CHAPTER ONE
INTRODUCTION

1.1 General Review

In recent years, a considerable attention has been paid to wind energy for being one of the promising, clean and safe renewable source. To generate electricity, a wind turbine generator can be used. This system is composed of a rotor and a generator. By exposing the rotor to wind, winds kinetic energy is transferred into electrical energy. The rotor turns a generator typically mounted aft of the rotor, driving the generator to create electricity. The wind turbine generator is mounted at the top of a tower high above the ground to expose it to high winds. The tower is attached to a foundation and is configured to endure significant structural loads [1].

According to the relation between the rotor and wind speed, wind turbines can be divided into two main types: constant and variable speed wind turbines. The first type allows the use of simple generators whose speed are fixed by the frequency of the electrical system, whereas, in the variable speed wind turbines the rotor is allowed to run at variable speeds, thus the power electronics needed are more complex and expensive [2]. On the other hand, there are two controllers for the variable-speed wind turbines. In low wind speed, the controller can continuously adjust the rotor speed to maintain the tip speed ratio constant at the level which gives the maximum power coefficient, so the efficiency of the turbine will be significantly increased. Pitch angle control is necessary in conditions above the rated wind speed when the rotational speed is kept constant which can have a dramatic effect on the power output.

1.2 Problem Definition

Variation of the wind speed has a great impact on the power generated by the turbine and the stability of the system state. The required maximum power and desired stability could be achieved by the proper control of the turbine blades. It is therefore imperative that good algorithms and control mechanisms be designed and implemented to achieve the best possible performance of the turbine system.

1.3 Objective of Study

The main objectives of this thesis is to

- Synchronize the speed of the wind with the blade movement using blade pitch angle control.
- Suggest various controlling variables strategy.
- Simulate and analyze the whole system using MATLAB.
- Stabilize and enhance the outputs of the system.

1.4 Methodology

(a) In this study, the components of (WTCS) have been modeled using MATLAB/SIMULINK tool.

(b) The pitch angle has been adjusted with aid of a PI controller with the objective of adjusting the rotational speed.

(c) Different strategies have been studied to evaluate the performance of the system.

1.5 Layout of Thesis

The research consist of five chapters in addition to list of references. Chapter two is the literature review of this study. In chapter three, there is review of wind turbine control system model. Chapter four includes the results and discussions. Chapter five provides the final conclusion and recommendations for future studies

CHAPTER TWO

LITERATURE REVIEW

2.1 General Review

Renewable energy is energy that is collected from renewable resources, which are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat [3]. Renewable energy often provides energy in four important areas: electricity generation, air and water heating/cooling, transportation, and rural (off-grid) energy services [4]. Based on the Renewable Energy Policy Network for the 21^{st} Century (REN21's) 2016 report, renewables contributed 19.2% and 23.7% to humans' global energy consumption to their generation of electricity in 2014 and 2015, respectively. This energy consumption is divided as 8.9% coming from traditional biomass, 4.2% as heat energy (modern biomass, geothermal and solar heat), 3.9% hydroelectricity and 2.2% is electricity from wind, solar, geothermal, and biomass. Worldwide investments in renewable technologies amounted to more than $286 billion in 2015, with countries like China and the United States (US) heavily investing in wind, hydro, solar and biofuels [5]. Globally, there are an estimated 7.7 million jobs associated with the renewable energy industries, with solar photovoltaic being the largest renewable employer [6]. As of 2015 worldwide, more than half of all new electricity capacity installed was renewable [7].

Renewable energy resources exist over wide geographical areas, in contrast to other energy sources, which are concentrated in a limited number of countries. Rapid deployment of renewable energy and energy efficiency is resulting in significant energy security, climate change mitigation, and economic benefits [8]. The results of a recent review of the literature concluded that as GreenHouse Gas (GHG) emitters begin to be held liable for damages resulting in climate change, a high value for liability mitigation would provide powerful incentives for deployment of renewable energy technologies [9]. In international public opinion surveys there is strong support for promoting renewable sources such as solar power and wind power [10].

In Sudan the Department of Renewable Energy was established in 1980 as one of the departments of the National Energy Administration, which was affiliated to the Ministry of Energy and Mining as an applied research department for renewable energy technologies. In 1995, the National Energy Administration was incorporated in the name of the General Directorate for Energy Affairs of the Sudanese Oil Corporation [11]. In 2010, the ministry established a Directorate for Renewable and Alternative Energy which consists of four divisions: solar energy division, wind energy division, geothermal energy division, and Alternative energy division. A wind atlas has published in March 2012. Figure 2.1 shows the wind resource potential in Sudan [12].

Sudan Rural Electrification Program aims to provide the electricity service to the households in rural areas far from the grid by installing Solar Home Systems (SHS). Currently 10,000 (SHS) implementation ongoing. The renewable energy master plane 2031 is to arrive to 29.3% of the installed capacity. Figure 2.2 shows the renewable energy sources in Sudan [13]. At the national level, at least 30 nations around the world already have renewable energy contributing more than 20 percent of energy supply. National renewable energy markets are projected to continue to grow strongly in the coming decade and beyond [14]. Some places and at least two countries, Iceland and Norway generate all their electricity using renewable energy already, and many other countries have the set a goal to reach 100% renewable energy in the future. For example, in Denmark the government decided to switch the total energy supply (electricity, mobility and heating/cooling) to 100% renewable energy by 2050 [15].

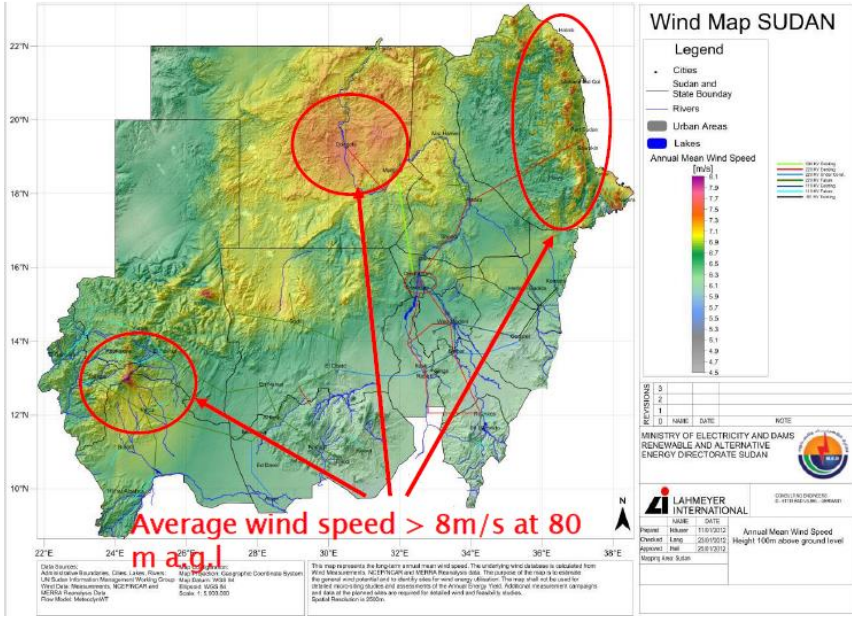


Figure 2.1: Wind resource potential in Sudan

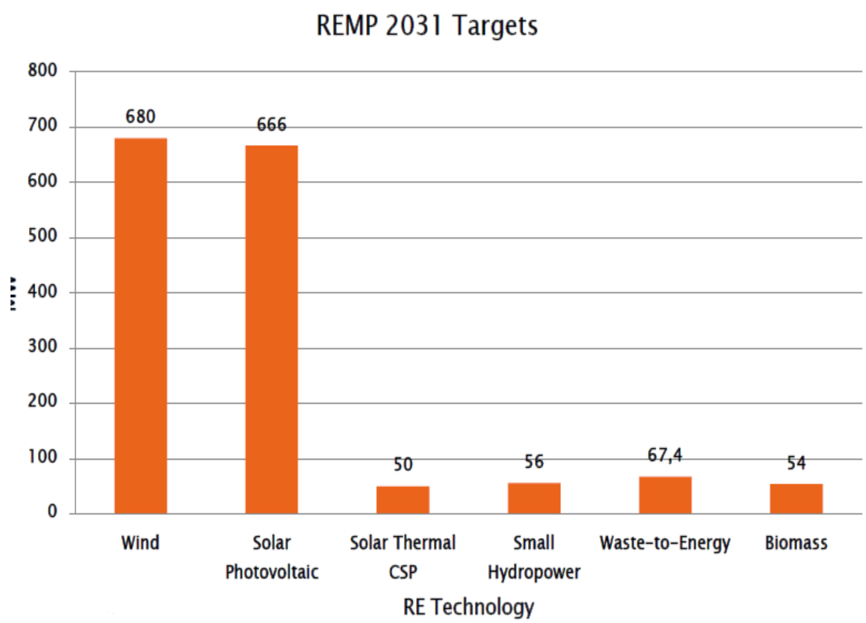


Figure 2.2: Renewable energy (long term plan) in Sudan

2.2 History of Wind Turbine

The wind wheel of the engineer Heron of Alexandria in 1st century Anno Domini (AD) Roman Egypt is the earliest known instance of using a wind-driven wheel to power a machine [16]. The first practical windmills were in use in Sistan, a region in Iran and bordering Afghanistan, at least by the 9^{th} century and possibly as early as the 7^{th} century. These panemone windmills were horizontal windmills, which had long vertical driveshaft with six to twelve rectangular sails covered in reed matting or cloth [17]. These windmills were used to pump water, and in the grist milling and sugarcane industries [18]. The use of windmills became widespread across the Middle East and Central Asia, and later spread to China and India [19]. Vertical windmills were later used extensively in Northwestern Europe to grind flour beginning in the 1180s, and many examples still exist [16]. By 1000 AD, windmills were used to pump seawater.

The first windmills in Europe appear in sources dating to the twelfth century. These early European windmills were sunk post mills. By the 14^{th} century Dutch windmills were in use to drain areas of the Rhine River delta. In 18^{th} century, windmills were used to pump water for salt making on the island of Bermuda, and on Cape Cod during the American Revolution [20]

The first wind turbine used for the production of electricity was built in Scotland in July 1887 by Prof. James Blyth of Anderson's College, Glasgow (the precursor of Strathclyde University) shown in figure 2.3 [21]. Blyth's 10m high, cloth-sailed wind turbine was installed in the garden of his holiday cottage at Marykirk in Kincardineshire and was used to charge accumulators developed by the Frenchman Camille Alphonse Faure, to power the lighting in the cottage [21], thus making it the first house in the world to have its electricity supplied by wind power [22].

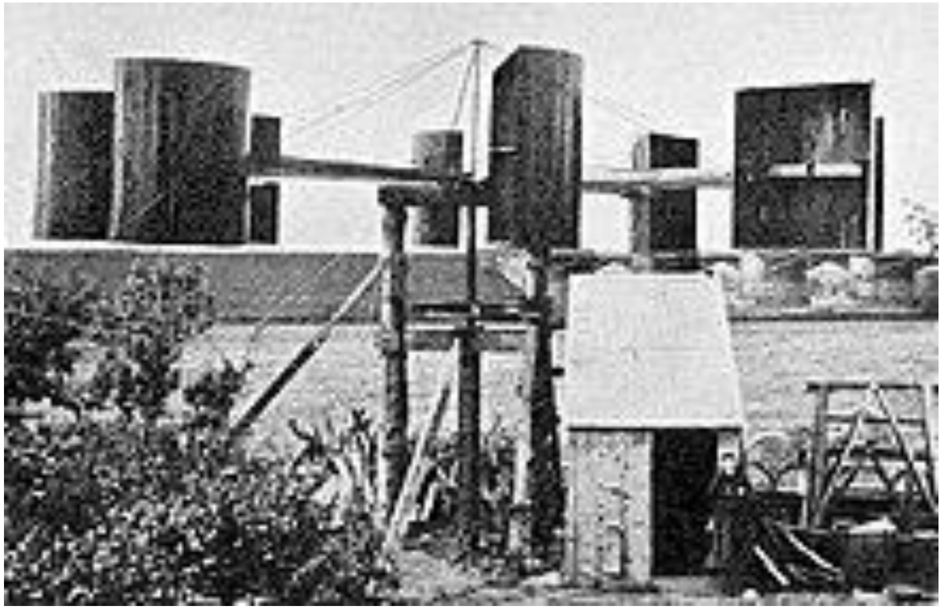


Figure 2.3: Blyth's "windmill" at his cottage in Marykirk in 1891.

2.3 Types of Wind Turbine

Wind turbines can be divided into two basic types as follows [23].

2.3.1 Horizontal axis wind turbines

Horizontal axis wind turbine, also shortened to HAWT, is the common style that most people think of when they think of a wind turbine. A HAWT has a similar design to a windmill, it has blades that look like a propeller that spin on the horizontal axis. Horizontal axis wind turbines have the main rotor shaft and electrical generator at the top of a tower, and they must be pointed into the wind. Small turbines are pointed by a simple wind vane placed square with the rotor (blades), while large turbines generally use a wind sensor coupled with a servo motor to turn the turbine into the wind. Most large wind turbines have a gearbox, which turns the slow rotation of the rotor into a faster rotation that is more suitable to drive an electrical generator. Figure 2.4 shows the HAWT.

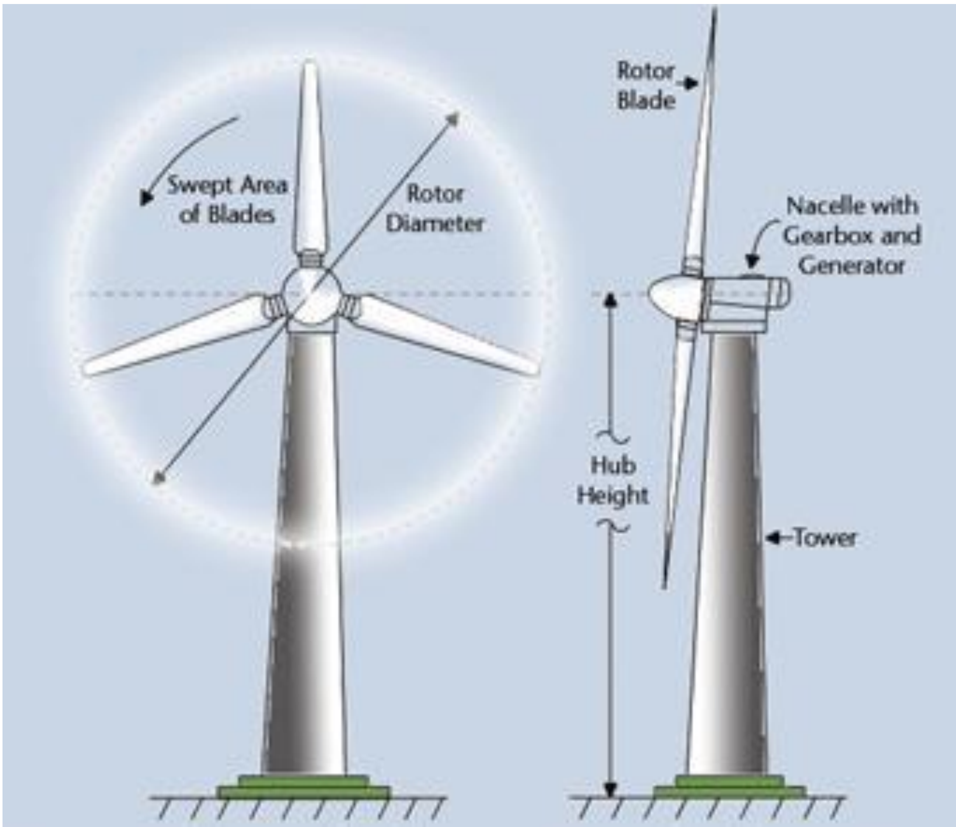


Figure 2.4: Horizontal axis wind turbine

2.3.2 Vertical Axis Wind Turbines

Vertical axis wind turbines, as shortened to VAWTs, have the main rotor shaft arranged vertically. The main advantage of this arrangement is that the wind turbine does not need to be pointed into the wind. This is an advantage on sites where the wind direction is highly variable or has turbulent winds. With a vertical axis, the generator and other primary components can be placed near the ground, so the tower does not need to support it, also makes maintenance easier. The main drawback of a VAWT generally create drag when rotating into the wind.

