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GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

NONLINEAR CONTROL OF POWER COEFFICIENT IN WIND TURBINES

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ACCEPTANCE AND APPROVAL PAGE

On 07/02/2019, **Alieu Khama BADJIE** successfully defended the thesis, entitled **"Nonlinear Control of Power Coefficients in Wind Turbines"**, which he prepared after fulfilling the requirements specified in the associated legislation, before the jury members whose signatures are listed below. This thesis is accepted as a **Master's Thesis** by Istanbul Commerce University, Graduate School of Natural and Applied Sciences **Mechatronics Engineering Department.**

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08/01/2019

Alieu Khama BADJIE

TABLE OF CONTENT

ABSTRACT

M.Sc. Thesis

NONLINEAR CONTROL OF POWER COEFFICIENT IN WIND TURBINES

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In this paper, the power coefficient is used for the first time as the control input to control the output power of a wind turbine. Wind speed above the rated value causes high power and generator over speed. This leads to overloading and breakdown of the generator. As a result, control systems are required to maintain the desired generated electrical power. Wind speed is highly variable but it cannot be controlled, therefore other parameters have to be regulated to maintain the desired generated electrical power when wind speed is above rated. Many researches were done using the blade pitch angle, which is highly non-linear as control input to achieve this goal. The power coefficient is used as control input in this research due to its simplicity, noting that power coefficient is a linear coefficient of the rotor power. A non-linear controller called Sliding mode is used to command the power coefficient to regulate the rotor speed to the desired value. The actual pitch angle for every wind speed is determined by designing some algorithms which are used with the power coefficient from the controller. The simulation results show that this control strategy is able to regulate the generator power by setting the rotor speed to its desired value. Another non-linear controller called feedback linearization is also used to compare its results to the sliding mode controller. This is to show that other controllers can also be used. The simulation results of the two controllers are indistinguishable

Keywords: generator speed, pitch angle, power coefficient, sliding mode control, wind turbine electrical power.

ÖZET

Yüksek Lisans Tezi

RÜZGAR TÜRBINLERINDE GÜÇ KATSAYISININ LİNEER OLMAYAN KONTROLÜ

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Bu çalışmada, bir rüzgar türbininin çıkış gücünü kontrol etmek maksadıyla kontrol girişi olarak güç katsayısı ilk kez olarak kullanılmıştır. Nominal değerin üzerindeki rüzgar hızlarında jeneratör gücü ve hızı çok yüksek değerlere çıkabilmektedir. Bu durum jeneratörün aşırı yüklenmesine ve bozulmasına neden olur. Bu nedenle, üretilen elektrik gücünü arzu edilen değerlerde tutabilmek için kontrol sistemlerine ihtiyaç duyulmaktadır. Oldukça değişkenlik gösteren rüzgar hızını kontrol etmek imkansız olduğundan, özellikle nominal rüzgar hızının üzerindeki rüzgar hızlarında, sistemdeki diğer kontrol değişkenlerini ayarlayıp sistemin üretmesi gereken elektrik gücünü elde etmek amaçlanmaktadır. Bu hedefe ulaşmak için son derece nonlinear kontrol değişkeni olan türbin pervanene tespit açısının(pitch açısı) kullanıldığı birçok araştırma literatürde mevcuttur. Bu araştırmada, sistemi daha anlaşılabilir ve kolay kontrol edebilme maksadıyla kontrol değişkeni olarak pitch açısı yerine "güç katsayısı" kullanılmıştır. Rotor hızını istenen değere getirip bu değerde tutabilmek için güç katsayısı "Sliding Mode Control" metodu ile ayarlanmaktadır. Bu kontrol stratejisi için tasarlanan ve içinde değerlerin tespit edildiği (look up table) tabloların da yer aldığı algoritmalar ile herhangi bir rüzgar hızına herhangi bir güç katsayısına karşılık gelen pitch açısı belirlenebilmektedir. Simülasyon sonuçları, bu kontrol stratejisinin, rotor hızını istenen değere ayarlayarak jeneratör gücünü düzenleyebildiğini göstermektedir. "Feedack Linearization" adı verilen doğrusal olmayan başka bir kontrol organı ile elde edilen sonuçlar ile "Sliding Mode Control" metodu ile elde edilen sonuçların karşılaştırılmıştır. Bu sonuçların ayırt edilemeyecek kadar örtüştüğü görülmüştür.

Anahtar kelimeler: güç katsayısı, jeneratör hızı, kayan kipli kontrol, pitch açısı, rüzgar türbini elektriksel gücü.

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Alieu Khama BADJIE
Istanbul, 2019

LIST OF FIGURES

LIST OF TABLES

Page

SYMBOLS AND ABBREVIATIONS

Cp	Power Coefficient
VAWT	Vertical Axis Wind Turbine
HAWT	Horizontal Axis Wind Turbine
SMC	Sliding Mode Control
λ	Tip speed ratio
P_t	Mechanical power
E	Wind kinetic energy
V	wind speed
m	Mass
P_w	Wind power
$\dot{m}$	Mass flow rate
ρ	Air density
A	Area of the blade
R	Blade radius
β	Pitch angle
ω_r	Rotational speed of the rotor
T_a	Aerodynamic torque
Cq	Torque coefficient
T_{ls}	Low speed shaft torque
b_r	External rotor damping
J_r	Rotor inertia
b_{ls}	Low speed shaft damping coefficient
k_{ls}	Low speed shaft spring constant
ω_{ls}	Low speed shaft rotational speed
θ_r	Rotor position
θ_{ls}	Low speed shaft position
T_{hs}	High speed shaft torque
T_{em}	Generator electromagnetic torque
b_g	External generator damping
ω_g	Rotational speed of the generator rotor
J_g	Generator inertia
b_{hs}	High speed shaft external damping
k_{hs}	High speed shaft spring constant
ω_{hs}	High speed shaft rotational speed
θ_{hs}	High speed shaft position
n	Gear ratio
f	Frequency
p	Number of pole pairs of the generator
λ_{opt}	Optimum value
Cpmax	Maximum power coefficient
ω_{ropt}	Rated rotor speed
ω_d	Desired rotor rotational speed

ω_e	Rotor speed error rate
$\hat{T}_{em}$	Estimated generator electromagnetic torque
$\tilde{T}_{em}$	Generator electromagnetic torque error
${\omega_g}^*$	Desired generator speed
e_g	Generator speed error rate
ε_p	Power tracking error
P_{ref}	Reference power
T_c	Demanded generator torque
P_e	Electrical power

1. INTRODUCTION

To improve the stability and reliability of wind Turbines, advance control systems should be designed. This improves the behaviour of wind turbines making them more profitable.

Variable speed wind turbines have higher energy production, less stress on components and less grid connection peaks than fixed speed turbines (Boukhezzar and Siguerdidjane, 2005). Researches in wind energy control have shown many ways of controlling wind turbines. (Hwas and Katebi, 2012) introduced PI control and used analytical and simulation methods to calculate the gains. (Hand and Balas, 1999) used PID controller with the gain design performed using a non-linear turbine model and two linear models. Optimal control has been introduced in (Martinez, 2007). In (Jing, et al., 2017), a quasi-continuous high-order sliding mode method is used to design controllers. In (Boukhezzar and Siguerdidjane, 2005), 2 nonlinear controllers were investigated using the generator torque to track the power output. (Mullane et al, 2001) used an adaptive feedback linearization controller. (Boukhezzar, et al., 2007) used a multivariable control strategy by combining a nonlinear dynamic state feedback torque control strategy with a linear control strategy for blade pitch angle. Model predictive control (MPC) was applied to (Wijewardana, et al., 2016) to guarantee the stability of the equilibrium point. Control of variable speed wind turbine pitch angle was done using fuzzy logic control technique in (Zhang et al. 2008). Ziegler – Nichols method was used to design a PID controller for controlling the pitch angle of a variable speed wind turbine (Roussos et al. 2013).

In most of these papers, the controller uses the pitch angle of the blades which is highly non-linear as control input. These controllers are used when the wind speed is above its rated value. This is to ensure that constant desired generator power and speed are obtained to maintain grid stability energy supply. When the wind turbine is running below rated wind speed (variable rotor speed), no pitch controller is needed. Generator torque is used to help obtain maximum available power.

In this work, the power coefficient Cp is used for the first time as control input to regulate the generator speed when the wind speed is above the rated value. Algorithms are developed and used with the Cp to determine the required pitch angle for every wind speed above its rated value. Another non-linear controller is also used to further validate the control strategy implemented in this paper.

This paper is organized as follows:

- Section 2 entails the background and literature review of wind Turbines. An overview of the history of wind turbines is given. Types of wind turbine and the different types of rotor characteristics are discussed. Furthermore, the types and comparison of the power control techniques used in wind turbines. The chapter is closed with the discussion of wind farm types, their configuration and their control techniques.
- Section 3 describes the modelling of the wind turbine system. Mathematical models describing a variable speed wind turbine scheme is presented. The types of generators used in wind turbines are also discussed.
- Section 4 discusses the aim and methodology of designing a controller for a variable speed wind turbine. The wind turbine modes of operations are explained in details. The novel Cp controller is designed using sliding mode and feedback linearization controllers. Generator torque controller is also presented.
- Section 5 presents the research findings and discussion. The designed novel Cp controller and algorithms are implemented and tested. The two non-linear controllers are then compared.
- Finally, Section 6 gives the conclusion of this work.

2. LITERATURE REVIEW

2.1 Wind Turbine History

Wind power has been in use for centuries. It was first used as a windmill to perform mechanical tasks like pumping water, grain grinding, sawing wood etc. It is recorded that the Persians build the first windmills at the Persian-Afghan border region of Seistan. It depicts a windmill with a vertical axis of rotation. It was obviously used for milling grain. Similar, extremely primitive windmills have survived in Afghanistan up to the present time. This is shown in Figure 2.1

Figure 2.1. Vertical-axis windmill for milling grain, Afghanistan (Hau, 2006).

In the middle ages, windmills were used in Europe. These windmills had horizontal axis of rotation. Until around the 1800, many windmills were been used in Europe but the Industrial Revolution led to their gradual demise. This is because wind energy cannot be saved or transported to where it's needed as compared to coal. One significant development in the 18th century was the introduction of scientific testing and evaluation of windmills. The Englishman John Smeaton, discovered three basic rules that are still applicable (Manwell et al. 2002):

- The speed of the blade tips is ideally proportional to the speed of wind

- The maximum torque is proportional to the speed of wind squared
- The maximum power is proportional to the speed of wind cubed

Wind turbine generator was first built in 1891. During the energy shortages in World War 1 and II, it was improved by the Danish to overcome the energy deficit. After World War II, the interest in wind power generation reduced. It was used mainly to power remote areas or to charge batteries. With the oil crises in the beginning of the 1970s, the interest in wind power generation returned. As a result, financial support for research and development of wind energy became available (Ackermann and Soder, 2000). Wind energy innovation moved fast towards new measurements. Toward the end of "1989", a" 300kW" wind turbine with a 30-meter rotor measurement was the best in class. Just 10 years after the fact, "1500kW" turbines with a rotor distance across of around 70 meters are accessible from numerous producers. The primary showing undertakings utilizing "2MW" wind turbines with a rotor distance across of 74 meters were introduced before the turn of the century. "2MW" turbines are presently monetarily accessible and "4 to 5MW" wind turbines are as of now a work in progress. To start with models will be introduced in 2002 (Abed et al. 2018). This is shown in Table 2.1

Table 2.1. Development of wind turbine size between 1985 and 2000 (Abed et al. 2018).

Year	Capacity	Rotor Diameter
1985	50kW	15m
1989	300kW	30m
1992	500kW	37m
1994	600kW	46m
1998	1500kW	70m
2002	3500-4500kW	88-112m

2.2 Wind Turbine Technologies and Types

Wind energy is a converted form of solar energy which is produced by the nuclear fusion of hydrogen (H) into helium (He) in its core. The H → He fusion process creates heat and electromagnetic radiation streams out from the sun into space in all directions. Though only a small portion of solar radiation is intercepted by the earth, it provides almost all of earth's energy needs (Tong, 2010)**.**

2.2.1 Wind turbine definition

A wind turbine is a machine for converting the kinetic energy in the wind into mechanical energy which is later converted to electrical energy by a generator. If the mechanical energy is used by machines to do mechanical work like milling grains, it's referred to as a windmill. To generate electricity from a wind turbine, it is usually desirable that the driving shaft of the generator operates at considerable speed. The energy in the wind turns two or three propeller-like blades around a rotor. The rotor is connected to the main shaft, which spins a generator through a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electrical generator to create electricity. There are two types of wind turbines, vertical axis wind turbine (VAWT) and horizontal axis wind turbine.

2.2.2 Wind turbine types

There are two types of wind turbines which are determined by the orientation of the shaft and rotational axis. A turbine with a shaft mounted horizontally parallel to the ground is known as a horizontal axis wind turbine or (HAWT). A vertical axis wind turbine (VAWT) has its shaft normal to the ground (Schubel and Crossley, 2012). This is shown in Figure 2.2

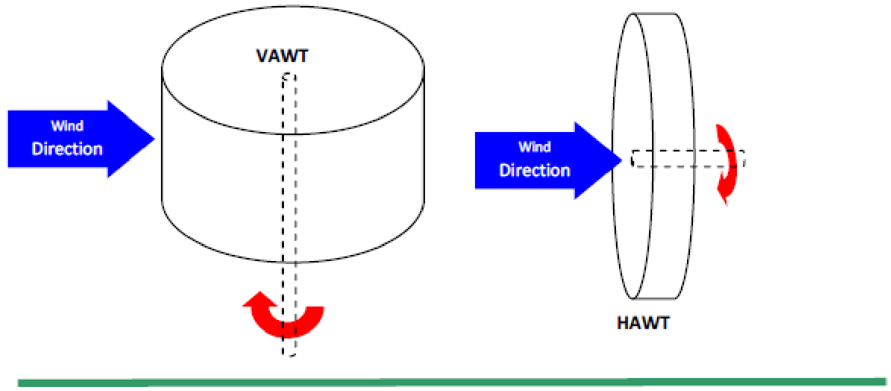

Figure 2.2. Alternative configurations for shaft and rotor orientation (Schubel and Crossley, 2012).

2.2.2.1 Vertical axis wind turbine.

The main components of a vertical axis wind turbine (VAWT) are located at the base of the tower of the turbine. VAWT doesn't require wind direction sensors and yaw mechanism as it doesn't need to face the direction of the wind. This is because they can capture the wind from all directions. This makes it good for gust conditions. Its principle of operation depends on the fact that its blade speed is a multiple of the wind speed, resulting in an apparent wind throughout the whole revolution coming in as a head wind with only a limited variation in angle. From the perspective of the blade, the rotational movement of the blade generates a head wind that combines with the actual wind to form the apparent wind. If the angle of attack of this apparent wind on the blade is larger than zero, the lift force has a forward component that propels the turbine (Ragheb, 2013). The Darrieus VAWT is shown in Figure 2.3.

Figure 2.3. Darrieus VAWT (Deisadze et al. 2013).

2.2.2.2 Horizontal axis wind turbine

The main components of a horizontal axis wind turbine (HAWT) are located at the top of the tower of the turbine as shown in Figure 2.4. The components are enclosed in a nacelle. Horizontal axis wind turbines utilize airfoil design to generate the spinning of the blades. The concept of the wind foil of a HAWT blade is that the wind travels over the top of the blade rather than under it, creating less pressure on top of the blade generating lift and creating rotational movement (Deisadze et al. 2013).

