iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 6 Issue: I Month of publication: January 2018

DOI: http://doi.org/10.22214/ijraset.2018.1321

www.ijraset.com

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor :6.887
Volume 6 Issue I, January 2018- Available at www.ijraset.com

Performance Analysis of Permanent Magnet Synchronous Generator Wind Turbine for Variable Wind Velocity

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Abstract: The interest in wind energy system is growing worldwide to reduce dependency on fossil fuel and to minimize the adverse impact of climate change. Currently, doubly fed induction generator (DFIG) based variable speed wind turbine technology with gearbox is dominating the world market share. However, the problems associated with induction generator based wind turbines are reactive power consumption, mechanical stress and poor power quality. Moreover, the gearbox requires regular maintenance as it suffers from faults and malfunctions. Therefore, it is important to adopt technologies that can enhance efficiency, reliability and reduce system cost of wind based power generation system. The performance of a variable speed wind turbine can be enhanced significantly by using a low speed permanent magnet synchronous generator (PMSG) without a gearbox. The main features of PMSG based wind turbines are; gearless operation, higher efficiency, enhanced reliability, smaller size, reduced cost and low losses.
Keywords: Wind Energy, Wind Velocity, pitch angle, Cut-in Speed, Cut-out Speed, Wind Turbine, PMSGWT-Modal, WECS, MATLAB/SIMULIK.

I. INTRODUCTION

Wind energy is available and clean source of energy that has been used to generate electrical power. The focus on electrical power generated from wind energy has been increased due to the environmental problems that fossil fuels make. Global warming and green house emissions are the main harmful results of fossil fuel consumption. The first wind turbines appeared at the beginning of the last century and technology was improved step by step from the early 1970s. By the end of the 1990s, wind energy has re-emerged as one of the most important sustainable energy resources. Currently, five countries (Germany, USA, Denmark, India and Spain) concentrate more than 83% of worldwide wind energy capacity in their countries. The wind farms are located on land and due to scarcity of land and wind energy extraction wind turbine site are located offshore. The electrical wind turbine generators are an interface connection between the mechanical part of the system and the electrical part. The main function of the electrical generator is to convert the mechanical energy coming from the wind turbine which acts as a prime mover to electrical energy that is transferred to the electrical grid. Wind turbines are different types and generally categorized in two types according the wind speed, variable wind speed turbines and fixed wind speed turbines.

Wind turbines electrical generators commonly used are:

1. Squirrel-Cage rotor Induction Generator (SCIG).2-Wound-Rotor Induction Generator (WRIG).3-Doubly-Fed Induction Generator (DFIG).4- Synchronous Generator (SG) with external field excitation.5- Permanent Magnet Synchronous Generator (PMSG).

Moreover, the Permanent Magnet Synchronous Generator (PMSG) offers better performance than other generators because of its higher efficiency and of less maintenance since they don't have rotor current and can be used without a gearbox, which also implies a reduction of the weight of the nacelle and a reduction of costs *[1]*. WECS can be used in two different ways namely isolated standalone system and Grid connected system. Standalone systems are employed to the needs of small scale industries for rulers areas, such system are located at for off places/remote areas. Grid connected system increased energy efficiency, robustness, voltage support, diversification of energy sources, reduced transmission and distribution losses and reliability of the system *[2]*. MATLAB/SIMULINK is a graphical software package for modeling, simulating and analyzing dynamic systems. It supports linear and nonlinear systems both in continuous time and sample time *[3]*. This paper described the modelling and simulation of PMSG based on WECS and modelling of converter and inverter and control system are does not included.

II. WIND TURBINE OUTPUT EQUATION

The actual power output of a wind turbine generator (WTG) system depends on the actual wind speed, rated wind speed, cut in speed (i.e., speed at which system losses equal the extracted wind power) and cut out speed (i.e. speed at which the wind mill has to be shut down for safety reasons.) The power output can be approximated by the relation *[4]*.