It is difficult to mount vertical-axis turbines on towers, meaning they are often installed nearer to the base on which they rest, such as the ground or a building rooftop. The wind speed is slower at a lower altitude, so less wind energy is available for a given size turbine. Air flow near the ground and other objects can create turbulent flow, which can introduce issues of vibration, including noise and bearing wear which may increase the maintenance or shorten its service life. However, when a turbine is mounted on a rooftop, 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 minimum wind turbulence. Figure 2.5 shows the VAWT.

2.4 Variable Speed and Fixed Speed Wind Turbine

A major distinction in the wind turbines includes variable and constant speed wind turbines i.e. the rotor is allowed to run at variable speed or constrained to operate at constant speed. The constant speed wind turbines allow the use of simple generators whose speed is fixed by the frequency of the electrical system [2]. During the past few years the variable-speed wind turbine has become the dominant type among the installed wind turbines. Variable-speed wind turbines are designed to achieve maximum aerodynamic efficiency over a wide range of wind speeds. With a variable-speed operation it has become possible continuously to adapt (accelerate or decelerate) the rotational speed ω of the wind turbine to the wind speed v. The ratio between the speed of the tips of the blades of the wind turbine and the speed of the wind (λ) is kept constant at a predefined value that corresponds to the maximum power coefficient. Contrary to a fixed-speed system, a variable-speed system keeps the generator torque fairly constant and the variations in wind are absorbed by changes in the generator speed. The electrical system of a variable-speed wind turbine is more complicated than that of a fixed-speed wind turbine.

A variable speed wind turbine is typically equipped with an induction or synchronous generator and connected to the grid through a power converter. The power converter controls the generator speed; that is, the power fluctuations caused by wind variations are absorbed mainly by changes in the rotor generator speed and consequently in the wind turbine rotor speed. The advantages of variable-speed wind turbines are an increased energy capture, improved power quality and reduced mechanical stress on the wind turbine. The disadvantages are losses in power electronics, the use of more components and the increased cost of equipment because of the power electronics.

2.4.1 Main Operating Region of Variable Speed Wind Turbine

Variable speed wind turbine has three main regions of operation as shown in Figure 2.6. The use of modern control strategies are not usually critical in region I, where the monitoring of the wind speed is performed to determine whether it lies within the specifications for turbine operation and if so, the routines necessary to start up the turbine are performed. Region II is the operational mode in which the goal is to capture as much power as possible from the wind. Region III is called rated wind speed [24]

2.4.2 Adjustable speed generators

Modern high-power wind turbines are capable of adjustable speed operation. Key advantages of Adjustable Speed Generators (ASGs) compared to Fixed-Speed Generators (FSGs) are [25]:

■They are cost effective and provide simple pitch control; the controlling speed of the generator (frequency) allows the pitch control time constants to become longer, reducing pitch control complexity and peak power requirements.

At lower wind speed, the pitch angle is usually fixed. Pitch angle control is performed only to limit maximum output power at high wind speed.

■They reduce mechanical stresses; gusts of wind can be absorbed, i.e., energy is stored in the mechanical inertia of the turbine, creating an “elasticity” that reduces torque pulsations.

■They dynamically compensate for torque and power pulsations caused by back pressure of the tower. This back pressure causes noticeable torque pulsations at a rate equal to the turbine rotor speed times the number of rotor wings.

■They improve power quality; torque pulsations can be reduced due to the elasticity of the wind turbine system. This eliminates electrical power variations, i. e., less flicker.

■They improve system efficiency; turbine speed is adjusted as a function of wind speed to maximize output power. Operation at the maximum power point can be realized over a wide power range. Typical output power-speed curves can be as a function of turbine speed and wind speed. As a result, energy efficiency improvement up to 10% is possible.

Electrical output power as a function of turbine speed. Parameter curves are plotted for different wind speeds. Maximum power point tracking can be realized with a speed variable system.

■They reduce acoustic noise, because low-speed operation is possible at low power conditions.

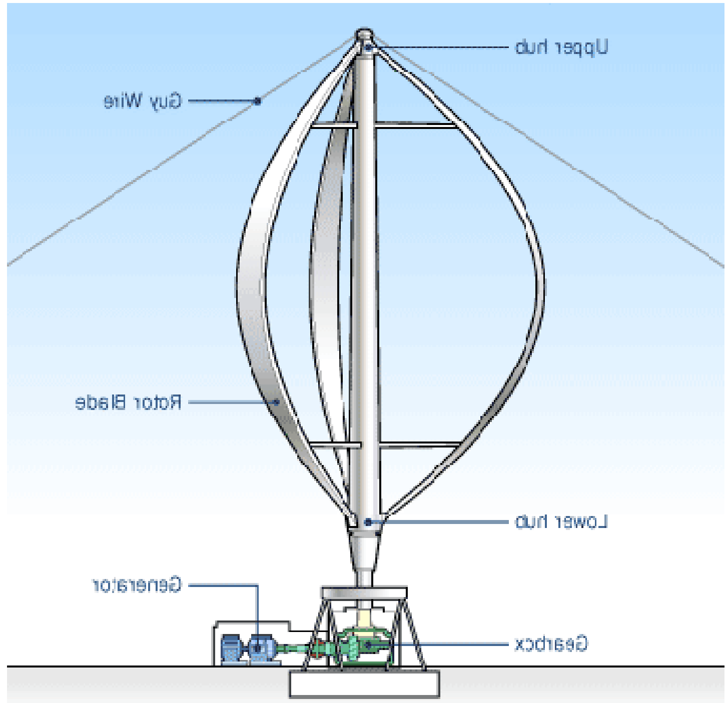


Figure 2.5: Vertical axis wind turbine

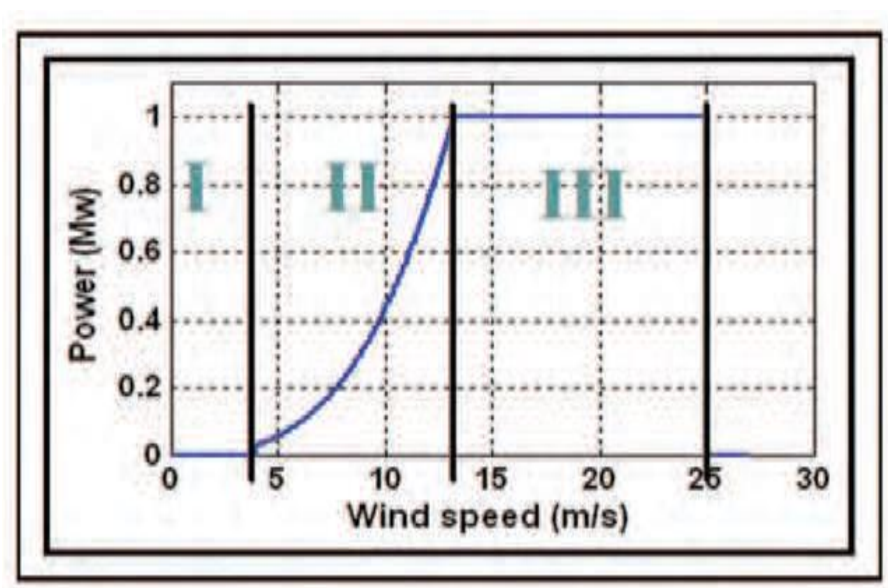


Figure 2.6: operation region of variable speed wind turbine

2.5 Wind Characteristic and Factors

The kinetic energy in a flow of air through a unit area perpendicular to the wind direction is $\frac{1}{2}.v^2$ per mass flow rate. For an air stream flowing through an area A the mass flow rate is $\rho.A.v$, therefore the power in the wind is given by

$$p = \rho.A.v\,\frac{1}{2}.v^2 = \frac{1}{2}.\rho.A.v^3 \qquad (2.1)$$

Where:

ρ is the air density ($\frac{kg}{m^3}$).

A is the area (m^2).

v is the wind speed (m/s).

p is the power of the wind (watt or J/s).

Only a portion of the power in the wind can be converted to useful energy by wind turbine. The fraction of energy extracted by the wind turbine of the total energy that would have flowed through the area swept by the rotor is the power coefficient C_p

$$C_p = p_{extracted}/p_{wind} \qquad (2.2)$$

It is also is given as a nonlinear function of the tip speed ratio λ and the pitch angle β.

$$C_p(\lambda, \beta) = (0.44 - 0.0167\beta)\sin\left[\frac{\pi(\lambda-3)}{15-0.3\beta}\right] - 0.00184(\lambda-3)\beta \qquad (2.3)$$

Where λ is the ratio between the speed of the tips of the blades of the wind turbine and the speed of the wind. And can be calculated as:

$$\lambda = v_{tip}/v_{wind} = \omega . R/v \tag{2.4}$$

Where ω is the blades angular velocity (rad/s), R the rotor radius (m) and v the wind speed (m/s). A typical C_p versus λ characteristics is depicted in Figure 2.7. For a fixed-speed wind turbine, where ω is constant, this corresponds to a particular wind speed. For all other wind speeds the efficiency of the turbine is reduced. The aim of variable-speed wind turbines is to always run at optimal efficiency, keeping constant the particular λ that corresponds to the maximum C_p, by adapting the blades velocity to the wind speed changes. Hence, variable speed wind turbines are designed to operate at optimum energy efficiency, regardless of the wind speed [2].

2.6 Type of Generator in Wind Turbine

There are three main types of generators that could be used in a wind turbine [26].

2.6.1. Induction generator

An induction generator is a type of electrical generator that is mechanically and electrically similar to an induction motor. Induction generators produce electrical power when their shaft is rotated faster than the synchronous frequency of the equivalent induction motor. Induction generators are often used in wind turbines and some micro hydro installations. Induction generators are mechanically and electrically simpler than other generator types. They are also more rugged, requiring no brushes or commutator.

Induction generators are not self-exciting, meaning they require an external supply to produce a rotating magnetic flux, the power required for this is called reactive current. The external supply can be supplied from the electrical grid or from the generator itself, once it starts producing power or by using a capacitor bank to supply it. The rotating magnetic flux from the stator induces currents in the rotor, which also produces a magnetic field. If the rotor turns slower than the rate of the rotating flux, the machine acts like an induction motor. If the rotor is turned faster, it acts like a generator, producing power at the synchronous frequency. In the United States it would be 60Hz. The common down side of using an induction generator in a wind turbine is gearing. Typically, it needs an induction motors to run 1500+ Revolution Per Minute (RPM) to meet the synchronous so a gearing is almost always needed. Figure 2.8 illustrated the induction generator construction.

2.6.2 Permanent magnet alternators

Permanent Magnets Alternators (PMA) have one set of electromagnets and one set of permanent magnets. Typically the permanent magnets can be mounted on the rotor with the electromagnets on the stator. Permanent magnet motor and generator technology has advance greatly in the past few years with the creation of rare earth magnets (neodymium, samarium-cobalt, and alnico). Generally the coils can be wired in a standard three phase wye or delta. Permanent magnet alternators are can be very efficient, in the range of 60%-95%, typically around 70% though. As a generator they do not require a controller as a typical three phase motor would need. It is easy to rectify the power from them and charge a battery bank or use with a grid tie. Figure 2.9 shows the main components of PMA.

