PITCH ANGLE CONTROL OF WIND TURBINE USING SLIDING MODE CONTROL

A DISSERTATION

Submitted in partial fulfillment of the
Requirements for the award of the degree
of
MASTER OF TECHNOLOGY
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(With Specialization in System and Control)

by

MEDA CHANDRA SEKHAR
(17530008)

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE-247667 (INDIA)
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CANDIDATE’S DECLARATION

I hereby certify that this dissertation work titled **PITCH ANGLE CONTROL OF WIND TURBINE USING SLIDING MODE CONTROL** in partial fulfillment of the requirement of award of Degree of **Master of Technology** in **Electrical Engineering** with specialization in **System And Control**, submitted to the Department of Electrical Engineering, Indian Institute of Technology Roorkee, is an authentic record of the work carried out during a period from June 2018 to May 2019 under the supervision of **Dr. Indra Gupta**, **Department of Electrical Engineering, Indian Institute of Technology, Roorkee**. The matter presented in this dissertation has not been submitted by me for the award of any other degree of this institute or any other institute.

Date:
Place: Roorkee

(MEDA CHANDRA SEKHAR)
Enrollment No: 17530008

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to best of my knowledge.

Date:
Place: Roorkee

(Dr. INDRA GUPTA)
Associate Professor
Department of Electrical Engineering,
Indian Institute of Technology,
Roorkee-247667, India

Abstract

The renewable energy is one of the best form energy which can be generated without any pollution and is best resources which lasts for very long period. In wind energy conversion systems, the unpredictability and incoherence of wind is one of the operational problems. In most cases, speed of wind can vary hastily and as the power generated from wind is directly proportional to cube of the wind speed, the power generated will increase rapidly with wind speed. But when the power reaches rated value then after that point power could not increase beyond rated value by considering the internal wiring of the turbine. So somehow we need to control the power which is more than the rated value.

There are different methods of controlling the power to be at rated value but the best method of controlling is Active Regulation which means controlling the power to limit to the rated value by adjusting the pitch angle of the wind turbine blades.

In this dissertation the performance of wind turbine with out controller, with PI and SMC controllers have been analysed in MATLAB simulation. It is observed that the performance of wind turbine is best when SMC is used and further PI controller gives better response then wind turbine without controller.

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(Meda Chandra Sekhar)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Historical Development

Wind has always been a dependant energy source for mankind from the earlier days. Wind power was used for sailing ships before steam engine came into existence. Over the period of time the process of extraction of energy from wind has changed a lot and is harnessed to its fullest extent with the arrival of wind mills. Wind energy is transformed to mechanical power by using windmills. Earlier windmills were used to drive water through pipes for irrigation, Grinding grains and many more. After the advent of steam engine the dependence and usage of wind power was drastically dropped resulting in minor significance in exploration into the field of wind energy [5].

Electricity has become one of the major form of energy by the late nineteenth century, thermal and hydel being the major sources for electricity generation. As every country do not have the luxury of fossil fuel and water resources, some of them has shown interest to depend on wind energy. Denmark is one among those countries who has spent in the advancement of wind turbines in meeting their electricity needs. Denmark has shown the path for the rest in the development of wind turbines.

Although Nuclear power also turned up as an equivalent source of power, its usage is limited due the fact that is hazard prone. Intense revelation to radiation has been realized as one of the worst infirmity to occur to man. Chernobyl disaster has led to the unwillingness to depend thoroughly on nuclear power which made people to look for developing alternative ways for production of electricity [5].

Wind power being one of the hygienic way of generating electricity, has emerged as one of the most favoured sources of generation of electricity. It is also sufficient and can be generated in a cost efficient way. The maximum inferable energy from the 0-100 m layer of air has been predicted to be of the order 10^{12} kWh per a year, and it same as that of hydroelectric potential [5].

1.2 Present Scenario

Production of wind energy moderately depends on the speed on the wind. It mainly depends on the wind densities i.e. time period during which wind flows.

Wind energy is the fastest growing energy generation practice in the world but studies indicate that, only 1% of the overall electricity requirement is presently derived from wind power in contempt of 40% annual growth in wind producing capacity over the past 25 years. It is also overwhelming fact that greater than 98% of total present wind power plants is installed in the advanced countries like China and India. It has been predicted that wind power can able to supply 7 to 34% of international electricity demands by 2050. Nonetheless, wind power faces a large number of economic, institutional, technical, market, financial, and other barriers. To overthrow these problems, many countries have signed various policy instruments, which includes capital subsidies, tradable energy certificates, tax incentives, feed-in tariffs and mandatory standards. In addition to these policies, climate change mitigation actions resulting from the Kyoto Protocol (e.g., CO2-emission decrement targets in advanced countries and Clean Development Mechanism in growing countries) have played an important role in advertising wind power [5].

India took a pledge that by the end of 2030 around 40% of total energy should be renewable energy which means energy from clean sources. India is in plan of increasing renewable capacity to 175 GW by the end of 2022 which including 60 GW from wind. The present share of renewable energy in total generating energy is as of shown in Table 1.1.

The share of renewable energy in total energy generation is around 22% and India now ranks

Table 1.1: Percentage energy generating from different sources [10]

Source	**Installed Capacity (GW)**	**Percentage**
Thermal	221.76 GW	63.84%
Nuclear	6.78 GW	1.95%
Hydro	45.48 GW	13.09%
Renewable	73.35 GW	21.12%
Total	347.37 GW	100%

as a ”wind superpower” with an installed wind power capacity of 34.98 GW (as on 2018) and more than billion units of electricity have been fed to the national grid so far.

In the total renewable energy shown in above table, the major part of energy that we are getting is from wind and the percentage of power we are getting from different sources is as shown in Table 1.2.

Table 1.2: Generation capacity from different renewable energy sources [15]

Sector	Installed Capacity (GW)
Solar	24.33
Wind	34.98
Bio	9.54
Small Hydro	4.5
Total	73.35

1.3 Formation Of Wind

The sun’s radiation on earth surface will be absorved differently and the different places on earth get’s heated differently like mountains, dessert lands, valleys and water bodies.

Because of this uneven heating, the air from the places of higher temperature rises high due it’s low density and creates low pressure and the air which is on surface with cooler temperature will sink and creates high atmospheric pressure. Due to this difference in pressure the air flows from high pressure area to low pressure area and so wind forms. Depends on the closeness of higher and lower pressure areas, the pressure gradient will exist and proportionally strong wind flows.

1.4 Benefits From Wind Energy

1.4.1 Clean and inexhaustible fuel

This is one of the best energy source that can generate power without producing any greenhouse gas,toxic waste and without using any type of fossil fuel for very long time. It creates cost-effective, reliable and pollution free energy.

Running of a single megawatt (1MW) wind turbine for a year can replace nearly 1,500 tonnes of carbon dioxide, 6.5 tonnes of sulphur dioxide, 3.2 tonnes of nitrogen oxides, and 60 pounds of mercury [7].

1.4.2 Decentralized power generation

Wind turbines for power generation can be installed in all locations where the wind speed exceeds a particular value. As it does not create any environmental problems it can be easily installed at all locations provided a small land is available for its set up (unlike fossil fuel fired power plants which requires vast expanse of land along with major environmental clearances).

1.4.3 Promotes energy security

Installation of wind farms greatly reduces our energy's dependence on conventional fossil fuels that are volatile in both availability and price, for power generation. More the investment on renewable energy more secure is the power scenario for a particular geographic location.

1.4.4 CDM prospects

Besides other advantages, installation of wind turbines offers attractive CDM benefits to the investor. These benefits range from carbon credits, soft loans etc., to the consumer. Wind plants can also generate a steady flow of income to landlords who lease their land for wind development, while increasing property tax revenues for local communities [7].

1.5 Power Contained in Wind

Production of wind energy mainly depends on wind density rather than wind speed. Wind density is the time period during which wind flows.

The power generated from the wind is nothing but the kinetic energy of the mass of the air flowing per unit time. The Kinetic energy of the wind is given by [9]

$$KE = \frac{1}{2} m v_{wind}^2. \tag{1.1}$$

Where,

Volume of air through the swept area in unit time =Av_{wind}

Mass flow rate = $\rho A v_{wind}$

Power contained in the wind (P) = $\frac{1}{2}(massflowrate)v_{wind}^2$

$$P = \frac{\rho A}{2} v_{wind}^3 \tag{1.2}$$

1.6 Importance of Wind Turbine

In the area of renewable energy wind has broad applications. Now a days wind has become very popular and the power stations based on wind power has gradually increasing. In some islands which are very far from inland are not having proper power supply or power transmission sources but have very good wind resources so we can use wind turbines to generate power for their usage.

1.7 Problem Statement

Wind power as renewable energy has broad application prospects. In eastern china, some islands are far from inland and the power transmission is inconvenient to construct, but there has rich wind resources. However, wind energy is chattering and the windmill output is proportional to the cube of wind speed, it is very necessary to control and optimize the active output power of wind turbine generator (WTG).

Pitch angle control is an important part of the WTG system. The conventional pitch angle control is designed by PID controller mostly [11]. In order to optimize the controller performance, many modern control method are used together with the PID control. In this thesis, the method used for pitch angle control of non-linear wind turbine generator systems is sliding mode control (SMC) to regulate and optimize output power of WTG. The hitting condition is decided by reaching law which can simplify the solution of the controller. In the simulation test SMC was compared with traditional PI control and it is proved the effectiveness of the SMC.

CHAPTER 2

WIND TURBINE

2.1 Basic Concepts

A wind turbine is defined as a rotary device that distillates energy from the wind. A windmill uses the energy grabbed from the wind and is used for machining purposes such as piercing lumber and crushing stones. A wind pump is used to pump the water and it works by using energy captured from wind. In this case the wind's kinetic energy is getting converted to electrical energy through generator [10].

Generally the wind turbines can be divided into two types and they are Constant speed wind and variable speed wind turbines. A constant speed WT is a turbine in which the generator may be linked to the grid directly and then locking the speed of rotor rotation to the grid frequency which is a fixed one and because of this locking there is no need of speed regulation. In case of variable speed WT the generator is indirectly linked to the grid like through an inverter or rectifier so that decoupling of the speed of rotor rotation from grid frequency happens. As the speed is not constant there is a need of regulation by varying reaction torque from the generator in reply to the generated power.

Fig. 2.1: Horizontal and Vertical axis wind turbine [14]

Wind turbines are classified into two types [14]

1. Horizontal axis wind turbine
2. Vertical axis wind turbine

2.2 Horizontal Axis Wind Turbine

For a horizontal axis wind turbine the rotor shaft and electrical generator are generally at top of a tower. It is designed in a way to capture maximum power (always pointed towards wind) and this procedure is called yawing. The turbine shaft is attached to the shaft of the generator generally with a gearbox that makes the slower rotation of the turbine blades into a quick rotation which is more convenient to drive a generator. Internal structure of a horizontal axis wind turbine (HAWT) is shown in the below Fig. 2.2 [14].

Depends upon the position of rotor, the horizontal axis wind turbines broadly classified into

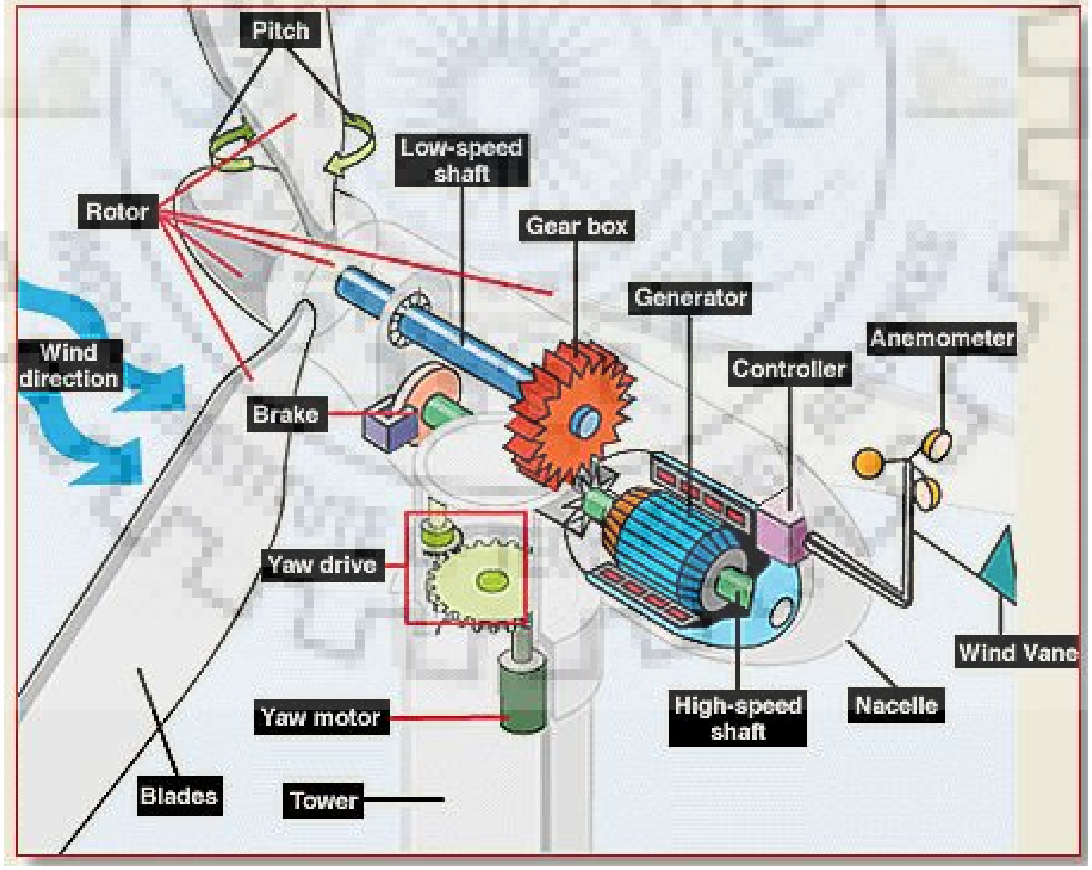

Fig. 2.2: Various parts of horizontal axis wind turbine [14]

two types

1. Upwind Turbine
2. Downwind Turbine

2.2.1 Upwind turbine

It is the turbine in which the wind is getting faced by the rotor first and then by the tower [15].