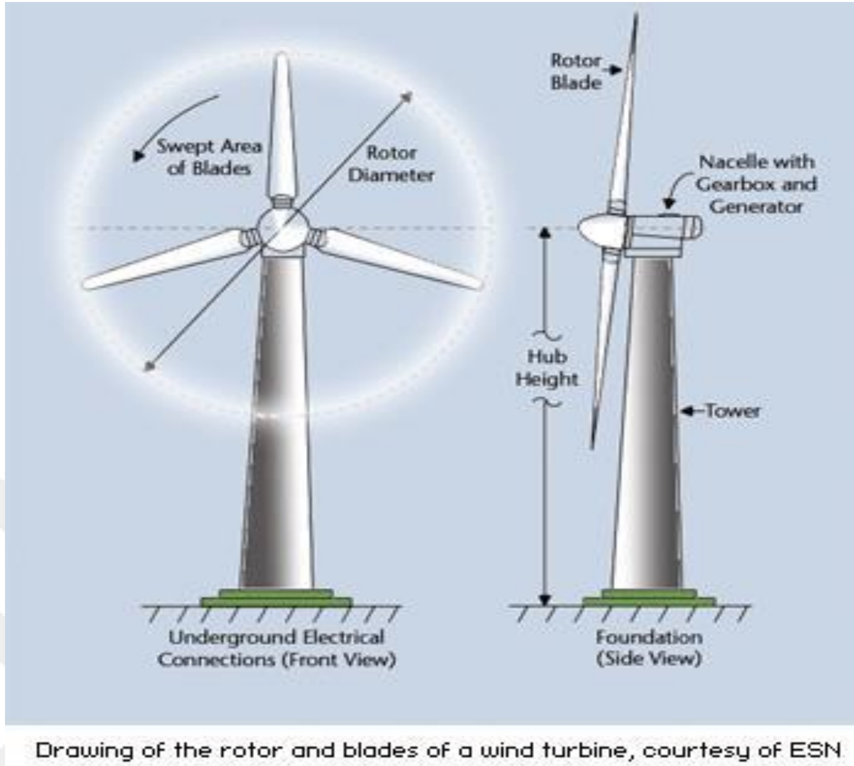

Figure 2.4. HAWT configuration (Deisadze et al. 2013).

2.2.2.3 Comparison between HAWT and VAWT

The choice of the type of wind turbine can depend on individuals or locations as both types of turbines have benefits over the other. Some of their comparison of the two wind turbines is summarized in Table 2.2 using (Dvorak, 2014) and (Saad and Asmuin, 2014),

Table 2.2. HAWT vs VAWT

	Vertical Axis Wind Turbine	Horizontal Axis Wind Turbine
Orientation of main components	At the base of the tower	At the top of the tower
Construction	simple as it doesn't require the likes of wind direction sensors and yaw	complex

	mechanisms	
Control	No yaw or pitch angle required	yaw or pitch angle required
Maintenance cost	Low maintenance cost as climbing gears are not needed.	High maintenance cost as lifts, climbing gears and danger pay compensation may be needed
Noise	Low	high
Location of installation	designed for urban areas	Not suitable for urban areas
Efficiency	Low efficiency as when the wind blows only a portion of the blades will generate torque while the other parts will only be running without generating.	High efficiency as all of them contribute to energy production when the wind blows
Duration	Not good for long term investment	Good for long term investment.
Maintenance	More maintenance as forces on the machine are more turbulent	Less maintenance
Rotating speed	Low	High

2.2.3 Wind turbine rotors

Some turbine rotors run on constant/fixed speed throughout their running period while some rotors run on variable speed when the wind speed is below the rated value. The choice of rotor speed type can have impact on the system design.

2.2.3.1 Fixed-speed wind turbines

Majority of the wind turbines in the early years were fixed/constant speed wind turbines. During start up, the rotor is held stopped but upon the release of the brakes, the wind will raise the rotor speed until the desired speed is reached. Grid connection will be made after the desired speed is reached and held constant so that the system can run on constant speed throughout (Anonym, 2011). When the wind is beyond its rated value, the generated power is maintained at its desired value by using control techniques to lower the power coefficient, Cp. The name “Fixed-speed” is given to this turbine type because when in operation their rotor speed variation is less than 2% (Tapre and Veeresh, 2016). From the theorem of wind turbine, the extraction and conversion of the maximum wind energy can only be achieved at corresponding rotating speed and certain wind speed (Manwell et al. 2002), “i.e. rotating speed of the wind turbine must be adjusted when the wind speed varies, whereas fixed-speed wind turbines keep the constant frequency at the sacrifice of capturing the maximal energy” (Li and Chen, 2004). Two winding sets type of generators are sometimes used in fixed-speed wind turbines in order for power production to be increased because turbines maximum efficiency is achieved at a specific wind speed (Tiwari et al. 2014). Fixed/constant wind turbines were used because of their reliability, robust in nature, simple to design and low cost (Kanabar et al. 2006).

2.2.3.2 Variable speed wind turbines

The most common wind turbine rotor used is the variable speed type rotor. With this type of design, the turbine is connected to the grid as soon as when the wind speed reaches its cut-in value. Its electrical system is complicated as the generator is connected to the grid with the use of a power converter. The rotor speed increases with the wind speed and with the help of the converters, the generator torque can be used to control the rotor speed in order extract the maximum power from the wind thereby achieving maximum efficiency for wind speed below rated. With this technique, the tip speed ratio λ is made constant at a value that gives the maximum power coefficient thereby reducing the mechanical stress on the turbine (Tapre and Veeresh, 2016). When the wind speed increases beyond its rated value, control techniques are used to maintain both the generator speed and power to their rated values.

2.2.3.3 Comparison of fixed-speed and variable-speed wind turbines

Both types of rotor designs have some advantages and disadvantages so the choice of selecting one depends on the priorities of the designer. Fixed-speed wind turbines have low cost and simpler electrical parts as compared to the variable speed wind turbine (Tiwari et al. 2014). This is because the variable speed wind turbine uses power electronics which serves as the interface between the grid's constant frequency and the generator's variable frequency (Arnaltes, 2003). (Tapre and Veeresh, 2016) Concluded using the simulation results that the current and voltage waveform for any wind speed is constant in fixed-speed systems while in variable speed systems they are proportional to the change in wind speed.

(Arnaltes, 2003) Concluded that variable speed wind turbines have lower power fluctuations and yields higher energy than fixed-speed wind systems. (Li and Chen, 2004) Uses a method to calculate the capacity factor of both systems to conclude that the energy efficiency in variable wind turbines is higher than in fixed-speed wind turbines. This is shown in Figure 2.5 and Figure 2.6. There is less mechanical stress on variable wind turbine system as compared to fixed-speed wind turbines (Tapre and Veeresh, 2016).

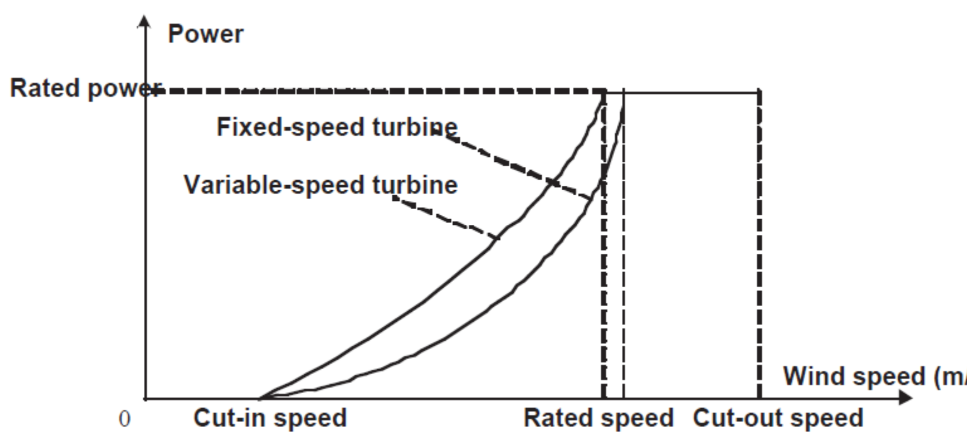

Figure 2.5. Power vs. wind Speed (fixed-speed and variable speed turbines) (Li and Chen, 2004).

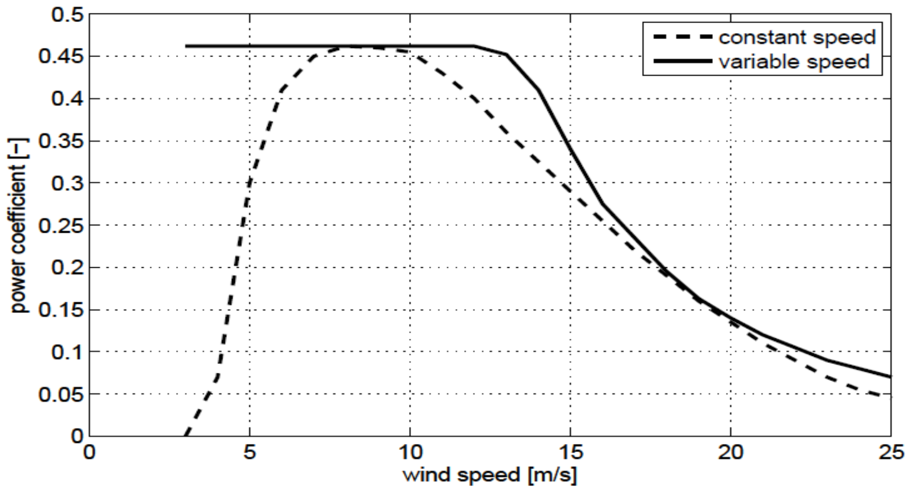

Figure 2.6. Cp vs. wind speed (fixed-speed and variable speed turbines) (Verdonschot, 2009).

2.3 Power Control

Managing the safe and automatic operation of wind turbines is the main aim of a control system. This provides consistency in the dynamic response, good product quality, lowers the cost of operation and ensures safe operation of the system (Manwell et al. 2002). This is to capture the maximum energy from the wind and still minimize turbine loads. When the turbine is running below rated wind speed, no power control is required but instead extracting the maximum energy from the wind is the target. Power control is needed when the wind speed is above its rated value to limit the power and maintain it close to its rated value. This reduces the forces on the blades of the rotor and the load on the turbine itself (Ackermann and Soder, 2000). When the output power changes during high wind speeds, it can be very high as compared to the power when the wind speed is equal to its rated. As a result, the controllers must adapt continuously to the control loop gain variation affected by the changes of the wind speed (Hoffmann, 2001). This will result to a complex control system.

2.3.1 Passive stall control

This control technique requires the wind turbine rotor to run on constant speed regardless of the wind speed. This means that this control technique is used for fixed-speed wind turbines. During wind speed above the rated value, there is a change in the condition of the air stream at the blade where turbulence is created on the blade side that is not facing the wind. This is called the stall effect (Ackermann and Soder, 2000). (Verdonschot, 2009) Defined stall effect as the limitation of the power caused by the separation of the air flow at the rotor blade surface when the "critical angle of attack is reached" An airfoil profile is shown in Figure 2.7. Based on the power criteria and the wind, this control technique only requires the turbine starting and stopping. When the brakes are released, the turbine will accelerate to the operating speed before grid connection is made with the generator or motoring of the turbine to reach the operating speed is done (Manwell et al. 2002). To make sure that at a particular wind speed there is a separation in the flow in order to avoid the increase of power, the rotor speed must be less than the optimum rotor speed (Hau, 2006).

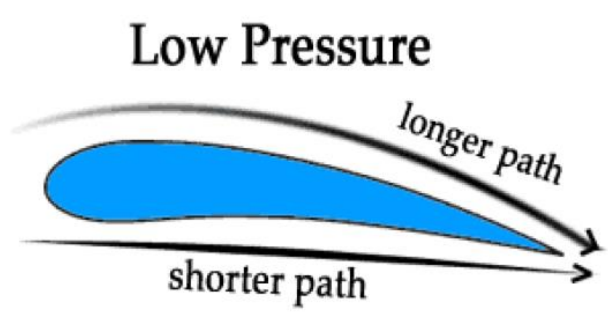

Figure 2.7. Airfoil (Deisadze et al. 2013).

The advantage of stall control is that both complex control systems and movements in rotor are avoided. The downside is that it has a complicated aerodynamic design problem and challenges in designing the wind turbine structural dynamics (Danish Wind Industry Association, 2018). **"**In Stall controlled wind turbines the blade is slightly twisted along its longitudinal axis. This ensures that the blade stalls gradually rather than abruptly as the wind speed reaches its critical stall value" (Ragheb, 2016).

2.3.2 Active pitch control

As mentioned, power control is needed when it is above the rated value in order to avoid overloading of the turbine. Pitch angle control enables active control of the power captured from the wind. It reduces the production of power when the operator requires the regulation of the power (Akhmatov, 2003). This control of turbines reduces the extracted or converted power by turning the blades to feathered position. This increases the blade pitch angle and decreases the angle of attack. The pitch angle allowable range is 0 and +90degrees ("or even a few degrees to the negative side") (Resende et al. 2013). This control system in grid connected turbine systems (both medium and large) is usually a hydraulic system that is adjusted with the use of computer systems. This is shown in Figure 2.8**.** "Electronically controlled electric motor" is also used to pitch the blades (Ackermann and Soder, 2000). Electric motor pitch control system is shown in Figure 2.9. This is a good control method as the blade angle is adjusted to lower the aerodynamic forces unlike the stall controlled wind turbines that will shut down when the rotor speed is beyond a certain value (Martinez, 2007).

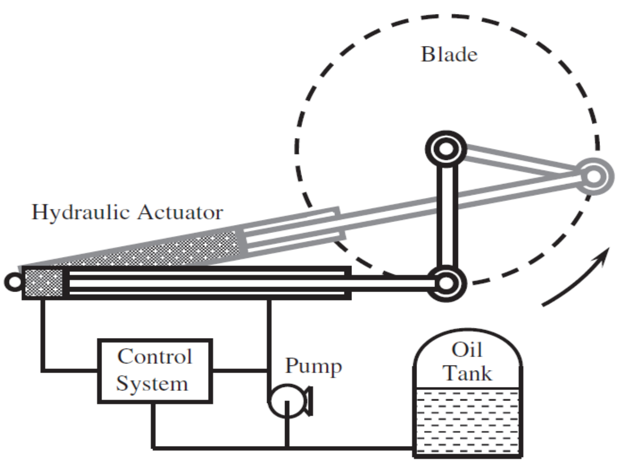

Figure 2.8. Hydraulic pitch control system (Tong, 2010).

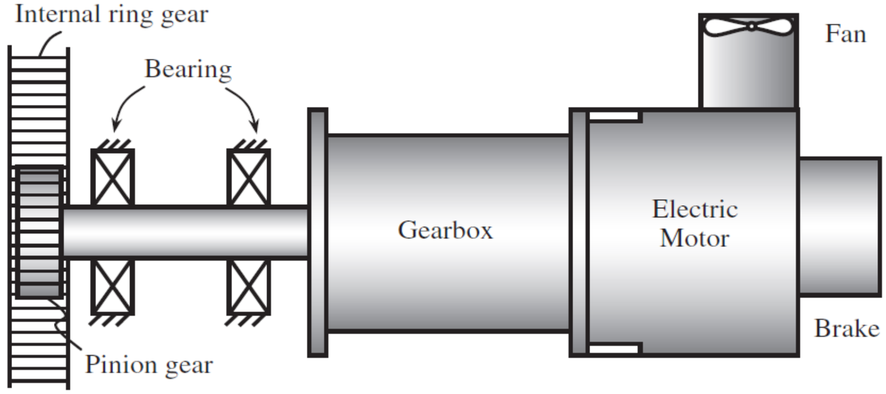

Figure 2.9. Electric pitch control system (Tong, 2010).