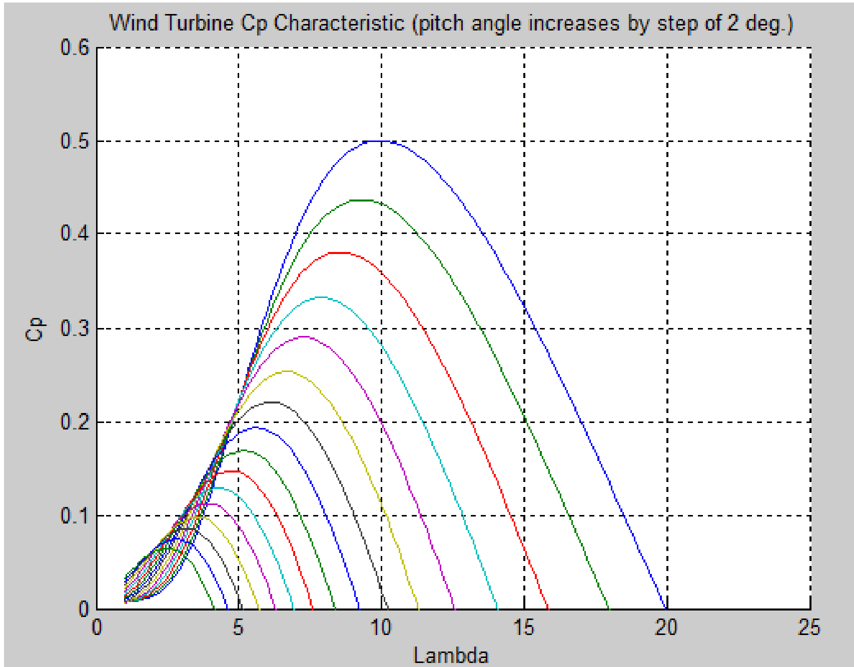


Figure 2.7: Cp characteristic curve

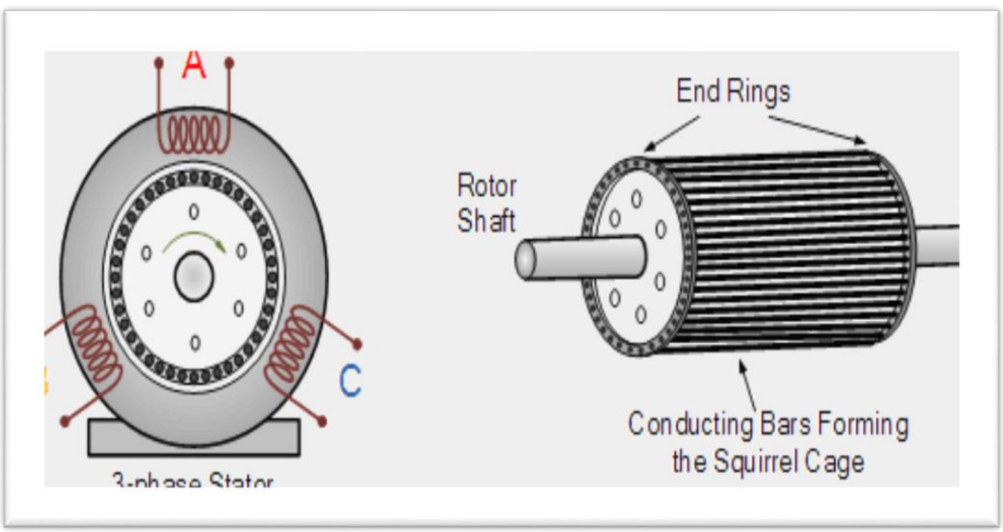


Figure 2.8: Induction generator construction

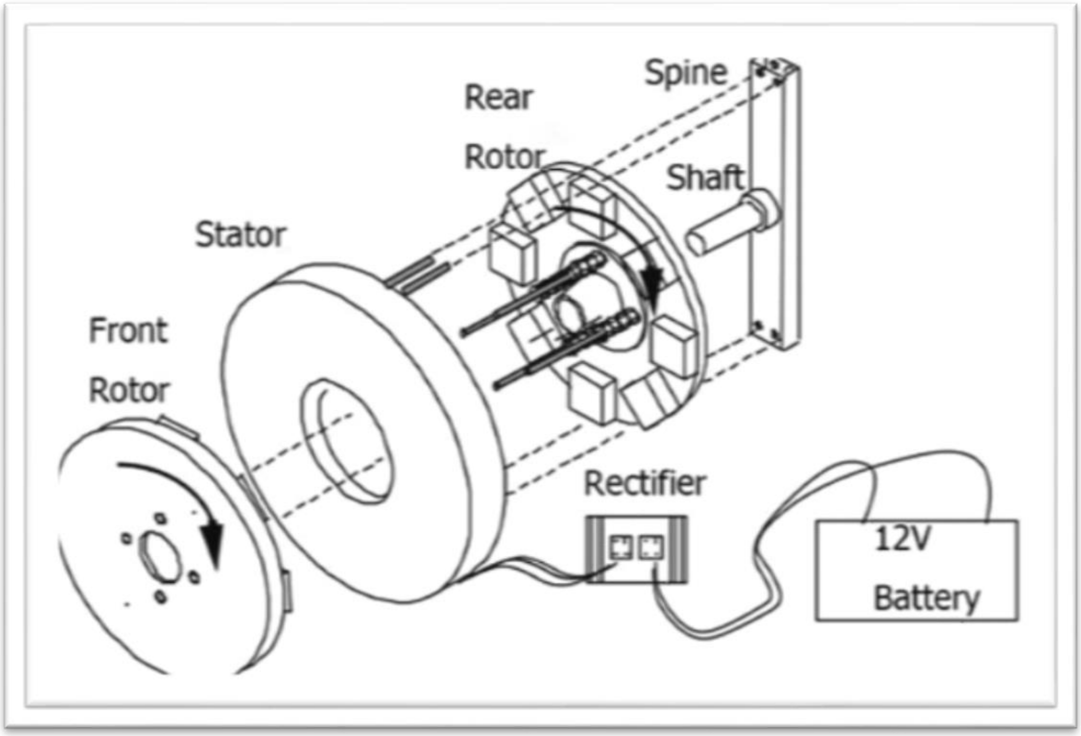


Figure 2.9: The main components of permanent magnet alternators

2.6.3 Brushed direct current motor

Brushed DC Motors are commonly used for home built wind turbines. They are backwards from a permanent magnet generator. On a brushed motor, the electromagnets spin on the rotor with the power coming out of what is known as a commutator. This does cause a rectifying effecting outputting lumpy DC, but this is not an efficient way to "rectify" the power from the windings, it is used because it's the only way to get the power out of the rotor. A good brushed motor can reach a good efficiency, but are typically at most 70%.

There are many great advantages to using a brushed motor. One of the biggest reasons is not requiring any gearing and still get a battery charging voltage in light wind.

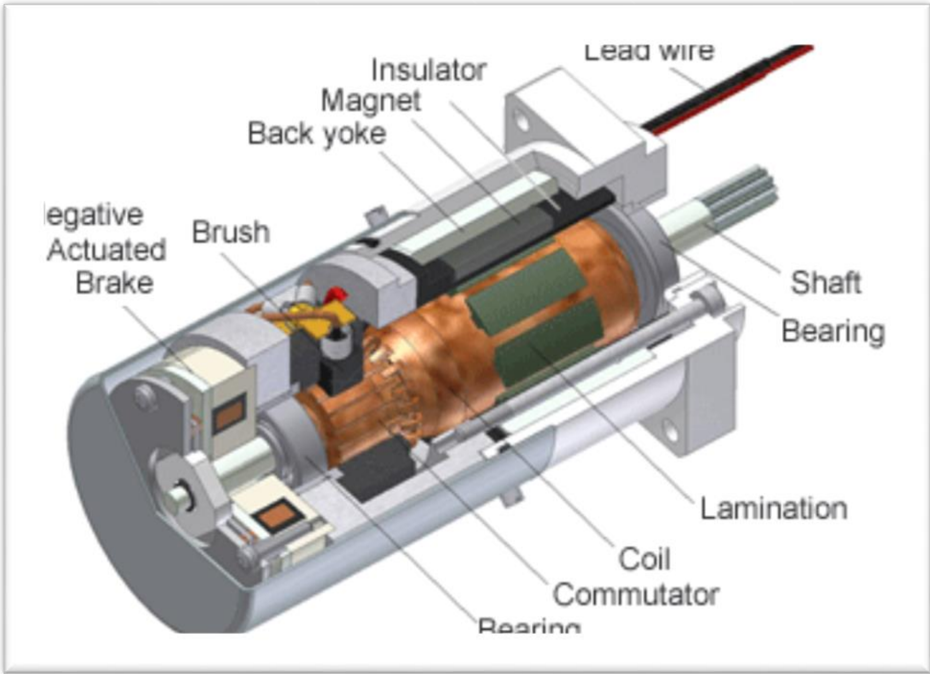


Figure 2.10: Construction of brushed DC motor

2.7 Proportional integral derivation controller

A proportional–integral–derivative controller (PID controller or is a control loop feedback mechanism widely used in industrial control systems and a variety of other applications requiring continuously modulated control. A PID controller continuously calculates an error value as the difference between a desired Set Point (SP) and a measured Process Variable (PV) and applies a correction based on proportional, integral, and derivative terms (denoted P, I, and D respectively) which give the controller its name. The first theoretical analysis and practical application was in the field of automatic steering systems for ships, developed from the early 1920s onwards. It was then used for automatic process control in manufacturing industry, where it was widely implemented in pneumatic, and then electronic, controllers. Today there is universal use of the PID concept in applications requiring accurate and optimized automatic control [27].

2.8 Pitch Controller:

Recently, pitch-adjusting variable-speed wind turbines have become the dominating type of installed wind turbines. Pitch angle control method is a basic approach to improve the performance of the power generation system including different types of wind turbines. The purpose of the pitch angle control might be expressed as follows [28, 29]:

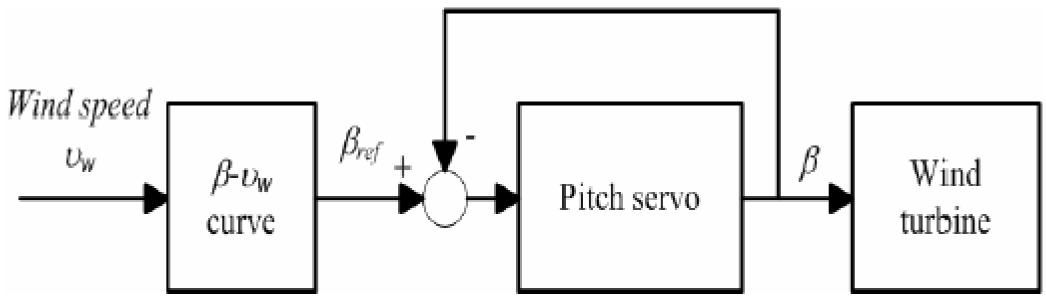
- Optimizing the wind turbine power output. Below rated wind speed, the pitch setting should be at its optimum value to give maximum power.
- Preventing the mechanical power input to beat the design limits. Above rated wind speed, pitch angle control provides an effective method of regulating the aerodynamic power and loads produced by the rotor.
- Minimizing fatigue loads of the turbine mechanical component. It is clear that the action of the control system can have a major impact on the loads experienced by the turbine. The design of the controller must take into account the effect on loads, and the controller should ensure that excessive loads will not result from the control action. It is possible to go further than this, and explicitly design the controller with the reduction of certain fatigue loads as an additional objective.

Adjusting the pitch angle of the blades, provides an effective means of limiting turbine performance in strong wind speeds. To put the blades into the desired position, electric or hydraulic pitch servos are employed. The pitch angle reference β_{ref}, is controlled by the input signals, which may be as follows:

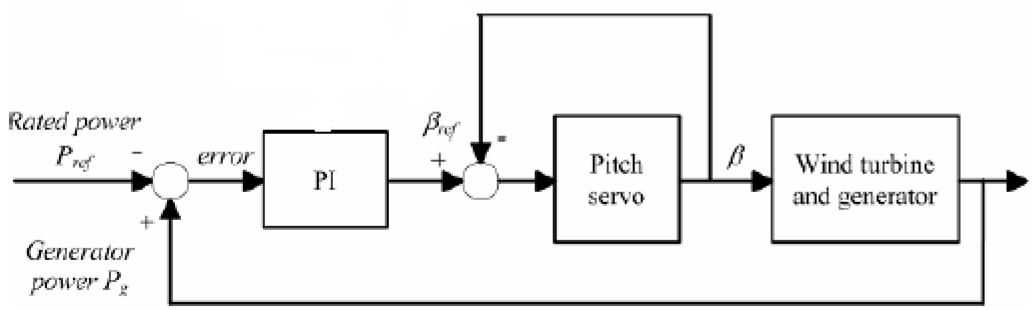
• Wind speed, as shown in Figure 2.11a. Ideally, the pitch angle reference can be obtained from the curve of the pitch angle versus wind speed. This control strategy is not an acceptable method, as the effective wind speed cannot be measured accurately

• Generator power, the error signal of the generated power is sent to the PI controller to produce a reference pitch angle, as shown in Figure 2.11b

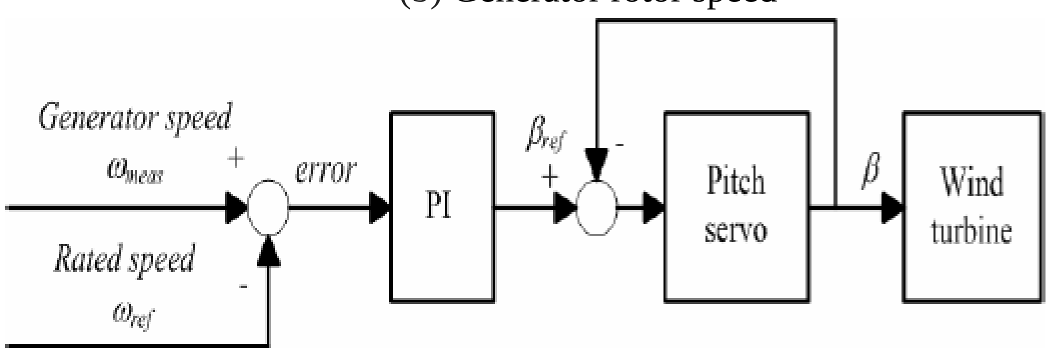
• Generator rotor speed, as shown in Figure 2.11c. The error between the generator rotor speed and its set point is sent to the PI controller to produce a reference value for the pitch angle. This method is most popular, since it is more accurate.



(a) Wind speed



(b) Generator rotor speed



(c) Generator power

Figure 2.11: Pitch control input signals

2.9 Previous Studies

Sachin Khajuria and Jaspreet Kaur used a PI controller to generate a fixed value of voltage at the output**,** the Simulink showed that as the wind speed changes then there is a corresponding change in the values of rotor speed, and the PI controller has maintained the output at some constant value [30].

Abdulhamed Hwas and Reza Katebi suggested two methods to calculate the gains of a proportional-integral pitch angle controller for a 5MW wind turbine. The first method is analytical and the second one is based on simulation. Firstly, the power coefficient characteristics for different pitch angles are calculated. Secondly, the output powers vs. rotor speed curves from cut-in to cut-out wind speeds are simulated. The results demonstrated good performance for both proposed PI schemes [31].

Wind energy is not constant and windmill output is proportional to the cube of wind speed, which causes the generated power of Wind Turbine Generators (WTGs) to fluctuate. In order to reduce fluctuation, different methods are available to control the pitch angle of blades of windmill. T. Senjyu , R. Sakamoto , N. Urasaki , T. Funabashi , H. Fujita and H. Sekine proposed the pitch angle control using minimum variance control, and output power leveling was achieved. However, it is a controlled output power for only rated wind speed region as their results shows [32].

P. M. Anderson and Anjan Bose described use the model of a wind turbine using a large scale transient stability computer program. Computed results illustrate the wind turbine-generator system dynamic performance for changes in wind velocity [33].

Sasmita Behera, Bidyadhar Subudhi and Bibhuti Bhusan Pati were built a PI pitch angle controlled with gain Kp and Ki which tuned through Particle Swarm Optimization (PSO) and Pattern Search (PS) algorithms. And they compared the performances of the algorithms in designing the controller. It found that the PSO takes less time for same number of iterations and independent of initial point, hence achieves global optimum. Whereas, PS and SA attain similar results with proper setting of initial condition, with increased iteration and increased time [34].

Mouna Ben Smida and Anis. Sakly deal with the operation and the control of the direct driven Permanent Magnet Synchronous Generator (PMSG). And PI controller to control the pitch at high wind speed. The simulation results show that the power controller has lower torque peak and lower power peak [35].

S. Muller, M. Deicke, R.W and De Doncker show that adjustable speed generators for wind turbines are necessary when output power becomes higher than 1MW. The Doubly Fed Induction Generator (DFIG) system presented in their article offers many advantages to reduce cost and has the potential to be built economically at power levels above 1.5MW. Measurements obtained from 1.5MW units currently in operation confirm the theoretical results [31].

Pitch angle control is the most common means for adjusting the aerodynamic torque of the wind turbine when wind speed is above rated speed and various controlling variables may be chosen, such as wind speed, generator speed and generator power. Jianzhong Zhang , Ming Cheng , Zhe Chen and Xiaofan Fu developed a fuzzy logic pitch angle controller which it have the potential when the system contains strong nonlinearity, such as wind turbulence is strong, or the control objectives include fatigue loads. Strategy may have the potential when the system contains strong nonlinearity, such as wind turbulence is strong, or the control objectives include fatigue loads. The design of the fuzzy logic controller and the comparisons with conversional pitch angle control strategies with various controlling variables are carried out. The simulation shows that the fuzzy logic controller can achieve better control performances than conventional pitch angle control strategies, namely lower fatigue loads, lower power peak and lower torque peak [36].