- These days most of the practical HAWT is manufactured using this design
- This design is capable of avoiding the wind shade behind the tower

2.2.2 Downwind turbine

It is the turbine in which the wind is getting faced by the tower first and then by the rotor. The rotor of this type of turbine present at the downside of the tower [15].

- The design is like that the rotor faces the wind shade of the tower because of which the fluctuations will be there in the power generating.
- The nacelle allows the wind to flow in a controlled manner because of which there is no need of Yaw mechanism in these type of turbines.

2.3 Vertical Axis Wind Turbine

In vertical axis wind turbines the main rotor shaft arranged vertically. The structure of these turbines helps in a way that they can grab the wind regardless of wind direction. So, using of these turbines in places at which wind direction varies continuously is of greater advantage. Unlike the HAWT in this turbine the gearbox and the generator are usually located near the ground where in the horizontal axis wind turbine the gearbox and generator are placed on top of the tower [14]. This makes it more easier for maintenance and comfortable in accessing. There are some drawbacks to this kind of turbines too like it generates pulsating torque that results in fatigue and another drawback is that its not easy to place vertical axis turbines on towers. They usually placed nearer to the base of the turbine on which they generally rest. Less wind energy is available for a given size turbine because of the slower wind speed at lower altitudes.

The vertical axis wind turbines are classified as [10]

1. Darrieus Turbine
2. Giromill Turbine
3. Savonius Turbine

2.3.1 Darrieus turbine

Fig. 2.3: Darrieus turbine [12]

This turbine is one of vertical axis wind turbine. It is also said as egg beater turbine because the rotor of this turbine is in egg beater shape. The blades are mounted on vertical rotor with vertical orientation. In this turbine we generally use small powered motors to start the rotation of the turbine since it is not a self starting turbine. The powered motor is just to start the rotation at starting till it attains sufficient speed, once if it reaches the sufficient speed the wind flowing across turbine blades generates lift forces which provides the necessary torque for the rotation. The rotating rotor is tied to generator through a shaft and so generator also starts rotating so that power is produced [10].

2.3.2 Giromill turbine

This turbine is a type of vertical axis wind turbine. The working principle of both Sarrieus and Giromill turbine are same and the only difference is that the rotor in this type of turbine is in H-shape. It generally have 2-3 rotor blade. The egg beater shaped rotor blades in Darrieus design are replaced with vertical blades which have horizontal support. Giromill turbine is easy to build and cheap in cost compared to Darrieus Turbine. It needs a small powered motor to start the rotation till it reaches sufficient speed and the main advantage is that it is capable of working in turbulent conditions.

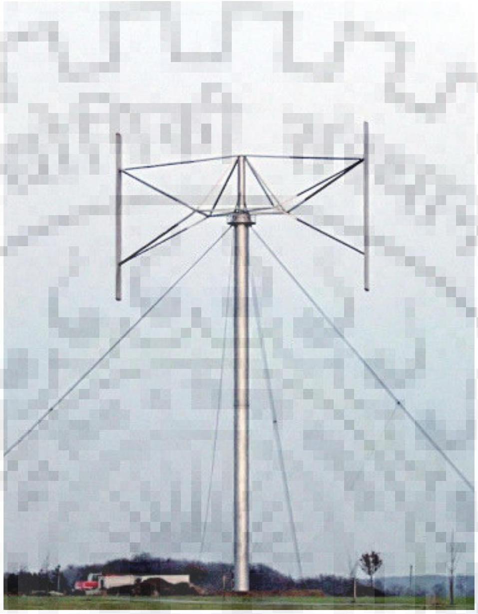

Fig. 2.4: Giromill turbine [12]

2.3.3 Savonius turbine

Savonius turbine is a type of vertical axis wind turbine. It is one of the simplest turbine among all the Vertical Axis turbines. In cross-section this turbine looks ’S’ shape when we look it from the top. It is a drag-type device and it consists of either two or three scoops and they are in curvature shape. This turbine experiences low drag because of its curvature shape. This turbine is a drag-type machine, because of the it can extract very less amount of wind power when compared with other similar sized lift-type turbines.

Fig. 2.5: Savonius turbine [12]

2.4 Various Parts of Wind Turbine

The main basic parts of a wind turbine is Tower, Nacelle, Generator and Rotor blades.

2.4.1 Tower

The tower is the main part of the wind turbine because it need to carry the nacelle and the rotor. Generally, the speed of wind is high when we go farther from the ground, so it's advantageous if we have taller tower. Higher the tower height, higher will be the captured energy because of high wind speed.The height of tower will be of 50 to 80 metres (150 to 240 ft.) for a typical modern 1000 kW turbine Generally the towers used are either tubular towers or lattice towers. Out of the two towers, tubular towers are more safer for the persons who maintains the turbines because of the ladder present inside the tower to get to the top of the turbine [12]. The main advantage of lattice towers is their low cost. There are different types of towers and they are namely

- Tubular Tower
- Lattice Tower
- Guyed Wind Tower
- Tilt up Wind Tower
- Free standing Tower

The tower height versus power out is shown in Fig. 2.6.

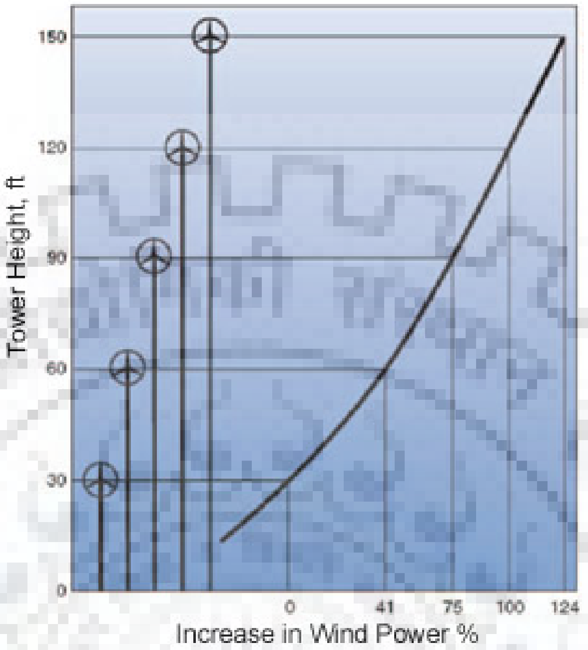

Fig. 2.6: Height versus power curve [12]

2.4.2 Nacelle

Nacelle is made of reinforced fibre glass cover that contains all the essential components that are required to operate the turbine efficiently. It mainly contains the key components like the gearbox, and the electrical generator, controller and brakes. Service personnel uses the ladder present in the tower to enter the nacelle of the turbine. An Anemometer which is used to measure wind speed and a wind vane are mounted on the nacelle [15].

2.4.3 Rotor blades

Rotor blades are made up of fibre glass-reinforced polyester or wood-epoxy. Wind turbine blades are used to extract the kinetic energy of wind and sends to the rotor hub by converting it to mechanical energy. Wind turbines may consists either one or two or three or multiple blades depends upon the construction. On a modern 1000 kW wind turbine the length of each rotor blade measures about 27 metres (80 ft.) and is designed much like an aeroplane wing.

In these days most of the HAWT are having three blades which generally connected to rotor hub. In earlier days these multiple blade concept is used for pumping water and grinding [15]. The main differences between single,double and triple blade wind turbines are as shown in the Table

2.4.4 Hub

The hub houses the blades for the wind energy generator. It is common practice to employ a 3 blade system with each displaced by 120 from the adjacent blade. To avoid turbulence, spacing between blades should be great enough, so that one blade will not encounter the disturbed, weaker air flow caused by the blade which passed before it [12]. Because of this requirement, that most of the wind turbines have only three blades on their rotor. The rotor hub is connected to the both low speed shaft and wind turbine Blades. Generally Rotor hubs are made with welded sheet steel, cast iron, forged steel. There are two types of rotor hubs and they are,

1. Hinge-less Hub
2. Teetering Hub

2.4.5 Shaft

Drive shafts are a hollow or solid steel hardened shaft under very high stresses and considerable torque. The rotational mechanical energy is transferred to the generator from blade hub through these drive shafts. A wind turbine generally consists of two shafts namely

- Main Shaft
- Generator shaft

2.4.5.1 Main shaft

Main shaft is the shaft connected between rotor hub and the input of the Gear box. On a Modern 1MW wind turbine the rotor connected to this shaft rotates slowly, about 20 to 30 revolutions per minute(RPM) and because of this slow rotation this shaft is also called as ’Low Speed Shaft’ [12].

2.4.5.2 Generator shaft

Generator shaft is the shaft that connected between Gear box output and The Generator input. Gear box gets the input from Low speed shaft and gives output of very high speed around 1500 revolutions per minute(RPM) and this output is connected to electrical generator from where the electrical power is generated. As the rotation of the shaft is very high it is also referred as 'High Speed Shaft'. This shaft is equipped with mechanical disc brakes which helps when the turbine is being serviced.

2.4.6 Gear box

Gear Box is device that is used to convert low speed high torque power from rotor blade to high speed low torque power and that is used for generator. Generally this device is connected between low speed shaft (main shaft) and high speed shaft (generator shaft) to increase rotational speeds from about 30 to 60 rotations per minute (rpm) to about 1000 to 1800 rpm. Gearboxes are made up of aluminium alloys, stainless steel and cast iron [15]. The various gear boxes used in wind turbines are:

i Planetary Gear Box

ii Helical Gear Box

iii Worm Gear Box

2.4.7 Anemometer

The power generated from wind turbine is directly proportional to cube of wind speed. So the speed of wind is the most crucial factor in determining the wind power.When we are locating turbine in a particular place we should know the wind profile in that place and the device used for this measurement of speed is called as Anemometer. Generally these are placed on top of Nacelle [12]. Anemometer generates electronic signals and those will be sent to the electronic controllers to start the wind turbine if the speed reaches cut in wind speed and used to stop the turbine when the speed is greater than cut out wind speed in order to protect the turbine and its surroundings.

2.4.8 Wind vane

Wind vane is a device located on top of the Nacelle and these devices measures the direction of wind and sends the signals to electronic controller which turns the turbine using Yaw mechanism so that we can extract maximum possible power from the wind [12].

2.4.9 Yaw mechanism

Yawing is moving of the rotor blades in a particular intended direction. This is done in order to match the blade direction with the varying wind direction. The wind is made either to impinge on the blade or to be spilled.

Three yaw motors controlled by AC-drives and motor brakes, are used for the alignment of the nacelle to the main wind direction. The drive utilizes 3 motors in order to rotate the nacelle (and also the hub, generator & blades) depending upon the direction of wind that is measured by a wind vane mounted at top of the nacelle [15].

The yaw drives enable the rotation of wind turbines hub up to 90 degrees (maximum) in both clockwise and counter clockwise direction. This nacelle rotation is continuously monitored by a nacelle position rotary switch which continuously feeds its analogue data output to a controller in the top box for processing. Thus the rotary switch, located at the bottom of nacelle will have adequate control of yaw motors by moving along with the teeth of nacelle. Also this nacelle position rotary limit switch helps in limiting the movement of nacelle on reaching the maximum position. In brief, electromechanical yawing is done in order to ensure that the rotor always faces directly the wind and stall controls to keep the rotor from turning too fast in gusty wind speeds.

