EU GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

EGE UNIVERSITY

MASTER OF SCIENCE THESIS

OBSERVER BASED CONTROL OF WIND TURBINE

Rao Muhammad ASAD

Supervisor: Prof. Dr. Aydoğan SAVRAN

Department of Electrical and Electronics Engineering

Date of Presentation: 23.09.2016

Bornova-İZMİR

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Rao Muhammad Asad tarafından Yüksek Lisans tezi olarak sunulan "Rüzgar Türbini Sistemlerinin Gözetleyici Temelli Kontrolü" başlıklı bu çalışma E.Ü. Lisansüstü Eğitim ve Öğretim Yönetmeliği ile E.Ü. Fen Bilimleri Enstitüsü Eğitim ve Öğretim Yönergesinin ilgili hükümleri uyarınca tarafımızdan değerlendirilerek savunmaya değer bulunmuş ve 23.09.2016 tarihinde yapılan tez savunma sınavında aday oybirliği ile başarılı bulunmuştur.

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23/09/2016

Rao Muhammad Asad

ÖZET

RÜZGAR TÜRBİNİ SİSTEMLERİNİN GÖZETLEYİCİ TEMELLİ KONTROLÜ

ASAD, Rao Muhammad

Yüksek Lisans Tezi, Elektrik-Elektronik Mühendisliği Anabilim Dalı

Tez Danışmanı: Prof Dr. Aydoğan SAVRAN

Eylül 2016, 59 sayfa

Dünyanın enerji talebindeki artışlar, bilim adamlarının, mühendislerin ve araştırmacıların, temiz ve çevre dostu olan yenilenebilir kaynaklardan enerji çıkartma konusunda çalışmalarını yoğunlaştırmalarını sağlamıştır. Yenilenebilir enerji kaynakları arasında rüzgar enerjisi, en çabuk büyüyen ve sosyal olarak faydalı ve ekonomik olarak rekabet edilebilir bir kaynaktır. Rüzgar sürekli olarak değiştiği ve düşük seviyede kestirilebilir olduğu için bir takım kontrol düzenekleri gereklidir. Bu tez çalışmasında, küçük ölçekli bir rüzgar türbini (SSWT) modelleme, modern bir durum uzay kontrol şeması ve simülasyon yapılmıştır. Sistem performansını geliştirmek amacıyla küçük ölçekli rüzgar türbini parametreleri, dinamiklerinin matematiksel bir modelini oluşturmak için kullanılmıştır. Jeneratörün hızını ve kanat açısını kontrol etmek için sabit hızlı değişken kanat açısı konfigurasyonu kullanılarak, kontrol hedefleri ulaşılmıştır. Bilindik kontrol sistemleri kullanılarak sistemin durum uzayı gösterimi türetilmiştir. Tam durum geri besleme oluşturmak için gözetleyici tabanlı bir kontrol sistemi tasarlanmıştır. Çıkış gücünü sınırlamak için sabit hız ve tork üretecek durum uzay kontrolcüsü tasarlanmıştır. Önerilen sistem, simulasyonlarla test edilmiştir.

Anahtar Kelimeler: Küçük ölçekli rüzgar türbinleri, Tam durum geri besleme kontrol sistemi, Durum uzayı gözletleyici

ABSTRACT

OBSERVER BASED CONTROL OF WIND TURBINE

ASAD, Rao Muhammad

M.Sc. in Electrical and Electronics Engineering

Supervisor: Prof. Dr. Aydoğan SAVRAN

September 2016, 59 pages

As the world's energy demands are on the rise, engineers, scientists, and researchers are working extensively in extracting energy from renewable resources which are clean and environmentally friendly. Among various other renewable energy resources, wind energy is the fastest-growing energy source in the world which is a clean fuel source, socially beneficial and economically competitive. As the wind is constantly changing and only to a certain extent predictable, some form of control scheme is required. In this thesis, the study is carried on the modeling, the design of the modern state-space controller and the simulation of a small scale wind turbine (SSWT). The small scale wind turbine parameters are used to develop a mathematical model of its dynamics with the objective of enhancing the system performance. Control objectives are achieved by using the fixed speed variable pitch configuration of the wind turbine for controlling the pitch and the speed of the generator. Applying the control system scheme, a state-space representation of the model is derived. An observer based control system is designed to construct the full state feedback. The state-space controller is designed to maintain a constant speed and torque for limiting the output power. Simulation is used to validate the proposed system.

Keywords: Small scale wind turbines, full state feedback control system, State-space observers.

ACKNOWLEDGEMENTS

First and foremost I would like to give my appreciation to my supervisor, Prof. Dr. Aydoğan SAVRAN for his guidance, kind support, encouragement, valuable discussions and great patience throughout the course of this research, without whom this work would not have been possible

I would like to show my gratitude to my colleague and also my friend Araş. Gör. Hazin İNCİ for his guidance, advice and criticism throughout this work.

I thank for the financial support provided by the Yurtdışı Türkler ve Akraba Topluluklar Başkanlığı (YTB), which made my studies in Turkey possible. I would like also to show my appreciation to the people of Turkey, and from other countries that I met here, who have been welcoming and supportive throughout this experience.

I express my appreciation and gratitude to my parents and to Sandra Higareda for their constant support and motivation throughout my work. Without them I couldn‟t feel the necessary energy to be productive.