When the wind speed is below rated, the pitch angle is used to adjust the tip speed ratio. The pitching rate and rotor speed change reaction time discourages the use of the pitch control to track the tip speed ratio. The disadvantage of this control technique when the wind speed is below the rated value is shown in Figure 2.10. This will result to the reduction in the extracted energy from the wind and therefore, a reduction in the efficiency (Verdonschot, 2009).

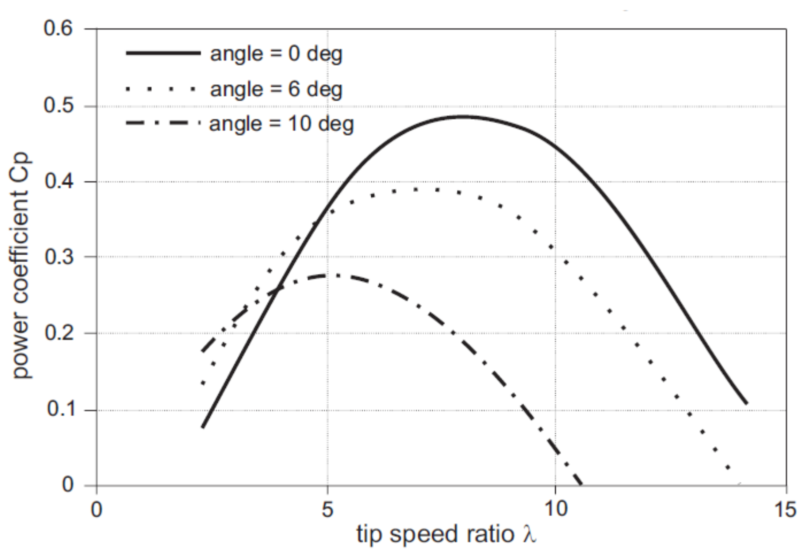

Figure 2.10. Power coefficient-tip speed ratio¸ curves for different pitch angles (Muljadi and Butterfield, 1999; Verdonschot, 2009).

2.3.3 Active stall control

This control technique combines the pitch and stall control techniques. During wind speed below the rated wind speed, the controller behaves like a pitch controller. When the turbine is at its rated value, the controller pitches the blades' direction opposite to that of a pitch controller. This result to the blades going into deeper stall as the blades angle of attack is increased (Ackermann and Soder, 2000). Active stall operation range is -90 and 0degrees ("or even a few degrees to the positive side") (Resende et al. 2013). The advantage of this technique is that at the beginning of wind gusts, overshoot of the rated generator power can be avoided by controlling the output power (Ragheb, 2016).

2.3.4 Comparison of passive stall, pitch angle and active stall control

All these 3 control techniques have proven to be effective in the control of wind turbine power but the choice of selecting the perfect one for a specific wind turbine is the problem. The choice of selection can depend on the type of wind turbine rotor (fixed-speed or variable speed rotor), designer's expertise, desired output power curve characteristics and the resources available.

Passive stall control has proven to be very simple to design as compared to both the active stall and active pitch control that have complex designs. Passive stall control is cheap to construct as it does not require electronic components while both the active stall and active pitch control needs them for the pitching of the blades. When the controller is action in passive stall controlled turbines, power oscillations are smaller than in pitch controlled turbines in a coinciding regulated mode. Thrust is higher on the structure of the turbine for stall controlled turbines (Ackermann and Soder, 2000).

It is likely that the speed limit of the blade pitching is higher for active pitch controlled turbines than for active stall controlled turbines, as their angular sensitivity is higher (Ackerman, 2005; Resende et al. 2013). Better power quality and energy yields in both active stall and active pitch controlled wind turbines than in passive stall controlled turbines (Bang et al. 2007). During high winds, both active stall and active pitch controlled wind turbines will deliver rated power unlike in passive stall controlled turbines where the power drops during high winds (Ragheb, 2016). Figure 2.11 shows the power characteristics for passive stall, pitch angle and active stall controlled wind turbines.

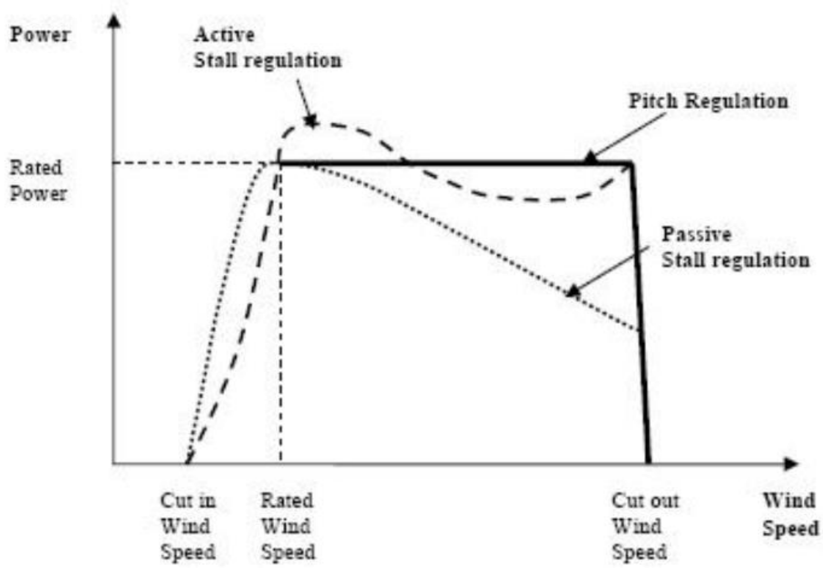

Figure 2.11. Passive stall, pitch angle and active stall control (Ragheb, 2016).

3. MODELLING OF WIND TURBINE SYSTEM

Wind turbines extract energy from the wind through the rotors and convert them to mechanical energy. This energy is then used to turn a shaft connected to a generator through a gear box which steps up the rotation speed to the generator desired value. The modelling of wind turbines helps with the understanding of the insights of the system. It provides the knowledge of the system behaviour and reaction to certain changes and external forces. (Kollár and Sterbinszky 2014) defines model as the summary of the system under study. It also explains that models can be developed for both the developing and existing system.

- New system models are used by engineers to analyse design proposals and log the system for implementation. The system model can be used to generate the implementation of a partial or whole system in model-driven engineering processes.
- Existing system models helps in the explanation of the system's strengths and weaknesses which can be used in the development of new systems.

System modelling is very important in control engineering as it shows what to expect after using a designed controller. Figure 3.1 shows the global scheme of a variable speed wind turbine.

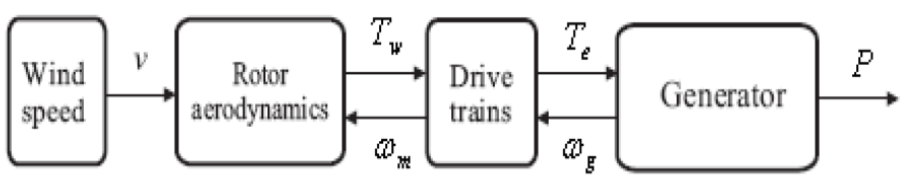

Figure 3.1**.** Wind turbine scheme (Martinez, 2007).

Figure 3.1 shows that a variable speed wind turbine mainly consists of rotor blades and a shaft, a gearbox and a generator. The wind speed dictates the behaviour of the entire system of the wind turbine as it is the input to the rotors of the turbine. The rotors capture the maximum energy possible from the wind and convert it to mechanical energy. The Drive train increases the rotation speed of the rotor shaft to a desired speed suitable to turn a generator that converts the mechanical energy to electrical energy. The generated power is then connected to the grid directly or through a converter. This chapter discusses the modelling of the dynamics involve in the wind turbine but excludes the dynamics of the generator. This is because the generator used in this work is from (VEM, 2000).

3.1 Wind and Rotor Aerodynamics

As mentioned, the rotors extracts energy from the wind and convert it to mechanical energy P_t. The wind kinetic energy E, is written as:

$$E = \frac{1}{2} m V^2 \quad (1)$$

Where V is the wind speed and m is the mass of the wind

Wind power P_w is given as the rate of change of the wind energy,

$$P_w = \frac{dE}{dt} = \frac{1}{2} \dot{m} V^2 \quad \text{(Assuming constant wind speed)}$$

Where $\dot{m}$ is given as the mass flow rate, $\dot{m} = \rho A V$

Where ρ is the air density and A is the area of the blade given as

$A = \pi R^2$, Where R is the blade radius.

The wind power is then given as;

$$P_w = \frac{1}{2} \rho A V^3 \quad (2)$$

The ratio between the mechanical energy extracted P_t and P_w is called power coefficient (Cp).

$$Cp(\lambda, \beta) = \frac{P_t}{P_w} \tag{3}$$

The power coefficient (Cp) depends on the tip speed ratio (λ) and the pitch angle (β), where

$$\lambda = \frac{\omega_r R}{V} \tag{4}$$

ω_r is the rotational speed of the rotor.

Betz's Elementary Momentum Theory shows that the entire wind power cannot be extracted or converted to mechanical energy. For an ideal wind turbine, the power coefficient is 0.593 as shown in Figure 3.2. This means that the maximum amount of power that can be extracted from the wind and converted to mechanical energy by a regular wind turbine is 16/27 (59.3%) of the wind power (P_w). The extracted or converted wind power for a typical good wind turbine is 35% - 45%.

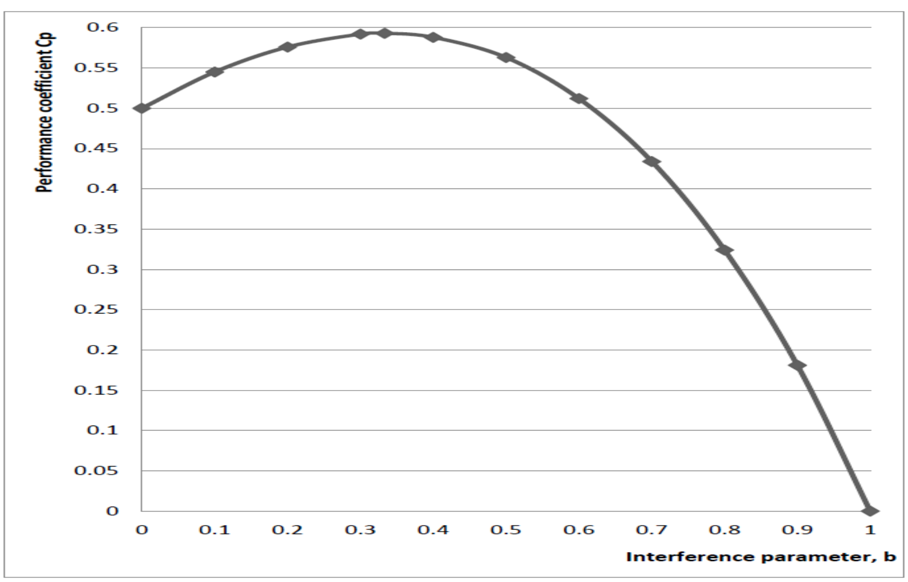

Figure 3.2. Power coefficient performance (Ragheb, 2016).

Using equation (2) and (3), P_t is then given as:

$$P_t = \frac{1}{2}\rho\pi R^2 V^3 Cp \qquad (5)$$

The power coefficient (Cp) is written in (Martinez, 2007) as

$$Cp\,(\lambda,\beta) = C_1(C_2\frac{1}{\gamma} - C_3\beta - C_4\beta^x - C_5)e^{-C_6\frac{1}{\gamma}} \quad , \beta \text{ is in degree.} \qquad (6)$$

Where $\frac{1}{\gamma} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{1+\beta^3}$

and

$C_1 = 0.5$, $C_2 = 116$, $C_3 = 0.4$, $C_4 = 0$, $C_5 = 5$, $C_6 = 21$

From equation (4), at constant rotational speed, the tip speed ratio changes when wind speed change. This will reduce the efficiency of the wind turbine. For maximum extraction of power, the rotor speed is allowed to change with wind speed in order to achieve the tip speed ratio that corresponds to the maximum power coefficient at a given wind speed when the wind speed is below the rated value. This is shown in Figure 3.3. The figure shows that the tip speed ratio that gives maximum power coefficient is 7.918. The pitch angle remains constant when the wind speed is below rated. Figure 3.4 shows that the pitch angle that gives maximum Cp is 0degrees. The change in the tip speed ratio and the pitch angle has impact on the power coefficient as shown in Figure 3.5

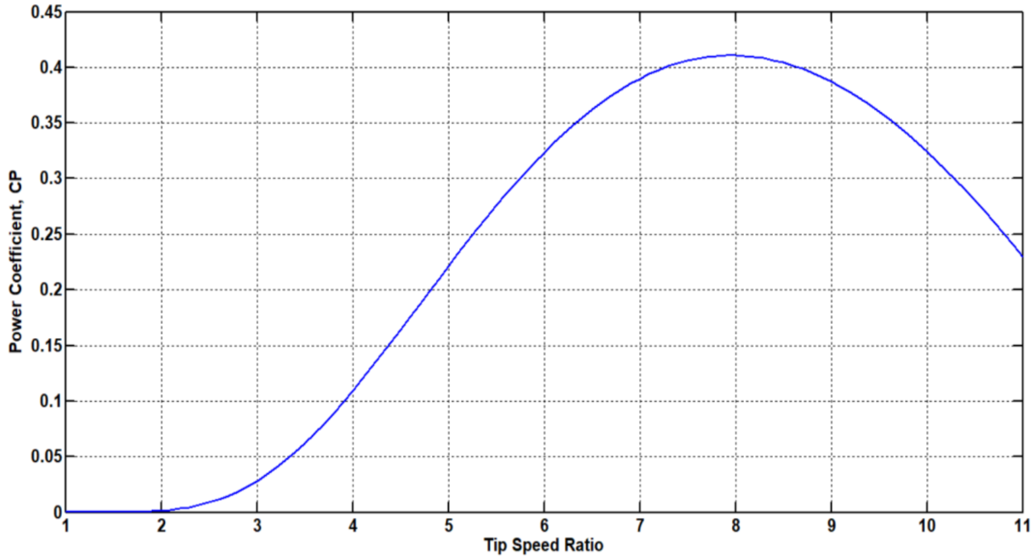

Figure 3.3. Power coefficient versus Tip Speed Ratio.

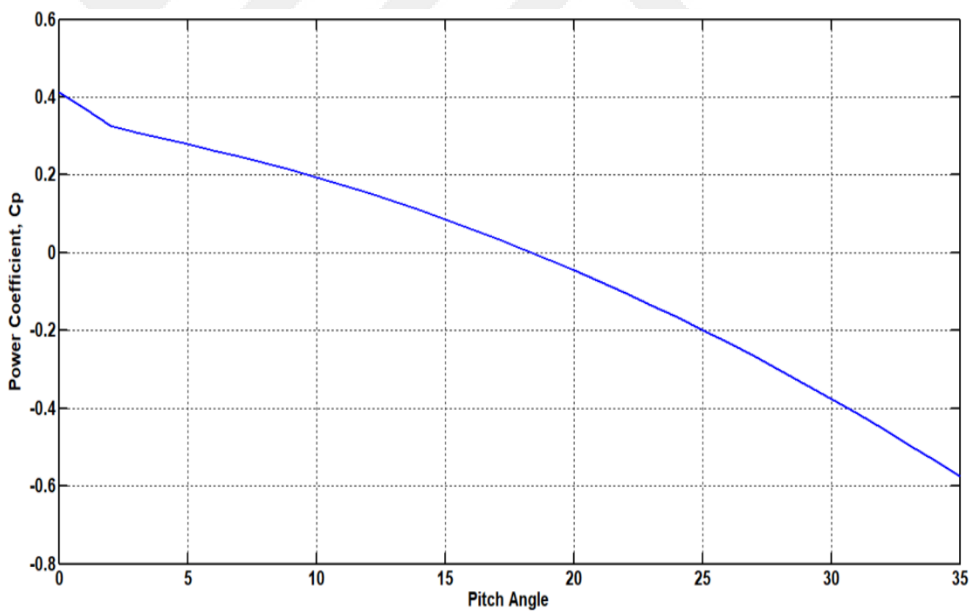

Figure 3.4. Power coefficient versus pitch angle.

