. The variation of load voltage in time for each change in load is tabulated in Table 4.3.

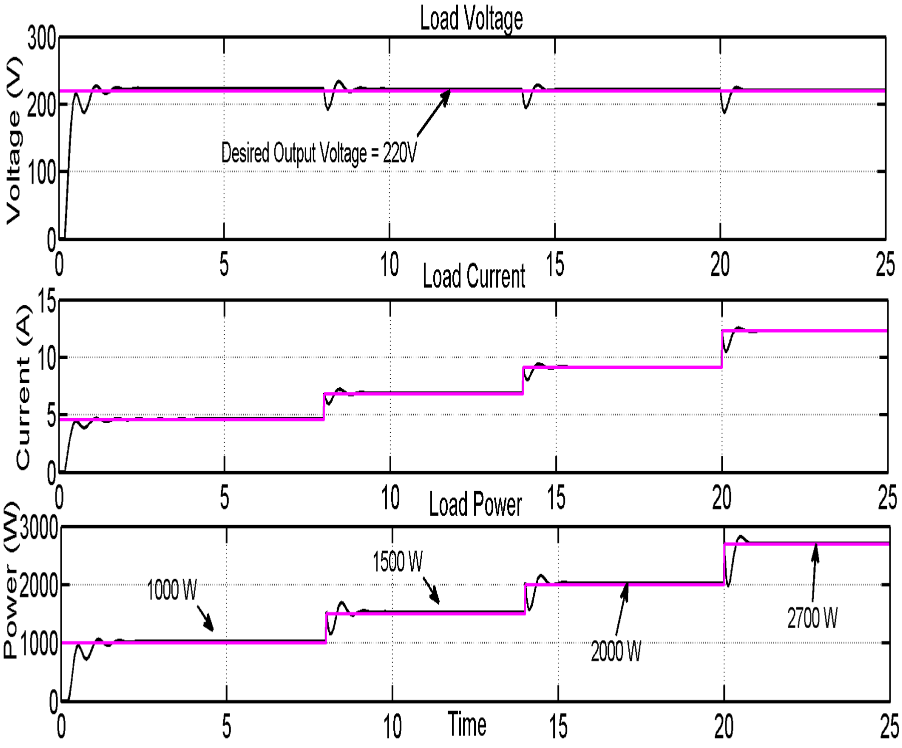

FIGURE 4.24: Simulated Load Voltage, Current, and Power

TABLE 4.3: The output voltage variation in time and steady state error under varying wind speed and constant load condition

S No	Time of Load Change (sec)	Settling Time (sec)	Effective Time (sec)	Steady State Error
1	8	9.7	1.7	4 V
2	14	15.35	1.35	4 V
3	20	21.1	1.1	1.8 V

4.5.3 Case iii: Varying wind speed and constant resistive load:-

Considering the real-time data of wind speed measured at BITS-Pilani, Hyderabad campus is utilized to evaluate the performance of the MPPT controlled boost converter. The wind speed pattern is represented in the Figure 4.25. The variable wind speed is applied as input to the wind power system for a constant resistive load of 2.7 kW and the output DC voltage, current and Power measured at the load are graphically represented in Figure 4.26 From The Figure 4.26 it can be comprehended that the output voltage was boosted up to the desired value of 220 V and the controller maintains the output voltage at 220 V with sight fluctuations with a minimum voltage dip of 210 V and brings back the voltage to 220 V. Similar