2.5 Terminology for Wind Speed

2.5.1 Cut-in speed

Cut in wind speed is the minimum wind speed at which the wind turbine will start generating usable power. In present existing wind turbines the cut-in wind speed is around 3m/s [5].

2.5.2 Cut-out speed

The wind turbine will be programmed to stop at high wind speeds in order to avoid damaging the turbine or its surroundings. This speed of the wind is called as cut out wind speed. In other words, the stop wind speed is called the cut out wind speed. In present existing wind turbines the cut-out wind speed is around 22 m/s [5].

2.5.3 Rated speed

The rated speed is the minimum wind speed at which the wind turbine will generate its designated rated power. At wind speeds between cut-in and rated, the power output from a wind turbine increases as the wind speed increases. The output of most machines levels off above the rated speed. In this work the wind turbine has rated wind speed as 12.5 m/s [5].

CHAPTER 3

MATHEMATICAL MODEL OF WIND TURBINE

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3.1 Wind Turbine

This chapter explains the mathematical model of wind turbine used in this work. Mainly wind turbine with controller can be modelled by joining three parts [6]. Those three parts are as follows

1. Pitch Angle Controller
2. Hydraulic Servo System
3. Wind Rotor & Generator (Power Generating System)

The pitch angle controller receives the difference of rated power and generated power as input and gives control signal to the Hydraulic Servo System which generates some command signal and will be given to the Power Generating system such that the pitch angle of blades will be adjusted to generate maximum power from the wind. The block diagram [3] of Wind Turbine Generating System is as shown in Fig. 3.1.

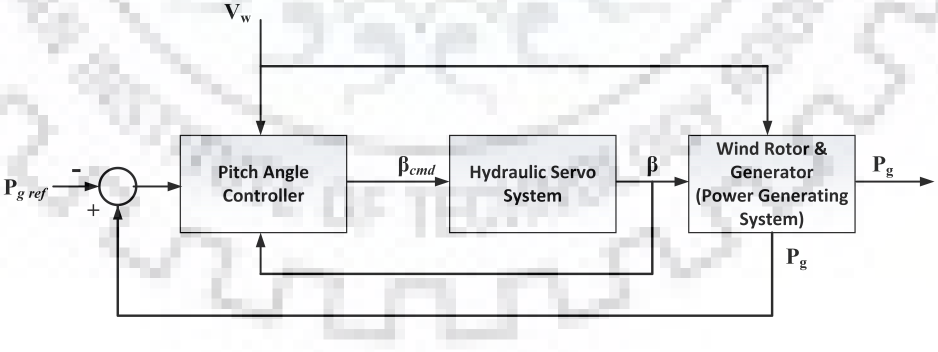

Fig. 3.1: Block diagram of wind turbine with controller [6]

In this figure, V_w is Wind Velocity

P_{ref} is Rated Power of Wind Turbine

P_g is Output generated Power

β_{cmd} is command pitch angle

β is Pitch angle from servo system

From the Fig. 3.1, it is clear that group of those three blocks gives the wind turbine power generation system. In further coming chapters, the in-detail explanation about Pitch angle controller and different control methodologies will be explained.

3.1.1 Hydraulic servo system

When the speed is above the rated wind speed, then the controller produces the control output based on the difference of reference rated power and generated rated power and gives the controller output to the Servo system [2]. This hydraulic servo system generates the required pitch angle and makes the wind turbine blades rotate according to that generated pitch angle around blades length wise axis. This pitch actuator or hydraulic servo system is modelled as a first order transfer function with time constant T_c

$$T_c \frac{d\beta}{dt} = \beta_{cmd} - \beta \tag{3.1}$$

Where β_{cmd} is the control input to the servo and β is the output from the servo. The rate of change of blade position can't be faster than 5.7° sec^{-1}

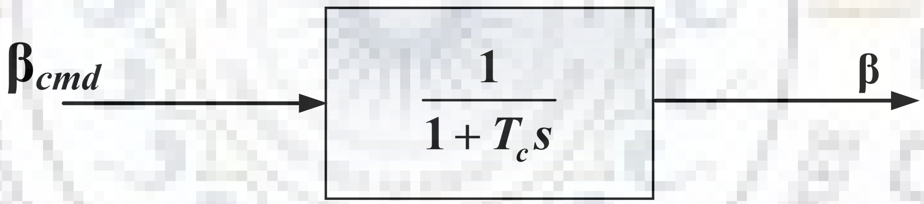

Fig. 3.2: First order transfer function of hydraulic servo system [6]

3.1.2 Wind rotor & generator (power generating system)

The output power of wind rotor (P_w) is given by the equation shown below.

$$P_w = \frac{C_p(\Lambda, \beta) V_w^3 \sigma \psi}{2} \tag{3.2}$$

Where V_w^3 is the cube of wind speed

ψ is the cross section of wind rotor and is given by

$$\psi = \pi R^2 \tag{3.3}$$

σ is air density factor

$C_p(\Lambda, \beta)$ is the Power coefficient and the expression for C_p is given as below

$$C_p(\Lambda, \beta) = a_1(\beta)\Lambda^2 + a_2(\beta)\Lambda^3 + a_3(\beta)\Lambda^4 \tag{3.4}$$

where $a_1(\beta) = a_{10} + a_{11}\beta + a_{12}\beta^2 + a_{13}\beta^3 + a_{14}\beta^4$

$a_2(\beta) = a_{20} + a_{21}\beta + a_{22}\beta^2 + a_{23}\beta^3 + a_{24}\beta^4$

$a_3(\beta) = a_{30} + a_{31}\beta + a_{32}\beta^2 + a_{33}\beta^3 + a_{34}\beta^4$

where all these constants a_{10} to a_{34} are given by the performance characteristics of wind turbine. In Equation (3.4), β represents pitch angle of the wind turbine & Λ represents the tip speed ratio of turbine.

Tip speed ratio can be expressed as,

$$\Lambda = \frac{W_r R}{V_w}$$

Where,

R is radius of wind turbine, W_r is the angular velocity of the wind rotor, W_r is given by

$$W_r = \sqrt{\int \frac{2}{J}(P_w - P_g)dt}$$

Here, J is the moment of inertia

P_g is the generator output power and the expression for P_g is given by [3]

$$P_g = \frac{-3V_p^2 s(1+s)R_2}{(R_2 - sR_1)^2 + s^2(X_1 + X_2)^2}$$

Where, V_p is phase voltage,

S is Slip, R_1 is stator resistance, R_2 is rotor resistance, X_1 is stator reactance, X_2 is rotor reactance.

The slip s is given by,

$$s = \frac{W_0 - W_r}{W_0}$$

Where, W_0 is the angular synchronous speed

W_r is the angular velocity.

From all the above equation, if we interconnect all the variables mentioned in above equations we will get system configuration of Wind Rotor and Generator and the same is shown in Fig. 3.3.

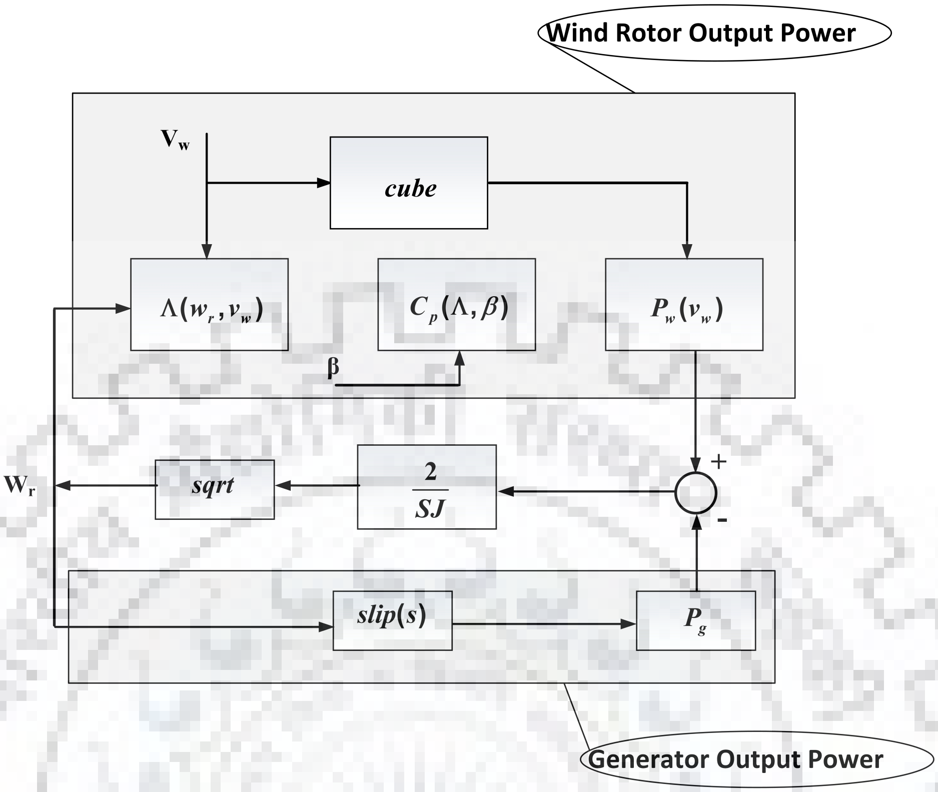

Fig. 3.3: System configuration of wind rotor and generator

Table 3.1: Simulation Parameters

Parameters of Wind turbine		
Blade Radius	Inertia Coefficient	Air Density
14 m	62993 $kg.m^2$	1.225 $kg/(m^3)$
Parameters of Induction Generator		
Rated Output Power	Phase Voltage	Stator Resistance
275 kw	$400/\sqrt{3}$	0.00397 Ω
Stator reactance	Rotor Resistance	Rotor Reactance
0.00376 Ω	0.00443 Ω	0.0534 Ω
Operating Point		
Wind Speed	Pitch angle	Angular Speed
V_{wop}= 13 m/sec	β_{op} = 12 deg	ω_{rop} = 5.104325 rad/sec
$\bar{A}$ =-5794	$\bar{B}$ = 10607	$\bar{C}$ = -2263

CHAPTER 4

CONTROLLERS

4.1 Operating Regions and Control Strategy

The relationship between power generated and wind speed is divided into three regions and they are as shown in the below Fig. 4.1.

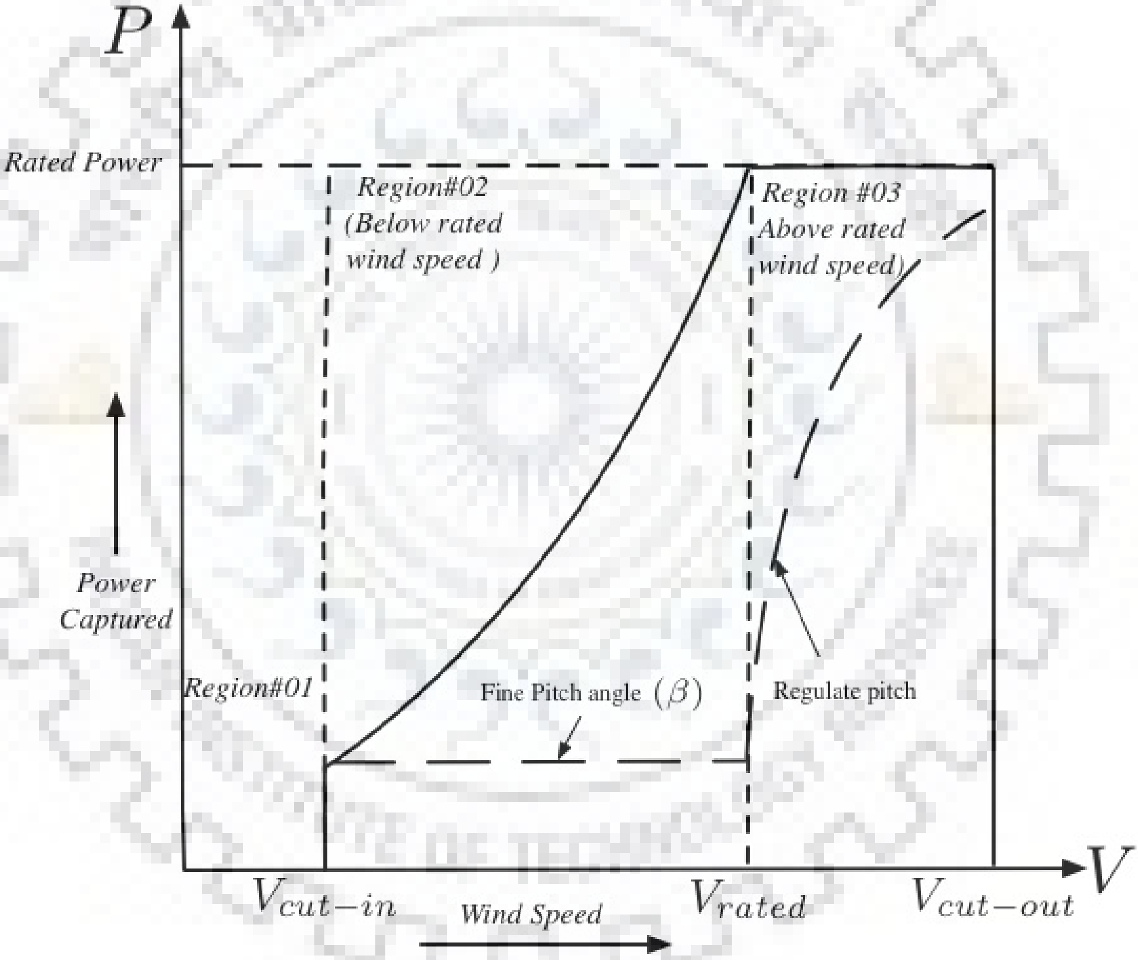

Fig. 4.1: Different regions of operation of wind turbine [3]

The slowest speed at which wind turbine can capture the power is said to be Cut in Wind Speed(v_{cutin}) while the min speed at which the turbine procures rated power is said to be rated wind speed (V_{rated}) and the max speed at which the turbine able to capture the power from wind is said to be cut out wind speed (V_{cutout}). From Fig. 4.1 in the region I that is when the speed of wind is lesser than that of V_{cutin} then turbine fails to capture and generate the power and in general the pitch angle remains at 90^o in this region because of less wind speed. The region II that is region from V_{cutin} to V_{rated} is considered as the region for operation of wind turbine where wind is captured and converted to valuable power. The region III located between V_{rated} and V_{cutout} is called as full load region and in this region the generated power is consistent [3].