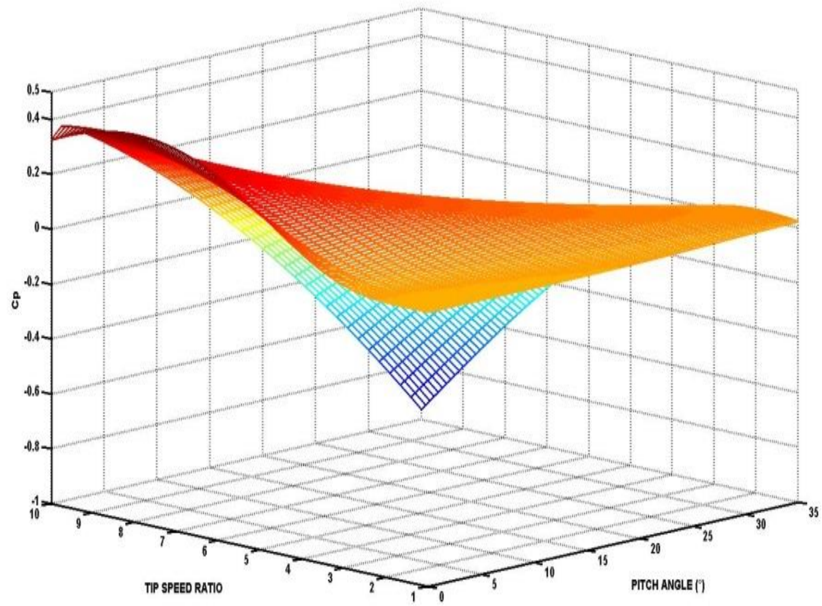

Figure 3.5. Power coefficient (Cp) curve.

The aerodynamic torque T_a is the ratio between the extracted power and the rotor rotational speed ω_r. This is given as:

$$T_a = \frac{P_t}{\omega_r} \tag{7}$$

Substituting (5) in (7) yields,

$$\begin{cases} T_a = \frac{1}{2}\rho\pi R^2 V^3 \frac{Cp}{\omega_r} \\ T_a = \frac{1}{2}\rho\pi R^3 V^2 \frac{Cp}{\lambda} \\ T_a = \frac{1}{2}\rho\pi R^3 V^2 Cq \end{cases} \tag{8}$$

Where $Cq = \frac{Cp}{\lambda}$ is the torque coefficient

3.2 Drive Trains

Most wind turbine generators need a very high speed shaft to turn its rotor to produce electrical power. The speed of the turbine rotor (around 25rpm is this research) is normally very low compared to the required speed of the generator which is 1508rpm in this research, as a result they cannot be connected directly. Therefore, a gear box that has an output to input speed ratio is required to raise the turbine rotor speed to match the generator requirements. A drive train consist of a gearbox, turbine rotor (low speed) shaft and generator rotor (high speed) shaft.

The two-mass model of the horizontal axis wind turbine is shown in Figure 3.6. This system includes a turbine rotor, gearbox and a generator. Since the turbine rotor is needed to be raised, the wheel in the gear on the turbine rotor side has to be larger than the one on the generator side. This means that the rotor torque T_a is then the generator torque.

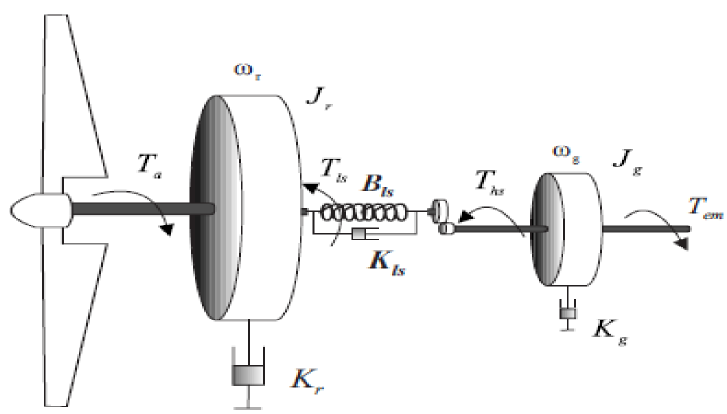

Figure 3.6. Two-mass model (Boukhezzar and Siguerdidjane, 2005).

3.2.1 Turbine rotor

The turbine is driven by the aerodynamic torque T_a and braked by the low speed shaft torque T_{ls}, with its external damping b_r to damp the rotor in order to reduce or prevent large number of oscillations. The turbine rotor transmits the converted mechanical energy through the gear box to the generator. The dynamics is given by:

$$J_r \dot{\omega}_r = T_a - b_r \omega_r - T_{ls} \quad (9)$$

Where $T_{ls} = b_{ls}(\omega_r - \omega_{ls}) + k_{ls}(\theta_r - \theta_{ls})$,
J_r is the rotor inertia, b_{ls} is the low speed shaft damping coefficient, k_{ls} is the low speed shaft spring constant, ω_{ls} is the low speed shaft rotational speed, θ_r is the rotor position and θ_{ls} is the low speed shaft position.

Note: b_r is represented in Figure 3.6 as K_r

3.2.2 Generator

The generator converts the mechanical energy from the turbine rotor to electrical energy which is connected to the grid either directly or through a converter. Fixed-speed wind turbines can be connected directly to the grid as its frequency variation is within the acceptable range while variable speed wind turbines must be connected to the grid through power converters. The power converters serve as the interface between the grid's constant frequency and the generator's variable frequency (Arnaltes, 2003).
There are 2 types of generators, asynchronous or induction generator and synchronous generator. Both types of generators are used in wind turbines depending on the type of wind turbine (fixed-speed or variable speed wind turbine) and other factors. In short, they both have their advantages for different purposes.

3.2.2.1 Synchronous generators

Synchronous generators are generators that their rotors run at the same rotational speed with the magnetic field in the air gap (1500rpm for a 4 pole generator). The rotational speed of the magnetic field in the air gap is called synchronous speed. The rotating rotor of a synchronous generator contains a magnetic field that rotates together and a stationary winding that has multiple winding. A DC field current that is supplied by a small DC generator electromagnetically creates this field on the rotor (Manwell et al. 2002). This DC generator is built on the shaft of the rotor of the synchronous generator. Since synchronous generators run at synchronous speed no slip in the system where,

$$slip = \frac{synchronous\ speed - generator\ \text{speed}}{synchronous\ speed}$$

As a result, when the generator is connected to the grid directly, any disturbance in the generator rotor speed will move to the mechanical components directly which results to high dynamic loads. Early components failure can be a result of these loads (Verdonschot, 2009). There are two types of synchronous generators, cylindrical rotor used mainly when high speed is required and salient pole generator used mainly slow speed is required. The basic structure of a synchronous generator is shown in Figure 3.7.

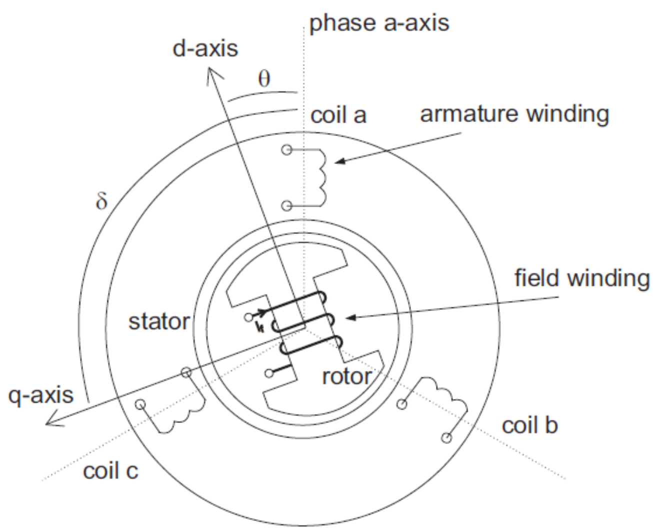

Figure 3.7. Basic structure of a synchronous generator (Verdonschot, 2009).

3.2.2.2 Asynchronous or induction generators

Induction generators are generators that their rotors run at a rate faster than the rotational speed of the magnetic field in the air gap (higher than 1500rpm for a 4 pole generator), i.e. higher than synchronous speed. This will result to a negative slip which when small, will absorb some of the rotor loads during wind gusts. Small percentage of slip reduces the wearing on the gearbox but when high, it leads to the reduction of the efficiency though better damping of the dynamic loads will be achieved. The armature and field windings are both located on the stator of induction generators unlike synchronous generators that have their field windings on the rotor. In order to create and maintain the air gap magnetic flux, magnetizing current is being supplied to the two windings. Since there is constant frequency in the grid, it can be used to supply the magnetizing current. This will result to the magnetic stator field to rotate at a constant synchronous speed (Verdonschot, 2009). Conducting bars “embedded in a solid, laminated core” are present on the rotor of most induction machines instead of windings. These types of machines are called squirrel cage machines. The induction machines that have windings are called wound rotor machines. Squirrel cage machines are cheaper and more rugged than Wound rotor machines (Manwell et al. 2002).

Induction generators are very common because (Manwell et al. 2009):

- Their construction is simple and rugged,
- they are cheaper,
- connecting and disconnecting them from the grid is simple.

The basic structure of an induction generator is shown in Figure 3.8

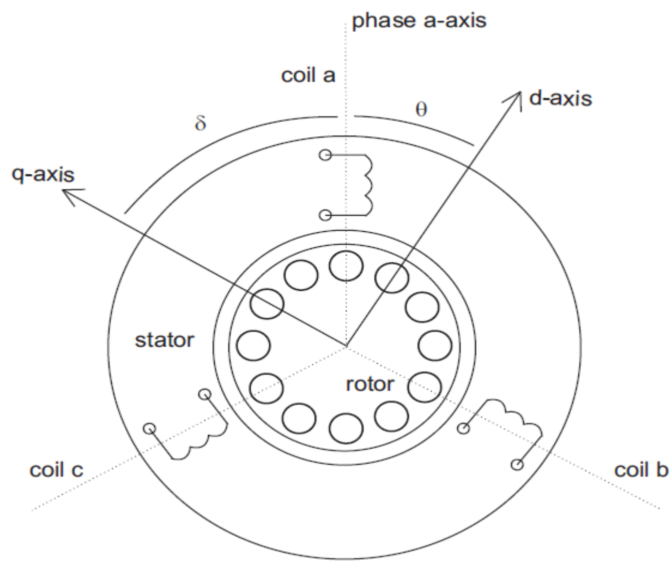

Figure 3.8. Basic structure of an induction generator (Verdonschot, 2009).

In this study, a 400KW squirrel cage induction generator “G22R 355 MX4” is used (VEM, 2000). From Figure 3.6, the Generator is driven by the high speed shaft torque T_{hs} and braked by the generator electromagnetic torque T_{em}, with its external damping b_g to damp the generator. The dynamics is given by:

$$J_g \dot{\omega_g} = T_{hs} - b_g \omega_g - T_{em} \tag{10}$$

Where $T_{hs} = b_{hs}(\omega_g - \omega_{hs}) + k_{hs}(\theta_g - \theta_{hs})$,
ω_g is the rotational speed of the rotor, J_g is the generator inertia, b_{hs} is the high speed shaft external damping, k_{hs} is the high speed shaft spring constant, ω_{hs} is the high speed shaft rotational speed, θ_g is the generator position and θ_{hs} is the high speed shaft position.

Note: b_g is represented in Figure 3.6 as K_g.

3.2.3 Gear ratio

The gear ratio n, is used in wind turbines to step up the rotor rotational speed to the desired generator rotational speed. Some wind turbines doesn't require this ratio or its jus 1:1 (input and output are the same). With these turbines, low speed generators are needed which are more expensive and lager in size. The gear ratio n is given as;

$$n = \frac{T_{ls}}{T_{hs}} = \frac{\omega_g}{\omega_{ls}} \tag{11}$$

With a rigid low speed shaft, $\omega_{ls} = \omega_r$. The gear ratio n will increase the rotor speed ω_r to reach the desired generator speed ω_g value.

To get a one-mass model as shown in Figure 3.9, the generator dynamics is transferred to the rotor side using equation (11) and adding it to equation (9). This gives:

$$J_t \dot{\omega}_r = T_a - b_t \omega_r - T_g \tag{12}$$

Where

$J_t = (J_r + J_g n^2)$, $\quad b_t = (b_r + b_g n^2)$, $\quad T_g = nT_{em}$

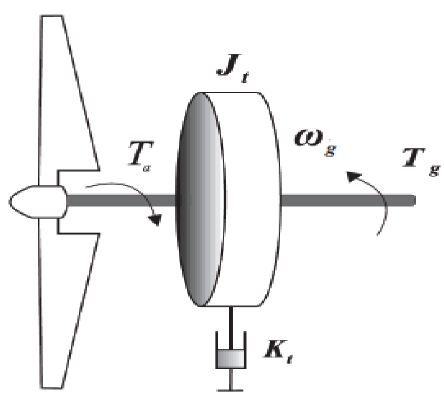

Figure 3.9. One-mass model of a wind turbine (Vidal et al. 2012).

4. CONTROL OF WIND TURBINE SYSTEM

4.1 Control Aim

The aim of the control system is to ensure that the wind turbine system works according to the system requirements. Wind energy is very unstable in nature so control systems are required to protect the system and the grid itself. When the wind speed is fluctuating, the generator speed ω_g also fluctuates. This will cause the generator frequency to also fluctuate as

$$f = \frac{\omega_g p}{60},$$

Where f is the frequency of the generator and p is the number of pole pairs of the generator. Connecting the generator directly to the grid will disrupt the grid system as the grid operates on constant frequency of 50Hz (Europe) or 60Hz (America). For the wind turbine to supply power to the grid, it has to be synchronized to the system i.e. its generator frequency, voltage and phase angle has to be the same as the grid. Control systems and power electronics are required to achieve this.

Before any control system can be build, a proper understanding on the operation of wind turbines is necessary. Variable Speed Wind Turbine operates in three modes: mode 1, mode 2 and mode 3 as shown in Figure 4.1.