E. Koutroulis and K. Kalaitzakisa presented a Wind-Generator (WG) Maximum-Power-Point-Tracking (MPPT) system. The proposed method operates at a variable wind speed and the measurement of the speed was not required. Experimental results of the proposed system indicate increasing by 11%-50% compared to a WG directly connected via a rectifier to the battery bank. Their method is useful under low wind speeds [37].

J. G. Slootweg , S. W. H. De Haan , H. Polinder and W. L. Kling presented a model that can be used to the types of variable speed wind turbines in power system dynamics simulations. The models of the subsystems of which a variable speed wind turbine consists were discussed. The results obtained after incorporation of the model in PSS/E, a widely used power system dynamics simulation software package, were presented and compared with measurements [38].

Large wind plants have a significant influence on power system operation since they are related to unpredictability of the primary source. Wind energy is not constant and, since wind turbines output is proportional to the cube of wind speed, this causes the power output of Squirrel-Cage Induction Generator Wind Turbine (SCIG WT) to fluctuate. Minh, Quan Duong, Francesco Grimaccia, Sonia Leva, Marco Mussetta and Emanuele Ogliari presents a hybrid controller based on PI and fuzzy technique for the pitch angle controller [39].

Ahmad Y Hassan and Donald Routledge Hill has presented a PID pitch angle controller for a fixed speed active-stall wind turbine, using the root locus method is described in their paper. Simulations show that in most operating points the pitch controller can effectively contribute to power system stabilization [40]. Their results shows that in most operating points the pitch controller can effectively contribute to power system stabilization. In the active PID pitch controller, the sensitivity of aerodynamic power to the rotor collective blade-pitch angle is negative. With positive control gains, the derivative term will then increase the effective inertia of the drive train. Hansen et al. recommend using PI controller [41]. However, Boukhezzar et al. suggest using only a proportional pitch controller based on the test results that show a more complex controller (PI and PID) will make the pitch control more turbulent without a significant improvement of the power regulation performance [42]. Moreover, it is shown that using an advanced control strategy such as Linear Quadratic Gaussian (LQG) control design technique ensures a better power tracking than the PID, but this turns out to be still insufficient to meet all the control objectives [43].

CHAPTER THREE

WIND TURBINE CONTROL SYSTEM MODEL

3.1 Components of Horizontal Axis Wind Turbine

Although a wind turbine can be built in either a vertical-axis or horizontal-axis configuration. Here the (HAWTs) are illustrated, because they dominate the utility-scale wind turbine market. At the utility scale, HAWTs have aerodynamic and practical advantages [44]. Smaller (VAWTs) are more likely to use passive rather than active control strategies. In fact, generally for vertical axis wind turbine, which consists of several blades rotating about axis in parallel direction, the cycloid blade system and the individual active blade control system are adopted. As shown in Figure 3.1, the HAWT consist of major component as the follows:

- Nacelle:

The nacelle contains the key components of the wind turbine, including the gearbox, and the electrical generator. Service personnel may enter the nacelle from the tower of the turbine. To the left of the nacelle we have the wind turbine rotor, i.e. the rotor blades and the hub.

- Rotor blades:

The rotor blades capture the wind and transfer its power to the rotor hub. On a modern 1000kW wind turbine each rotor blade measures about 27 meters (80ft.) in length and is designed much like a wing of an airplane.

- Hub:

The hub of the rotor is attached to the low speed shaft of the wind turbine.

- Low speed shaft:
- The low speed shaft of the wind turbine connects the rotor hub to the gearbox. On a modern 1000kW wind turbine the rotor rotates relatively slowly, about

19 to 30 RPM. The shaft contains pipes for the hydraulics system to enable the aerodynamic brakes to operate.

- Geer box:

The gearbox has the low speed shaft to the left. It makes the high speed shaft to the right turn approximately 50 times faster than the low speed shaft.

- High speed shaft and the brake:

  The high speed shaft rotates with approximately. 1,500RPM and drives the electrical generator. It is equipped with an emergency mechanical disc brake. The mechanical brake is used in case of failure of the aerodynamic brake, or when the turbine is being serviced.

- Tower:

  The tower of the wind turbine carries the nacelle and the rotor. Generally, it is an advantage to have a high tower, since wind speeds increase farther away from the ground.

- Generator**:**

  At its most basic, a generator is a pretty simple device. It uses the properties of electromagnetic induction to produce electrical voltage.

- Transformer**:**

  It converts the electrical generator voltage to the right voltage for the electricity grid

3.2 Modeling of Wind Turbine Control System

The Wind Turbine Control System (WTCS) can be model as shown in Figure 3.2. The speed of wind travelled through the wind blades and transformed it into mechanical energy by coupled to the shaft of an Induction Generator (IG) through a gear box. The wind power energy obtained from a windmill is sent to IG through a gear, and the speed of IG is controlled to give the suitable angle to the aerodynamic wind blade to give the require power. Wind speed (V) is converted into mechanical torque (T_M) then into electric power (P) to supply the power system. Note that the converter loss of the speedup gear is not the focus of this study and is ignored, and the proposed control system can also be applied to the direct-drive system without a gear box.

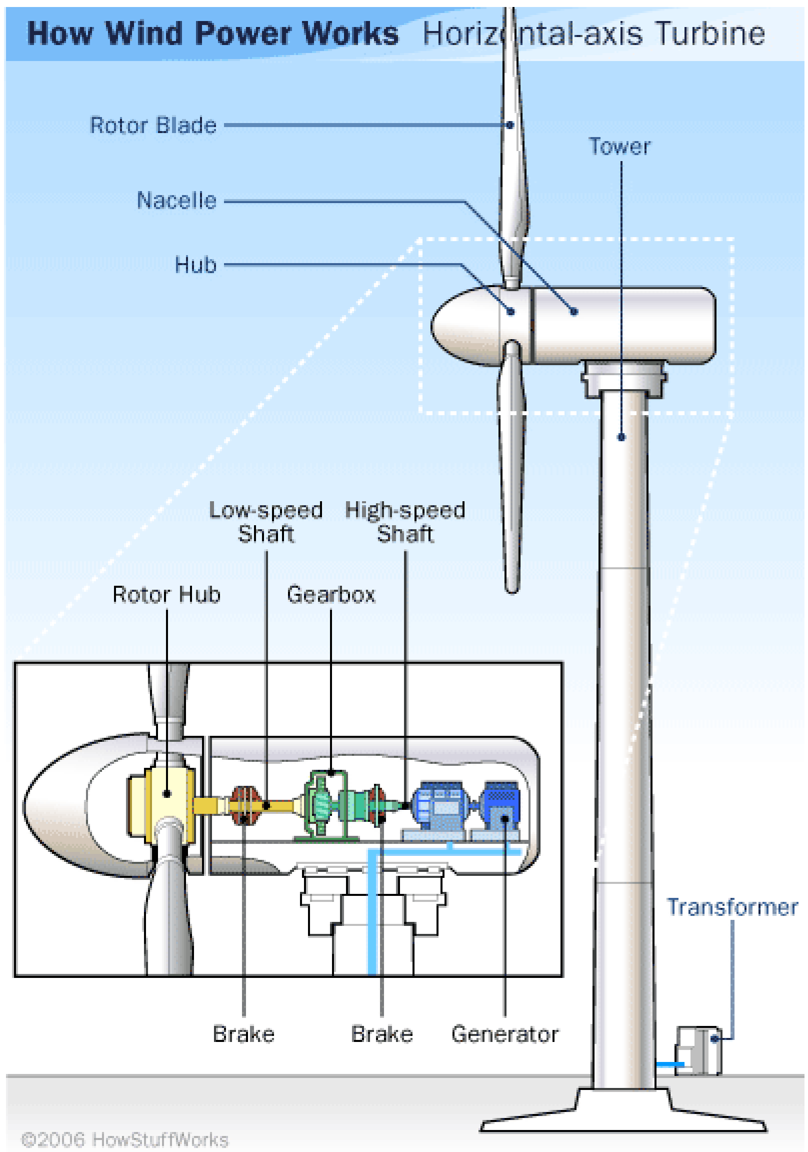


Figure 3.1: Horizontal-axis turbine components.

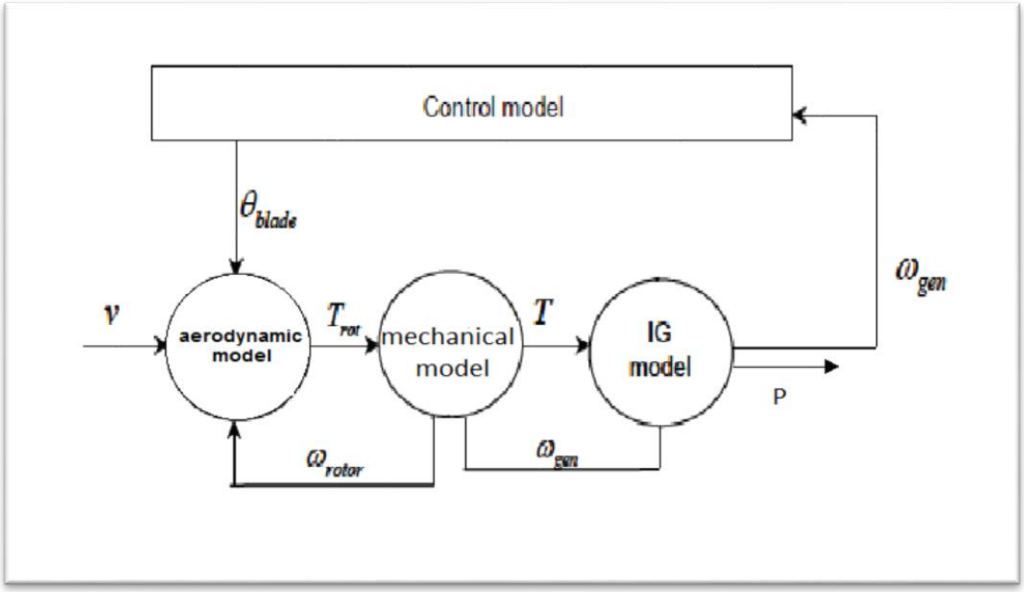


Figure 3.2: Scheme of Wind Turbine Control System

3.3 Simulation Model of the System without PI Controller

This model was represented using MATLAB/SIMULINK tools as shown in figure 3.3.

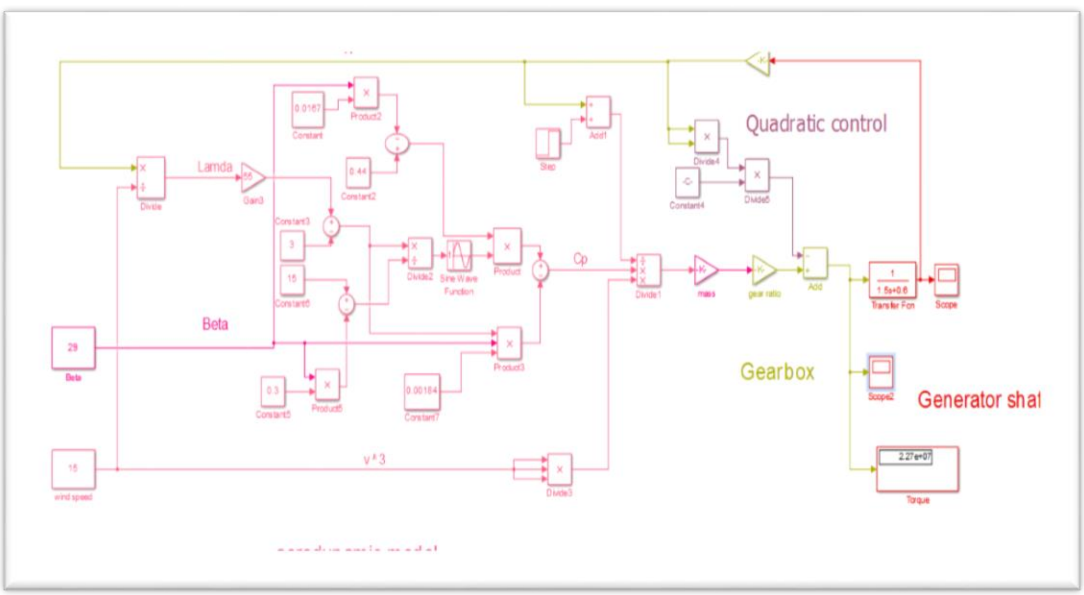


Figure 3.3: Simulation model of wind turbine without PI controller

Wind speed (v) and pitch angle (β) were the inputs, β was kept constant during simulation time. The generator speed ω was fed back to lamda λ, which has an effect on C_p value, the generated power, torque and rotor speed.

3.4. Simulation Model of WTCS with PI Controller

Figure 3.4 shows the MATLAB/SIMULINK model of the WTCS with PI controller. The generator speed ω was fed back to λ and to the compiler of the controller, and the rated generator speed reference ω_{ref} is set to a value. The error $(\omega - \omega_{ref})$ is input to the controller, which commands a change in the blade pitch angle. The new pitch angle requested is $\beta = \beta_d - \beta$. The actuator operates on a pitch rate command. The pitch rate is determined from the difference between the desired pitch angle and the measured blade pitch angle. Then according to the new angle C_p, the outputs would be edited.