Actual power output $= 0$ for $0 < \nu < \nu_{ci}$

$= (A + B\nu + c\nu^2)\, p_r$ for $\nu_{ci} < \nu < \nu_r$ ………1

$= P_r$ for $\nu_r < \nu < \nu_{co}$

$= 0$ for $V > V_{co}$

Where ν = actual wind speed

P_r = rated power output

ν_{ci} = cut in wind speed

ν_r = rated wind speed

ν_{co} = cutout wind speed

A, B, C are functions of ν_{ci} and ν_r

Fig. 1 shows three circular at inlet, turbine blade and exit of wind

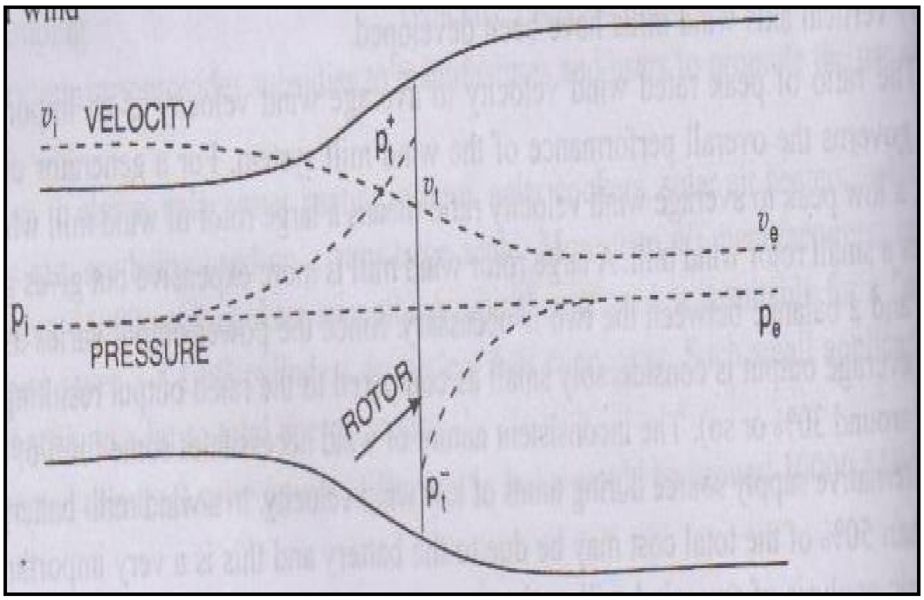

Fig.1: Energy Extraction by Wind Turbine Rotor *[5]*

Let A_i = area at inlet, m^2

A_t = area at turbine rotor, m^2

A_e = area at exit, m^2

ν_i = wind velocity at inlet, m/s

ν_t = wind velocity at turbine rotor, m/s

ν_e = wind pressure at exit,m/s

p_i = wind pressure at inlet, N/m^2

p_e = wind pressure at exit, N/m^2

p_t^+ = wind pressure at rotor upstream, N/m^2

P_t^- = wind pressure at rotor downstream, N/m^2

ρ = density of air, kg/m^3

The mass flow rate must be the same across the three areas i.e. inlet, turbine rotor and exit. Therefore

$$\rho A_i \nu_i = \rho A_t \nu_t = \rho A_e \nu_e \quad \text{……….2}$$

The rotor induces a velocity variation which is superimposed on the free stream velocity. The induced flow at rotor is $- a\,\nu_i$ where 'a' is called the axial flow induction factor. Therefore

$$\nu_t = \nu_i(1 - a) \quad \text{……….3}$$

The air undergoes a change in velocity $\nu_i - \nu_e$ from inlet to exit. The rate of change of momentum is equal to mass flow rate multiplied by change of velocity. Therefore

Rate of change of momentum = $(\nu_i - \nu_e)\,\rho A_t \nu_t$ ………4

The force which causes change of momentum is due to pressure difference across the rotor. The change in pressure is form p_t^+, to p_t^-,. Therefore

$(p_t^+ - p_t^-)\,A_t = (\nu_i - \nu_e)\,\rho A_t \nu_i = (\nu_i - \nu_e)\,\rho A_t \nu_i (1-a)$ ………5