In wind turbine with variable speed the controller is designed by categorizing the Speed of wind into two regions of operation. In the region termed as below rated region, turbine tries to lower the coefficient of power in order to increase the wind power to the extent of generator capacity. The blade pitch angle position is almost kept constant at one particular angle while the torque control of generator is used to maintain the wind turbine work remains at its optimal power coefficient or aerodynamic efficiency [16].

In the region termed as above rated region the strategy of controller is to reduce the aerodynamic load and to maintain constant rated power of wind turbine. In this region the power is given by the product of generator torque and rotational velocity. If we keep these quantities constant by adjusting the pitch angle then we could able to maintain the constant power.

4.2 Different Possible Controllers

Pitch angle controller is an hydraulic or electromechanical device, used for actuation of pitch in high power rated region of wind turbines. Primarily pitch control relies on the rate limiter and time constant of pitch actuator.

4.2.1 Fuzzy logic control

Fuzzy logic could able to tackle non-linear systems but requires prerequisite knowledge of mathematical description and inputs of the system. Generally fuzzy logic reads the behaviour of the system in the form of common sense knowledge which is expressed as a set of rules. These rules are designed by expecting that the plant generally operates within a desired range. Wind turbine is highly uncertain system [16]. Here two fuzzy logic controllers are used to regulate the output power and one is for the speed lower than rated and another is to regulate power when the speed of wind is higher than the rated wind speed. Fuzzy logic differs from ”computing with words rather than numbers”, it can be described simply as ”control with sentences rather than with equations”.

4.2.2 H_∞ control

H_∞ robust control for pitch angle is designed by considering maximum speed of wind. H_∞ control method’s standard form is modified to get the good performance under allowable loads on wind turbine. It gives almost same results as PI controller, besides contain fixed parameters. When we use this method, to reduce the fluctuations in wind turbine for all the speeds one generally combines this technique with some other technique [16].

4.2.3 PID controller

The PID and PI controllers are the simplest and mostly implemented control technique. The non-linear PI and PID control technique is best suited for controlling the pitch of wind turbine for high speeds of wind. The dependency of the controller on both mathematical model and gain controller is the only down side of PID and because of this it has become very challenging to get the gain for different operating points of wind turbine and to design an accurate mathematical model [16].

4.3 Sliding Mode Control

While we formulate a practical problem, as we are using its mathematical model there will be some discrepancies which arises due to some external disturbances, some internal parameter changes or due to un-modelled dynamics of the system. So we must have a controller that gives the performance same as that of desired performance even when disturbances occurs and it is one of the challenging task for a controlling engineer. These reasons led to the development of a controlling mechanism called robust control and one particular procedure to design a robust controller is so called Sliding Mode Control (SMC) Technique [16].

The advantages of SMC techniques includes finite time convergence, robustness, and reduced order dynamics with some compression. Sliding mode technique is robust and acts satisfactorily despite the presence of uncertainties like parameter changes, un-modelled dynamics, un-modelled time delays, unpredicted disturbances, changes in equilibrium point and sensor noise etc.

Designing of sliding mode controller involves two steps [14]

- First, choosing some switching surfaces that represents some sort of motion which is called as reaching phase
- Second, designing of control law that guarantees the sliding of unstable behaviour of the plant and this is called sliding phase

4.3.1 Concept of sliding mode control

Let us consider the following system and introduce some dynamics.

$$\begin{aligned} \tfrac{dx_1}{dt} &= x_2 & x_1(0) &= x_{10} \\ \tfrac{dx_2}{dt} &= u + f(x_1, x_2, t) & x_2(0) &= x_{20} \end{aligned} \tag{4.1}$$

The below shown LTI differential is the best equation for the sliding surface and it is shown the proof for that it brings back the system into stable region when it enters into unstable in some finite time.

$$\frac{dx_1}{dt} + kx_1 = 0, \qquad k > 0 \tag{4.2}$$

since $\frac{dx_1}{dt} = x_2$, the solution and derivative of the solution for above shown differential equation is shown below.

$$\begin{aligned} x_1(t) &= x_1(0)e^{(-kt)} \\ x_2(t) &= \tfrac{dx_1}{dt} = -kx_1(0)e^{(-kt)} \end{aligned} \tag{4.3}$$

Here both x1(t) as well as x2(t) converges to zero asymptotically. If we observe the above equations then there is no influence with disturbances on compensated dynamics. Lets take a new variable σ called sliding variable and introduce it in the systems state space [14].

$$\delta = \delta(x_1, x_2) = x_2 + kx_1 \qquad k > 0 \tag{4.4}$$

We must choose a sliding surface such that its derivative should consist of the control input then only we can guarantee that the system reaches zero asymptotically.

To make the state variable reach to zero asymptotically i.e. $\lim_{t \to \infty} x_1, x_2 = 0$ with some given finite convergence while disturbances are acting we need to make the sliding variable reach zero in some finite time. And this process of making stated to reach zero using some sliding variable can effectively done by using some controller *u*. The task of finding such best suitable *u* can be possible by applying some techniques of Lyapunov function to sliding variable dynamics that are derived in Equations (4.4).

$$\dot{\delta} = kx_2 + f(x_1, x_2, t) + u \qquad \delta(0) = \delta_0 \tag{4.5}$$

For the sake of sliding variable dynamics lets take the below function as Lyapunov candidate.

$$V = \frac{1}{2}\delta^2 \tag{4.6}$$

There are some conditions for above said Lyapunov function in order to get stability asymptotically and those are as shown below [14].

1. $\frac{dV}{dt} < 0 \qquad\qquad \delta \neq 0$
2. $\lim_{|\delta| \to \infty} V = \infty$

By observing V it is clear that when tends to infinity the value of V also tends to infinity so now if condition (a) gets satisfied then we can say that system gets converges asymptotically. In order to get convergence in finite time then condition 1 can be modified as follows

$$\dot{V} \leq -\alpha V^{\frac{1}{2}}, \qquad\qquad \alpha > 0 \tag{4.7}$$

If we solve the above differential equation using variable and separable method in the time interval $0 \leq \tau \leq t$ then we will get the following equation.

$$V^{\frac{1}{2}}(t) \leq -\frac{1}{2}\alpha t + V^{\frac{1}{2}}(0) \tag{4.8}$$

If find the time at which V(t) reaches zero then we will get the finite time equation and it is given by

$$t_r \leq \frac{2V^{\frac{1}{2}(0)}}{\alpha} \tag{4.9}$$

Therefore, if we design a control u which satisfies the assumed Lyapunov equation then automatically it drives the sliding variable to zero in some finite time and if once it reaches zero then it makes it to stay there only.

The derivative of Lyapunov V is as shown below

$$\dot{V} = \delta\dot{\delta} = \delta(cx_2 + f(x_1, x_2, t) + u)$$

Assume $u = -cx_2 + v$ and substitute it in above Lyapunov differentiation equation then we get

$$\dot{V} = \delta(f(x_1, x_2, t) + v) = \delta f(x_1, x_2, t) + \delta v \leq |\delta| L + \delta v \tag{4.10}$$

Select $v = -\rho sign(\delta)$ where

$$\mathrm{sgn}(\delta) = \begin{cases} -1, \delta < 0 \\ +1, \delta > 0 \\ \in [-1, +1], \delta = 0 \end{cases}$$

Substitute the above equations in the Lyapunov derivative then we get

$$\dot{V} \leq |\delta| L - |\delta| \rho = -|\delta| (\rho - L) \tag{4.11}$$

From Equations (4.6) and (4.7) it can be rewritten as

$$\dot{V} \leq -\alpha V^{\frac{1}{2}} = \frac{-\alpha}{\sqrt{2}} |\delta|, \alpha > 0 \tag{4.12}$$

From equations (4.11) and (4.12) we get

$$\dot{V} \leq -|\delta| (\rho - L) = -\frac{\alpha}{\sqrt{2}} |\delta| \tag{4.13}$$

If we make control gain as subject then we will get the following equation

$$\rho = L + \frac{\alpha}{\sqrt{2}} \tag{4.14}$$

Here L is the bounded value of the disturbance occurring while $\frac{\alpha}{\sqrt{2}}$ is responsible for the time taken to reach the sliding surface. Larger the α shorter the reaching time.

And the control law u which drives to zero in some finite time is [14]

$$u = -cx_2 - \rho\mathrm{sgn}(\delta)$$

If we rewrite the sliding variable equation in the form shown below then that straight line equation is termed as **Sliding Surface**

$$\delta = x_2 + cx_1 = 0, c > 0$$

And we also able to judge that the controller drives the trajectory towards the sliding surface S if the sliding variable satisfies the following condition [14].

$$\delta\dot{\delta} \leq -\frac{\alpha}{\sqrt{2}}|\delta|$$

And thus the designed controller *u* drives the trajectory towards surface and makes it to reach zero asymptotically even when the disturbance exists and this controller is called as a **sliding mode controller**.

CHAPTER 5

CONTROL SYSTEM DESIGN

In this chapter, the control techniques were explained and the work done on those controllers has been shown. Even though a wind turbine can be available in both Horizontal and Vertical configurations we design controller for horizontal axis wind turbine as they are highly used. The main aim of the controller design is controlling the power to rated value at above rated wind speeds by adjusting the pitch angle.

5.1 PI Control

The controller might have altered configurations. Many design approaches are there for designing the controller to achieve anticipated performance level. But the most standard among them is Proportional-Integral (PI) type controller. Indeed more than 95% of the industrial applications use PI controller. A PI controller computes the error value as the difference between a measured value and a desired value. ”The controller tries to reduce the error by altering the process through use of a manipulated variable.” [5]

The PI controller contains two distinct constant parameters.The proportional denoted by P and the integral denoted by I. P term determined by the present error, I term determined by the past errors and the control input is given as shown in the below equation.

$$u(t) = K_p e(t) + K_i \int_0^t e(t)$$

K_p is the proportional gain, K_I is the integral gain, e(t)= the difference between a measured variable and a desired value and t is time.

Similarly, the transfer function of PI controller is

$$T(s) = K_p + \frac{K_i}{s}$$

Where, S is complex frequency

5.1.1 Proportional term

The proportional term gives an output value that is relative to the present error value. The response of proportional part can be attuned by multiplying the error by a constant Kp, called

the proportional gain constant.
The proportional term is given by

$$P_{out} = K_p e(t)$$

Higher the proportional gain greater the change in the output for a given change in the error. The system becomes unstable, if the proportional gain is too high. In contrast, ”a small gain consequences in a small output response to a high input error. If the proportional gain is too small, the control action may be too minor while reacting to system disturbances.” Industrial practice shows that the proportional term should give the most of the output change. In a proportional controller, steady state error depends inversely upon the proportional gain. A proportional controller (K_p) will have the influence of reducing the rise time and steady-state error, but never eliminate the steady-state error.