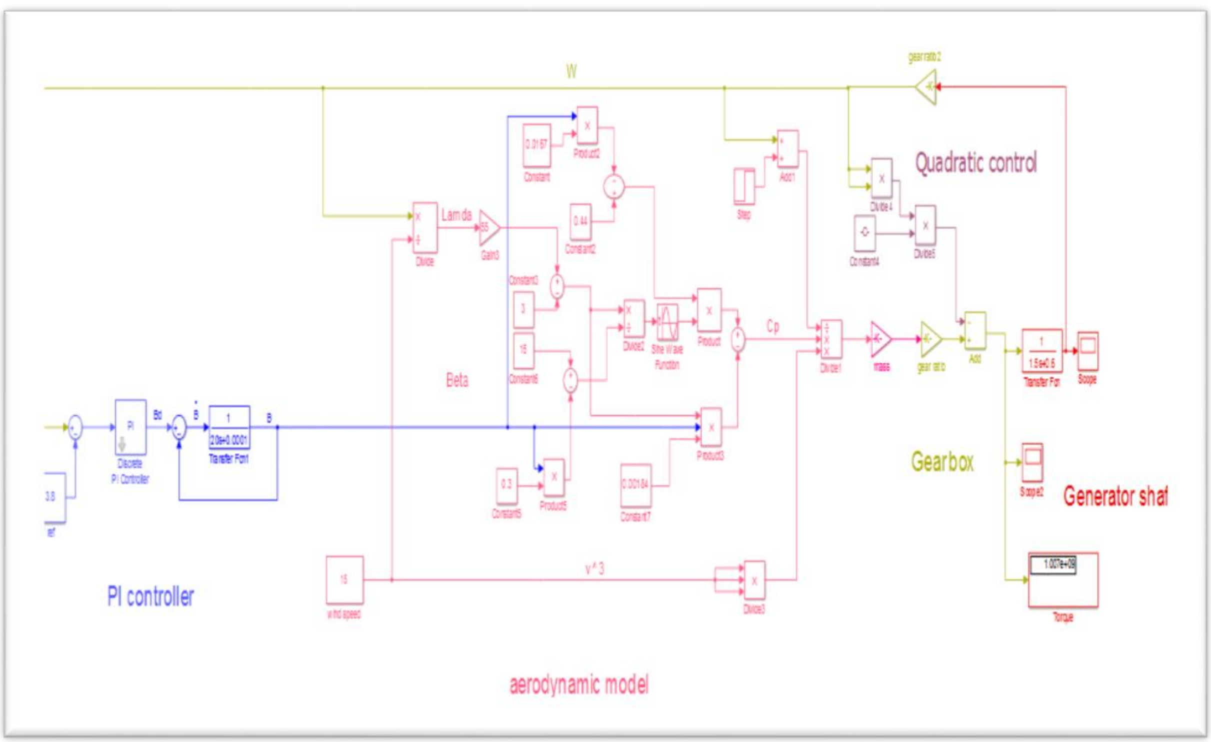


Figure 3.4: Simulation model of WTCS with PI controller

3.4.1 The aerodynamic model

The wind turbine blades extract the kinetic energy in the wind and transform it into mechanical energy. The kinetic energy in air of an object of mass m moving with speed v is given by:

$$E = \frac{1}{2}.m.v^2 \tag{3.1}$$

The power in the moving air (assuming constant speed velocity) is equal to

$$\mathrm{p_m} = \frac{\mathrm{dE}}{\mathrm{dt}} = \frac{1}{2}.m.v^2 \tag{3.2}$$

When the air passes across an area A swept by the rotor blades, the power in the air can be computed using Equation (3.1). The power extracted from the wind is given by:

$$P_{blade} = C_p(\lambda, \beta)P_{wind} = \mathrm{C_p}(\lambda\,, \beta)\,\frac{1}{2}\rho\, A\mathrm{v}^3 \tag{3.4}$$

The blade pitch angle β is defined as the angle between the plane of rotation and the blade cross-section chord as shown in figure 3.5.

The rotor torque T_w can be computed using the expression:

$$T_w = \frac{P_{blade}}{w_m} = \frac{1}{2}\mathrm{C_p}(\lambda\,, \beta)\rho\, A\mathrm{v}^3/w_m \tag{3.4}$$

The area covered by the blades is given by:

$$A = \pi R^2 \tag{3.5}$$

Substituting Equation (3.4) in Equation (3.5), we have:

$$T_w = \frac{1}{2}\,\pi\,C_p(\lambda\,,\beta)\,\rho\,R^2\,v^3/w_m \tag{3.6}$$

By using the tools in MATLAB program these equation can be represented as shown in figure 3.6.

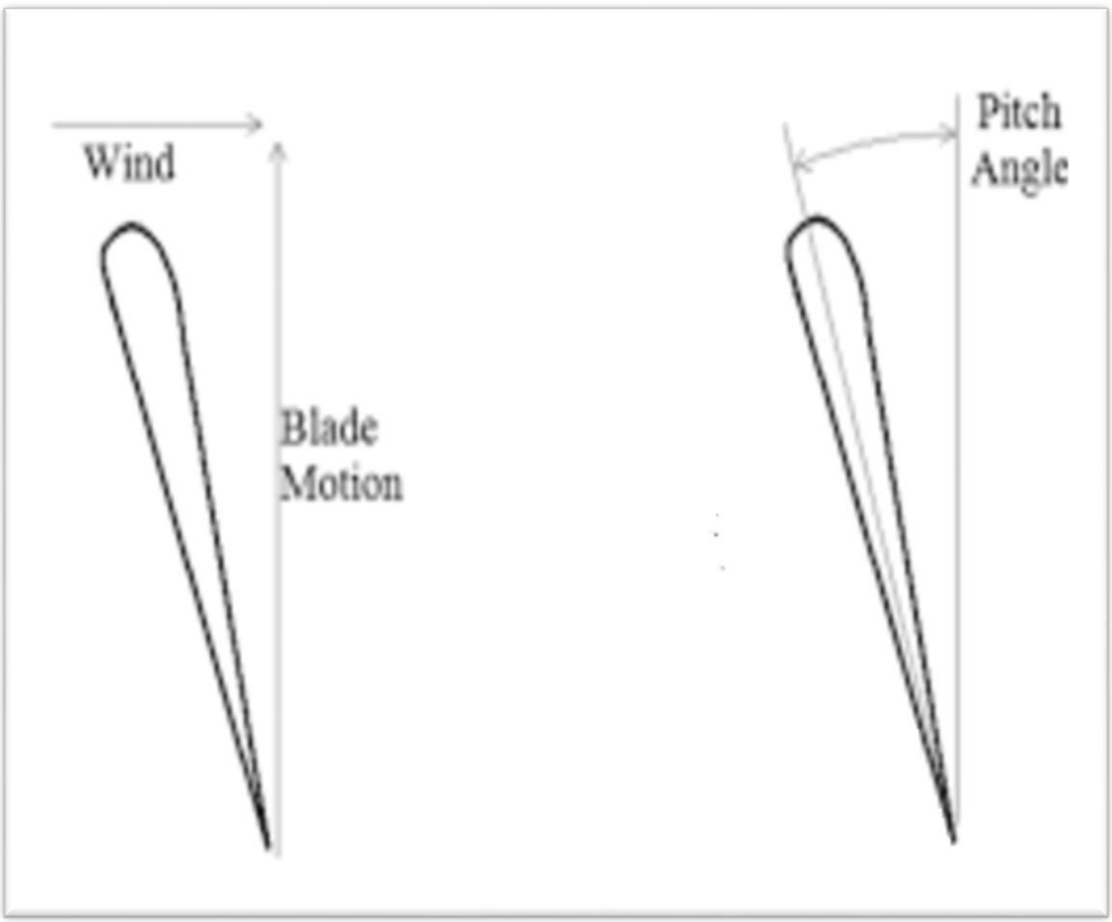


Figure 3.5: The pitch angle β

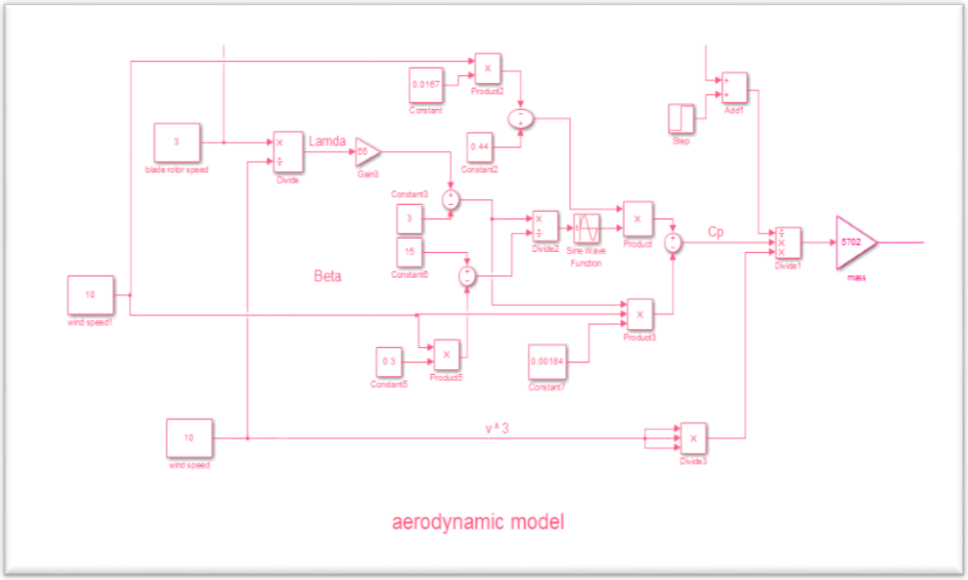


Figure 3.6: Aerodynamic model in MATLAB/SIMULINK

3.4.2 Mechanical model

In the mechanical model, the emphasis is only put on those parts of the dynamic structure of the wind turbine that contribute to the interaction with the grid. The drive train is only considered in the first place, because this part of the wind turbine has the most significant influence on the power fluctuations. The other parts of the wind turbine structure, e.g. tower and the flap bending modes, are neglected. The mechanical model is shown in Figure 3.7. It is essentially a two mass model connected by a flexible low-speed shaft characterized by a stiffness k and a damping c. The high-speed shaft is assumed stiff. The two masses correspond to the large turbine rotor inertia J_{rot}, representing the blades and hub, and to the small inertia J_{gen} representing the induction generator.

It is known that:

$$\frac{d\theta}{dt} = \omega \tag{3.7}$$

And the equation of motion of the induction generator is given by:

$$J_{gen}\ \frac{dw_{gen}}{dt} = T_e + \frac{T_m}{n} \tag{3.8}$$

The mechanical torque T_m can be modeled with the following equation:

$$T_m = c.\frac{\theta'}{n} + k.\frac{(\omega_{gen} - \omega_{rot})}{n} \tag{3.9}$$

Where:

$$\frac{d\theta'}{dt} = \omega_{gen} - \omega_{rot} \tag{3.10}$$

Where:

n is the gear ratio.

θ' is the angle between the turbine rotor and the generator rotor.

ω_{rot} is the turbine speed.

ω_{gen} is the generator rotor speed.

J_{rot} *and* J_{gen} are the inertia constants of turbine and generator respectively.

c is the drive train stiffness.

k is the damping constant.

T_{rot} is the torque provided by wind.

T_e is the electromagnetic torque.

Figure 3.8 shows the gear box model in MATLAB/SIMULINK.

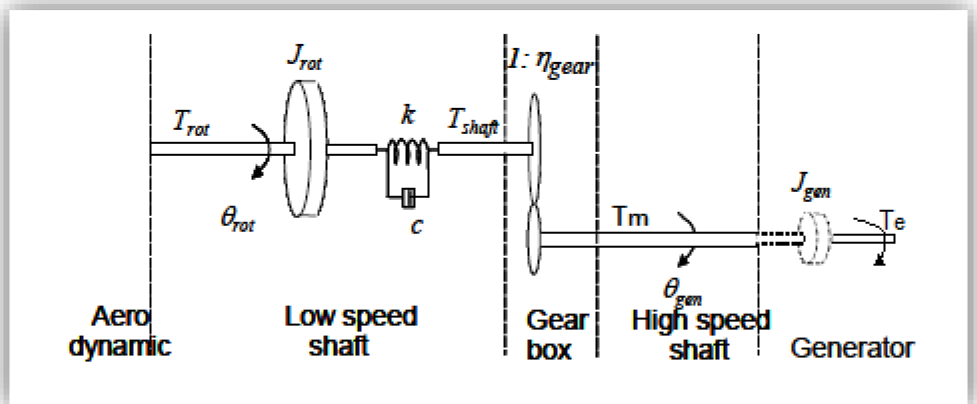


Figure 3.7: Drive train dynamics

3.4.3 Induction generator model

Both synchronous and DC machines can be used as either generators or motors and in the same way induction motors can be made to operate as an induction generator. Scientists and engineers have used induction motors as generators particularly in wind energy converters as they are a suitable mechanism for transforming mechanical energy into useful electrical energy [45]. The shaft speed of generator shaft was the only part interested in this study. This can presented as [44]:

$$J\ \omega'_{gen} = T_e - T_m \tag{3.11}$$

Where J is generator inertia, T_e is the electrical torque and T_m is the mechanical torque.

The generator shaft can be represent in the SIMULINK by the transferee function as shown in Figure 3.9.

3.4.4 The control model

There are two controllers. In low wind speed, the quadratic control is used to give the maximum power coefficient. And pitch angle control for above rated speed. Figure 2.6 shows the three regions of wind speed, the rated speed, below rated speed, and above it.

- Pitch actuator model:

The pitch actuator (pitch servo) consists of a mechanical and a hydraulic system, which is used to turn the blades along their longitudinal axis. The actuator model describes the dynamic behavior between a pitch demand $\beta_d$from the pitch controller and the measurement of a pitch angle β. The dynamics of the blades are nonlinear with saturation limits on both pitch angle and pitch rate. This saturation is caused by high frequency components of the pitch demand spectrum, via measurement noise, and spectral peaks induced by rotational sampling [46]. In this study, the constraint is not considered. The actuator dynamic is modelled as in [43]. The change in the pitch angle is:

$$\Delta\beta = (\beta_d - \beta)/\tau_\beta \tag{3.12}$$

From above equation, the transfer function for the actuator is:

$$\frac{\beta}{\beta_d} = 1/(\tau_\beta s + 1) \tag{3.13}$$

Where τ_β is a time constant depends on the pitch actuator.

- Quadratic control law

This method can be used for below wind speed. The output power of the wind turbine can optimized by using the torque control scheme for a variable-speed wind turbine [47].

$$\mathrm{T_e}(ref) = P_{wt(max)}/\omega_m \tag{3.14}$$

Where $\mathrm{T_e}(ref)$ is the reference electrical torque. From the Equation (3.6), the quadratic control law can be rewritten as:

$$\mathrm{T_e}(ref) = K_{opt}W_m^2 \tag{3.15}$$

Where:

$$K_{opt} = 0.5\rho\pi R_w^5 C_{p(max)/} \lambda_{opt}^3 n_g^3 \tag{3.16}$$

$C_{p(max)}$ is the maximum power coefficient and λ_{opt} is the tip speed ratio at $C_{p(max)}$. Note that the transmission friction losses are not considered [48]. And it is clear that the optimal gain varies from turbine to turbine, even if they have the same rated power. Furthermore, these can also be changed during a turbine life's period.

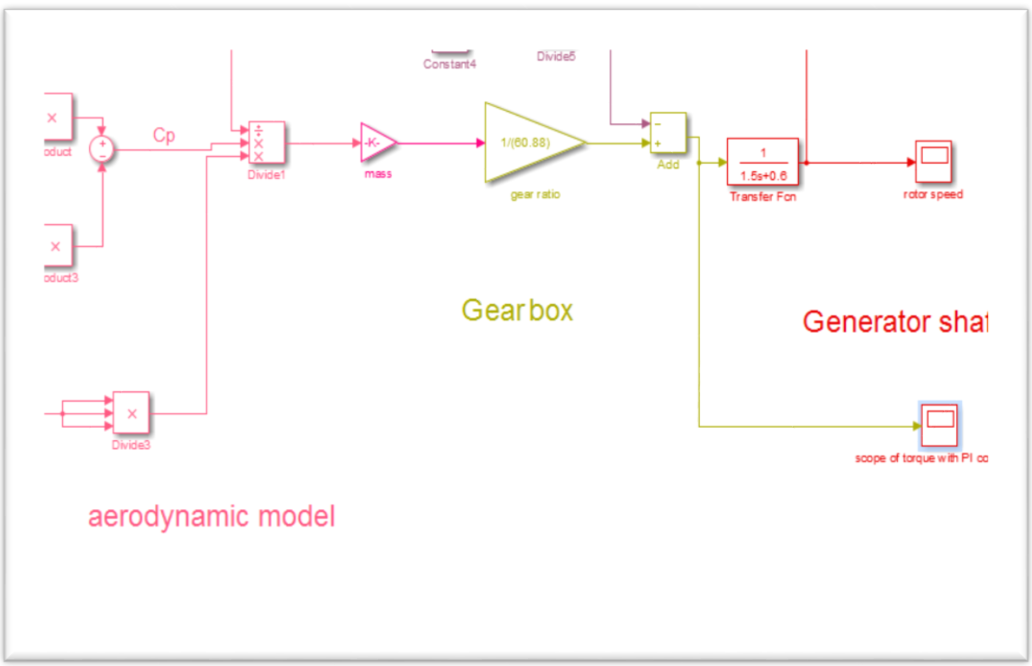


Figure 3.8: Gear box model

The gear box linked the aerodynamic model to generator shaft by gear ratio n=60.88.