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
AC	Alternating Current
DC	Direct Current
FS-FP	Fixed Speed-Fixed Pitch
FS-VP	Fixed Speed-Variable Pitch
GW	Gigawatt
HAWT	Horizontal Axis Wind Turbine
KW	Kilowatt
LQR	Linear Quadratic Regulator
MATLAB	Matrix Laboratory
MIT	Massachusetts Institute of Technology
MW	Megawatt
SSWT	Small Scale Wind Turbine
TW	Terawatt
TWEA	Turkish Wind Energy Association
VAWT	Vertical Axis Wind Turbine
VS-FP	Variable Speed-Fixed Pitch
VS-VP	Variable Speed-Variable Pitch
WECS	Wind Energy Conversion Systems
WWEA	World Wind Energy Association

1 INTRODUCTION

In today's society energy is a vital element that assure quality of life, as well is the main base of production, development and all the other elements of the world's economy, industrialization and almost of every sphere for individuals and nations. Since history humans have consumed most of the non-renewable sources of energy, and in modern times that is translated into the oil industry and consumption that defines our present situation. The fossil fuel energy consumption of Turkey and Pakistan particularly and the world in general has been increasing since prior decades. See figure 1.1. Nevertheless, as such energy resources are limited and therefore with a possibility for exhaustion, and furthermore have constituted as well a source for contamination and global warming, the demand for cleaner and unlimited energy sources have increased as an alternative approach. As asserted by Hossain (2015):

> "The world energy system, which is predominantly hydrocarbon based must now undergo a transition to make way for a renewable energy based system. The planetary environmental concerns, energy access and energy security issues, the geopolitics of oil and resulting conflicts in many parts of the world, all these aspects point towards the urgent need for this transition or Energiewende as it is called".

Energiewende, as the author stated, is a phrase in German that represents the conceptualization for this transition into using renewable energy. The logical points to change to using these energies and to expand the preservation of energy, according to Morris and Pehnt (2012), are:

- Fighting climate change
- Reducing energy imports
- Stimulating technology innovation and the green economy
- Reducing and eliminating the risks of nuclear power
- Energy security, and
- Promote strong regional and community economies

Figure 1.1 Fossil fuel energy consumption (% of total) in Turkey, Pakistan and the World

Moreover, non-renewable resources are consumed in a faster time lapse than the natural processes that produce them. It is estimated that the petroleum will be consumed in 44 years, uranium in 50 years and natural gas in 64 years. It is calculated that the non-renewable resources will be completely depleted after 185 years. To the contrary, renewable energy does not exhaust the finite and limited resources of the planet. Additionally, it is simply restored, faster and can be generated when demanded (Evren, 2012). Some of the most important renewable energy sources used are bioenergy, solar, geothermal, wind and hydropower energy.

Both the energies derived from the sun and the wind have huge potential for globally fulfilling our energy requirements. If we would install standard wind turbines in the land of 80 meters towers on thirteen percent of the earth, it will be approximately 72 terawatt (TW) of commercialized wind-power. That represents about 5 times the power consumption in all varieties in the entire world that at the present time has an average of about 15 TW. Wind energy is the faster expanding renewable energy used globally, with a potential that has increased three times in recent years, As it was asserted by the Institute of Electrical and Electronics Engineers in 2011. Therefore, it is realized the great relevance to develop the transition for the use and implementation of renewable energy in every country and the world and specifically the opportunity that represents wind harnessing as the best alternative to hydrocarbon consumption.

Wind Energy

The horizontal axis wind turbine, generally the most frequently identifiable icon of the renewable energy industry, has evolved from its ancient beginning in grain mills and water pumps into the massive large scale wind farms of today. The initial wind turbines generally had minimum four blades, and in some cases they have additional blades. The original MW turbine, constructed in USA in 1942, consisted of just a pair of large blades, nowadays standard utility-scales models usually consists of a trio of blades that generate capacities with a peak of 10 MW (Ferry and Monoian, 2012). The technology that is used in wind energy consists of transforming the energy of the motion of the wind into applicable mechanical power. This kinetic airflow energy supplies the force that causes the rotation movement on the blades of the wind turbine that, through a propeller shaft, supply the mechanical energy to power the generator in the wind turbine. (Freris and Infield, 2008).

The contemporary standard size of grid-connected wind turbines is generally of 1.16 megawatts, nevertheless actual ventures utilize wind turbines that consists of 2 and 3 megawatts. When wind turbines are jointly placed, it is known as a wind farm. These farms consist of the turbines, the buildings and the grid connection point. Wind power technologies are developed in a variation of sizes and designs and predominantly are classified by alignment: horizontal axis or vertical axis wind turbines (HAWT and VAWT), and by location: onshore or offshore. The power generation of the wind turbines is set by the capacity of the turbine (in kilowatts or megawatts), the wind speed, the elevation of the turbine and the diameter of the rotors (Gsanger et al., 2012).

A prominent and substantial international progress in the wind power industry, especially in the recent times, has collocated it in a very important place in the energy industrial sector. What makes also wind energy in such a high demand is that it represents the option that has less related costs among all the renewable energy options.

It is important to mention that recent technological progress and innovative designs has contributed in the increase of large-scale onshore and offshore programs (with higher development on onshore projects). Currently, wind energy projects contribute almost to the 4% of net electricity generation, with 393-GW of installed generation capacity and installations located in 100 countries. (Source: WWEA, as seen in Hossain, 2015).