5.1.2 Integral term

An Integral controller (IC) is proportional to both the magnitude of the error and the period of the error. An integral control will have the result of eliminating the steady-state error, but it might make the transient response poorer. The gathered error is then multiplied by the integral gain (K_i) and added to the controller output [5].

$$I_{out} = K_i \int_0^t e(t)$$

The integral term speeds up the movement of the process towards reference and eliminates the residual steady-state error that occurs with a pure proportional controller. Nevertheless, since the integral term reacts to collected errors from the past, it can source to the present value to overshoot the reference value.

In this work the PI controller has been used for the mitigation of power in the wind turbine. The turbine rated power was taken as set-value or reference value. The error signal is the input for the PI controller. PI controller generates required pitch angle. The pitch angle generated is given to the wind turbine simultaneously. The error signal is defines as

$$e(t) = P_{ref} - P_{gen}$$

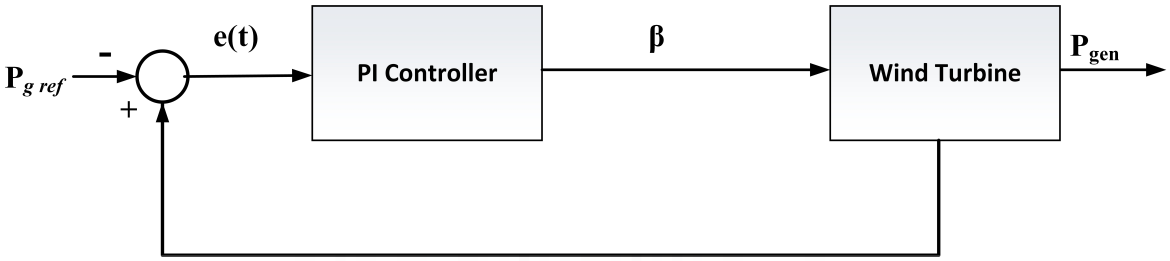

Fig. 5.1: Block diagram of PI controller for pitch angle control [5]

Table 5.1: Effect of time constants on time Domain specifications

Parameter	**Rise Time**	**Overshoot**	**Settling Time**	**Steady-State Error**	**Stability**
K_p	Decrease	Increase	Small Change	Decrease	Degrade
K_i	Decrease	Increase	Increase	Eliminate	Degrade

5.2 SMC Controller

From PI controller it is observed that, it has difficulties in dealing with the uncertainties in the WTG system which can be overcome using sliding mode control. SMC has advantages of robustness and the response is faster because of which it is widely used for non-linear systems.

Before designing of the controller we need to get linearization model of the non-linear plant.

5.2.1 Linearization of windmill output torque

The output torque T_w of windmill is given by the equation shown below

$$T_w(\beta, V_w, W_r) = \frac{C_p(\Lambda, \beta) V_w^3 \sigma \psi}{2W_r} \tag{5.1}$$

here,

T_w is the output torque of windmill.

The Taylor series expansion of the above torque equation after ignoring higher order terms is [3]

$$T_w - T_{wop} = \frac{\partial f}{\partial \beta}\Delta\beta + \frac{\partial f}{\partial V_w}\Delta V_w + \frac{\partial f}{\partial W_r}\Delta W_r \tag{5.2}$$

Let, $\frac{\partial f}{\partial W_r}_{op} = A$, $\frac{\partial f}{\partial \beta}_{op} = B$,$\frac{\partial f}{\partial V_w}_{op} = C$
then, we can say

$$\Delta T_w = A\Delta W_r + B\Delta\beta + C\Delta V_w \tag{5.3}$$

The dynamic model of wind turbine is given as follows

$$T_w = \frac{P_w}{W_r}, T_g = \frac{P_g}{W_g} \tag{5.4}$$

$$J\frac{dW_r}{dt} = T_w - \zeta T_g - bW_r. \tag{5.5}$$

Here, b is viscous friction coefficient

ζ is gear box ratio.

The entire work was done by assuming the WTG dynamic model without viscous friction coefficient, that is

$$J\frac{dW_r}{dt} = T_w - T_g \tag{5.6}$$

From Equations (5.3) and (5.6)

$$J\frac{dW_r}{dt} = A\Delta W_r + B\Delta\beta + C\Delta V_w$$

$$\Delta\dot{W}_r = \frac{A}{J}\Delta W_r + \frac{B}{J}\Delta\beta + \frac{C}{J}\Delta V_w. \tag{5.7}$$

Here, $\Delta\beta$ is control input to the Windmill Generator, ΔW_r is state variable and ΔV_w is the disturbance. A, B, C are the constants given by [3]

$$A = \frac{\sigma\psi V_w^2}{2W_r}(-C_p\frac{V_w}{W_r} + R\frac{\partial C_p}{\partial\Lambda}) \tag{5.8}$$

$$B = \frac{1}{2}\frac{V_w^3}{W_r}\sigma\psi\frac{\partial C_p}{\partial\beta} \tag{5.9}$$

$$C = \frac{\sigma\psi V_w}{2}(3C_p\frac{V_w}{W_r} - R\frac{\partial C_p}{\partial\Lambda}) \tag{5.10}$$

By substituting operating point in the above equations we will get the values of the constants A, B, C.

5.2.2 Controller design

The sliding mode control design can be separated into two stages, they are

- Reaching Law design
- Control law design.

5.2.2.1 Reaching law design

The hitting condition for reaching law design is as shown below

$$s\dot{s} < 0$$

i.e., $s\dot{>}0$ and $s < 0$ or $s\dot{<}0$ and $s > 0$.

When the selected sliding variable satisfies the above said hitting condition that means the trajectory reaches the sliding surface in infinite time and slides on the surface.

To design sliding phase we need to select a reaching law, the reaching law chosen in this work is

$$\dot{s} = -Ns - M\text{sgn}(s). \tag{5.11}$$

Where,

$$\text{sgn}(s) = \begin{cases} 1, s > 0 \\ -1, s < 0 \\ [-1, 1], s = 0 \end{cases}$$

and N, M >0. Where, M is speed of approaching.

5.2.2.2 Control law design

From system model, the error in speed that is difference between W and W_{ref} is taken as sliding surface. So the sliding surface is given as

$$S = cx = c\Delta W_r$$

$$\dot{s} = c\dot{x} = c\Delta\dot{W}_r \tag{5.12}$$

and from selected reaching law, that is Equation (5.11)

$$\dot{s} = -Ns - M\text{sgn}(s)$$

From Equations (5.11) and (5.12), we can write,

$$c\Delta \dot{W}_r = -Ns - M\text{sgn}(s) \tag{5.13}$$

Now from Equations (5.7) and (5.13),

$$\frac{A}{J}\Delta W_r + \frac{B}{J}\Delta\beta + \frac{C}{J}\Delta V_w = -Ns - M\text{sgn}(s)$$

$$J(-N\Delta W_r - M\text{sgn}(s)) = A\Delta W_r + B\Delta\beta + C\Delta V_w$$

$$\Delta\beta = -\frac{JM\text{sgn}(s) + (JN + A)\Delta W_r + C\Delta V_w}{B}$$

and here the control input is $\Delta\beta$ and generally control input is referred with variable u. Therefore, the control input is given as below

$$u = \Delta\beta = -\frac{JM\text{sgn}(s) + (JN + A)\Delta W_r + C\Delta V_w}{B} \tag{5.14}$$

CHAPTER 6

SIMULATION RESULTS

This chapter explains the simulation results of wind turbine with all the mentioned controllers like PI and SMC and the results with different controllers were compared and explained.

6.1 Different Wind Profiles

Three different type of wind profile have been used for testing of the wind model with different controllers.

6.1.1 Wind profile 1

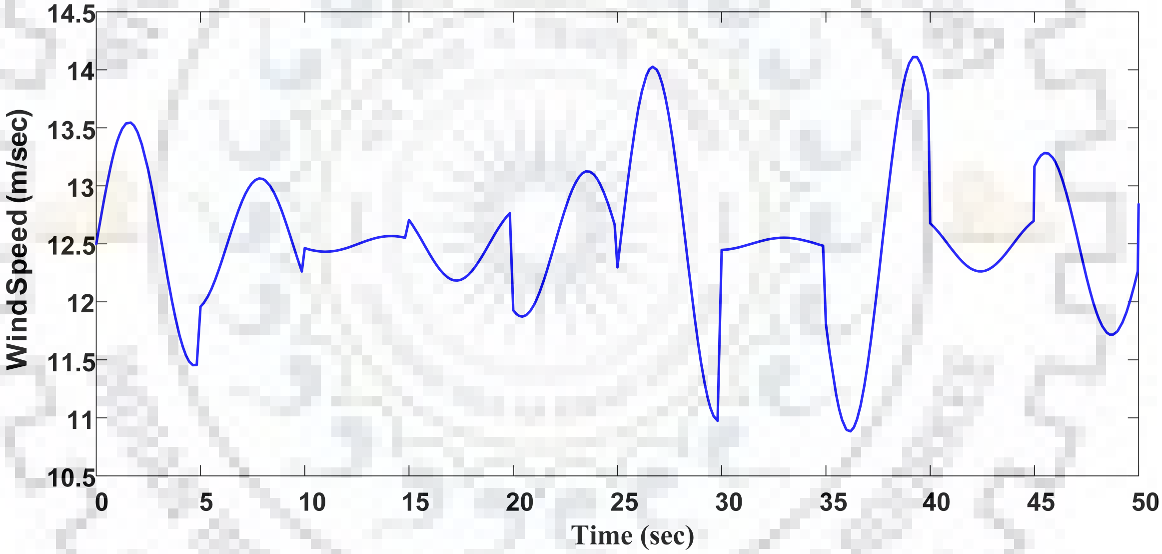

Fig. 6.1: Wind profile 1

The speed of wind is getting varied from 11 m/sec to 14 m/sec in the above Fig. 6.1 with average or mean speed of 12.5 m/sec.

6.1.2 Wind profile 2

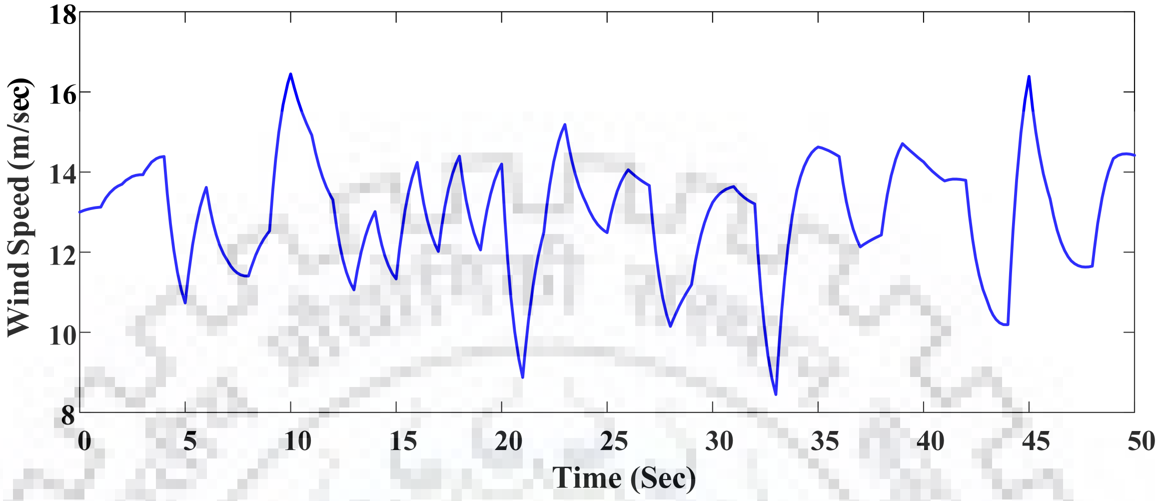

Fig. 6.2: Wind profile 2

6.1.3 Wind profile 3

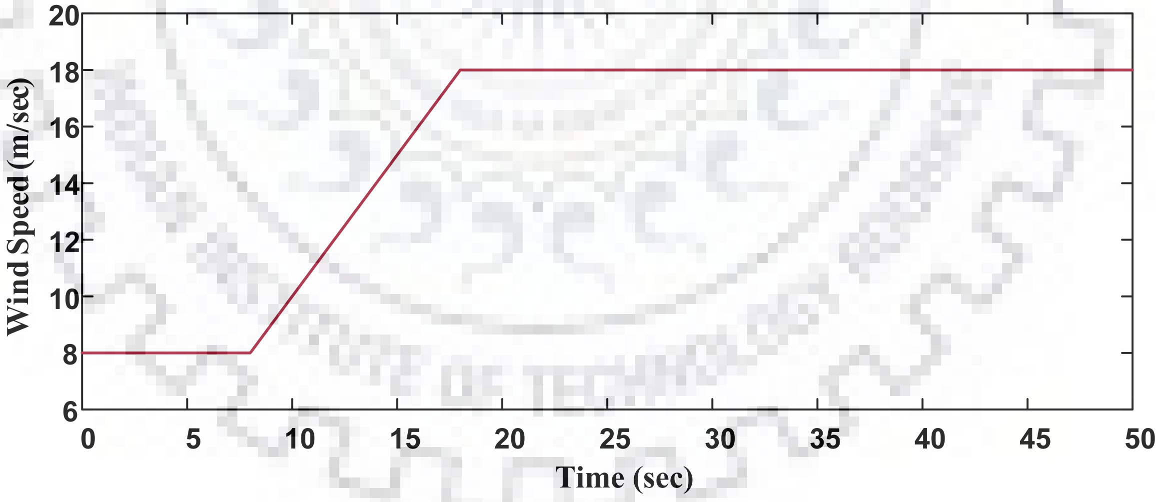

Fig. 6.3: Wind profile 3

The above shown wind profiles have been used for testing of the model with different mentioned controllers.