To find $(p_t^+ - p_t^-)$ we can use Bernaulli's equation. As per Bernaulli's equation, under state conditions the total energy in the flow (i.e. sum of kinetic energy, static pressure energy and gravitational potential energy) remains constant provided no work is done on or by the fluid. Thus for a unit volume of air

$$\frac{1}{2}\rho\nu^2 + p + \rho gh = \text{constant} \qquad \text{………6}$$

Upstream conditions give

$$\frac{1}{2}\rho_i\nu_i^2 + p_i + \rho_i gh_i = \frac{1}{2}\rho_t\nu_t^2 + p_t^+ + \rho_t gh_t \qquad \text{…………7}$$

Assuming the flow to be incompressible ($\rho_i = \rho_t$) and horizontal ($h_i = h_t$) we get

$$\frac{1}{2}\rho\nu_i^2 + p_i = \frac{1}{2}\rho\nu_t^2 + p_t^+ \qquad \text{…………8}$$

Downstream conditions give

$$\frac{1}{2}\rho\nu_e^2 + p_i = \frac{1}{2}\rho\nu_t^2 + p_t \qquad \text{………..9}$$

Subtracting Eq. (9) from Eq. (8)

$$p_t^+ - p_t^- = \frac{1}{2}\rho(\nu_i^2 - \nu_e^2) \qquad \text{………10}$$

Subtracting Eq. (10) into Eq. (5) we get

$$\frac{1}{2}\rho(\nu_i^2 - \nu_e^2)\,A_t = (\nu_i - \nu_e)\,\rho A_t \nu_i (1-a) \qquad \text{………..11}$$

Eq. (11) gives

$\nu_e = (1-2a)\,\nu_i$ ………..12

Thus half of axial speed loss occurs upstream of rotor and half downstream. From Eq. (5) the force F on air is

$F = (p_t^+ - p_t^-)\,A_t = 2\rho A_t \nu_i^2 a(1-a)$ ……….13

The rate of work done by force F is F ν_t. The power extracted from air is P_t and is given by

$P_t = F\nu_t = 2\rho A_t \nu_i^3 a(1-a)^2$ ………14

Power coefficient C_p is defined as

$$C_p = \frac{P_t}{\frac{1}{2}\rho\nu_i^3 A_t} \qquad \text{………15}$$

In Eq. (15), $\frac{1}{2}\rho\nu_i A_t$ represents power available in air.

Combining eq. (14) and (15)

$C_p = 4a(1-a)^2$ ………16

For maximum value of C_p, $\frac{dC_p}{da}$ should be zero.

$C_p = 4a\,(1-a)^2 = 4a\,(1+a^2 - 2a)$

or $C_p = 4a^3 - 8a^2 + 4a$

$$\frac{dC_p}{da} = 12a^2 - 16a + 4 = 0$$

or $3a^2 - 4a + 1 = 0$

Which gives $a = \frac{1}{3}$ ……….17

Therefore $C_{p.\max} = 4\left(\frac{1}{3}\right)\left(1 - \frac{1}{3}\right) = \frac{16}{27} = 0.593$ ……….18

This means that an ideal turbine cannot extract more than 59.3% of power in the undisturbed wind. This is known as Betz Criterion (named after German aerodynamicist Albert Betz)

ρ = Density of air = 1.293 kg/m^3

$A_t = \frac{\pi}{4} D^2$ = where D is diameter of rotor

Since $\nu_t = \nu_i$ (1-a) and $a = \frac{1}{3}$

$$\upsilon_t = \frac{2}{3}\upsilon_i$$

$$\upsilon_e = (1 - 2a)\upsilon_i = \frac{\upsilon_i}{3}$$

Though the power coefficient for an ideal with turbine is 0.593, it has been found that its more practical value is about 0.45. Further the generator also has some losses and the overall power coefficient is about 0.35 *[5]*.

III. WIND TURBINE POWER CHARACTERISTICS

The power curve is the most important technical information for a wind turbine. The power characteristics of a wind turbine are defined by the power curve and the power curve relates the mechanical power of the turbine vs. wind speed. The power curve is a wind turbines certificate of performance that is guaranteed by the manufacturer. A typical power curve is shown in Fig.2. This curve is characterized by three speeds:

A. Cut-in speed
B. Rated wind speed
C. Cut out wind speed

The cut in wind speed is the speed at which wind turbine starts to operate and deliver power. Below cut-in wind speed the turbine does not capture enough power to compensate for the power losses in the wind turbine drive train. Therefore, the wind turbine is shut down. The rated wind speed is the speed at which the wind turbine produce rated power. The cut-out speed is the highest wind speed at which the turbine is allowed to operate before it shut down. The turbine must be shut down to prevent mechanical damage if the wind speed is above the cut-out speed.