According to the publication: “Global Trends in Renewable Energy Investment 2016”, by the Frankfurt School of Finance and Management and the United Nations Environment Programme, the year 2015 set a record for international investment in renewable energy, the money dedicated to renewable energy, without including big water-power projects, increased 5% to $278.9 billion, surpassing that of 2011. It is also astounding that the total generating capacity in wind and solar photovoltaics was about 118GW. Having in 2015 a total international investment in renewable energy of $265.8 billion. See table 1.1 for a list of countries with over 4 GW of wind total installed capacity. However, as Camacho et al., 2010 stated:

“Although wind energy is a clean and renewable source of electric power, many challenges must be considered. For instance, wind turbines are complex machines, with large flexible structures working under turbulent and unpredictable environmental conditions. As well, the turbines are connected to a constantly varying electrical grid with changing voltages, frequency, power flow, and other similar elements. Wind turbines have to adapt to those variables, therefore, efficiency and reliability depend heavily on the control strategy applied. As wind energy penetration in the grid increases, additional challenges are presented, for example, response to grid disturbances, active power control and frequency regulation, reactive power control and voltage regulation, restoration of grid services after power outages, wind prediction, etc.”

Table 1.1 Countries with over 4 GW of total installed capacity* by the end of June 2015

Position	**Country**	**Total capacity June 2015 (MW)**	**Added capacity H1 2015 (MW)**	**Total capacity end 2014 (MW)**	**Added capacity H1 2014 (MW)**	**Total capacity end 2013 (MW)**	**Total capacity June 2013 (MW**
1	**China**	124,710	10,101	114,763	7,175	91,413	80,827
2	**USA**	67,870	1,994	65,754	835	61,108	59,884
3	**Germany**	42,367	1,991	40,468	1,830	34,658	32,458
4	**India**	23,762	1,297	22,465	1,112	20,150	19,564
5	**Spain**	22,987	0	22,987	0	22,959	22,918
6	**UK**	13,313	872	12,440	649	10,531	9,776
7	**Canada**	10,204	510	9,694	723	7,698	6,578
8	**France**	9,819	523	9,296	338	8,254	7,697
9	**Italy**	8,787	124	8,663	30	8,551	8,417
10	**Brazil**	6,800	838	5,962	1,301	3,399	2,788
11	**Sweden**	5,582	157	5,425	354	4,470	4,271
12	**Denmark**	4,959	76	4,883	83	4,772	4,578
13	**Portugal**	4,953	0	4,953	105	4,724	5,547
14	**Turkey**	4,193	431	3,763	466	2,958	2,619
15	**Poland**	4,117	283	3,834	337	3,390	2,798
16	**Australia**	4,006	200	3,806	699	3,049	3,059
	Rest of the World	34,600	2,400	32,219	1576	26,493	23,802
	Total	**392,927**	**21,678**	**371,374**	**17,613**	**318,577**	**296,581**

* Includes all installed wind capacity, connected and not-connected to the grid.

Previously, the renewable energy industry, including the wind energy, was generally categorized as a luxury that could be afforded just by the most developed countries, usually USA and Europe. But 2015, this idea changed, as the investment in renewable energy (without considering water-power projects) was higher in developing countries. Including, Turkey with an investment of $1 billion barrier in 2015 and Pakistan with more than $500 million.

Wind in numbers

1,100,000	Jobs created by the global wind industry at the end of 2015
63.5	The record number of GW of wind power installed in 2015
637	In 2015, wind power avoided over 637 million tonnes of CO2 emissions globally.
8,000	The number of parts a wind turbine has.
48.6	China’s share of global installations in 2015.
314,000	The number of wind turbines spinning in the world at the end of 2015.
48,500	The number of wind turbines in the US at the end of 2015.
314,000	The number of wind turbines spinning in the world at the end of 2015.
48,500	The number of wind turbines in the US at the end of 2015.
11.4	In an average wind energy year, the EU’s current wind power capacity covers 11.4% of the EU’s electricity consumption.
17 - 39	Wind power farms generate between 17 and 39 times as much power as they consume, compared to 16 times for nuclear plants and 11 times for coal plants.
109	Amount in $billion invested in wind power globally, making it one of the fastest growing industrial segments in the world.

Overview of Turkey's Modern Wind Energy Approach

As of end of August 2015, Turkey has 71,858 MW electricity generations installed capacity. From which 4053 MW of total installed capacity from facilities utilizing wind energy resources. With a minimum technical renewable energy potential of 48,000 MW of wind energy capacity and a target to 2023 of 20,000 MW capacity of wind power plants (Kaplan, 2015). The main regions in Turkey can be observed on figure 1.2.