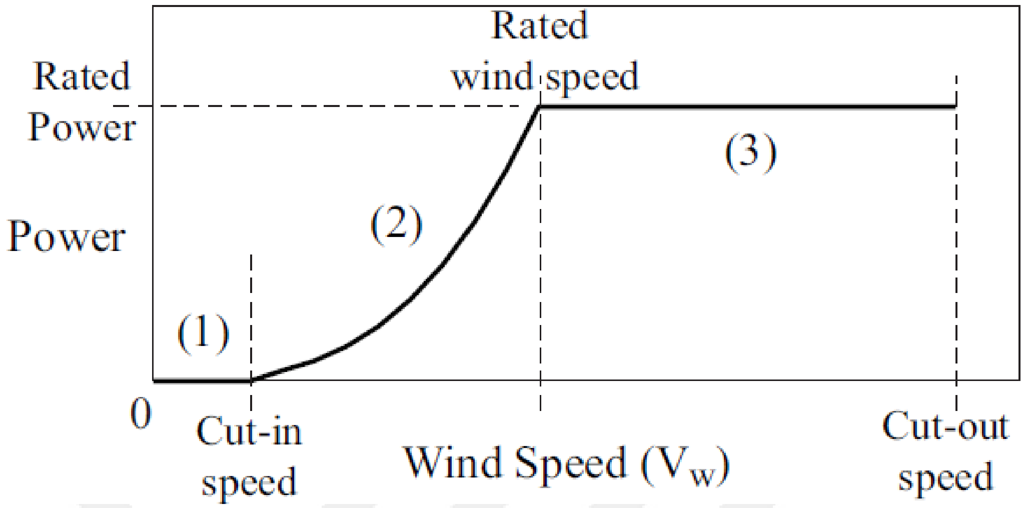

Figure 4.1. Wind turbine operation modes (Das et al. 2011).

4.1.1 Mode 1 (wind speed less than the cut-in value)

In this region, wind turbine is not in operation in this mode. This is because the wind speed is not enough to turn the rotor blades to capture wind power. Therefore, the power and rotor speed are zero. The wind turbine is off in this mode.

4.1.2 Mode 2 (wind speed is between the cut-in and rated value)

In this region, the wind speed is in operation. This mode is where the wind turbine runs at variable speed. The wind turbine starts to extract/capture wind power when the wind speed reaches the cut-in value (5m/s). Rated electrical power cannot be achieved in this mode so the main target is to extract the maximum power from the wind. This is achieved by running the wind turbine on constant blade pitch angle (0°) and tip speed ratio (optimum value) λ_{opt}. These constant blade pitch angle and λ_{opt} are the values when the wind turbine is operating on its rated condition. This ensures that the power coefficient Cp is always constant in this mode at its maximum value (Cpmax). The optimum tip speed ratio λ_{opt} is given as,

$$\lambda_{opt} = \frac{\omega_{ropt} * R}{V} \tag{13}$$

Where ω_{ropt} is the rated rotor speed.

The generator torque is also used in the extraction of maximum wind power by adjusting the rotor speed. This is called indirect speed control (ISC) (Boukhezzar and Siguerdidjane, 2005). With this control technique, the power electronics can be used to set the generator torque to almost any desired value as they determine the frequency and phase of the current flowing from the generator (Manwell, et al., 2002). This controlled generator torque is given as;

$$T_g = K\omega_r^2 - b_t\omega_r \tag{14}$$

Where $K = \frac{1}{2}\rho\pi R^5 \frac{Cpmax}{\lambda_{opt}^3}$

4.1.3 Mode 3 (wind speed between the rated and cut-out value)

In this region, the wind speed is equal to or higher than rated wind speed (10m/s) but not more than the cut-out wind speed (25m/s). This is where the controller is needed to ensure that power is constant. To achieve a constant electrical power, both the generator torque and speed are made constant at their rated values. As mentioned in chapter 2.3, there are different ways to control the generator power but the most commonly used is the control of the wind turbine blades pitching in order to reduce the power capture by the blades. Many papers did some research on blade pitch angle control using different non-control techniques as already discussed in chapter 1.

In this study, the generator speed is made constant by using a novel approach to control the Cp. Non-linear sliding mode control technique is used to achieve this. The sliding mode controller will make the generator speed constant by regulating the Cp value. Feedback controller is also used to regulate the Cp value and the result is compared to the sliding mode controller. The generator torque is made constant by using a similar control technique adopted in (Mullane et al, 2001). Other torque controllers used in wind turbine research will also be analysed. These control techniques will ensure safe operation of the wind turbine when running in this mode.

Summary of the control of the wind turbine rotor speed is shown in Figure 4.2. A sensor is placed either at the turbine or generator rotor side to measure the rotor rotational speed. This will determine the wind turbine’s mode of operation in order for the controlled generator torque (mode 2) or the pitch controller (mode 3) to be in operation. When the sensor measures a rotor rotational speed that is below rated, the controlled generator torque will be in operation to boost the rotor speed with the aid of the power converters in order to extract maximum power as shown in Figure 4.3. When the sensor measures a rotor rotational speed that is below rated, the non-linear controller will be in operation to maintain the rotor speed at its desired value as shown in Figure 4.4.

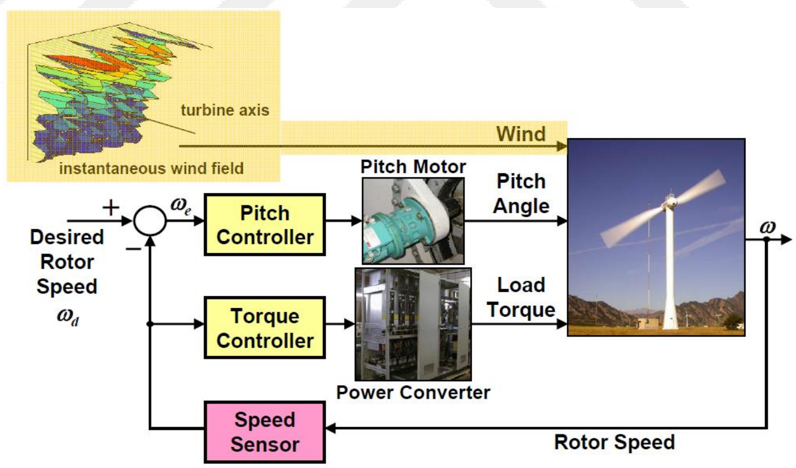

Figure 4.2. Summary of rotor speed control in mode 2 (Tg control) and mode 3 (Paoand Johnson, 2009; Darrow, 2010).

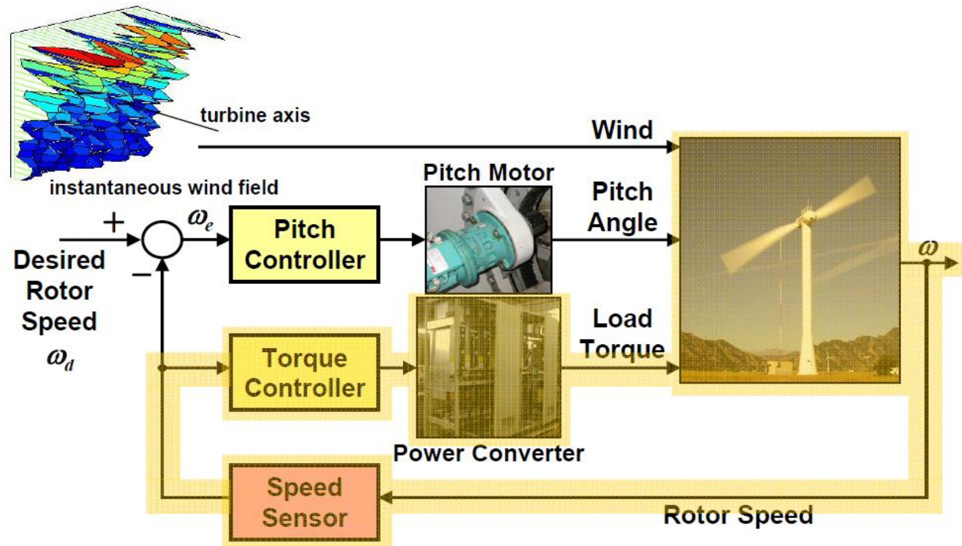

Figure 4.3. Mode 2 generator torque control loop.

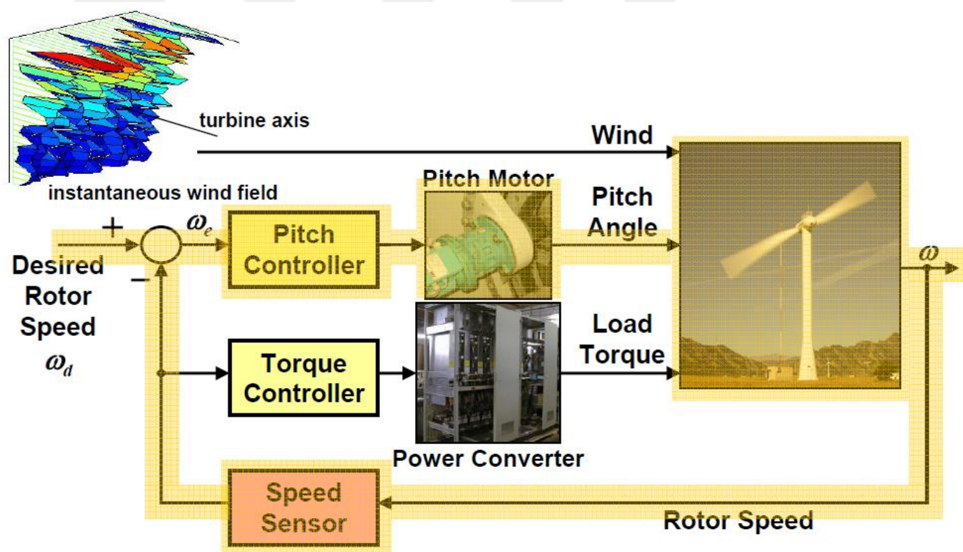

Figure 4.4. Mode 3 non-linear controller control loop.

4.2 Control Methodology

4.2.1 Cp as a control input

As already discussed in Chapter 3.1, power coefficient is the ratio between the mechanical energy extracted P_t and P_w. It measures the efficiency of the wind turbine. Controlling the power coefficient Cp controls the amount of power extracted by the rotor blades. This is a novel approach in wind turbine power control as most papers uses pitch control as a control input. Using equation (6) in equation (12) to control the pitch angle will be very difficult. This is because the equation is highly nonlinear as seen from the equation below

$$Cp\ (\lambda,\beta) = (58(\frac{1}{\lambda+0.08\beta} - \frac{0.035}{1+\beta^3}) - 0.2\beta - 2.5)e^{-21(\frac{1}{\lambda+0.08\beta} - \frac{0.035}{1+\beta^3})}$$

Therefore, Cp is used as a control input in equation (12) using a nonlinear controller called Sliding mode controller. This controller is designed by using matlab/simulink to command the Cp to regulate the rotor speed. Given Cp from the controller and λ from the simulator, computation of β is a root finding problem. An algorithm using fzero function is designed to find the roots of β but it requires the initial estimation of β as the initial value to the fzero in order to get the actual β from the roots. To obtain the initial estimation of β, a lookup table is designed and used with the designed algorithm. Thus, for each Cp obtained from the controller, the corresponding pitch angle must be calculated for every wind speed. Using Cp as a control input and designing these algorithms to obtain β are the main contribution of this paper. The simulink model of the algorithm with the lookup table used is shown in Figure 4.5.

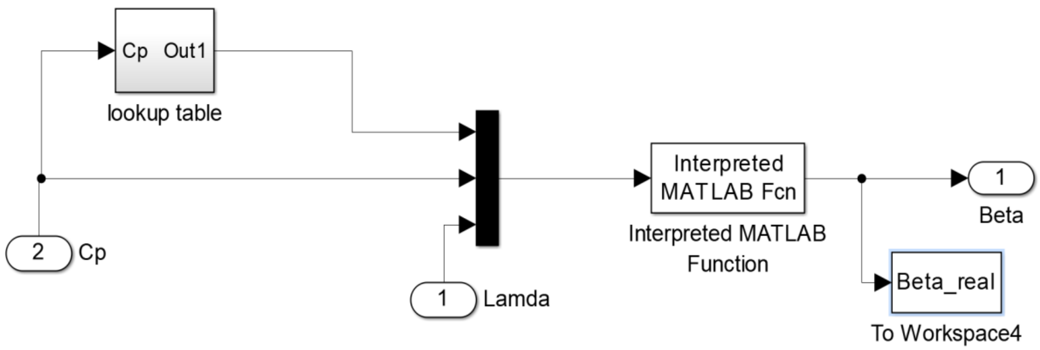

Figure 4.5. Pitch angle algorithms with lookup table simulink model.

An alternative non-linear controller called feedback linearization is also designed to compare its results with the sliding mode controller. This is to further validate the control strategy (using Cp as a control input) implemented in this study. As mentioned in Chapter 4.1.2, the pitch angle in mode 2 has to be 0°. In order to achieve this, a switch is used as shown in Figure 4.6.

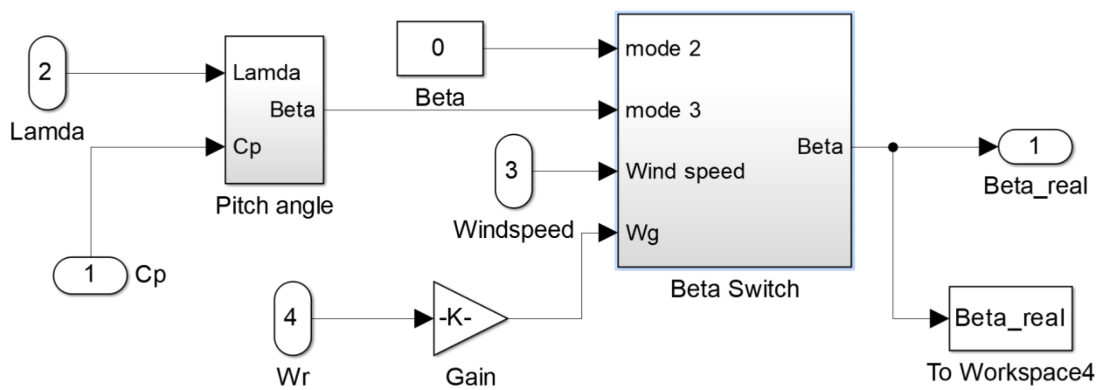

Figure 4.6. Pitch angle simulink model.

4.2.1.1 Sliding Mode Control (SMC)

SMC is a robust nonlinear control technique that changes the dynamics of nonlinear systems by applying discontinuous control signals that pushes the system to “slide along a cross-section of the system’s normal behaviour” (Jing et al. 2017). Robustness to the disturbances in the electrical grid and the turbine and generator parametric uncertainties are special features of SMC (Beltran et al. 2008). SMC is used in this study to make the generator speed reach its desired value. A typical phase portrait under sliding mode is shown in Figure 4.7. Noting that for one side of $s = 0$ line, $s > 0$ and the other side $s < 0$.

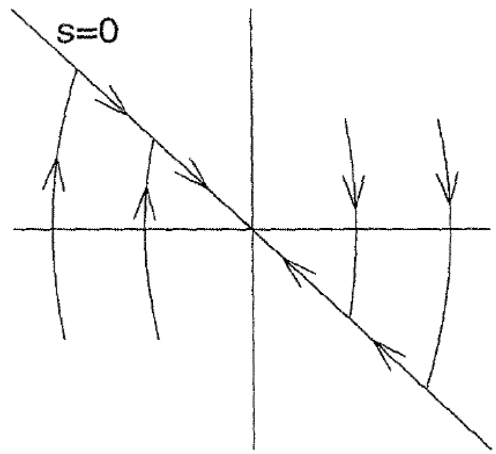

Figure 4.7. Sliding mode control phase portrait (Khalil, 2002).

Applying SMC to control the wind turbine rotor speed, let us first define the rotor error rate ω_e as the difference between the actual rotor angular velociy ω_r and desired rotor angular velocity ω_d.

$$\omega_e = \omega_r - \omega_d \tag{15}$$

For rate of change of error, noting that ω_d is constant and using equation (12), we obtain

$$\begin{cases} \dot{\omega_e} = \dot{\omega_r} \\ \dot{\omega_e} = \frac{T_a}{J_t} - \frac{b_t}{J_t}\omega_r - \frac{T_g}{J_t} \end{cases} \tag{16}$$

From equations (15) and (16),

$$\dot{\omega_e} = \frac{k_o V^3 u}{J_t(\omega_e + \omega_d)} - \frac{b_t}{J_t}(\omega_e + \omega_d) - \frac{T_g}{J_t} \tag{17}$$

Where $k_o = \frac{1}{2}\rho\pi R^2$ and control input u = Cp.