As indicated in Fig.2, the wind turbine starts to capture power at the cut-in speed and the captured power is a cubic function of wind speed. The turbine continues to capture power until the wind speed reaches the rated value. The wind turbine generator should be controlled properly with maximum power extraction under varying wind speeds. In this region, blade pitch angle is held constant. By varying generator torque, it is possible to vary rotor speed or tip speed in proportion to wind speed to deliver peak power coefficient Cp and therefore extract maximum power from wind. As the wind speed increases above the rated speed aerodynamic power control is required to keep the power at the rated value. Above the cut-out wind speed, the wind turbine should stop generating power and be shut down *[6]*.

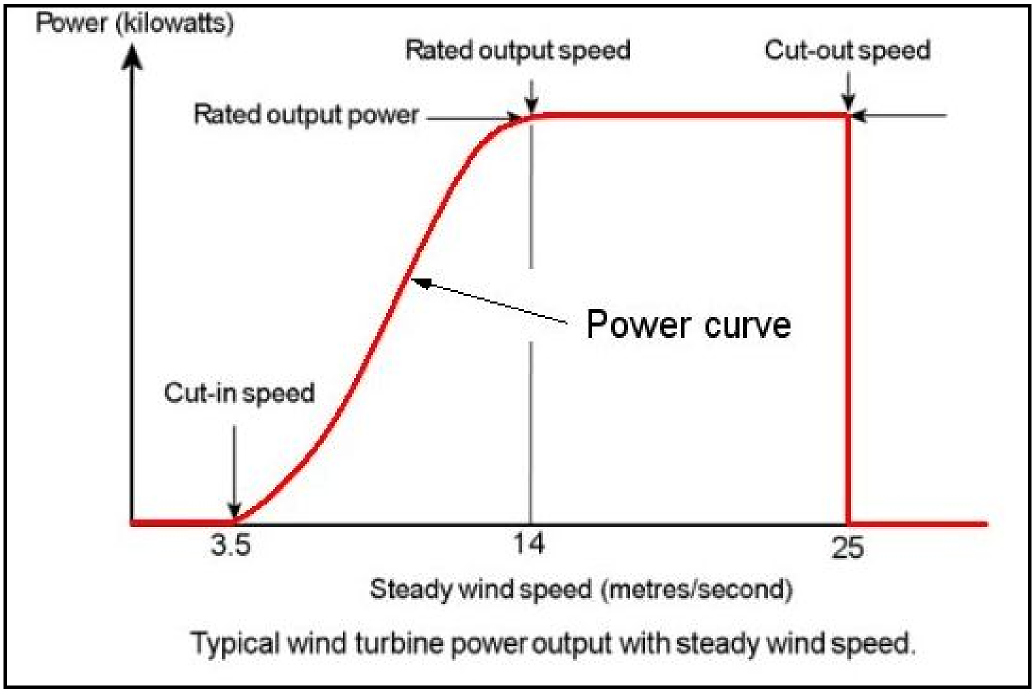

Fig.2: Wind Turbine Power Curve in Different Operating Region *[6]*

IV. DISCRETE WIND HISTOGRAM

Working with the mathematics of probability and statistics, which may be new territory for some. To help motivate our introduction to this material, we will begin with some simple concepts involving discrete functions involving wind speeds, and then we can move on to more generalized continuous functions.

What do we mean by the average of some quantity? Suppose, for example, we collect some wind data at a site and then want to know how to figure out the average wind speed during the measurement time. The average wind speed can be thought of as the total meters, kilometres, or miles of wind that have blown past the site, divided by the total time that it took to do so *[7]*.