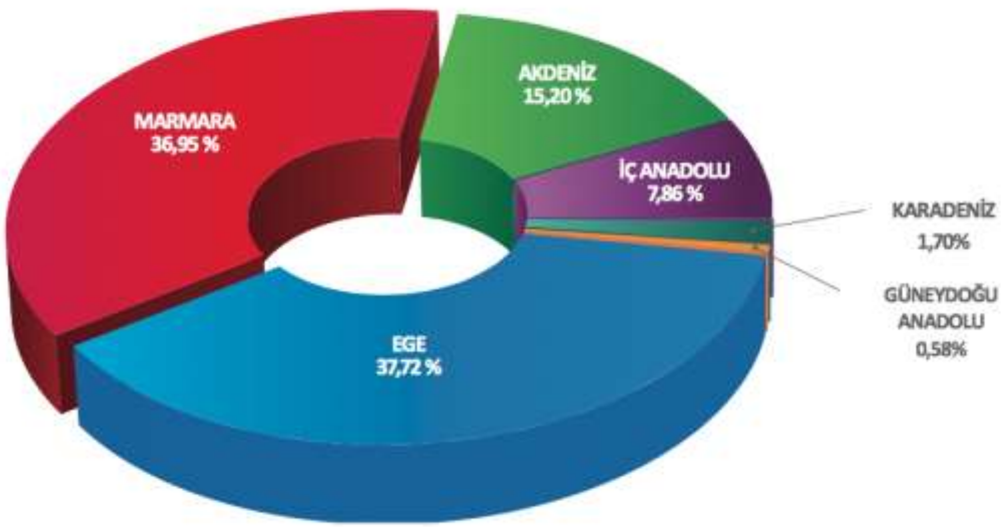

Figure 1.2 Regions according to Operational WPPs

With 113 wind power plants under operation, according to TWEA, and 11 GW stock of the current Project, in the future Turkey will have an important role in investment opportunities and wind energy production and development.

Overview of Pakistan's Modern Wind Energy Approach

Pakistan counts with a very good wind potential in southern and western parts of the country, which is estimate to harness from 20,000 to 30,000 MW of wind power. The government provides considerable appealing renewable energy incentives through its Renewable Energy Policy. It has a total realizable wind energy potential of 70,000 – 80,000 MW, a total installed wind energy of 6 MW, total wind energy projects in pipeline of 556 MW and a target of 9520 MW of renewable energy by 2030. Therefore, Pakistan has a substantial role in the Asian industrial development of wind energy. According to the Alternative Energy Development Board (AEDB), Pakistan counts with 29 wind projects (source: http://www.aedb.org/index.php/ae-technologies/wind-power/wind-current-status). For a complete detailed analysis of the wind industry in Pakistan: “Scaling up Wind Power Deployment in Pakistan” prepared by Sohaib Malik for the WWEA in 2014.

Thesis Structure

This thesis is divided into 6 chapters including this Introduction chapter.

Chapter 2 presents the preliminary concepts of wind turbine fundamentals. The necessary formulation for calculating various parameters or wind turbine are explained and control strategies for controlling the wind turbine are explained.

Chapter 3 is dedicated to the mathematical modeling of the small scale wind turbine and a state space representation of the system is achieved

Chapter 4 discusses the design of a closed loop feedback controller. A state feedback controller with observer is designed for the system.

Chapter 5 presents the simulation of the designed observer based control system in the Matlab/Simulink environment

Chapter 6 provides conclusion and recommendations for future work.

2 WIND TURBINE FUNDAMENTALS

In this chapter background information of the wind turbines is given and the necessary requirements for understanding the phenomenon of how power is extracted from the wind. Initially, the two most commonly used types of wind turbines are explained. Following after that are the challenges pertaining with wind turbines as a source of power are described. Furthermore, the general parameters which affects the power extracted from the wind energy is observed and explained in order to have an understanding about the wind turbine model parameters which are required to be controlled. Aimed at the control of a wind turbine, some different control schemes and strategies are explained.

2.1 The Wind Turbines

Wind Turbines are mechanical devices which are designed for the transformation of the kinetic energy stored in the wind into beneficial mechanical energy. There had been several designs of wind turbines during the course of time to harvest energy from the wind. Most of them consists of a rotor which rotates by the lift and drag forces experienced from the wind.

2.2 Types of Wind Turbines

According Bianchi et al., (2007), depending to the position of rotor axis, the wind turbines can be categorized into vertical axis (VAWT) and horizontal axis (HAWT) wind turbines. A vertical axis wind turbine and a horizontal axis wind turbine are shown in the figure 2.1

2.2.1 Vertical Axis Wind Turbines (VAWT)

Having various configurations of vertical axis wind turbines the couple of most unique categories are known to be Darrieus wind turbine and Savonius wind turbine. The construction of the Darrieus can also be known as eggbeater arrangement due to the 2 or having more number of blades which are linked at the top of the axis and the bottom of the axis. The construction of the Savonius contains two or a number of airfoils which are linked to the axis. The Darrieus utilizes the lift force from the wind to propel the axis and the Savonius utilizes drag force in order to propel the axis. The Darrieus form can achieve a rotational velocity much higher than the approaching winds, on the contrary the Savonius type can only approach rotational velocities lesser than that of the wind speed. The Darrieus type is comparatively much similar to the horizontal axis wind turbines as both uses lift force to rotate the blades. Some of the vertical axis wind turbines are considered to have pitch control mechanism for optimal performance.