Let the sliding variable "s" as;

$$s = \left(\frac{d}{dt} + \lambda\right)^{m-1} e$$

Where m is the order of the system. Since m is 1,

$$\begin{cases} s = \left(\frac{d}{dt} + \lambda\right)^{0} e \\ s = \omega_e \end{cases} \tag{18}$$

The two main rules of the sliding mode control are:

- As $s \to 0$, the error $\omega_e \to 0$
- $\dot{s}$ must contain the control input, u

$$\begin{cases} \dot{s} = \dot{\omega}_e \\ \dot{s} = \left(\frac{k_o V^3 u}{J_t(\omega_e + \omega_d)} - \frac{b_t}{J_t}(\omega_e + \omega_d) - \frac{T_g}{J_t}\right) \end{cases} \tag{19}$$

The control u is displayed as u $= \hat{u} + u_d$

Where $\hat{u}$ is the equivalent control that allows the elimination on the known terms on the right side of equation (19) and u_d is "the discontinuous part, ensuring a finite time convergence to the chosen surface" (Perruquetti and Barbot, 2002).

From equation (19), assuming $u \to \hat{u}$ as $\dot{s} \to 0$. Thus, we obtain the equivalent control as;

$$\begin{cases} \hat{u}\left(\frac{k_o V^3}{(\omega_e+\omega_d)}\right) = b_t(\omega_e+\omega_d)+T_g \\ \hat{u} = \left(\frac{\omega_e+\omega_d}{k_o V^3}\right)(b_t(\omega_e+\omega_d)+T_g) \end{cases} \tag{20}$$

Using Lyapunov theorem, we get

$$\begin{cases} \frac{1}{2}\frac{d}{dt}(s^2) = -|s| \\ s\dot{s} = -|s| \ \rightarrow \dot{s} = -k\ sgn(s) \end{cases}, \quad \text{k} > 0 \tag{21}$$

Note: $sgn(s) = \begin{cases} 1, & s > 0 \\ 0, & s = 0 \\ -1, & s < 0 \end{cases}$

From equation (17) and (19) and, noting that $u \rightarrow U$ as $\dot{s} \rightarrow -sgn(s)$, we solve for the control.

$$U = \left(\frac{\omega_e+\omega_d}{k_o V^3}\right)(b_t(\omega_e+\omega_d)+T_g) - k\ sgn(s)$$

To avoid the chattering caused by the "sign" function, the following "sat" function is used to obtain smooth responses.

$$U = \left(\frac{\omega_e+\omega_d}{k_o V^3}\right)(b_t(\omega_e+\omega_d)+T_g) - ksat(s)$$

The Cp controller is for the sliding mode is given as;

$$C_p = U = \left(\frac{\omega_r}{k_o V^3}\right)(b_t(\omega_r)+T_g) - ksat(\omega_r - \omega_d) \tag{22}$$

The simulink model for the sliding mode controller is shown in Figure 4.8.

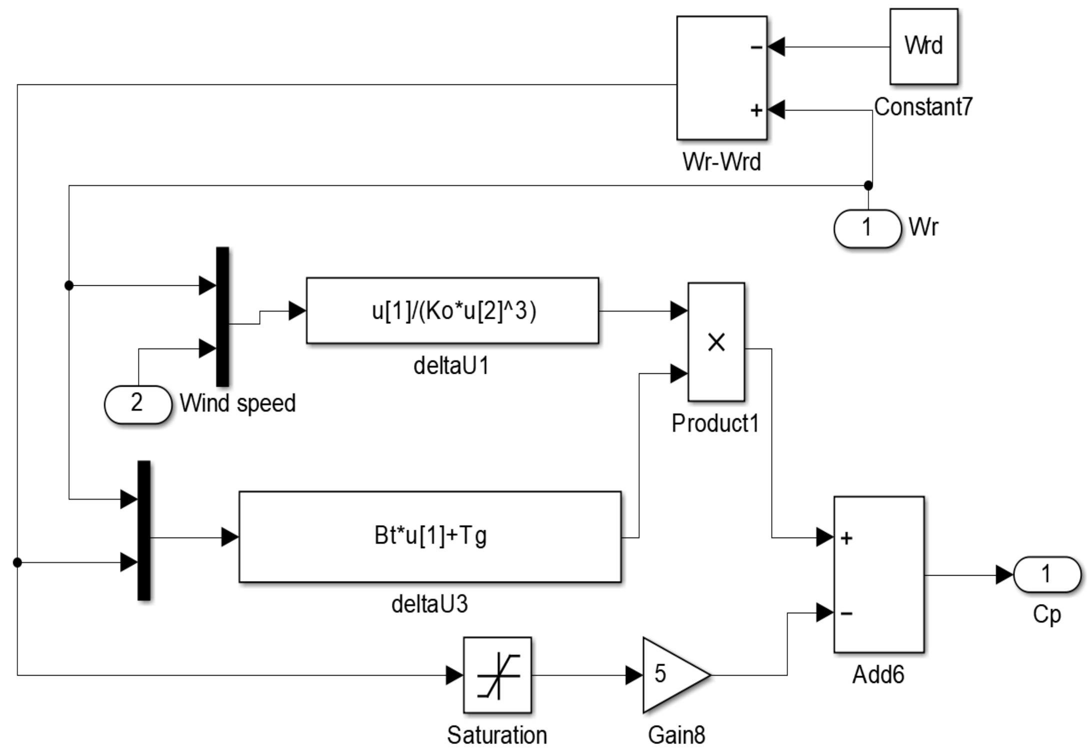

Figure 4.8. Sliding mode controller simulink model.

4.2.1.2 Feedback linearization control

This control technique, nonlinear system is first linearized to make the designing of the controller easier.

Linearizing the system and then uses equation (17)

$$\dot{\omega}_e = \dot{\omega}_r = \frac{k_o V^3 u}{J_t(\omega_e+\omega_d)} - \frac{b_t}{J_t}(\omega_e + \omega_d) - \frac{T_g}{J_t}$$

To eliminate the non-linear terms such as $\frac{k_o v^3 u}{J_t(\omega_e+\omega_d)}$, we choose the control input u $= u_{fb}$ so that the resulting equations become a stable linear system. For a stable error rate dynamics;

$$\dot{\omega}_e + K_c\omega_e = 0\,, \qquad K_c > 0$$

The error dynamics equation is to ensure that the rotor error rate ω_e goes to zero with time and with a large value of K_c, ω_e will go to zero very fast. This is given as:

$\omega_e = \omega_e(0)e^{-K_c t}$, where $\omega_e(0)$ is the initial value of the rotor error rate.

$$\begin{cases} \dot{\omega_e} = -K_c\omega_e , \quad \text{k} > 0 \\ -K_c\omega_e = \frac{k_o v^3 u_{fb}}{J_t(\omega_e + d)} - \frac{b_t}{J_t}(\omega_e + \omega_d) - \frac{T_g}{J_t} , \quad \text{k} > 0 \end{cases} \tag{23}$$

Solving for u_{fb} gives;

$$u_{fb} = \frac{J_t(\omega_e + \omega_d)}{k_o v^3}\left[\frac{b_t}{J_t}(\omega_e + \omega_d) + \frac{T_g}{J_t} - K_c\omega_e\right]$$

The Cp controller for the feedback linearized control is given as;

$$\mathrm{C_p} = \mathrm{u_{fb}} = \frac{\omega_r}{k_o v^3}\left[b_t\omega_r + T_g - J_t K_c(\omega_r - \omega_d)\right] \tag{24}$$

The simulink model for the feedback linearized controller is shown in Figure 4.9.

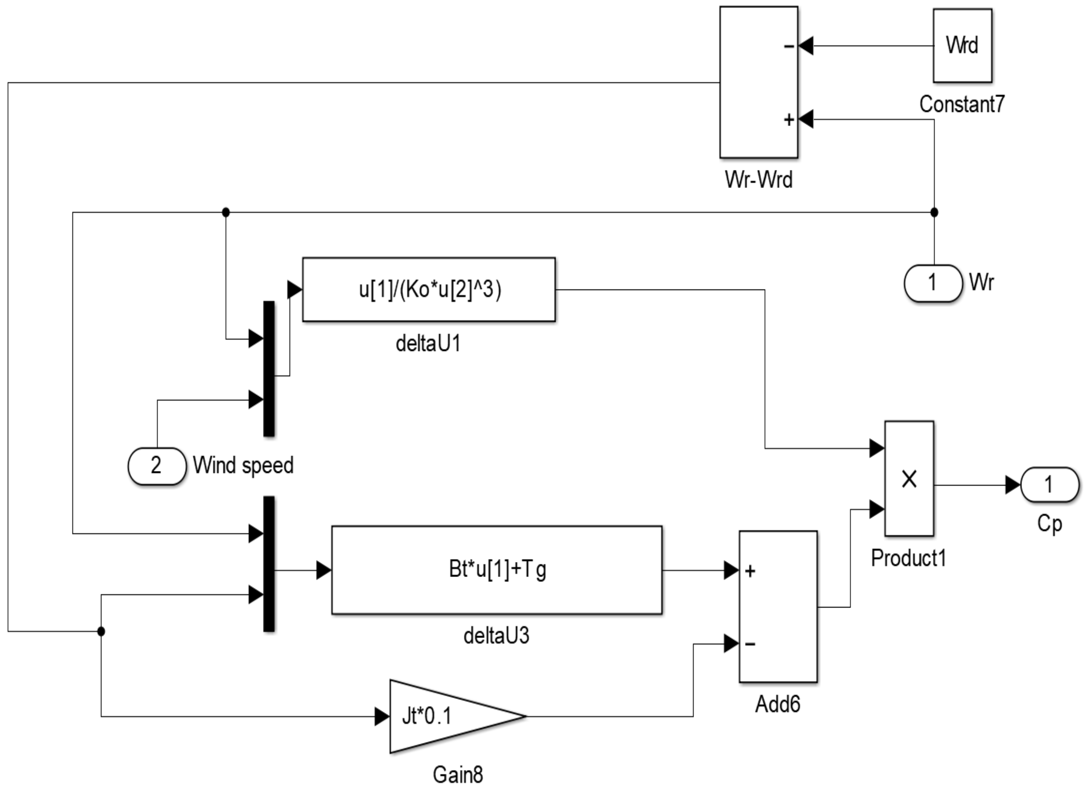

Figure 4.9. Feedback linearized controller simulink model.

4.2.2 Torque controller in mode 3

The purpose of the generator torque controller is to maintain the generator torque at its rated value when operating in mode 3. The one adopted in this wind turbine is similar to the one used in (Mullane et al, 2001). This torque controller first estimates the generator electromagnetic torque T_{em}.

$$T_{hs} = J_g v + b_g \omega_g + \hat{T}_{em} \tag{25}$$

Where v is the additional input (Mullane et al, 2001) and $\hat{T}_{em}$ is the estimated generator electromagnetic torque.

In this study, $\hat{T}_{em}$ is assumed to be constant and equal to the rated generator torque of 2533.25N.m. Putting equation (25) in (10) yields

$$\begin{cases} J_g\dot{\omega}_g = J_g v + \hat{T}_{em} - T_{em} \\ J_g\dot{\omega}_g = J_g v - \tilde{T}_{em} \end{cases} \tag{26}$$

Where $\tilde{T}_{em}$ is the error between the actual and estimated generator electromagnetic torque.

$$\dot{\omega}_g = v - \frac{\tilde{T}_{em}}{J_g} \tag{27}$$

As $\tilde{T}_{em}$ approaches zero, v approaches $\dot{\omega}_g$. The generator speed error rate e is given as:

$$e = \omega_g - {\omega_g}^* \tag{28}$$

Where ${\omega_g}^*$ is the desired generator speed.

For a stable error dynamics;

$$\begin{cases} \dot{e} + K_1 e = 0 \ , \ K_1 > 0 \\ \dot{e} = \dot{\omega}_g - \dot{\omega_g}^* \end{cases} \tag{29}$$

$$v = \dot{\omega_g}^* - K_1 e \quad \text{(When v approaches} \dot{\omega}_g\text{)} \tag{30}$$

Putting (27) in (30)

$$\dot{\omega}_g + \frac{\tilde{T}_{em}}{J_g} = \dot{\omega_g}^* - K_1 e$$

Thus

$$\dot{e} = -\frac{\tilde{T}_{em}}{J_g} - K_1 e \tag{31}$$

Using a Lyapunov equation,

$$V = \frac{1}{2} Pe^2 + \frac{\tilde{T}_{em}{}^2}{2} \quad , \quad P > 0 \tag{32}$$

$$\begin{cases} \dot{V} = Pe\left(-K_1 e - \frac{\tilde{T}_{em}}{J_g}\right) + \tilde{T}_{em}\dot{\tilde{T}}_{em} \\ \dot{V} = -PK_1 e^2 - \tilde{T}_{em}\left(\frac{Pe}{J_g} - \dot{\tilde{T}}_{em}\right) \end{cases} \tag{33}$$

In equation (33), by letting

$$\frac{Pe}{J_g} - \dot{\tilde{T}}_{em} = K_2 \tilde{T}_{em}\,, \quad K_2 > 0$$

One can guarantee that $\dot{V}$ is negative definite. Hence,

$$\dot{\tilde{T}}_{em} = \frac{P}{J_g} e - K_2 \tilde{T}_{em} \tag{34}$$

Using equations (31) and (34), the state equation becomes,

$$\begin{cases} X = \begin{bmatrix} e \\ \tilde{T}_{em} \end{bmatrix} \\ \dot{X} = \underbrace{\begin{bmatrix} -K_1 & -\frac{1}{J_g} \\ \frac{P}{J_g} & -K_2 \end{bmatrix}}_{A} \begin{bmatrix} e \\ \tilde{T}_{em} \end{bmatrix} \end{cases} \tag{35}$$

For the linear state equation (33) to be stable, all the eigenvalues of A must have negative real parts. Thus,

$$|A - \lambda I| = 0 = \begin{bmatrix} -K_1 & -\frac{1}{J_g} \\ \frac{P}{J_g} & -K_2 \end{bmatrix} - \begin{bmatrix} \lambda & 0 \\ 0 & \lambda \end{bmatrix} \tag{36}$$

Using the pole placement theory and selecting the eigenvalues as $\lambda_1 = -5$ and $\lambda_2 = -10$, we obtain

$$\begin{cases} K_1K_2 + \frac{P}{J_g{}^2} = 50 \\ K_1 + K_2 = 15 \end{cases} \quad (37)$$

Letting P = $36{J_g}^2$ yields

K_1 = 14 and $K_2 = 1$,

Hence, it is guaranteed that X→ 0 which implies that $\omega_g \rightarrow {\omega_g}^*$ and $T_{em} \rightarrow \hat{T}_{em}$.

The simulink model of the torque controller is shown in Figure 4.10.