Table-I: Wind data for a year *[7]*

Wind Speed (m/s)	Time (Hrs/yr)	Wind Speed (m/s)	Time (Hrs/yr)
0	24	13	243
1	276	14	170
2	527	15	114
3	729	16	74
4	869	17	46
5	941	18	28
6	946	19	16
7	896	20	9
8	805	21	5
9	690	22	3
10	568	23	1
11	444	24	1
12	335	25	0
		Total hrs in a year	8760

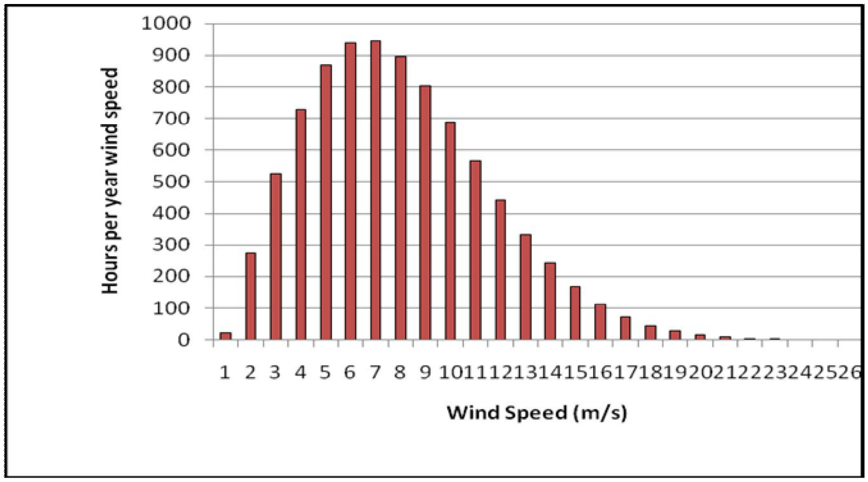

Fig. 3: wind histogram showing hours that the wind blows at each wind peed *[7]*.

V. PMSG BASED GEARLESS DIRECT DRIVE VARIABLE SPEED WIND TURBINE TECHNOLOGY

In this configuration, the generator rotor is directly connected to the turbine rotor without any gearbox and the generator is interfaced with the grid/load using full scale AC-DC-AC power converters as shown in Fig.4. This configuration is most suited for full power control as it is connected to the grid through a power converter. The permanent magnet synchronous generators (PMSGs) used in this configuration are low speed generators with suitable number of poles and able to produce higher torque at low speed. The full-scale power converter can perform smooth grid connection over the entire speed range. The power electronic converters used in this configuration have two primary goals: to act as an energy buffer (DC-link) for the power fluctuations caused by the wind turbine and for the transients coming from the grid side and enables the system to control active and reactive power. The main features of PMSG based wind turbines are -

1) Gearless operation and enhanced reliability.
2) Simple structure, smaller size and reduced cost.
3) Low mechanical and electrical losses.
4) Higher power factor and efficiency.
5) No requirement for reactive power support.
6) Higher cost and power losses in the converters.
7) No need of external excitation.

This type of wind turbine has a better fault ride through capability compared with the DFIG system with better efficiency and lesser complexity. Therefore, direct drive variable speed wind turbine is becoming more attractive. However, the reactive power requirements can be fulfilled through the power converter control for both DFIG and direct drive wind turbine with full scale converter concepts *[6]*.