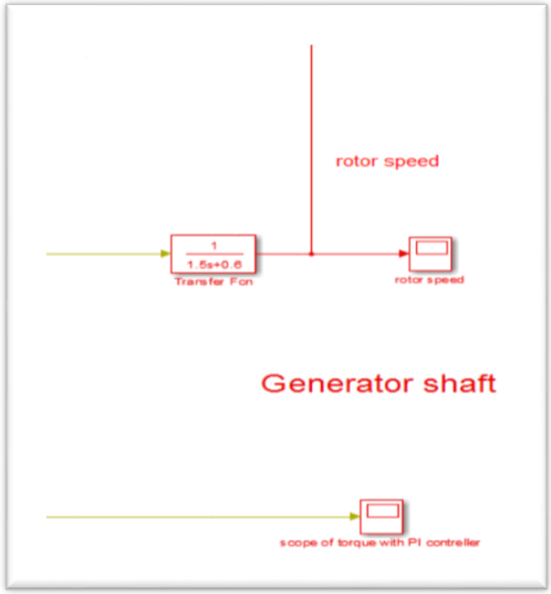


Figure 3.9: The generator shaft model

3.5 Selection of the Operating Point

Table 3. 1: Parameters of the 5MW WT and controller

Description	Parameters	Value
Rated Turbine Power	P	5MW
Turbine Blade Length	R	55m
Gearbox Ratio	n	60.88
Air Density	ρ	1.225 kg/m^3
Reference Generator Speed	ω_{ref}	113.85(rad/s)

Nominal parameters of a 5MW WT as shown in Table 3.1, are used in [49]. It is assumed that the wind speed is 15m/s. From Figure 2.6 this wind speed is above the rated speed, so in this case the rotational speed must be equal to rated rotor speed ($\omega_{rot-ref}$). Thus, the desired constant speed of the turbine is 1.87rad

/s. λ and C_p operating points were selected by using Figures 3.11 and 3.12. The pitch angle is 9.65° as selected from the power coefficient curve of Figure 2.7

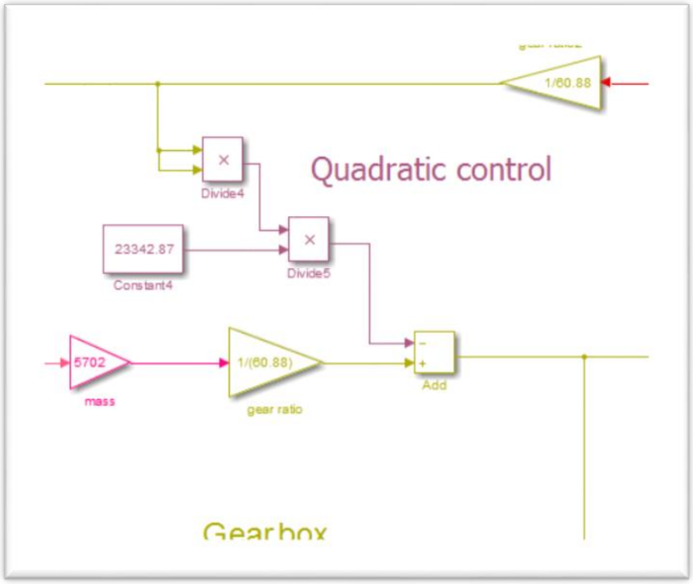


Figure 3.10: Quadratic control model

This controller was inserted with gear ratio in to the generator shaft model.

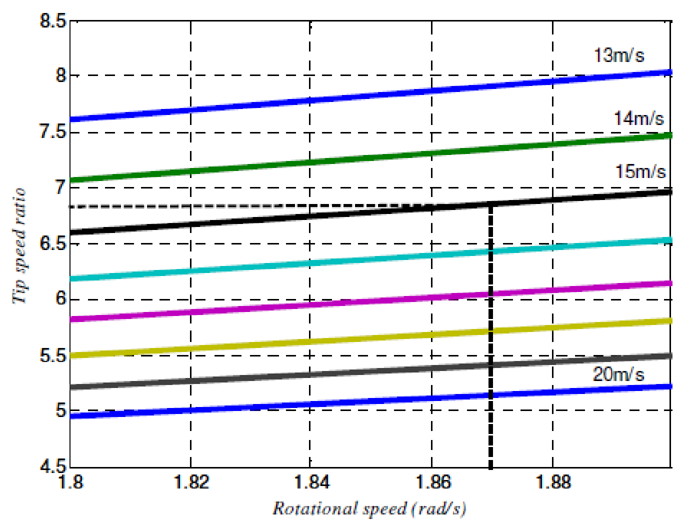


Figure 3.11: Tip speed ratio vs. wind turbine rotationa

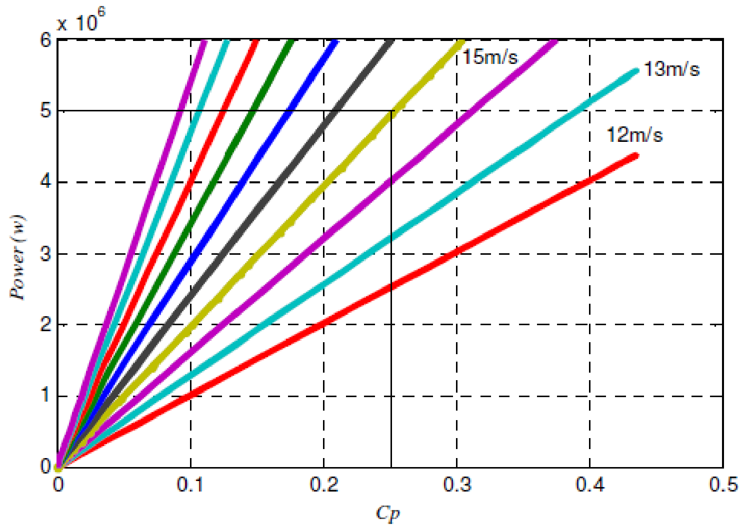


Figure 3.12: Wind turbine power output vs. c_p

3.6 Theoretical Method for PI Controller Gains

The output signal from PI controller is β_d as showing in the Figure 3.13, which also contains the actuator's transfer function that obtained from Equation (3.13). Then PI controller and desired pitch angle can be expressed as follows:

$$\beta_d = K_p e + K_i \int e \, dt \tag{3.17}$$

Where:

$$e = W_{rot-ref} - w_{rot} \tag{3.18}$$

To find the solution, let:

$$x = K_i \int e \, dt \tag{3.19}$$

Or:

$$\frac{dx}{dt} = K_i\, e \tag{3.20}$$

From Equations (3.17) and (3.19), the partial derivatives of β_d, with respect to e, is expressed as follows:

$$\frac{d\beta_d}{de} = K_p + \frac{dx}{de} = K_p + \frac{\frac{dx}{dt}}{\frac{de}{dt}} = K_p + \frac{K_i e}{(\frac{de}{dt})} \tag{3.21}$$

For an adjustable-slip asynchronous generator, the variation range of e is very small. Moreover, Kp is far greater than Ki. Hence Equation (3.21) can be simplified as follows:

$$K_p = d\beta_d/de \tag{3.22}$$

$d\beta_d = \beta_d$ (β_{d0}=0 (initial value)). To find the direct relation between β and β_d, the inner closed loop for the actuator in Figure 3.8, is reduced to the forward path, and assuming τ_β=1s. Thus, the following transfer function is obtained.

$$\frac{\beta}{\beta_d} = 1/(s+2) \tag{3.23}$$

In the steady state s⇒0, and $\beta = 2\beta_d$. From the Equations (3.18),(3,21) and (3.22), the K_p and K_i are:

$$K_p = 2\beta/(W_{m-ref} - W_m) \tag{3.24}$$

$$K_i = \frac{1}{W_{m-ref} - W_m} * \left(\frac{2\beta}{W_{m-ref} - W_m} - K_p\right) * \frac{\partial \Delta w}{\partial t} \tag{3.25}$$

From Equations (3.24) and (3.25) the value of the integral coefficient K_i= 0, since middle part of the Equation (3.25) equal zero.

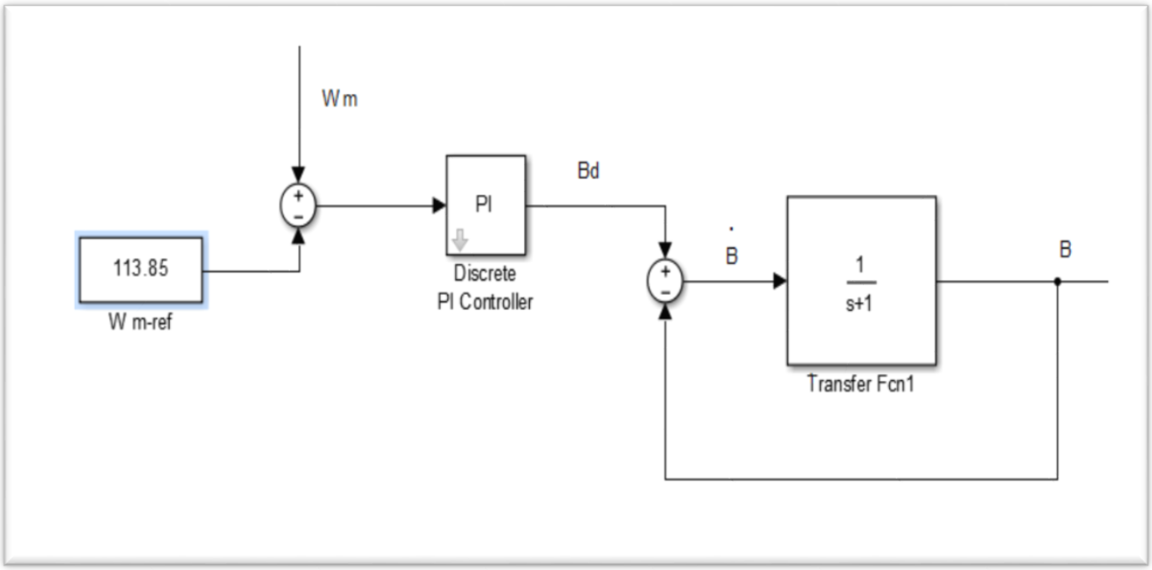


Figure 3.13: PI pitch controller

CHARTER FOUR

SIMULATION RESULTS AND DISCUSSIONS

4.1 Introduction

The system was modeled twice: first time without using the PI controller, while the second time model with PI pitch controller. Wind speed was varied from 7 m/s to 15m/s and finally 25m/s for each scenario. The power coefficient, speed of generator rotor and the torque were recorded in each case.

4.2 Simulation Results without PI Controller

The power coefficient when the wind speed went from 15m/s to 7m/s is recorded. Figure 4.1 shows the curve starting from 0.31 and raised until it reaches the maximum value of 0.44, then decreased to below 0.28.

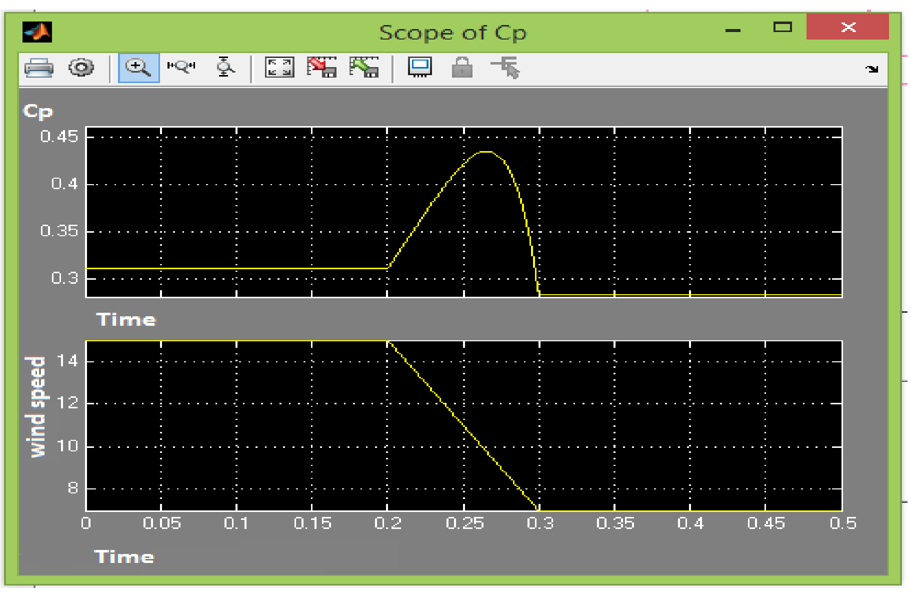


Figure 4.1: c_p curve at wind speed (15 to 7) m/s without PI controller

Figure 4.2 is the output torque without inserting the controller, it shows an oscillating behavior between 10 to 120N.m and decreasing with the time until the wind speed drops to 7m/s, the torque oscillated in negative values from 0 to 30N.m.