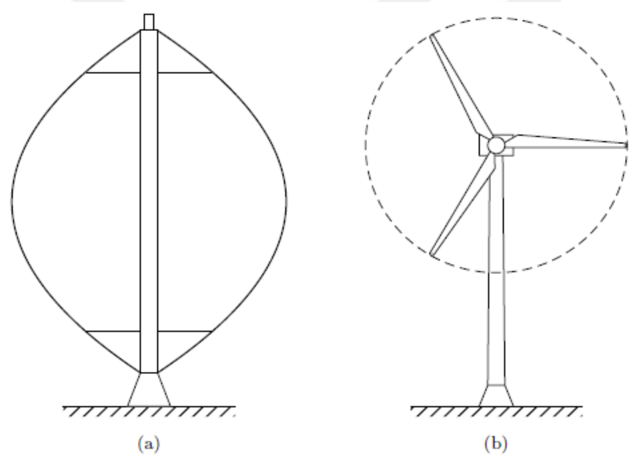

Figure 2.1 (a) Vertical Axis and (b) Horizontal axis wind turbines

In comparison to the turbines with horizontal axis arrangement, the vertical axis wind turbines have few benefits and advantages. Due to its omni-directional blade design, they do not require to rotate if there is a change in wind direction. The gearbox and generators can be positioned on the ground since its axis is positioned vertically. Furthermore, the Darrieus wind turbines generate less noise and allow the passage of wind without slowing it down in comparison with the turbines with horizontal axis arrangement and therefore the turbines with vertical axis arrangement can be closely placed together.

The drawbacks of the turbines with vertical axis arrangement are that they require big guy-wires for holding the framework firmly together in place and it frequently requires a starting torque from the motor. When the rotor rotates about the axis, at two points of the cycle it has maximum torque which generates a pulsing power cycle which can result in weakening the turbine at certain rotational speeds and damaging or even breaking the blades of the turbine.

2.2.2 Horizontal Axis Wind Turbines (HAWT)

The horizontal axis wind turbines can be of many types but majority of them consists of the similar primitive setup and structure which utilizes the lift force to rotate the two or a number of blades coupled with the horizontally positioned axis. Its axis is situated inside the tower which is quite in height above the ground level, having higher average wind speeds at greater heights allows a greater amount of energy to be harvested from the wind, correlated with the speeds of wind at the ground level. These turbines vary in correspondence to the different variety and disposition of the blades and the parameters which are required to be under control and restrained for achieving the desired power output. The horizontal axis wind turbines accomplish more power and are much more efficient than the vertical axis wind turbines, therefore they are more widely used. The turbines needs the direction of the wind vertical to the turbine blades' plane of rotation for that purpose the yaw mechanism can be designed for turning the tower and the blades.

Furthermore, horizontal axis wind turbines consists of aerodynamic, mechanical and electrical subsystems as shown in the Figure 2.2. Aerodynamic subsystems consist of blades and hubs. Drive trains (low speed shafts, high speed shafts, gearboxes) and brakes form mechanical subsystems. Some wind turbines do not have gearboxes; so low speed shafts are directly connected to high speed shafts. Electrical subsystems consist of generators and power converters. Generators convert mechanical power into electrical power. Towers carry wind turbines. There are nacelle mechanisms at the top of the towers. Nacelle includes the gearbox, the drive train, the generator and the controller. A yaw mechanism is a gear mechanism and it can turn the wind turbine depending on the wind direction. Thus, mechanical power extraction from the wind can be increased.

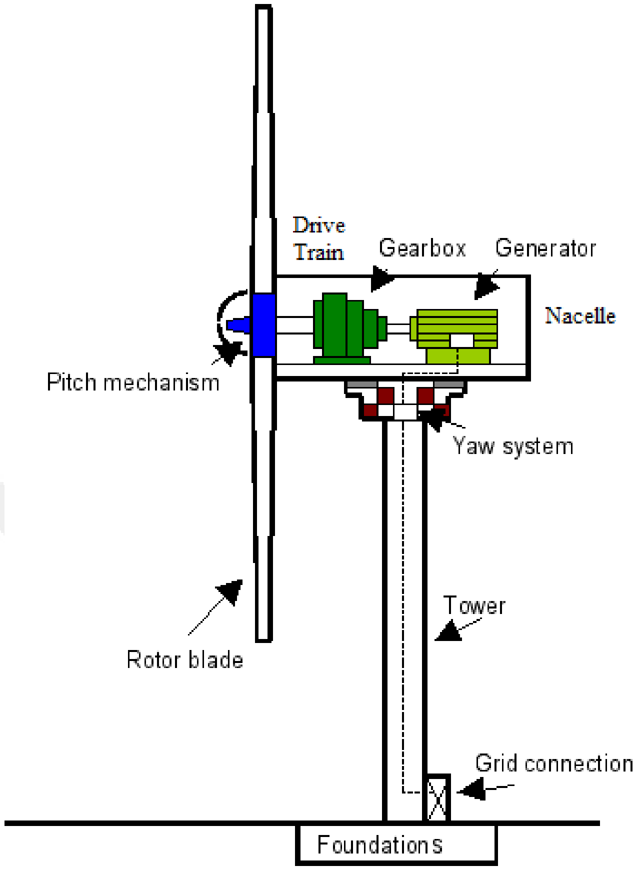

Figure 2.2 Small Scale Wind Turbine

For controlling the wind turbine, the above mentioned both types of wind turbines can be implemented with control schemes and smart control systems by which the blade pitch can be altered and controlled and also the load on the generator can be controlled. The control scheme explained on this thesis will be centered on the turbines with horizontal axis arrangement.

2.3 Wind Turbine Development Challenges

The challenges pertaining with the use of wind turbines arises in the generator electrical output along with the mechanical robustness and strength of the turbine rotor and the generator design and construction. Consequently, under which wind speeds the turbine can operate efficiently and effectively in a safe manner.