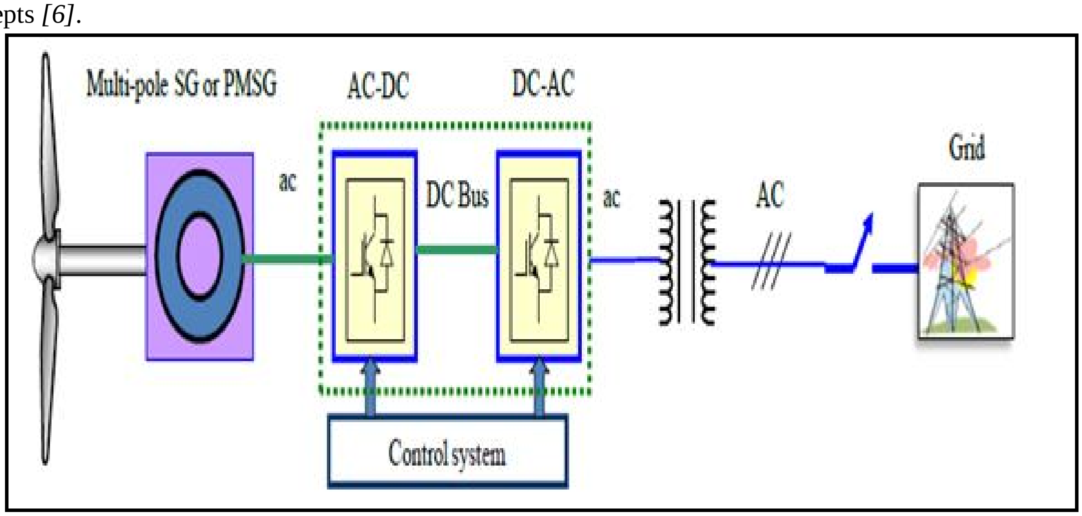

Fig. 4: Gearless Direct Drive Variable Speed Wind Turbine PMSG or Multi-Pole Synchronous Generator *[6]*

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VI. MODELLING OF THE PMSG WIND TURBINE

The Permanent Magnet Synchronous Generator (PMSG) offers better performance than other generators because of its higher efficiency and of less maintenance since they don't have rotor current and can be used without a gearbox, which also implies a reduction of the weight of the nacelle and a reduction of costs. VSWT wind turbine generator consists of another three parts: wind speed, wind turbine and drive train.

Fig. 5 shows a three phase two poles PMSG. It has 3 phase Y-connected stator windings and a permanent magnet in the rotor. The stator windings are identical windings displaced 1200, each with a turns number of *Ns* and resistance *Rs*. For our analysis we assume that the stator windings are sinusoidal distributed. Damper windings are neglected because the permanent magnet is a poor electrical conductor and the eddy current that flow in the nonmagnetic materials securing the magnets are small. Hence large armature current can be tolerated without significant demagnetization *[6]*.

The stator of a PM synchronous generator is similar to the wound rotor synchronous generator and the back emf produced by the permanent magnets is the same as that produced by an excited coil. In developing mathematical model for a PMSG we will assume the following;

A. The stator windings are sinusoidal distributed along the air gap
B. Magnetic saturation is negligible
C. The back emf is sinusoidal.
D. The variation of phase inductance is sinusoidal

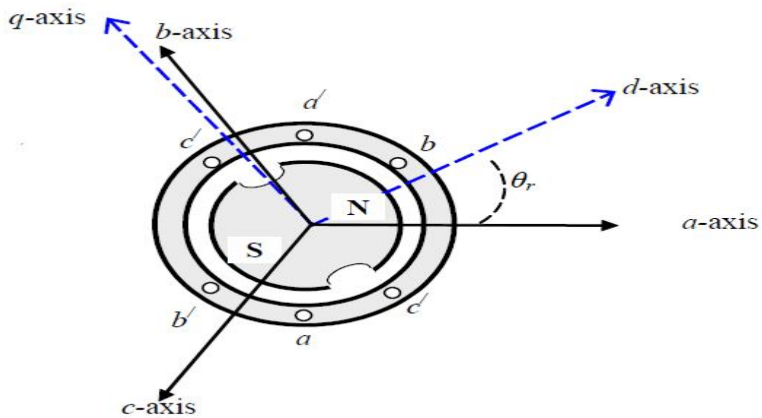

Fig.5: Three Phases, Two Pole PMSG *[6]*

VII. SIMULATION OF PMSG WIND TURBINE

The system analysed is a variable speed wind turbine 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, boost chopper circuit and a PWM voltage-source inverter. For this topology of converter, operation at relatively low wind speeds is possible due to the inclusion of the boost circuit. The boost circuit can maintain the DC bus link voltage at a constant value. A transformer is located between the inverter and the Point of Common Connection (PCC) in order to raise the voltage by avoiding losses in the transport of the current. It must be noted that this study is dedicated to analyse and implement the model from the wind turbine to the PMSG. For this reason, transformer, grid, rectifier and inverter models and their controls will not be considered *[6]*.The final model of PMSG wind turbine takes wind speed and pitch angle as input parameter and gives the rotor speed, torque, output current, output voltage and output active and reactive power.