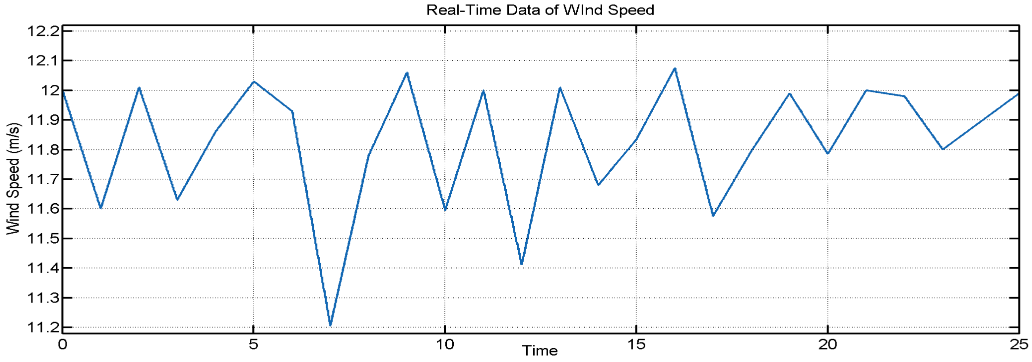

FIGURE 4.25: Real-Rime data of Wind speed

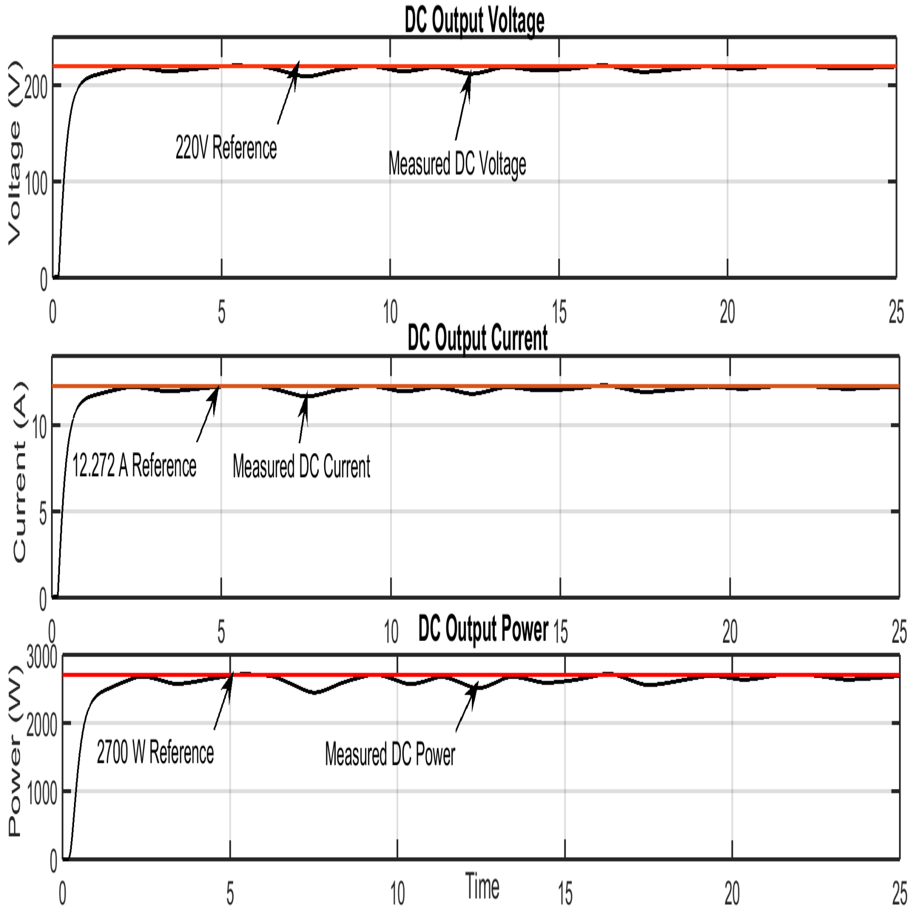

FIGURE 4.26: Simulated Load Voltage, Current, and Power

deviation in output current and Power delivered can be observed. The output voltage profile of the system is a constant value the controller tries to maintain the output voltage at desired value under varying wind speed condition with a constant load.

4.5.4 Case iv: Varying wind speed and variable resistive load:-

The performance of the MPPT controlled boost converter is evaluated under varying wind speed and load condition. The real-time data of wind speed is shown in Figure 4.25 and the resistive load on the system is varied from 1000W, 1500W, 2000W and 2700W. The simulated DC output Voltage, Current, and Power are shown in Figure 4.27.

The Figure 4.27 represents simulated DC output voltage, current and Power measured at the output of