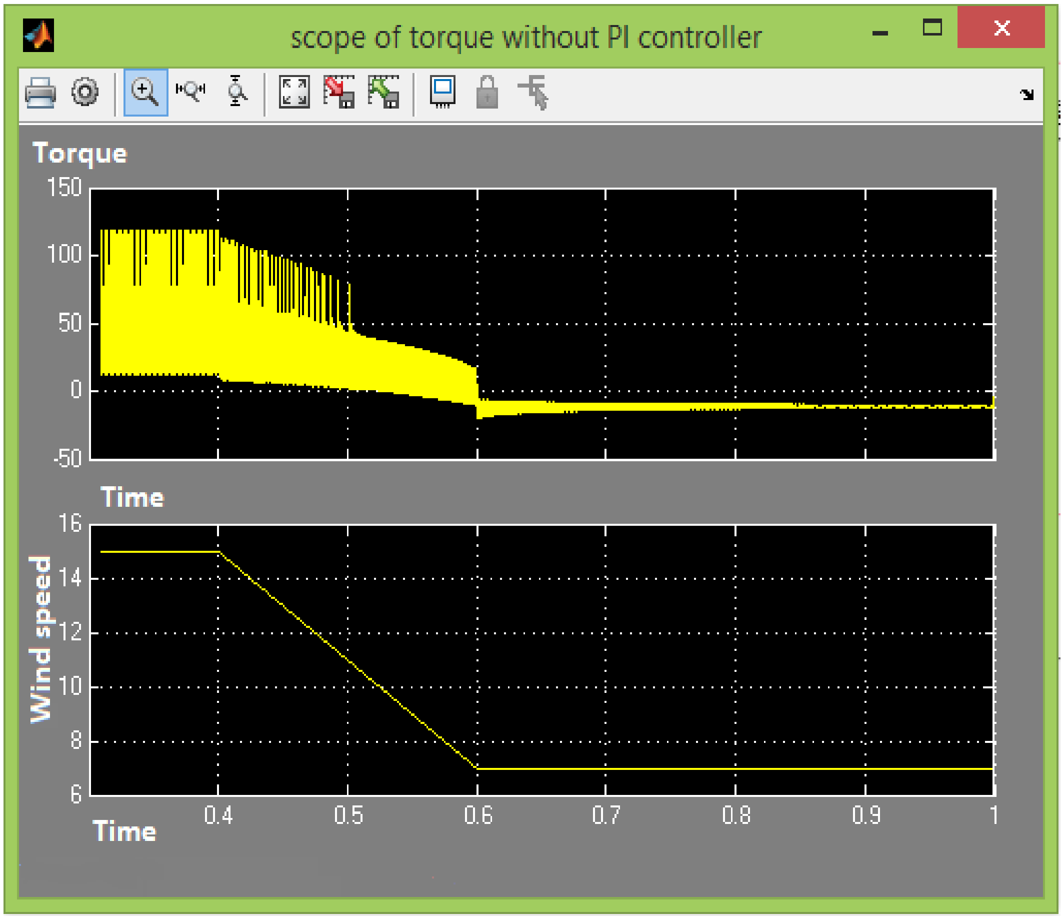


Figure 4.2: The torque without PI controller at wind speed 15 to 7m/s

Figure 4.3 shows the rotor speed. The speed decreases with the wind speed and takes a time of 0.2s to reach the constant speed in case of the model without the PI controller.

Figure 4.4 shows the record of power coefficient when the speed of the wind goes up to 30m/s, the curve started at 0.318 and decreases with the speed until it reaches 0.03 at 30m/s and set at this value. It notes that it started at higher value while the wind speed was in the lower one, and stated decreasing with the increase of the wind speed.

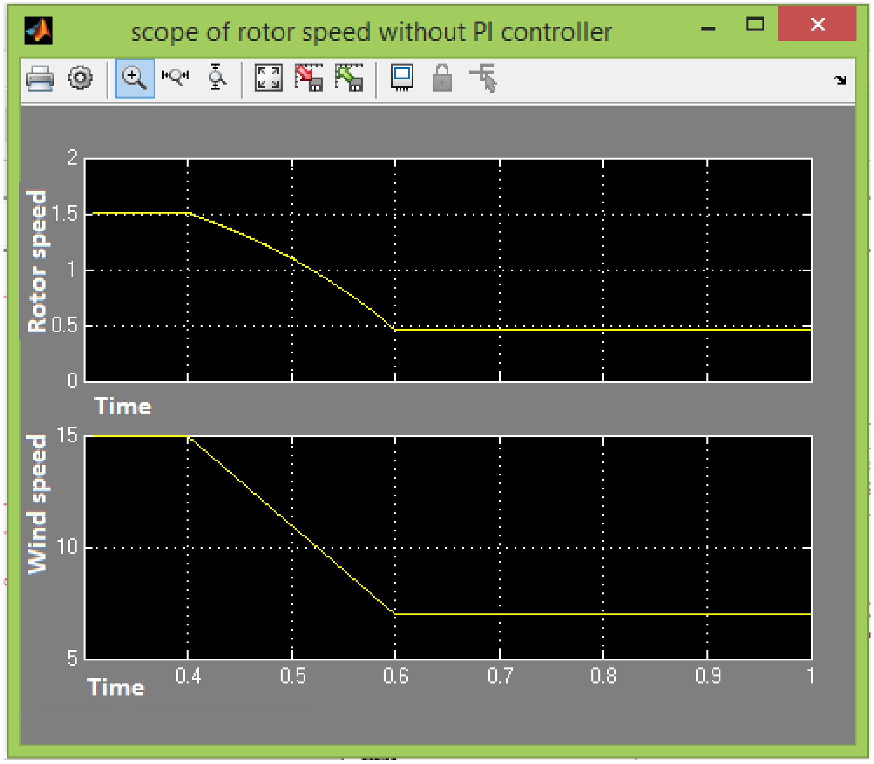


Figure 4.3: Rotor speed without PI controller at wind speed from 15 to 7m/s

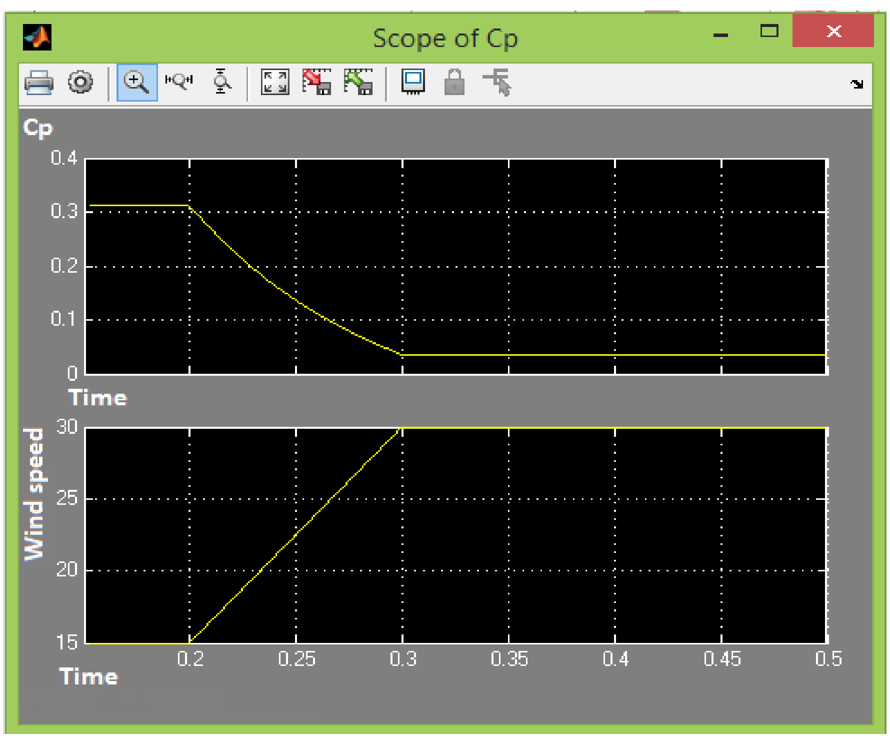


Figure 4.4: c_p Curve at wind speed 15 to 30m/s without PI controller

Figure 4.5 shows the torque. When the wind speed goes up to 30m/s, it is clear to see it oscillated between 20 and 120N.m, and when speed started rising, the torque oscillated up to 180N.m, in the case of model without the PI controller.

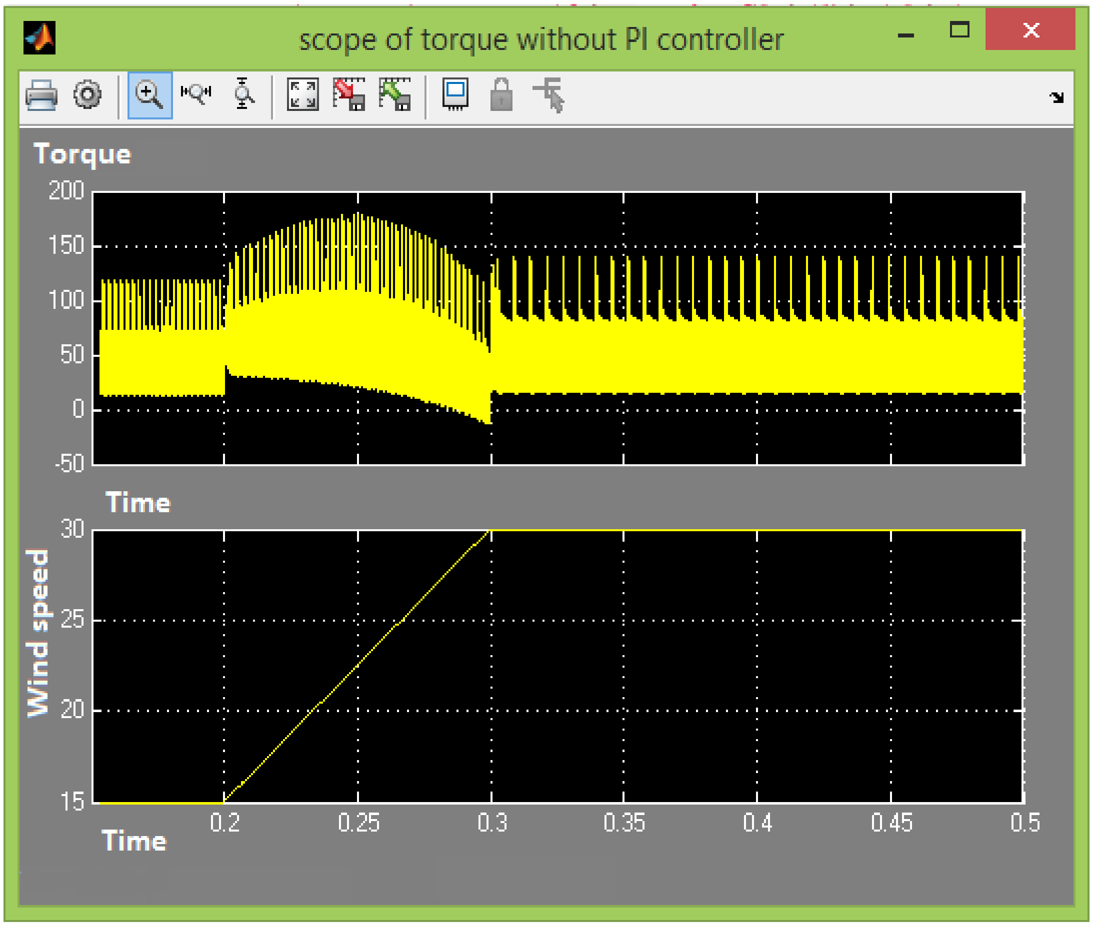


Figure 4.5: The torque at wind speed 15 to 30m/s without PI controller

Figure 4.6 shows the rotor speed when the wind speed raised to 25m/s, it is noticed that there is an overshot before the rotor speed getting stabile.

4.3 Simulation Results with PI Controller

In Figure 4.7, after inserting the PI controller, the power coefficient has recorded. The C_p started at 0.31 and raised to reach the top at value 0.44, then decreased until arrived 0.28 when the wind speed 7m/s and set at this value.

In Figure 4.8, the torque gave a constant value about 50N.m after inserting the PI controller while wind speed was decreasing from 15 to 7m/s.

Figure 4.9 shows the record for rotor speed in case of inserting the PI controller, when the wind speed went to 7m/s. It shows the same results for the system without PI controller but in shorter time (0.1s).

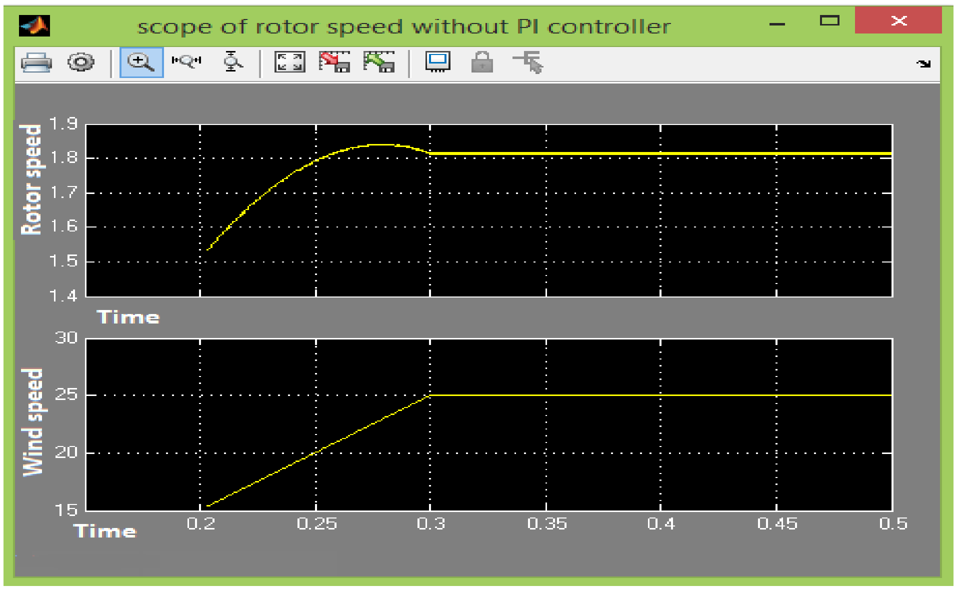


Figure 4.6: Rotor speed at wind speed 15 to 25m/s without inserting PI controller