The power stored in the wind can only be harvested within certain range of speed of the wind, due to the characteristics and attributes of wind energy. This is because of the wind turbines optimization and design to a greater range of wind speeds is proving to be inefficient and cost ineffective because of the high and better quality materials required to manufacture and design the tower and the rotor blades of the wind turbine. It is essential to overcome these strong wind forces acting on the wind turbine blades at such high speeds. An ideal power curve is illustrated in the fig 2.3. Considering the area I, the power harvested is proportionate with the actual power contained by the wind with a factor of C_{pmax}, which is the maximum C_p for the wind turbine. The power contained inside the wind is of smaller amount compared with the power rating of the wind turbine, therefore, it is configured to achieve maximal energy transformation.

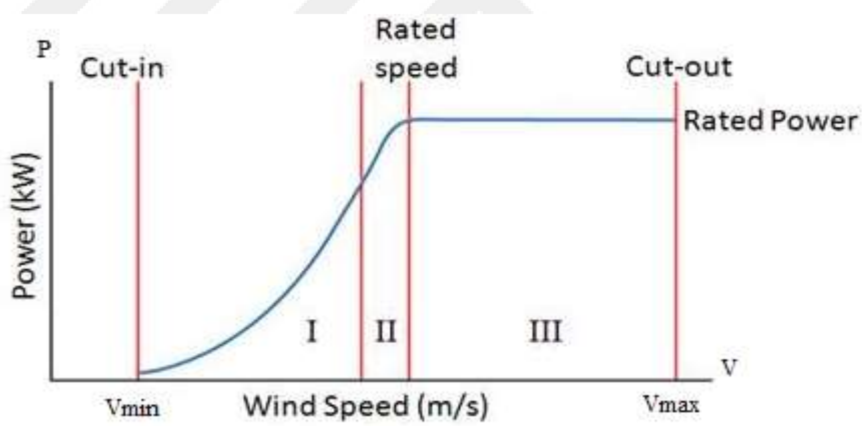

Figure 2.3 Ideal power curve. The three regions show different configurations of control required

As the speed of the wind rises, the wind turbine first goes through transitional area II beforehand advancing into the area III, on this area the harvested energy is deliberately bounded with the rated power of the wind turbine so that the wind turbine runs in its designated region of its operation which is also the wind turbine's maximum rated power which it designed to handle. Operating the wind turbine above its rated power at high wind speeds could damage the wind turbine or burn the windings of the generator and even cause complete failure of the structure.

The control strategies required to achieve the ideal power curve is mentioned in unit 2.4. Subsequently, maintaining the curve characteristics according to figure 2.3

for optimal performance of the system, implementing different control strategies for different regions can be quite useful.

The other concern is the electrical coupling of the wind turbine to the load which is in general case is the national electric grid. With numerous factors to consider, the main challenge arises in synchronizing the phase of the electricity that the wind turbine generated to that of the electric grid. Some methods are used to solve this problem. One method is to transform the alternating current power from the generator to direct current through power electronics and subsequently in reverse, which then modifies and adjusts the phase and frequency. This allows the flexibility to control and vary the speed of the turbine rotor for maximum power extraction from the wind and to achieve optimal system performance. Moreover, directly coupling the generator with the grid evades the addition of complex power electronic convertors. Merging these two methods creates another type of method in which the generator stator is specifically coupled with the grid and the rotor is coupled by means of a frequency convertor which specifically deals with a fragment of the power which a full alternating current to direct current, and DC to AC system will accomplish.

In an environment of constantly changing wind conditions, numerous challenges and demands comes forward in selecting the most effective control scheme for different generator types. The choice for selecting an appropriate generator type is based on the output desired being the size of the wind turbine and the total system cost. For the wind turbines which are larger in size, the variable speed is considered as a result of enhanced efficiency of energy extraction and the adjustability while coupling it with the grid.

2.4 Wind Turbine Essentials

The parameters and the elements that affect the output power of the wind turbines along with the necessary formulation for maximization of wind turbine output is expressed in the following section (Pramod, 2011).

2.4.1 Wind Energy Extraction

A wind turbine is designed to harvest the wind’s energy, which it’s achieved with help of allowing the wind to rotate the wind turbine rotor as the wind goes through it. The "energy in" is the energy from its motion derived from wind's velocity and the density of the air that circulate into the section pulled by the blades of the turbine. To transform all of the kinetic energy contained in the wind into mechanical energy is not achievable. Some energy has to stay in the air with the turbine. The "energy out" is the energy is transformed into mechanical energy by the blades of the turbine that is subsequently transformed in electricity. The amount of energy contained in the wind can be determined with the equation 2.1

$$E_k = \frac{1}{2} \cdot m \cdot V^2 \quad (2.1)$$

$$m = \rho \cdot A \cdot V \quad (2.2)$$

$$P_W = \frac{1}{2} \cdot \rho \cdot A \cdot V^3 \quad (2.3)$$

Where:

E_k Is the wind kinetic energy (J)

P_W Wind power (W)

ρ Air density (kg/m^3)

V Free wind speed (m/s)

m Mass of the wind (kg)

A Swept rotor area (m^2)

2.4.2 Wind Turbine Power Coefficient

The C_p is used to calculate the efficiency of a wind turbine. The power coefficient is the proportion resulted between the power extracted from the wind and the real power contained in the wind.