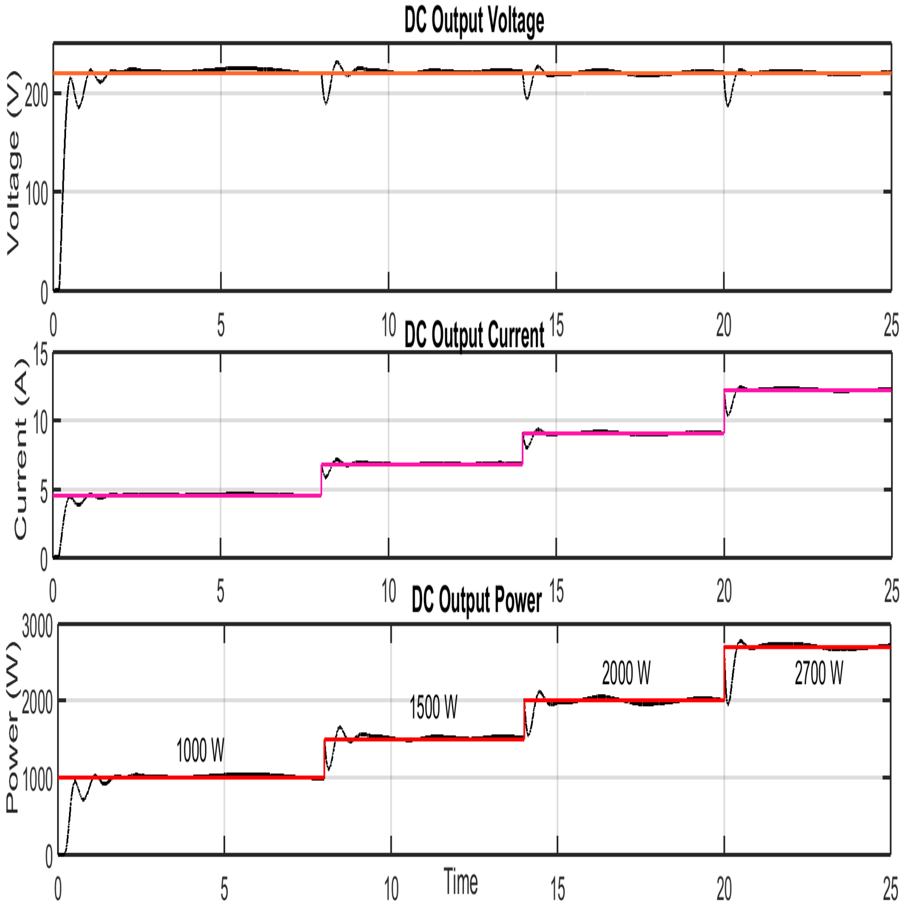

FIGURE 4.27: Simulated Load voltage, Current and Power

TABLE 4.4: The output voltage variation in time and steady state error under varing wind speed and load condition

S No	Time of Load Change (sec)	Settling Time (sec)	Effective Time (sec)	Steady State Error
1	8	10.2	2.2	0
2	14	15.6	1.6	0
3	20	21	1	0

wind power generation system under varying wind speed and load condition. From the output plot it can be comprehended that the output voltage is not constant during the load transitions and has a setting time which is tabulated in Table 4.4 . Similarly this can be observed in output current and power waveforms. The desired operation of the controller would be maintaining the output voltage constant irrespective of change in wind speed and load condition. The output voltage after the load change settles at 220 V.

4.6 Summary:

The dynamic modeling of Wind turbine, equation based modeling of PMSG, MPPT controller boost converter implementation using Hill Climb Search is studied and simulated MATLAB/Simulink. The performance of the wind power system is analyzed for four different conditions namely

1. Constant Wind Speed and Constant resistive load,
2. Constant Wind Speed and Varying resistive load,
3. Varying Wind Speed and Constant resistive load, and
4. Varying Wind Speed and Varying resistive load.

The simulation study is carried for a constant wind speed at 12 m/s and variable wind speed measured at BITS-Pilani, Hyderabad campus. The profile of varying wind is represented in Figure 4.25. A constant resistive load of 2.7 kW is considered and load variation of 1000 W, 1500 W, 2000 W and 2700 W is applied to the wind power system.

MPPT controller plays a key role in improving the efficiency and reliability of the wind power system under various conditions of wind speed and load. The performance of the direct driven PMSG wind power generations has been investigated under different cases mentioned above. The performance of the system and controller action is as desired for constant wind speed pattern and constant load condition.

The controller tries to maintain the output voltage constant under varying wind speed and constant load case.

For the case ii and case iv of the study the output voltage changes for every change in load. The settled output voltage have a slight steady state error for case iv as shown in Table 4.3 and Table 4.4. So, the output voltage profile is not constant and the load changes are affecting the system performance. In order to have a better and smooth control of output power, a Fuzzy Logic Control (FLC) based MPP tracking will be implemented to overcome the transients of voltage under varying wind speed and load conditions. This chapter presents mathematical modeling and Simulink implementation of Wind-based generation in the Hybrid power system. The performance of the HAWT coupled to PMSG based wind power generation is analyzed under varying load and wind speed conditions. The performance of the HCS MPPT algorithm to track the maximum power point under varying wind speed and load is simulated. From the simulations results, it can be comprehended that during load change the output voltage is not smooth. In order to overcome this effect and to have better output voltage a FLC-based MPPT controller implementation for the system will be investigated in the next chapter. The next chapter focus on the integration of PV and Wind based generation to form PV-Wind hybrid power system and the performance of the hybrid power system is analyzed with the real-time data of Solar illumination and wind speed measured at BITS-Pilani, Hyderabad campus.