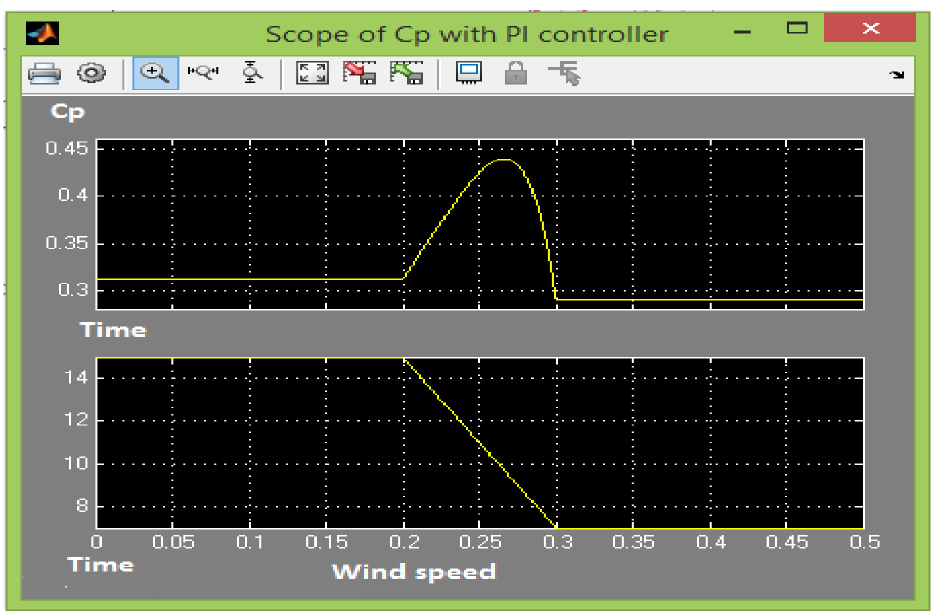


Figure 4.7: C_p curve at wind speed 15 to 7m/s with PI controller

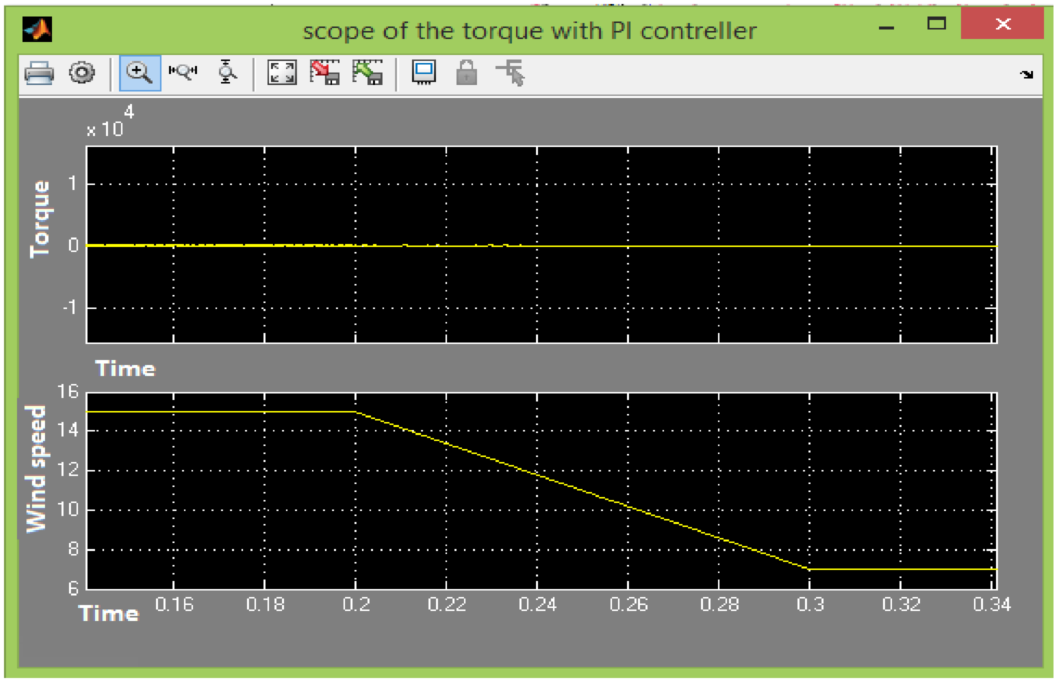


Figure 4.8: The torque with PI controller at wind speed 15 to 7m/s

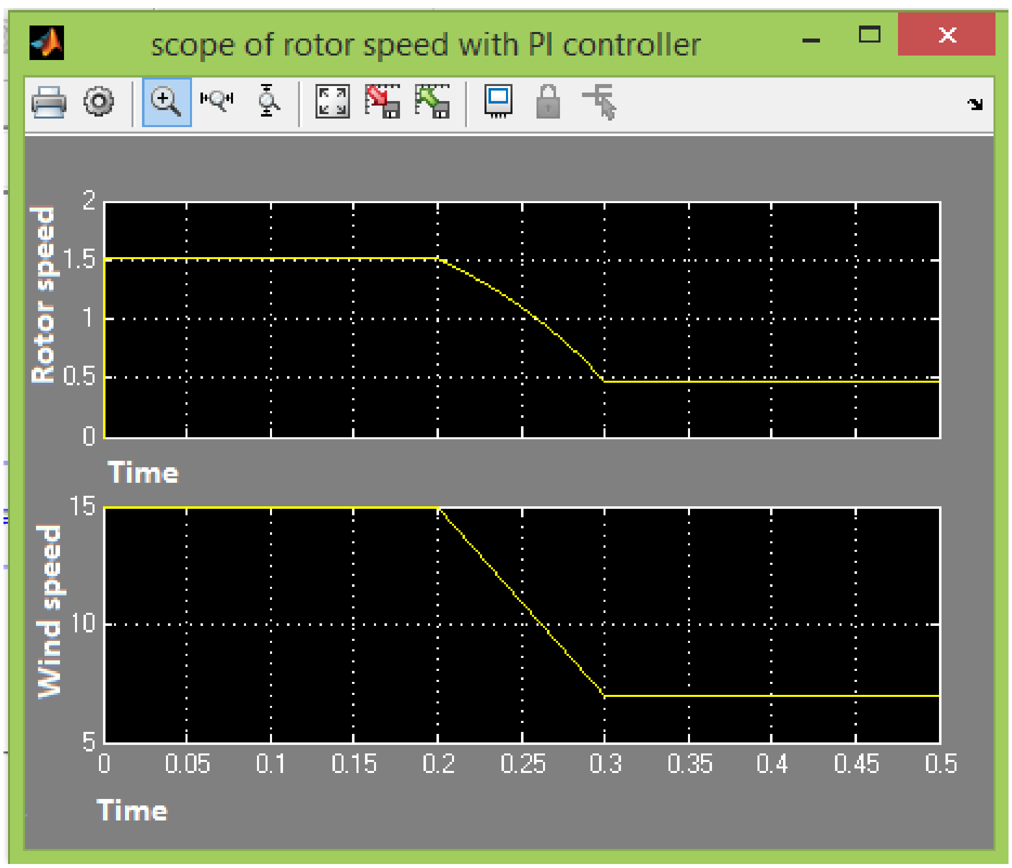


Figure 4.9: Rotor speed with PI controller at wind speed from 15 to 7m/s

Figure 4.10 shows the record of power coefficient withe the PI controller when the speed of the wind went up to 30m/s, the curve started at 0.318 and decrease with the wind speed until arrived 0.03 at 30m/s and set at this value.

After inserting the PI controller, the torque gives a constant value about 180N.m while wind speed was changing from 15 to 30m/s as shown in Figure 4.11.

As shown in Figure 4.12, the speed of the rotor of generator was record, it is obvious that the overshoot is enhanced and it reflects to the stability of the system.

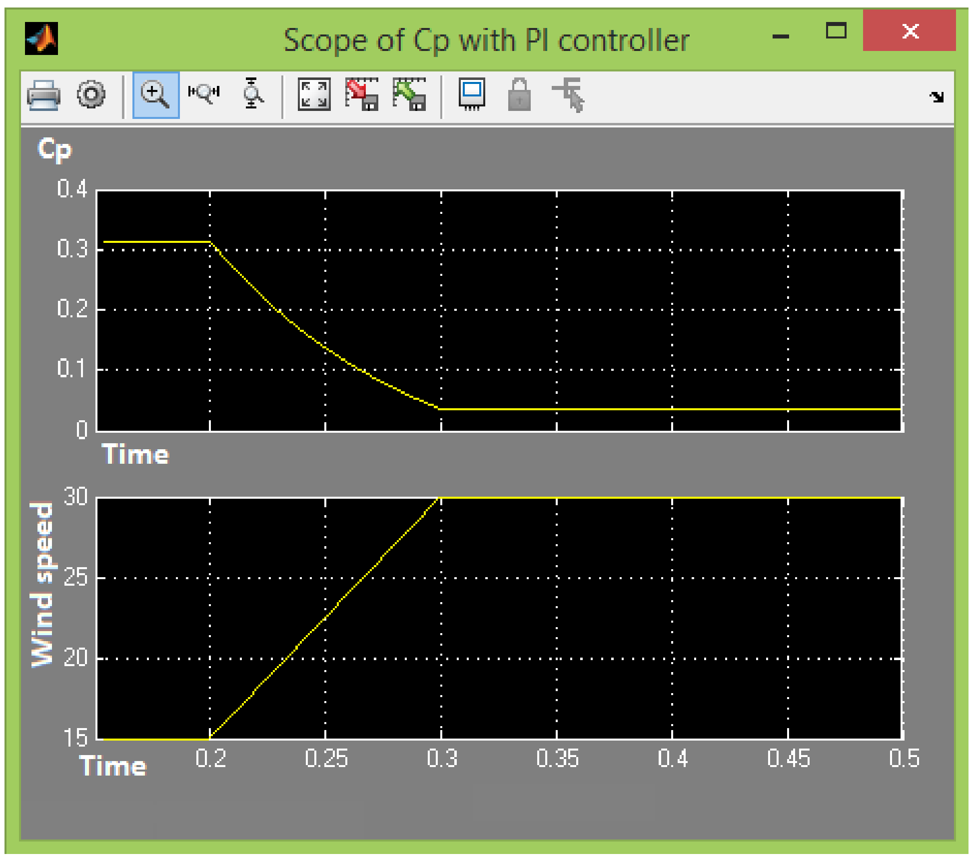


Figure 4.10: C_p curve at wind speed 15 to 30m/s with the PI controller

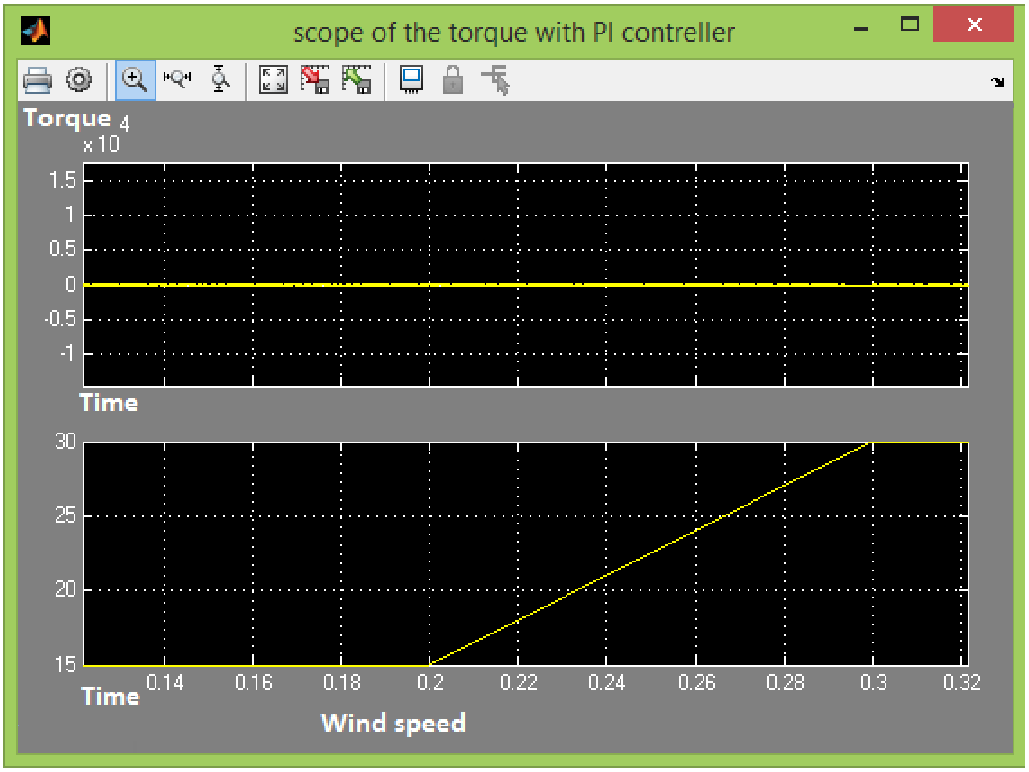


Figure 4.11: The torque at wind speed 15 to 30m/s with PI controller

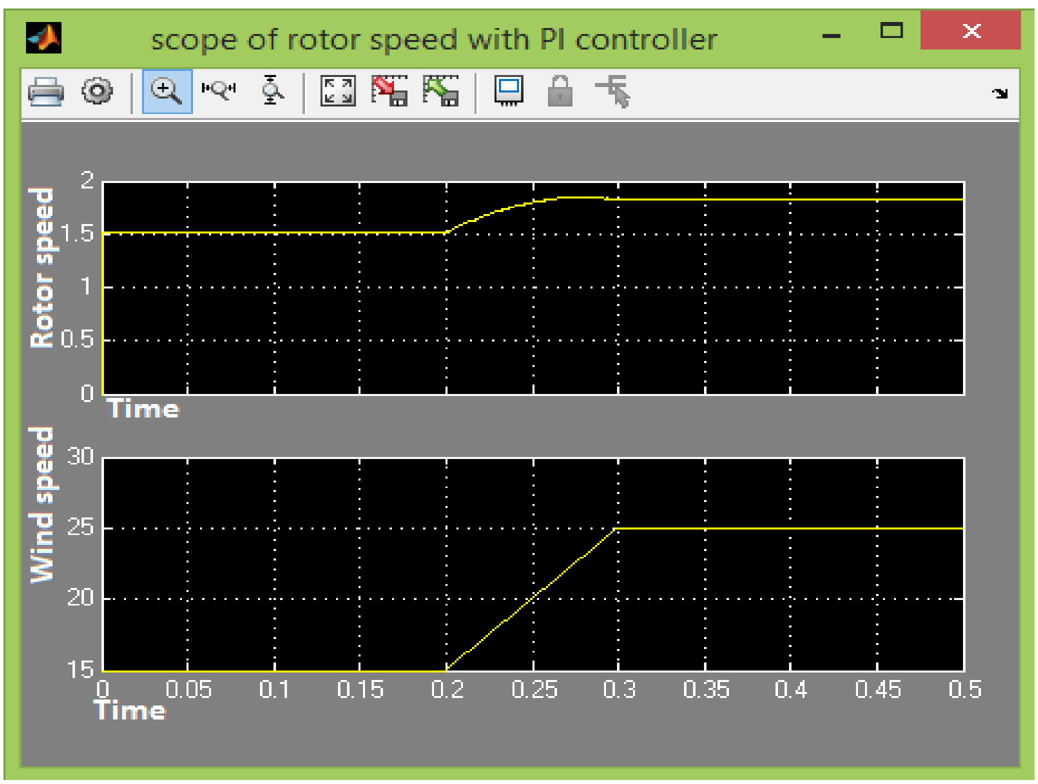


Figure 4.12: Rotor speed at wind speed 15 to 25m/s after inserting PI controller

4.4 Discussion

The graphs represented show the results of power coefficient, generator rotor speed and the torque of the system, for various flow conditions. In order to examine the performance, the outputs were recorded in the two cases: before and after inserting the PI controller and compared the results. The power coefficient (C_p) gave the same results, with and without PI controller as shown in Figures (4.1), (4.4), (4.7) and (4.10). When the wind speed was decreasing, the C_p was in shape of parabola. While when the speed was increasing, the $C_p$was decreasing.

In Figures (4.6) and (4.12), the profile of the rotor speed are different, before inserting the controller, when wind speed was increasing, the overshoot was high and obvious. After inserted it, the scope showed an enhanced in shape of the profile.

Finally, the torque signal set on a constant value, as shown in Figures (4.8) and (4.11), while it was oscillating before inserting the controller as shown in Figures (4.2) and (4.5).

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In this study, the WTCS components has been modeled mathematically. The performance of the system was evaluated by varying control strategy. This system has been represented and simulated by software program MATLAB version R2014a and suggest different controllers (PI controller and quadratic control) which lead to stabilize and enhance the outputs of the system.

5.2 Recommendations

This work could be extended for future research by the design of control system with different controllers to regulate the voltage and making analysis of its performance under various fault conditions.

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