6.2 Generator Output Power Without Controller

Generally, the output power is supposed to be maximum of rated power but when there is no controller and if the wind speed is higher than the rated wind speed then the power getting generated will be greater than the rated power. This is because the generating power is directly proportional to the cube of wind speed. So, to avoid this situation we need to use a controller to limit the power to rated value when the speed of wind is higher than rated speed.

6.2.1 Output power and pitch angle for wind profile 1

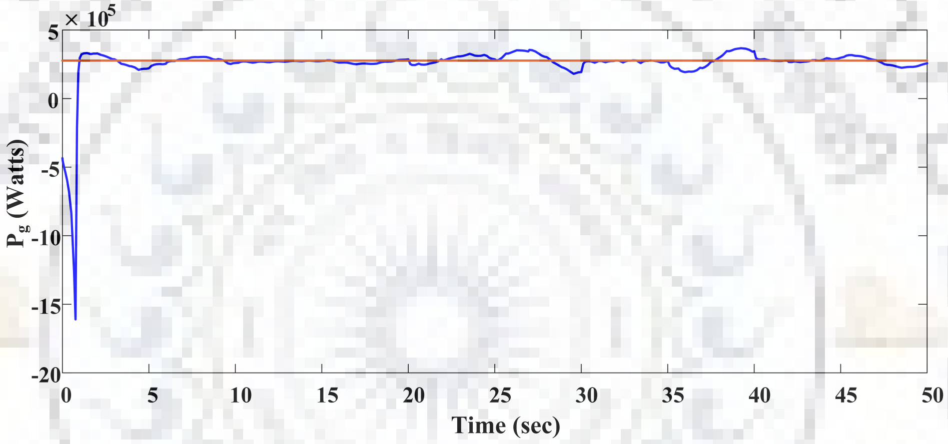

Fig. 6.4: Generator output power for wind profile 1

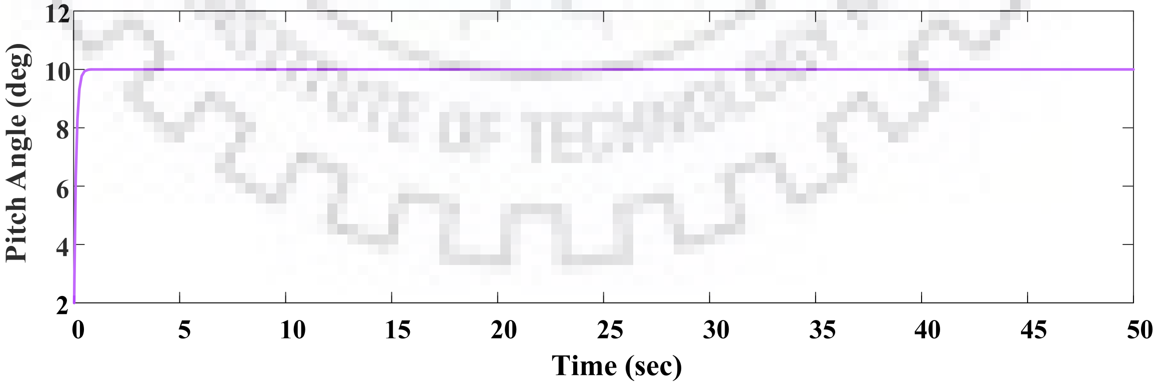

Fig. 6.5: Pitch angle of the wind turbine blades

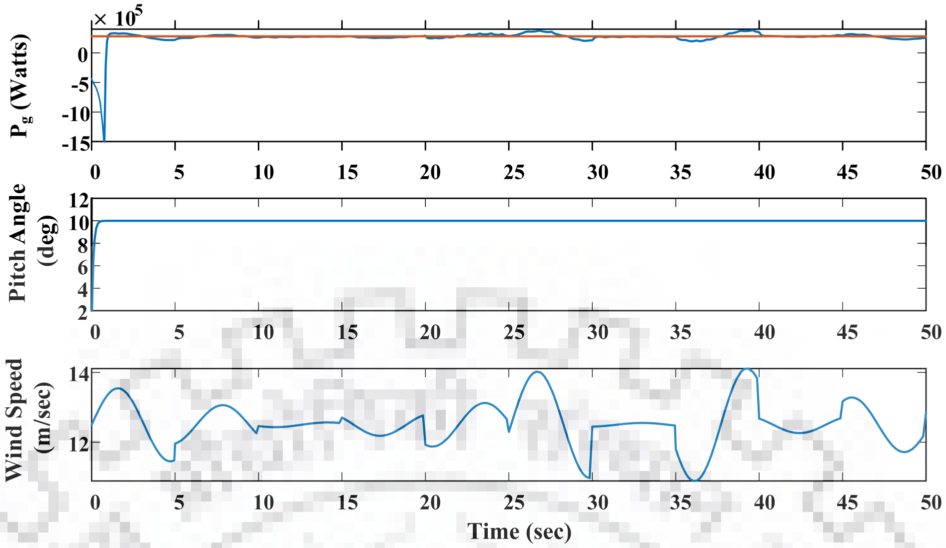

Fig. 6.6: Generator output power, Pitch angle and Wind speed for wind profile 1

From the above Fig. 6.4, it is clear that the power getting generated is more than the rated power, which is not satisfactory because, the wiring and the design of generator is such that they could withstand up to maximum power. So we need a controller to control the power to rated value when speed is more than rated speed.

6.2.2 Output power and pitch angle for wind profile 2

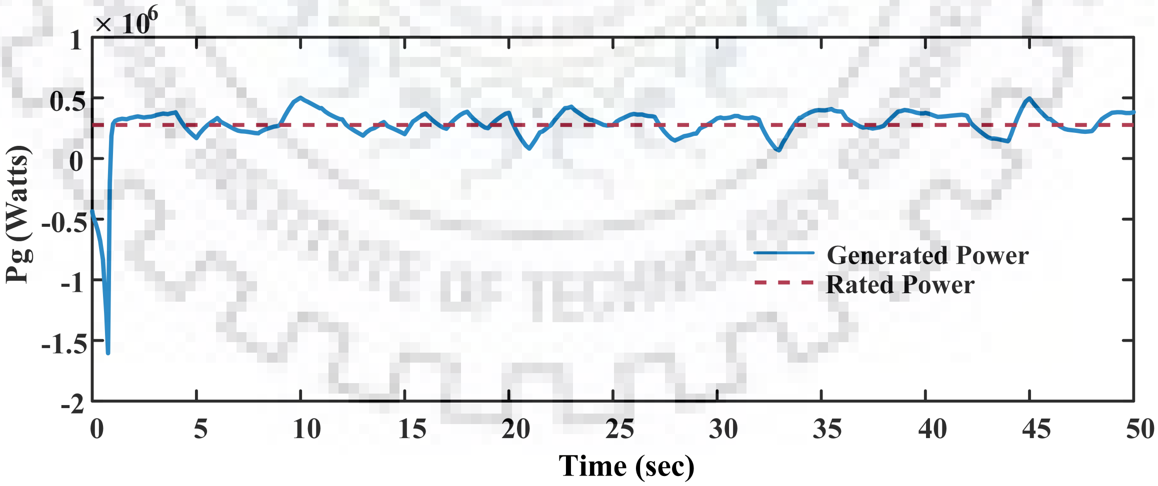

Fig. 6.7: Generator output power for wind profile 2

From the Fig. 6.7, it is more clear that the power getting generated is more than the rated power, when the power getting generated is beyond rated the generator windings and the transmission lines used for the power transmission can't able to withstand. So, it's mandatory to limit the power to rated value by using some controllers.