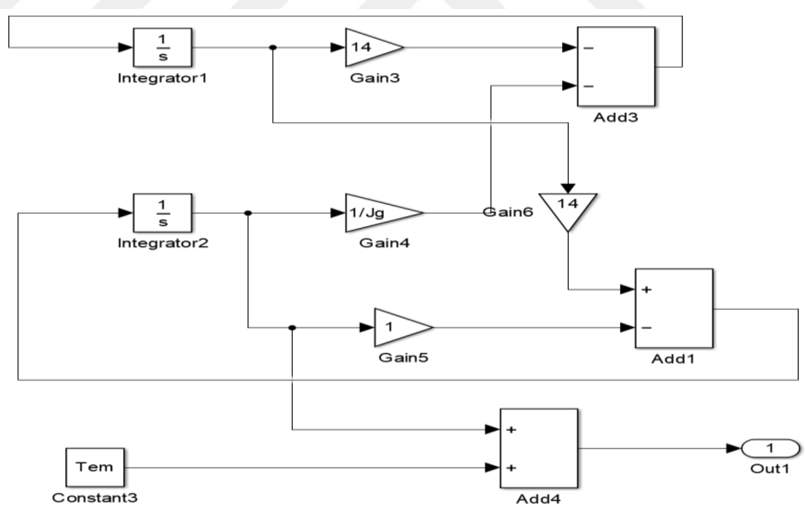

Figure 4.10. Torque controller simulink model.

Other generator torque control techniques has been adopted and used in other papers. (Boukhezzar and Siguerdidjane, 2005; Boukhezzar et al. 2007) used a technique whereby the torque controller tracts the power and regulates the torque to ensure that the power is maintained at its desired value.

The power tracking error is given as;

$$\varepsilon_p = P_{ref} - P \tag{38}$$

For a stable error rate dynamics;

$$\dot{\varepsilon_p} + K_t \varepsilon_p = 0 \quad , \; K_t > 0 \tag{39}$$

The electrical power is given as:

$$P = \omega_r T_g \tag{40}$$

Substituting equation (40) in equation (39), one obtains for a constant reference P_{ref}:

$$\begin{cases} -T_g \dot{\omega_r} - \omega_r \dot{T_g} + k\varepsilon_p = 0 \\ \quad \dot{T_g} = \frac{1}{\omega_r}\left(K_t \varepsilon_p - T_g \dot{\omega_r}\right) \end{cases} \tag{41}$$

Thus,

$$\dot{\mathrm{T}}_{\mathrm{g}} = \frac{1}{\omega_{\mathrm{r}}}(\mathrm{K_t}(\mathrm{P_{ref}} - \mathrm{P}\,) - \mathrm{T_g}\dot{\omega}_{\mathrm{r}}) \tag{42}$$

This torque control technique is not to maintain the generator torque at its rated value, instead it is to ensure that the power is always constant at its rated value when the wind turbine is operating in mode 3. This means that power control will be achieved but if there is no proper turbine or generator rotor speed control, the torque will go beyond or below acceptable values as the electrical power.

$$P = \omega_g T_{em}$$

In mode 3, using these control techniques, the power, rotor speed and the generator torque can be controlled and made constant at their desired values. At the same time by controlling the power coefficient Cp, the corresponding pitch angle is determined for a given wind speed. The controllers are designed in such a way that the torque controller will be faster than the Cp controller.

5. RESEARCH FINDINGS AND DISCUSSION

This thesis is to test a new approach to control the output electrical power of a wind turbine. This new controller entails the use of the power coefficient Cp as control input to control the wind turbine rotor speed when the wind turbine is operating in mode 3 (wind speed is between rated and the cut-off value). Nonlinear controllers called sliding mode and feedback linearized controllers were designed in chapter 4 and used to control the power coefficient Cp. These two nonlinear controls are then compared. Some algorithms were also designed to display the pitch angle for every wind speed. The wind turbine was modelled in Chapter 3 and all simulations were done using matlab/simulink as shown in Figure 5.1.

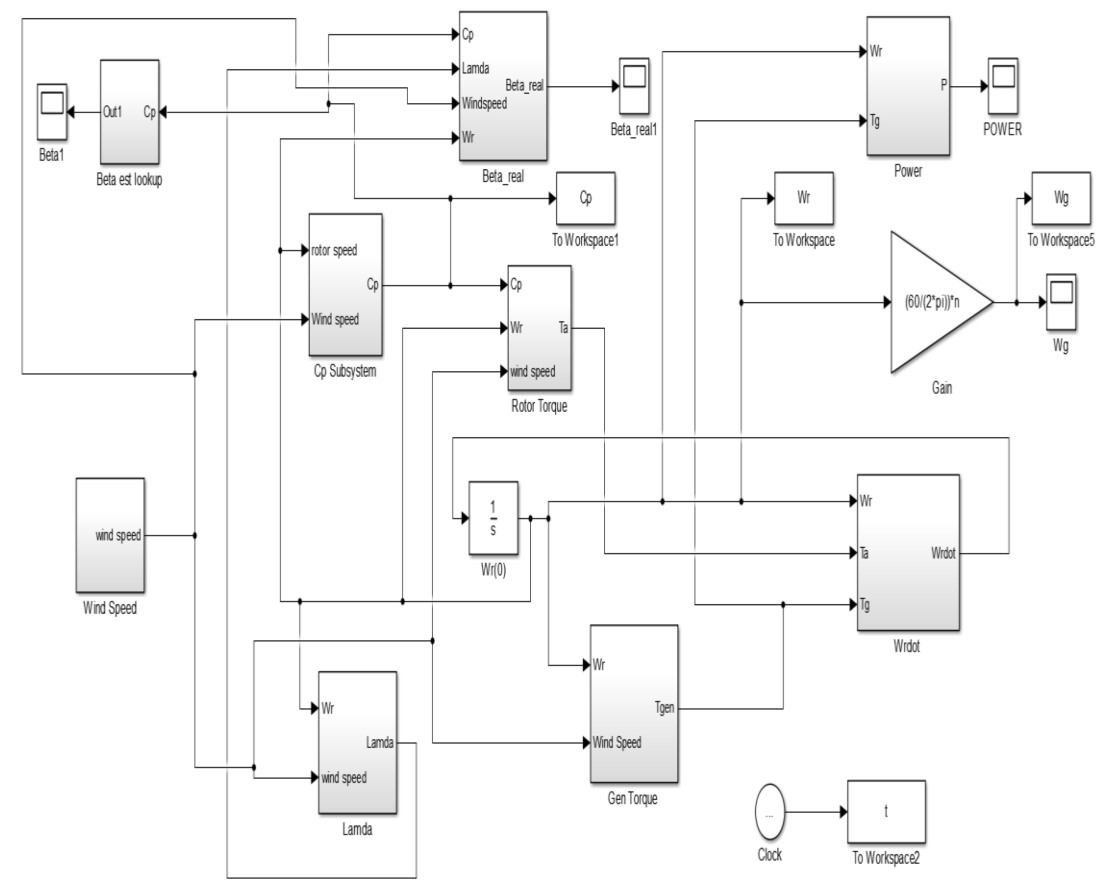

Figure 5.1. Simulink model of the wind turbine.

The wind turbine considered uses a “G22R 355 MX4” 400KW generator (VEM, 2000) connected to a rotor through a gearbox. The simulation was done using the parameters in Table 5.1. Running the simulation at rated values shows that the maximum Cp (Cpmax) is 0.4109 with an optimum tip speed ratio λ_{opt} of 7.918.

Table 5.1. Wind turbine parameters.

Name	**Value**	**Unit**
Rated wind speed	10	m/s
Air density	1.225	kg/m^3
Rotor radius	29.5	m
Maximum power coefficient	0.4109	----
Optimum tip speed ratio	7.918	----
Rotor inertia	1.6×10^6	kg. m^2
Rated rotor speed	2.6838	rad/s
Gear box ratio	58.84	----
Rated generator power	400	kW
Rated generator speed	1508	rpm
Rated generator torque	2533.25	N.m
Generator inertia	9.5	kg. m^2
Total external damping	4×10^4	N.m/rad/s

5.1 Mode 2

In this mode, the wind turbine runs on variable rotor speed. The wind turbine will start producing power when the wind speed reaches the cut-in value (5m/s). The rotor rotational speed increases with the wind speed. To achieve maximum extraction of the available power, the demanded generator torque T_c(same as T_g in this mode) is used to adjust the rotor speed. Cpmax and optimum tip speed ratio are kept constant without any power control.

The graph of the wind speed, power, generator speed and demanded generator torque in mode 2 is shown in Figure 5.2.

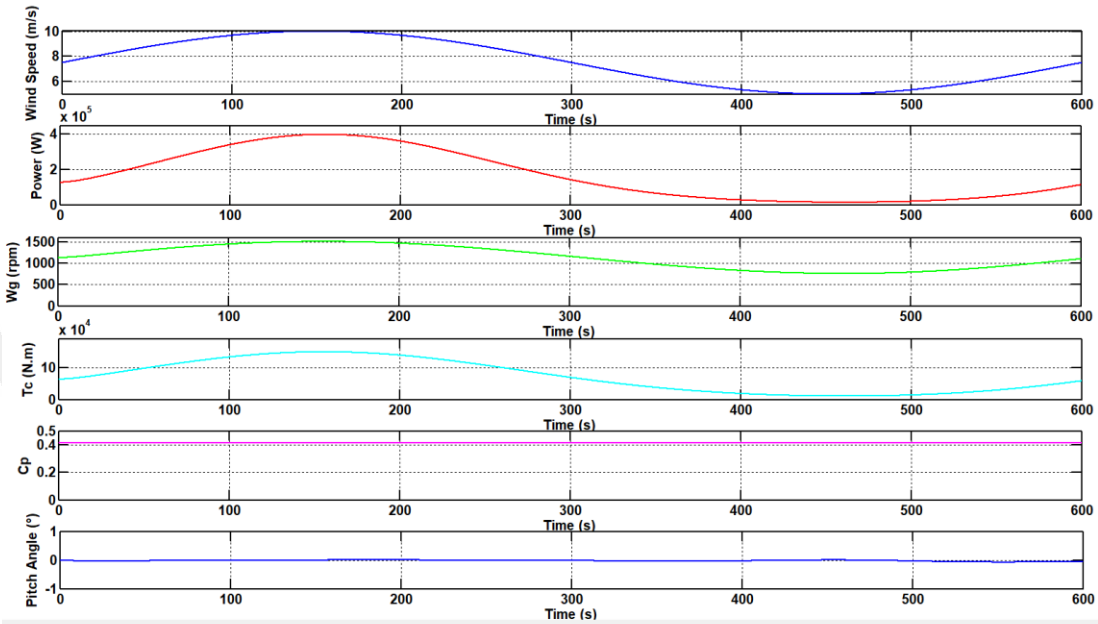

Figure 5.2. Wind speed, power, generator speed and demanded generator torque in mode 2.

The simulation results in Figure 5.2 shows the characteristics of the wind turbine in mode 2. The pitch angle was kept constant at zero while Cpmax and optimum tip speed ratio were kept constant 0.4109 and 7.918 respectively. The initial rotor rotational speed $\omega_r(0)$ value is set to 1.342rad/sec (rotor speed at the cut-in value). The wind speed was set to fluctuate between 5m/s and 10m/s with a frequency of 0.6rad/sec increasing from 7.5m/s to 10m/s and then decrease to 5m/s, i.e., V = 7.5+2.5*sin(0.6*t) as shown in Figure 5.2. This is to show that the wind turbine rotor speed will change with the wind speed. From Figure 5.2, the demanded torque from the generator was able to control the rotor speed to ensure maximum power was captured from the wind at every wind speed. When the wind speed is at its cut-in value, the generator output electrical power is 13.983kW while the generator speed is 745rpm. The wind turbine can be connected to the grid at this point to supply as power electronics are connected as an interface between the grid's constant frequency and the generator's variable frequency.

5.2 Mode 3

In mode 3, the control techniques are used when the wind speed is above the rated value to make the generator power, torque and speed constant at their rated values. This is to prevent the overloading of the system and reduces the forces acting on the blades. As both the wind power and the power extracted by the rotor blades are multiples of the cube of the wind speed (as shown in equations (2) and (5)), a small increment in wind speed above rated will create large forces on the wind turbine rotor blades. Therefore, control is required in this mode.

The graph of the wind speed, power, generator speed, generator torque, Cp and pitch angle in mode 3 is shown in Figure 5.3. For smooth transition between mode 2 and mode 3, the initial rotor speed, ω_r (0) is set to 2.6838rad/s.

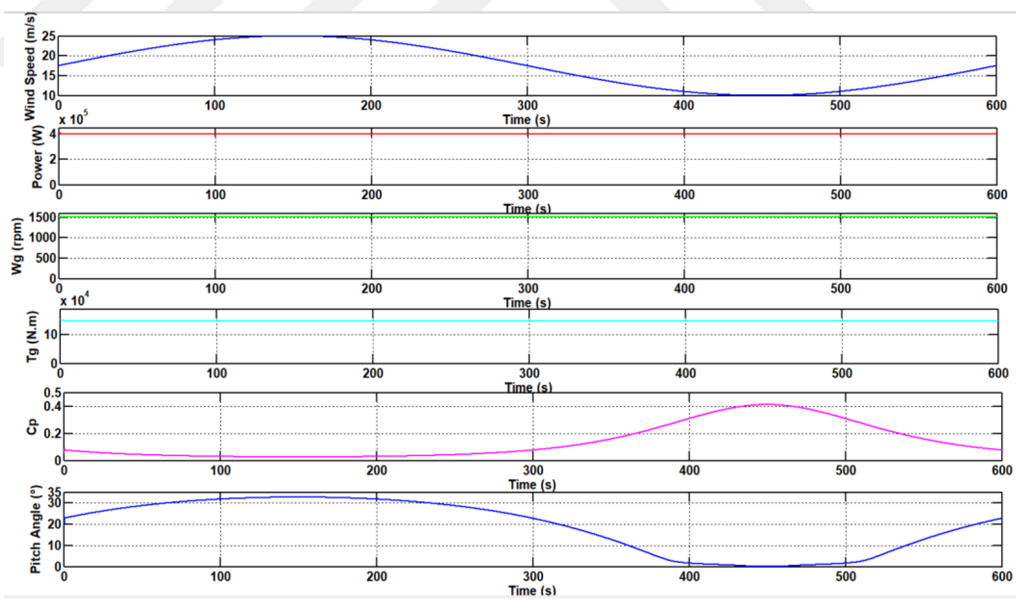

Figure 5.3. Wind speed, power, generator speed and generator torque in mode 3.

The simulation results in Figure 5.3 shows the characteristics of the wind turbine in mode 3. In this mode, the power coefficient Cp, tip speed ratio and the pitch angle are all not constant. This is because the Cp is used as the control input to the controller to ensure that both the generator and turbine rotor speed are constant at its rated values.

The turbine rotor speed being constant while the wind speed is changing means the tip speed ratio λ will also be changing as $\lambda = \frac{\omega_r R}{V}$. The designed algorithm using fzero function and the lookup table for the estimation of the blade pitch angle was able to solve the root finding problem to acquire the actual pitch angle for every wind speed. The estimated blade pitch angle was used as the initial value in the fzero function. The actual pitch angle is also shown in Figure 5.3. It can also be seen that as the wind speed increases, the controller decreases the power coefficient. This means the pitch angle of the turbine blades increases to reduce the surface area of the blades which will therefore reduce the extracted power.

The initial rotor rotational speed $\omega_r(0)$ value is set to 2.6838rad/sec (almost the rated rotor speed value which is the beginning of mode 3). The wind speed was set to fluctuate between 10m/s and 25m/s with a frequency of 0.6rad/sec increasing from 17.5m/s to 25m/s and then decrease to 10m/s, i.e., V = 17.5+7.5*sin(0.6*t) as shown in Figure 5.3. The torque controller was able to control the generator torque and maintain it at its rated value ($T_g = 1490.56.43N.m$ when transferred to the turbine rotor side). With the controllers maintaining both the generator speed and torque at their rated values, the output electrical power is also maintained at its rated value (400kW) in this mode as the electrical power $P_e = \omega_g T_{em}$.