VIII. SIMULATION RESULTS FOR PMSG WIND TURBINE-MODEL (PMSGWT-MODEL)

Find the value of power when different wind speed and fixed pitch angle. From Simulation find the value of Max. Power, Min. power, Current, voltage, torque and rotor speed. But in this paper mainly focus on Max. Power (Active Power). Simulation results are taken on same parameters of the PMSGWT-Model.

Study is done by keeping following parameters as

Fixed parameters = pitch angle in degree, Variable parameter = Wind speed in meter per second (m/s). The value of power for permanent magnet synchronous generator wind turbine model (PMSGWT-Model) is shown in Table-II.

Table-II: Simulation Results of Generated Power (P) in Watts for PMSGWT-Model

Wind Speed	P at Pitch angle =0	P at Pitch angle =2	P at Pitch angle =4	P at Pitch angle =6	P at Pitch angle =8	P at Pitch angle=10	P at Pitch angle=12
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	3564	3563	3563	3563	3563	3563	3563
2	3563	3563	3563	3563	3563	3563	3563
3	3564	3562	3562	3562	3562	3563	3563
4	3565	3562	3562	3562	3562	3562	3562
5	3568	3561	3561	3561	3562	3562	3563
6	3573	3561	3561	3562	3562	3563	3564
7	3580	3561	3561	3562	3564	3565	3566
8	3591	3562	3562	3564	3566	3568	3570
9	3604	3564	3564	3566	3569	3572	3574
10	3622	3567	3567	3570	3574	3577	3581
11	3644	3571	3571	3575	3580	3585	3590
12	3670	3576	3576	3481	3588	3594	3601
13	3701	3583	3582	3589	3597	3605	3614
14	3738	3590	3590	3599	3609	3619	3629
15	3780	3600	3600	3611	3623	3635	3647
16	3827	3611	3611	3624	3639	3653	3668
17	3882	3624	3624	3640	3657	3675	3692
18	3943	3639	3639	3658	3678	3699	3720
19	4011	3656	3656	3678	3701	3726	3750
20	4086	3675	3675	3700	3728	3756	3784
21	4169	3696	3696	3725	3757	3789	3822
22	4259	3719	3719	3753	3789	3826	3863
23	4357	3745	3745	3783	3824	3866	3909
24	4464	3773	3773	3816	3863	3910	3958
25	4579	3803	3803	3852	3904	3958	4012

The simulation results for PMSGWT model as shown in the Table-II. These results are achieved by different operating condition of PMSGWT model. To achieve the results as shown in the colomn-2 by measuring the generated power by keeping pitch angle zero-degree as a fixed parameter and vary the wind speed from 1 m/s to 25 m/s, in steps 1 m/s as an increment. The maximum power 4579 Watts is achieved at fixed pitch angle zero-degree, wind speed is 25 m/s. Similarly to achieve the results as shown in the colomn-3 by measuring the generated power by keeping pitch angle two-degree as a fixed parameter and vary the wind speed from 1 m/s to 25 m/s, in steps 1 m/s as an increment. The maximum power 3803 Watts is achieved at fixed pitch angle two-degree, wind speed is 25 m/s. Now to achieve the results as shown in the colomn-3 to 8 by varying pitch angle and wind speed.

IX. GRAPHICALLY REPRESENTATION OF PMSGWT-MODEL RESULT

The graphs between power and wind speed for permanent magnet synchronous generator wind turbine model are shown in figures 6 to 11.

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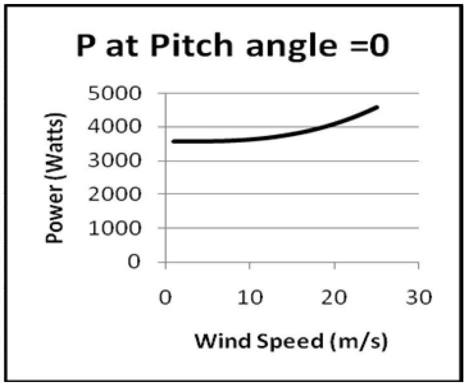