$$C_p = \frac{P_r}{P_W} \tag{2.4}$$

Where:

C_p Power coefficient

P_r Extracted power from the wind (W)

The P_r relies on the rotor ‘s potency and the wind speed experienced at the disc. The wind speed at the rotor of the turbine can be determined with the wind speed which is ahead the rotors and an axial flow interference factor. The factor ‘a’ explains the reduction in wind speed which is influencing on the rotor blades of the turbine when it is in operation. As the force acting in the rotor’s turbine is expressed as the mass flux through the wind turbine multiplied by the wind speed at the turbine rotor and the axial flow interference factor a. (Bianchi et al., 2007).

$$P_r = F_D \, . V_D \tag{2.5}$$

$$V_D = V \, . (1 - a \,) \tag{2.6}$$

$$F_D = 2 \, . \rho \, . A \, . V^2 \, . a \, . \; (1 - a) \tag{2.7}$$

$$P_r = 2 \, . \rho \, . A \, . V^3 . a \, . (\, 1 - a)^2 \tag{2.8}$$

Where:

F_D Is the wind force acting on the blades (N)

V_D Wind speed acting on the actuator disc (m/s)

a Axial flow interference factor

The ‘a’ differs from one turbine to another. It is a factor that has considerable significance in maximizing the output power of the wind turbine.

Now the power coefficient of the wind turbine can be determined from the equation 2.8 and 2.3 and the formulated power coefficient is shown in the equation 2.9. In order to maximize the power coefficient C_p , the value of a must be known. According to the theoretical findings the limit is found at $a = \frac{1}{3}$, where the C_p is calculated to be $C_p = \frac{16}{27} = 0.593 \; or \; 53.9\%$. This theoretical limit is known as The Betz Limit.

$$C_p = \frac{P_r}{P_W} = \frac{2\,.\rho\,.A\,.V^3.a\,.(\,1-a)^2}{\frac{1}{2}.\rho\,.A\,.V^3} \tag{2.9}$$

$$C_p = 4\,.\,a\,.\,\,(\,1-a)^2 \tag{2.10}$$

2.4.3 Tip Speed-Ratio and Pitch

The tip speed-ratio is the ratio of the speed of the rotor tip to the open flow wind speed. If a rotor turns too slowly, a large amount of wind is passed through undisturbed which results in less power capture from the wind. On the contrary, if the rotor turns too fast, the wind experiences a sizeable flat disc, that as a result produces a great quantity of drag. The Tip Speed-Ratio rotor, also called TSR is controlled upon on the blade airfoil outline that is utilized, how many blades and also the type of wind turbine. Generally, a wind turbine that has three blades functions with a TSR of between 6 and 8, with 7 being the most common value. The tip speed ratio λ is given in the following equation 2.11

$$\lambda = \frac{\Omega_r\,.R}{V} \tag{2.11}$$

Where:

λ Is the tip speed ratio

Ω_r Speed of the blades (rad/s)

R Radius of the blade (m)

V Speed of the wind (m/s)

The blade pitch is included on the control parameters that can be varied as to increase or decrease the speed of the wind turbine. The angle of attack is mentioned in the equation 2.12. The inclination between the relative wind speed experienced by the rotational direction of the blades ϕ and the blades varies taking the wind speed and the blades rotational speed. A high value of λ results in a small ϕ, while in contrast a low value of λ results in a larger ϕ.

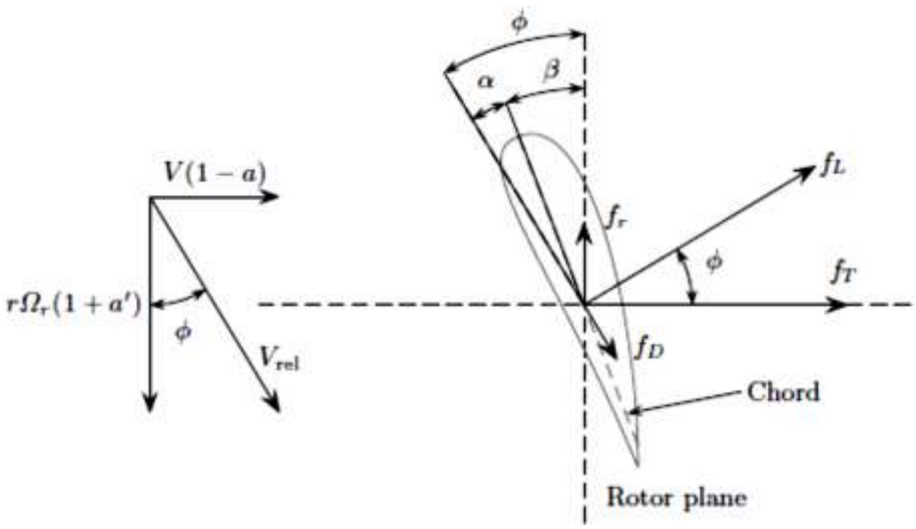

Figure 2.4 Forces on a blade element

$$\alpha = \phi - \beta \tag{2.12}$$

Where:

α Is the angle of attack (˚)

ϕ Angle between relative wind and the blades rotational direction

β Blade pitch angle (˚)

F_r Blade rotational force (N)

F_T Blade thrust force (N)

F_L Blade lift force (N)