5.3 Switching between mode 2 and 3

As mentioned, wind turbines run on different modes when in operation depending on the wind speed. Therefore, switching between the modes is necessary as the behaviour of the wind turbine in each mode is different from the other. The switch in Figure 5.4 was designed for the switching between the modes for the Cp shown in Figure 5.5, torque controller and the pitch angle. The “if” switch condition box is shown in Figure 5.6.

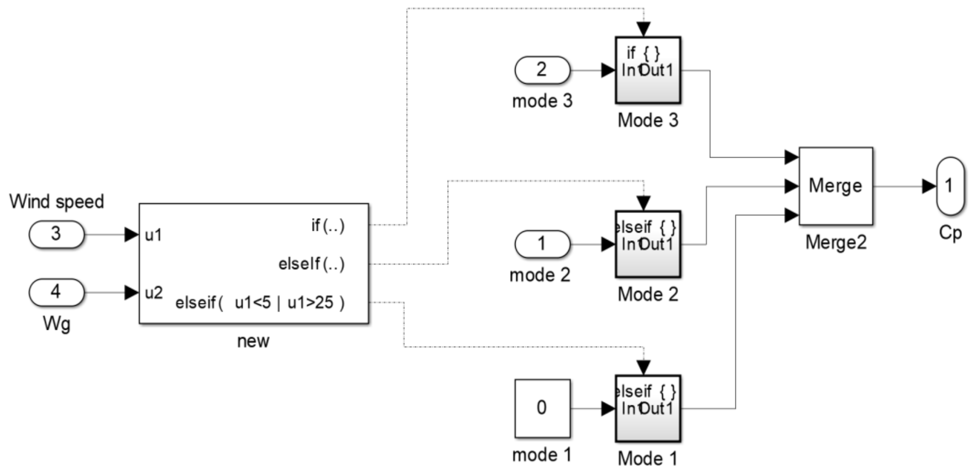

Figure 5.4. Switching logic for the modes.

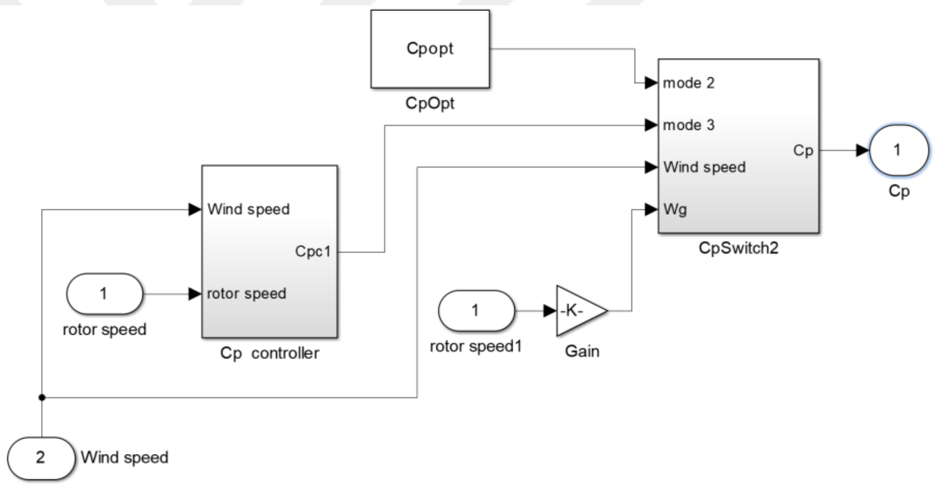

Figure 5.5. Cp switch.

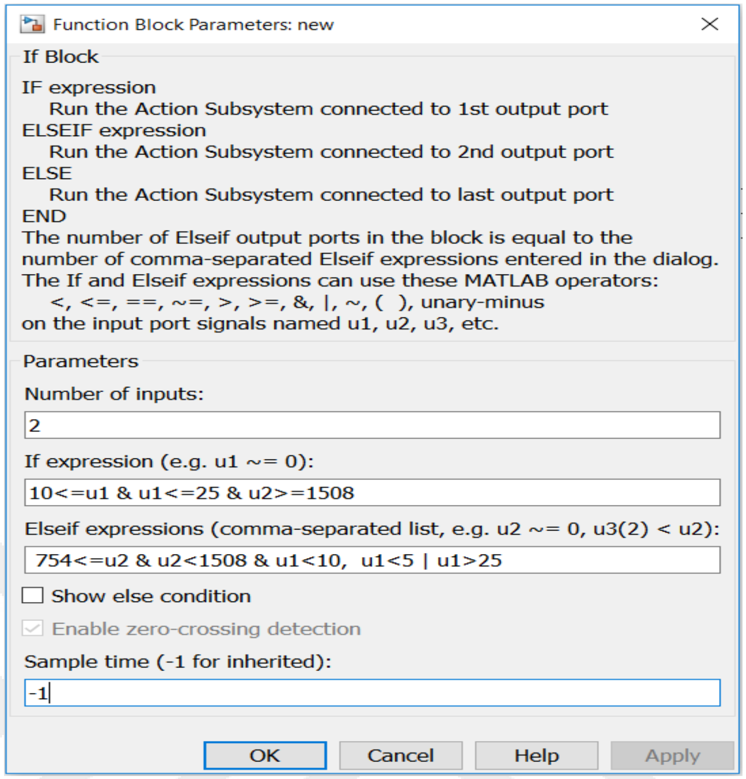

Figure 5.6. Switch box regarding “if” logic.

The switching logic shown in Figure 5.4 is to make the controller switch from mode 2 to mode 3 or vice versa. After the transition line from mode 2 to 3, power fluctuations/overshoot must be avoided or limited as much as possible. This can disrupt the entire connected electrical grid. As a result, the transition between the modes must be smooth. With the “if” command in Figure 5.6, the fluctuations are insignificant. With this technique, the fluctuation or overshoot after the transition is unnoticeable therefore it won’t disrupt the synchronized system. This is shown in Figure 5.7 for the wind speed, power, generator speed, generator torque, Cp and pitch angle. The simulation time was also 600secs.

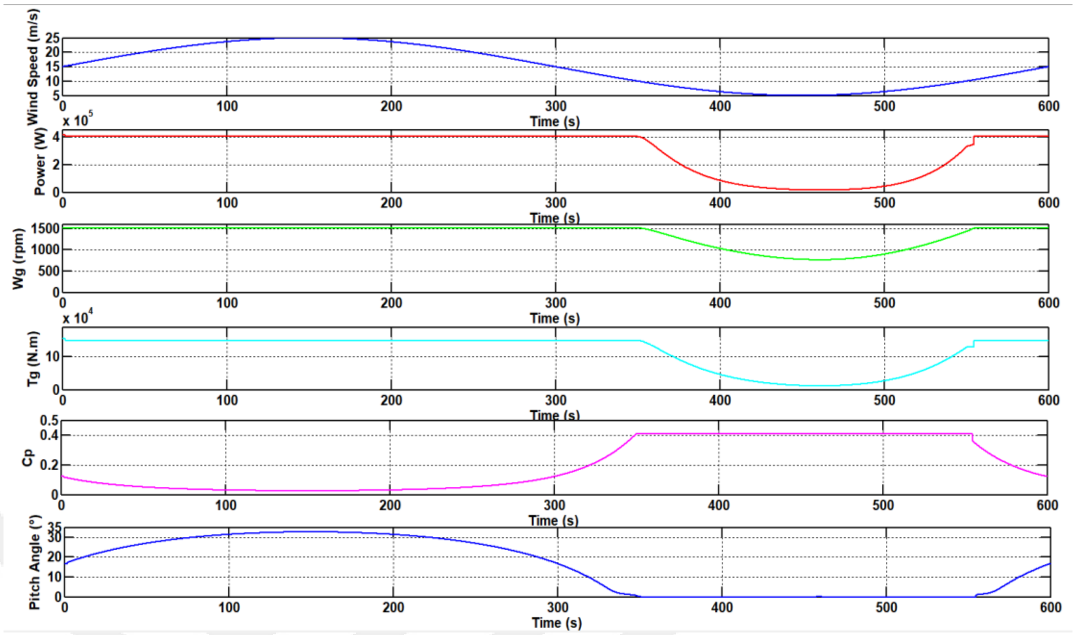

Figure 5.7. Smooth transition between mode 2 and 3.

5.4 Comparison between Sliding Mode and Feedback Linearization Controllers

Feedback linearization controller is also used to control the generator speed of the wind turbine. This non-linear controller is compared to the sliding mode controller to,

- Show that other non-linear controllers can also be applied to this new control approach.
- See whether there will be much difference when controlling the generator speed.
- See how they react with the designed algorithms to determine the actual pitch angle.

The generator speed and the turbine blade pitch angle when using the two non-linear controllers are compared in Figure 5.8 and Figure 5.9. The results show that the feedback linearization controller was able to control the generator speed when the wind speed is above the rated value and at the same time determined the blade pitch angle.

It is obvious that the response of the two controllers is fully coinciding such that they are indistinguishable.

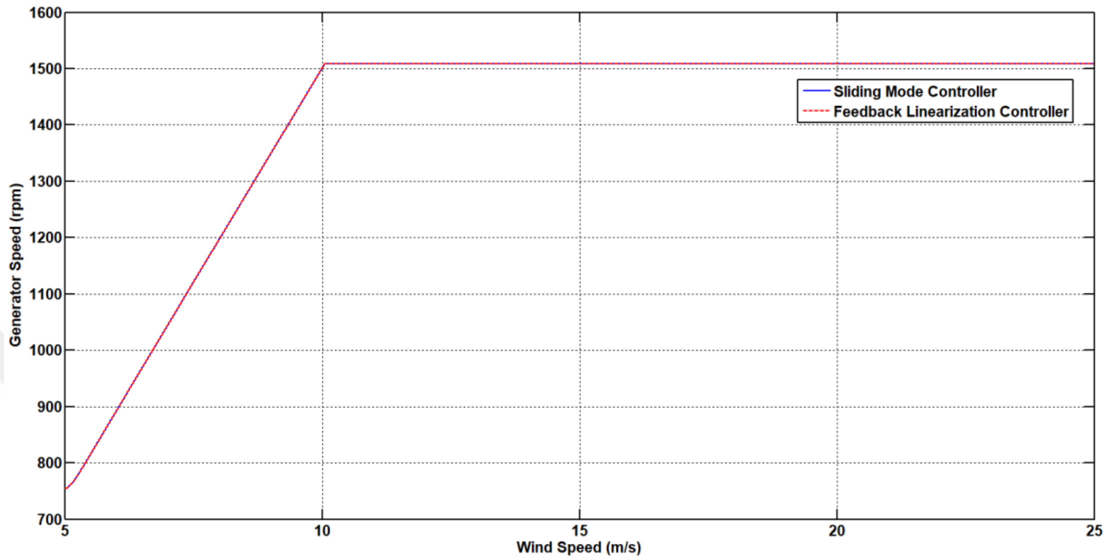

Figure 5.8. Generator speed, using feedback linearization and SMC

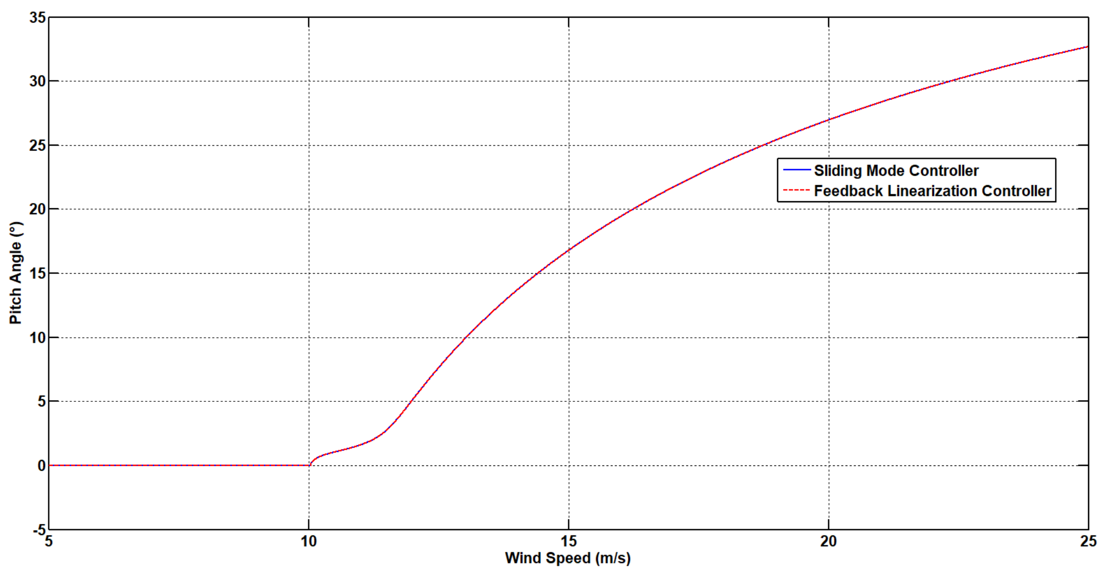

Figure 5.9. Pitch angle, using feedback linearization and sliding mode controls.

6. CONCLUSION AND IMPLICATION

6.1 Conclusion

In this work, the following two issues are considered and studied in detail.

- When the wind speed is below the rated value, the conditions under which the maximum generator power can be obtained.
- When the wind speed is above the rated value, how to control the generator speed and the generator torque in order to maintain a constant generator power and keep it at that value.

In order to control the generator speed and the generator torque, a mathematical model of the wind turbine control system based on the power coefficient Cp, as a control input has been developed and displayed in Matlab/Simulink environment. “Cp as a control input” is selected rather than “β as a control input” since $Cp\ (\lambda, \beta)$, as seen from equation (4), is a highly non-linear function of λ and β. For each Cp obtained from the two controllers, namely, Sliding Mode Control and Feedback Linearized Control, the corresponding pitch angle β is calculated for every wind speed. For this reason, an algorithm is designed and used with the lookup table. The algorithm uses fzero function, which handles the non-linear root finding problem for the pitch angle. Using “Cp as a control input” and using lookup table with the specifically designed algorithm to obtain β are the main contribution of this paper.

In this study, demonstration through analytical work, through the required simulation results that the two non-linear controllers, where Cp is chosen as control input, performed as desired. The results also show that feedback linearization controller acts almost like the sliding mode controller such that the responses are indistinguishable. The switching logic used in this paper guarantees smooth transitions when the turbine is operating from a low to high wind speed. The generator speed curve in Figure 5.8 satisfies the characteristics of a typical variable speed wind turbine. Considering the time interval 470s(cut-in value) <time< 600s(cut-off value) in Figure 5.7, the power curve resembles that of Figure 4.1, where the transition is smooth and the power is maintained at the rated value.

In conclusion, the two non-linear controllers (sliding mode control and feedback linearized control), where Cp is chosen as control input, performed as desired.

6.2 Recommendations

The results achieved from this novel approach to control a variable speed wind turbine using the power coefficient Cp as control input is encouraging. This control technique is simpler than using highly nonlinear pitch angle β as a control input, noting that in both cases the results are expected to be the same. As a future work, one can study the analytical proof of these results. The classical PI/PID control could also be applied to this control problem for comparison.

This control technique could be validated using an actual wind turbine (Vestas, Nordex, Enercon GmbH etc) data. Using this control technique to control a group of interconnected wind turbines in a wind farm is also recommended.

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