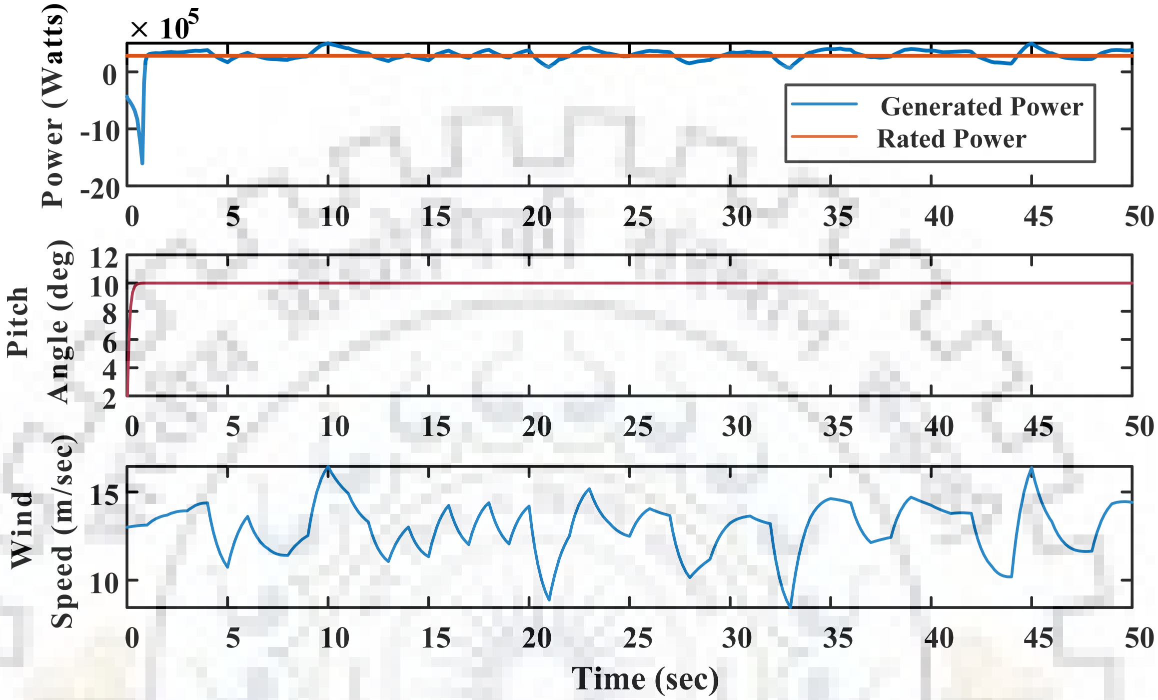

Fig. 6.8: Generator output power, Pitch angle and Wind speed for wind profile 2

6.2.3 Output power and pitch angle for wind profile 3

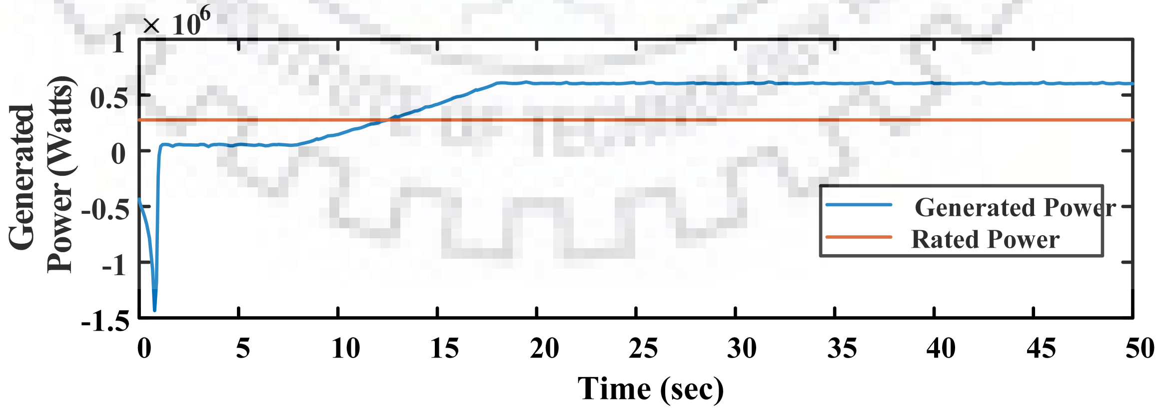

Fig. 6.9: Generator output power for wind profile 3

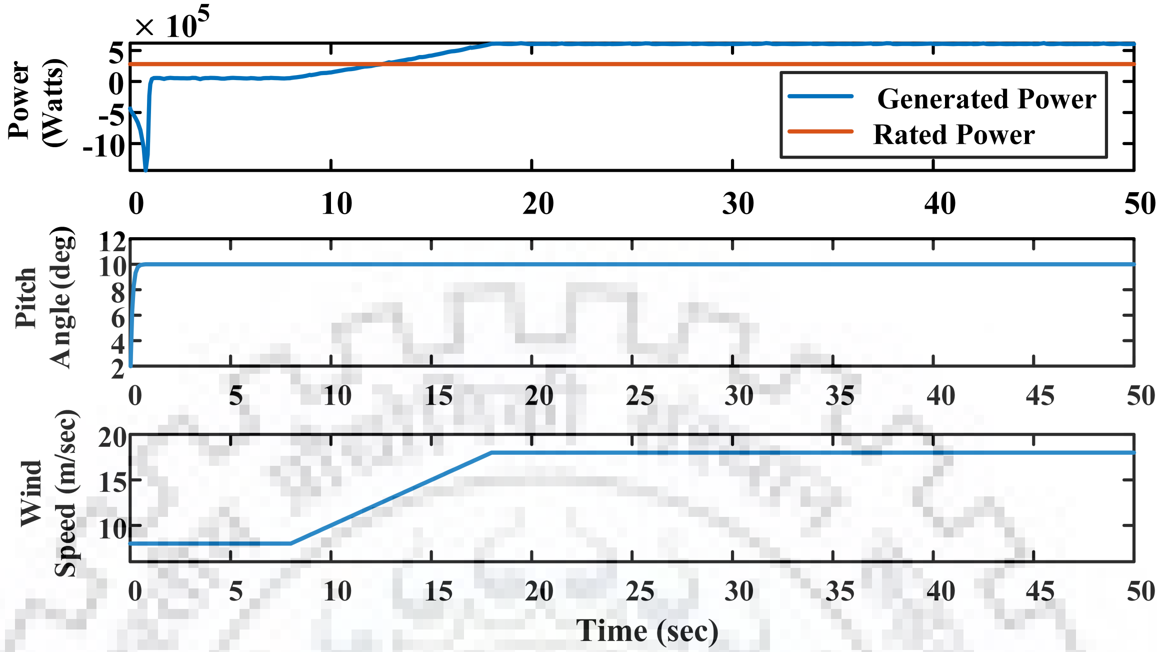

Fig. 6.10: Generator output power, Pitch angle and Wind speed for wind profile 3

6.3 Generator Output Power with PI Controller

6.3.1 Output power and pitch angle for wind profile 1

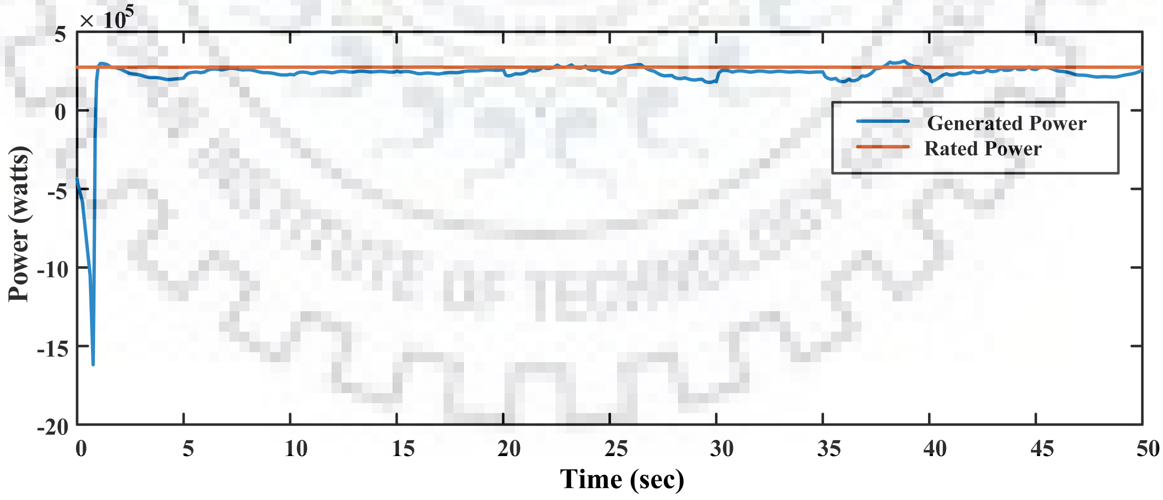

Fig. 6.11: Generator output power with PI controller for wind profile 1

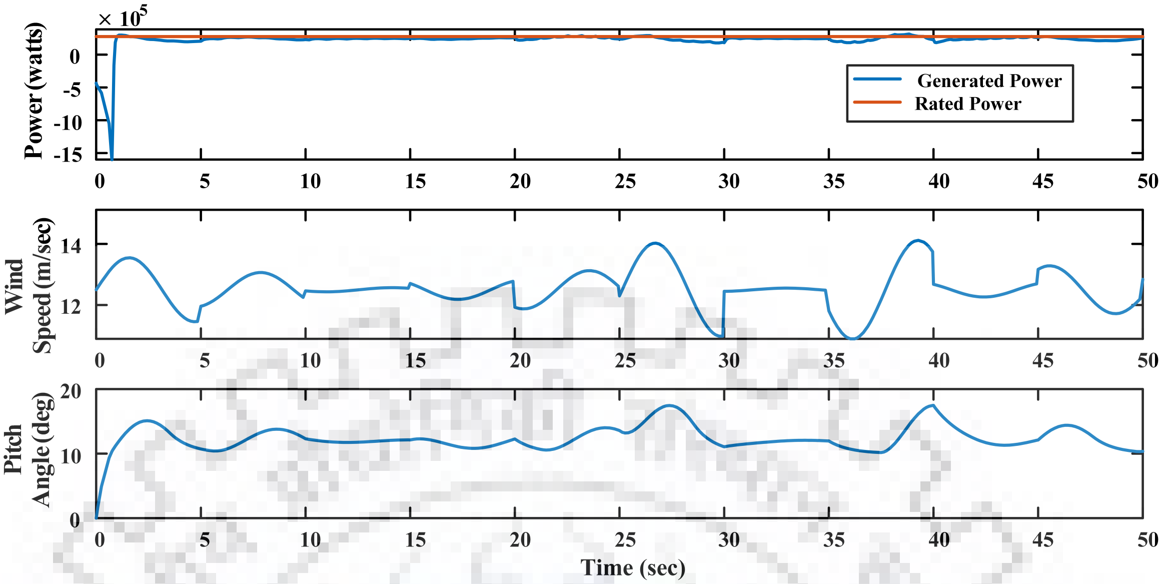

Fig. 6.12: Generator Output Power, Wind speed and Pitch angle with PI controller for wind profile 1

6.3.2 Output power and pitch angle for wind profile 2

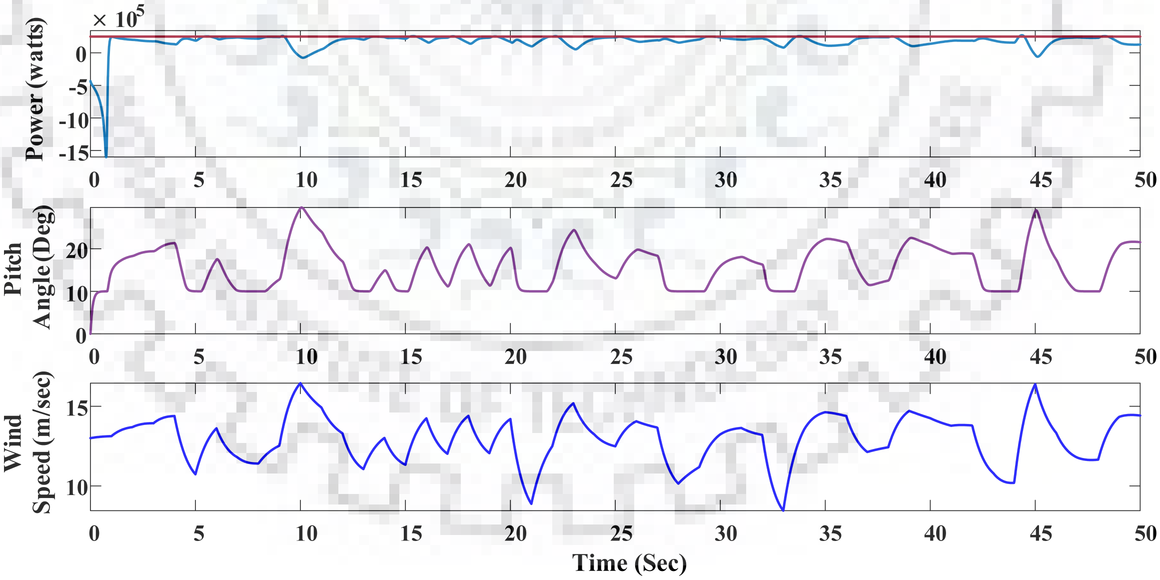

Fig. 6.13: Generator output power, Pitch angle and Wind speed with PI controller for wind profile 2

If we observe the output power curves of wind turbine with two different wind profiles which shown above, the power generation is controlled for the above rated speeds and it is limited to rated power. All this was happened because of the controller. The problem with this controller is that it can't work perfectly for all the different type of winds and the robustness of the controller is not up to the mark.

6.3.3 Output power and pitch angle for wind profile 3

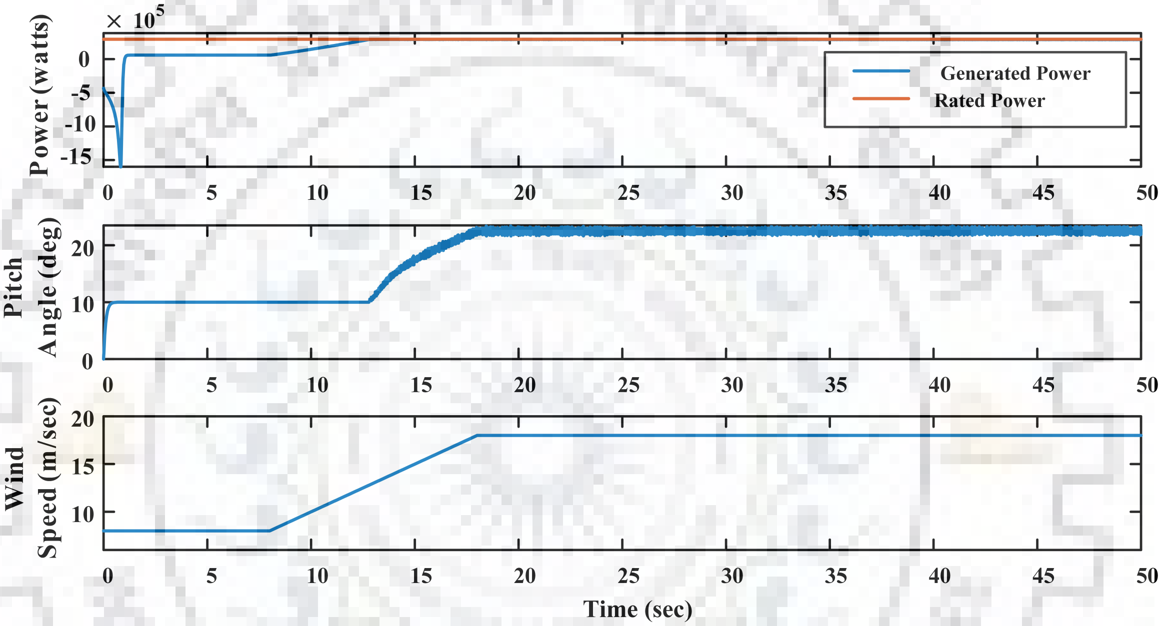

Fig. 6.14: Generator output power, Pitch angle and Wind speed with PI controller for wind profile 3

From the Fig. 6.13, it is clear that the power getting generated is limited to rated power when the speeds are higher than the rated value. When the speed is increasing beyond the rated value then the pitch is getting varied accordingly and the power is getting limited to rated power for all the speeds above the rated. The power is getting limited to rated power in some cases but it's generating beyond rated in some other cases. So we need to go for another controller which controls effectively.

6.4 Generator Output Power with SMC Controller

After observing the wind plant model with PI controller for different wind profiles, it is clear that the power is not getting exactly limited to rated value and so is the reason we were going for SMC Controller.