Fig. 6: Power v/s Wind Speed Curve

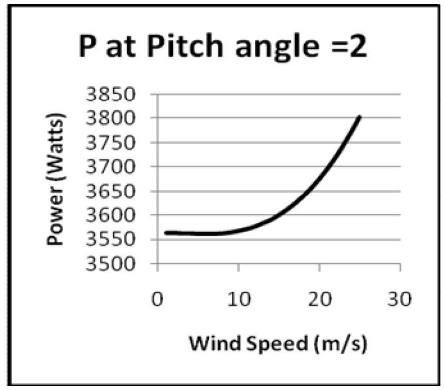

Fig. 7: Power v/s Wind Speed Curve

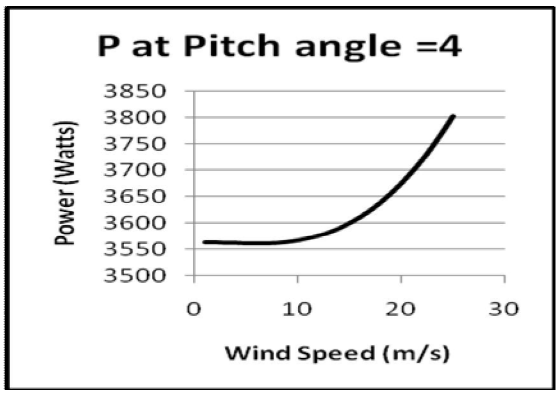

Fig. 8: Power v/s Wind Speed Curve

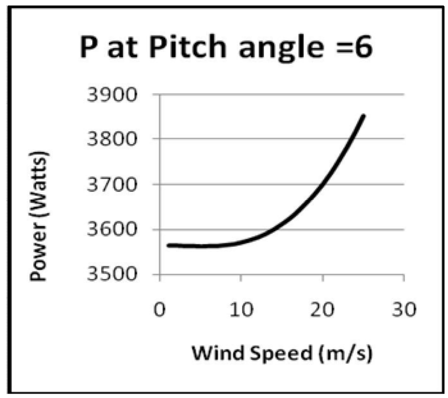

Fig. 9: Power v/s Wind Speed Curve

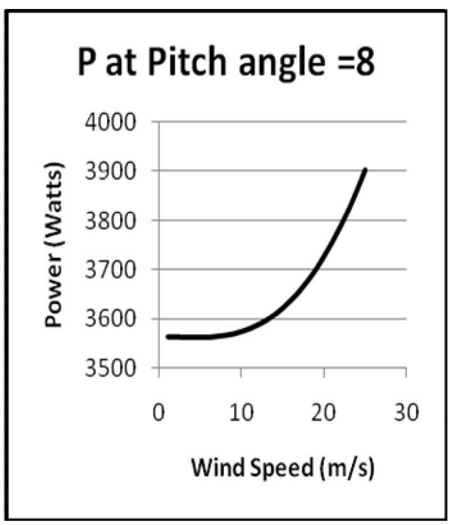

Fig. 10: Power v/s Wind Speed Curve

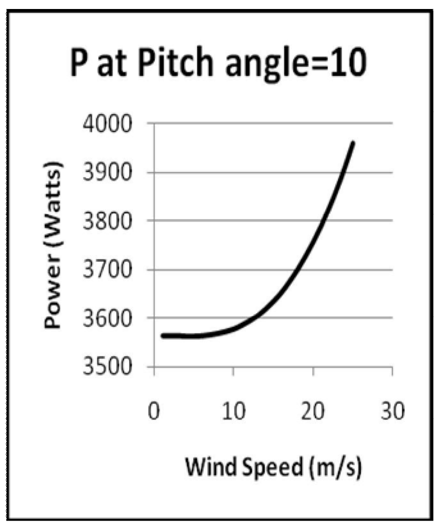

Fig. 11: Power v/s Wind Speed Curve

X. CONCLUSION

This paper has presented the simulation of permanent magnet synchronous generator wind turbine model (PMSGWT-Model) by using a MATLAB/Simulink. Variable values of power are obtained for fixed pitch angle and different wind speed. This paper gives the brief description of the output characteristics of wind turbine as well as permanent magnet synchronous generator. Also describes the effect of changes the value of wind speeds and pitch angle on output characteristics. This PMSGWT-Model is designed to give maximum power at different values of pitch angle and wind speed.

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