6.4.1 Output power and pitch angle for wind profile 1

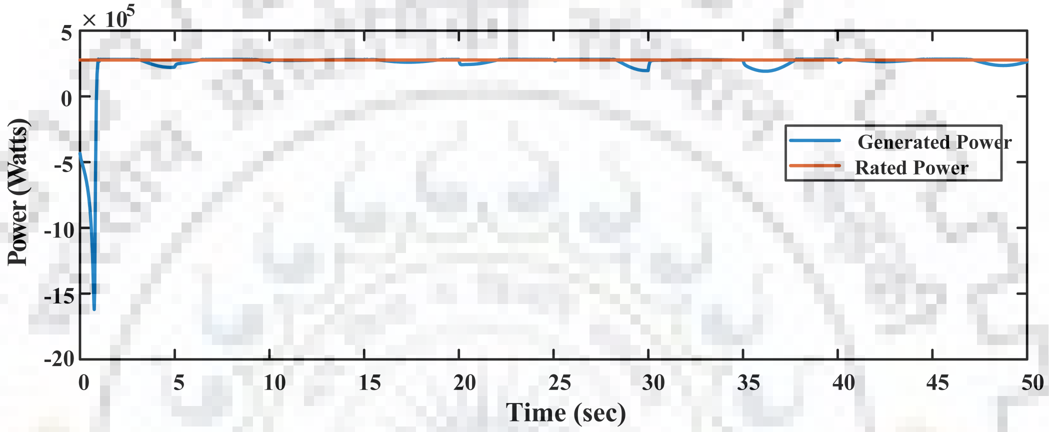

Fig. 6.15: Generator output power with SMC controller for wind profile 1

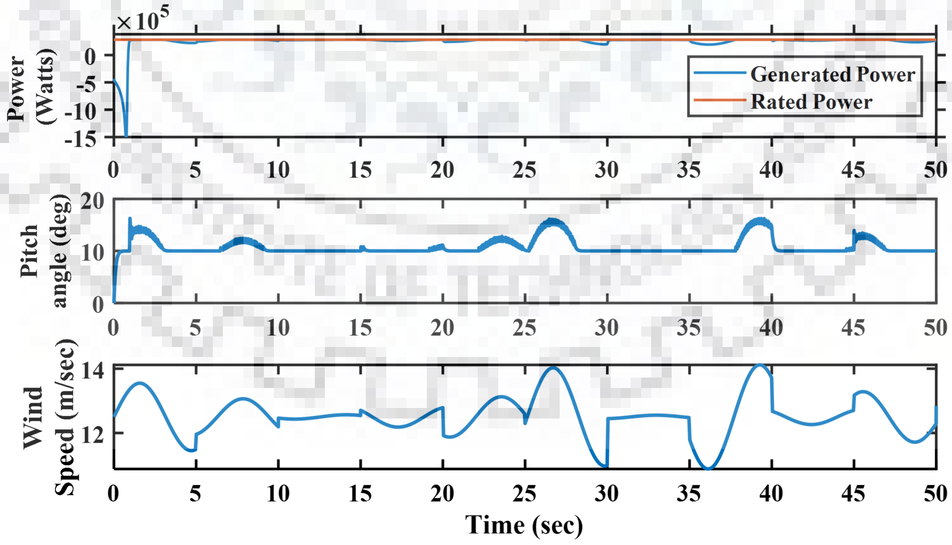

Fig. 6.16: Generator output power, Pitch angle and Wind speed with SMC controller with wind profile 1

6.4.2 Output power and pitch angle for wind profile 2

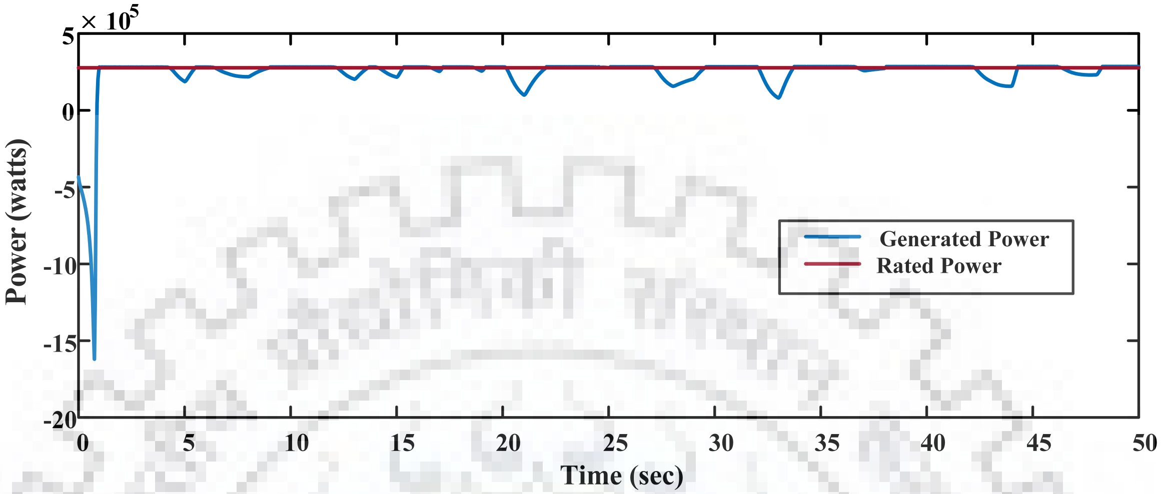

Fig. 6.17: Generator output power with SMC controller for wind profile 2

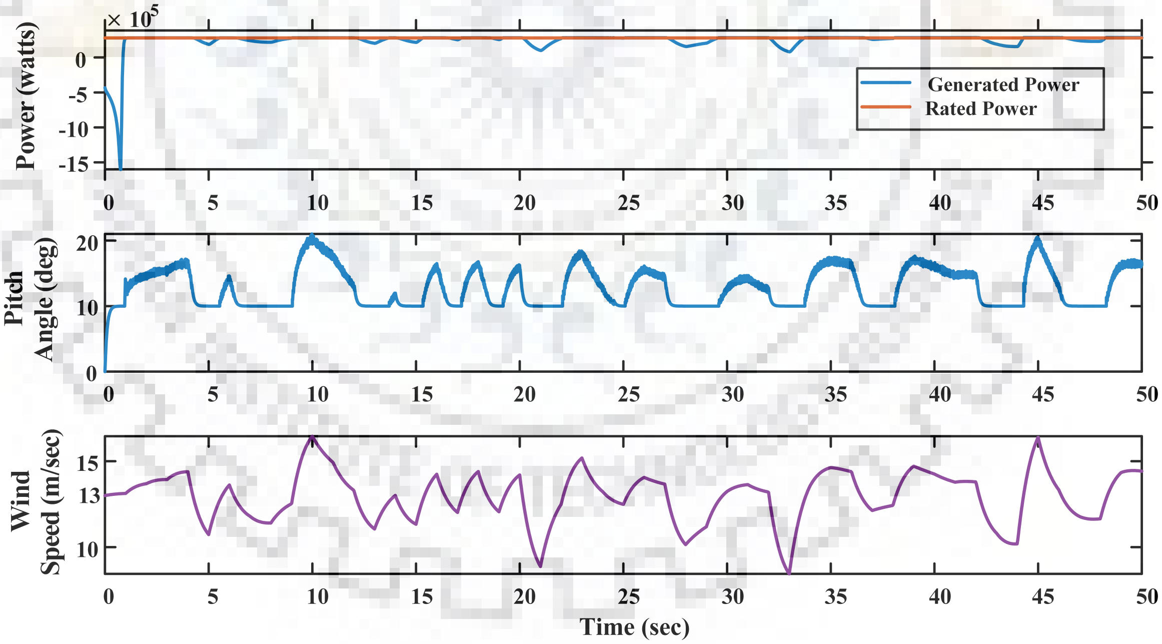

Fig. 6.18: Generator output power, Pitch angle and Wind speed with SMC controller with wind profile 2

6.5 Performance Comparision of Windturbine With and Without Controllers

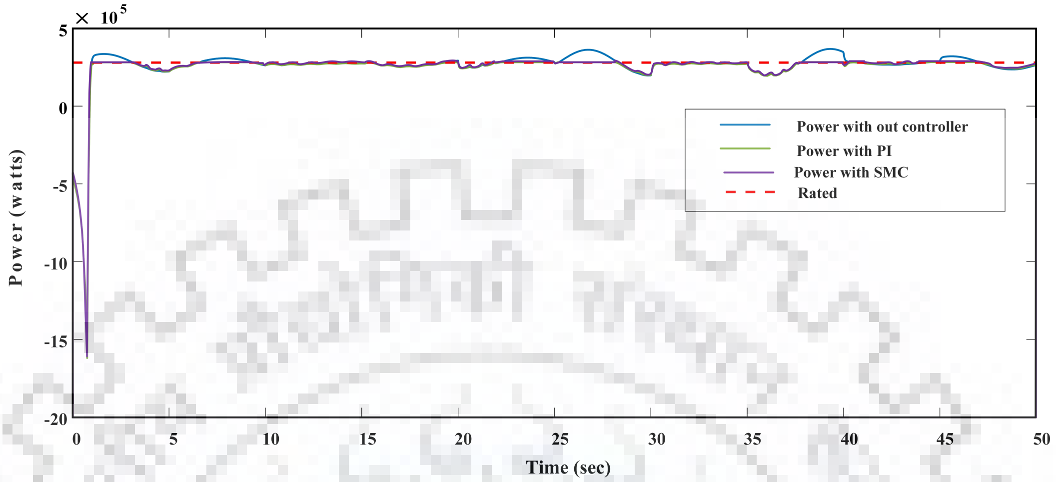

Fig. 6.19: Generation of power from windturbine generator with and without controllers for wind profile 1

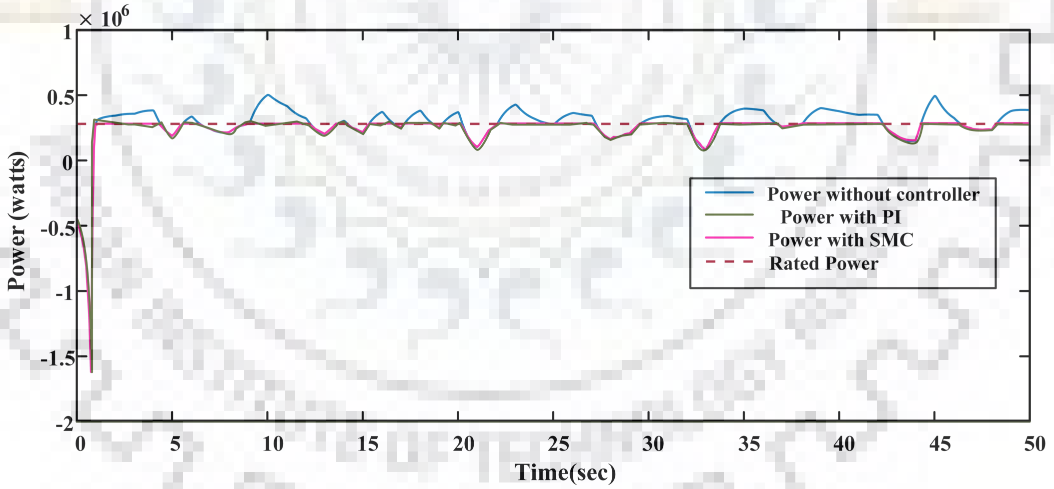

Fig. 6.20: Generation of power from windturbine generator with and without controllers for wind profile 2

From Fig. 6.19 and 6.20, it is clear that, the power generated is limited to rated power when speed is beyond rated and it is done more effectively with SMC controller in comparision to PI and wind turbine with out controller.

CHAPTER 7

CONCLUSIONS AND FUTURE SCOPE

7.1 Conclusions

The performance of wind turbine in terms of power is studied without controller, with PI and SMC controllers. When there is no controller the power getting generated for the above rated wind speeds are greater than the rated value which is not acceptable. To overcome this, some pitch angle is provided initially then the power getting generated is limited to rated power for small range of above rated speeds, but the performance at lower wind speeds is not satisfactory. For this reason, a PI controller is connected such that it gives control signal to pitch actuator by comparing power generated from turbine and the reference power. Then, the controller is providing some pitch angle to the blades when the wind is reaching beyond the rated value so that the power producing is limited to rated value even beyond the rated wind speeds. But, the PI controller isn't showing the satisfactory control action for some wind profiles, because of that SMC controller is used and it is found that the control action is more efficient in comparison to PI controller.

7.2 Future Scope

In this work, controlling of only pitch angle is discussed using SMC controller and getting some satisfactory results but even after controlling the pitch angle the power is getting generated beyond rated for very small time before the control action taking place. To avoid this, the work can be extended to the controlling of both the pitch angle and turbine speed.

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