F_D Blade drag force (N)

V Speed and direction of the wind (m/s)

V_{rel} Speed and direction of the relative wind affecting the blade (m/s)

The forces acting on the blade element F_r, F_T, F_L, F_D experience an effect by the direction of the wind. Since the relative wind direction varies in correlation with the speed of the wind and the speed of the rotation. Thus, the blade requires to pitch into the relative wind to capture the maximal torque from the wind. The rotational force F_r can be regulated by the pitching of the blades of the turbine. By apply control on the pitch of the blades, the rotational force F_r on the wind turbine can be altered or cancelled out. There are two ways by which it can be done, first is pitching to feather or feathering, so we have to increase the angle of pitch by moving the blades parallel to the airflow. Second is pitch to stall or stalling, which means that the stall stops the elevating force of the rotor blade from operating on the rotor (Martinez, 2007).

2.4.4 Wind Power

To maintain a constant output power, C_p value is minimized at high speeds experienced by the wind turbine. From the equation 2.4, can be rewritten to equation 2.13. The blades' swept area is determined from equation 2.15 as follows

$$P_r = P_w \, . C_p(\lambda, \beta) \tag{2.13}$$

$$P_r = \frac{1}{2} \, . \rho \, . A \, . V^3 . C_p \tag{2.14}$$

$$A = \pi \, . \, R^2 \tag{2.15}$$

$$P_r = \frac{1}{2} \, . \rho \, . \, \pi \, . \, R^2 \, . V^3 . C_p(\lambda, \beta) \tag{2.16}$$

Where:

P_r Is the power extracted from the wind by the rotor (W)

P_w Power in the wind (W)

C_p Power coefficient

ρ Air density kg/m^3

A Area of the swept by the blades m^2

V Wind speed (m/s)

R Blades radius (m)

2.4.5 Torque

The torque from the wind witnessed by the wind turbine is calculated by the power drawn from the wind and the rotational velocity of the rotor blades. The torque exerted in the rotor is the torque contained in the wind multiplied by the torque coefficient of the wind turbine C_Q. The determination of the torque coefficient C_Q is done from measurements or from the power coefficient C_p. The T_r as a function of C_Q is given in the following equation 2.20 derived from eq.2.11. The relationship between C_p and C_Q in shown in figure 2.7.

$$T_r = \frac{P_r}{\Omega_r} \tag{2.17}$$

$$T_r = \frac{1}{2} . \rho . \pi . R^2 . V^3 . C_p . \frac{1}{\Omega_r} \tag{2.18}$$

$$T_r = \frac{1}{2} . \rho . \pi . R^3 . V^2 . C_p . \frac{1}{\lambda} \tag{2.19}$$

$$T_r = \frac{1}{2} . \rho . \pi . R^3 . V^2 . C_Q(\lambda, \beta) \tag{2.20}$$

$$C_Q = \frac{C_p}{\lambda} \tag{2.21}$$

Where:

T_r Is the rotor torque (Nm)

Ω_r Blades angular velocity (rad/s)

C_Q Torque coefficient

The power coefficient C_p is a function of α, since α is a function of λ and β, $C_p$is considered as a function of λ and β. This parameter λ is of much significance and together with β in the case of variable-pitch rotors, defines the operating condition of a wind turbine. In the figure 2.5 the power coefficient C_p graph is plotted with respect to λ and β. It is displayed in a determined range, a few or without energy can be harvested from the wind i.e. from the graph in the time that the tip speed ratio is surpassing 5 and the pitch angle surpassing 10˚.

It can be observed that C_{pmax} approximately about the tip speed ratio of 6.1 and at a pitch angle of 0˚. The tip speed ratios which are above 5 have the highest C_p values at $\beta = 0$ seen in the figure 2.5.

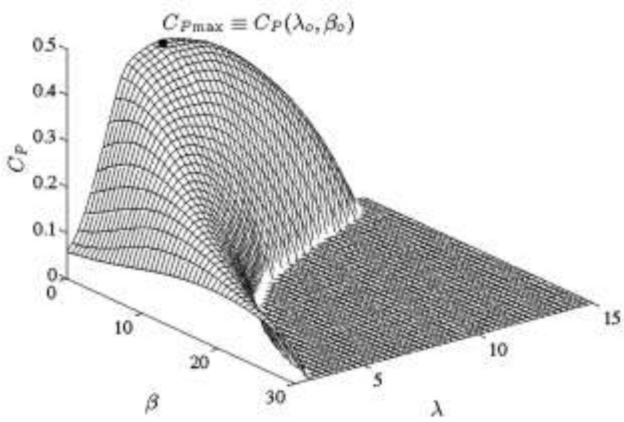

Figure 2.5 Typical changes C_p for the variable pitch wind turbine

The torque and the power coefficients are very important for control purposes. The figure 2.6 shows the variations in the values of C_Q and C_p with the tip speed ratio and the pitch angle deviation. In fixed pitched wind turbines, the values of C_Q and C_p

change only with λ, as $\beta = 0$. and its desirable to keep λ as close to λ_o, which is the optimal tip speed ratio. When the turbine is operational in region III, the turbines velocity should be held constant, thus λ diverges from λ_o, therefore the output power is maintained constant. Figure 2.7 describes typical coefficients of $C_Q(\lambda)$ and $C_p(\lambda)$ for the fixed pitch turbines.

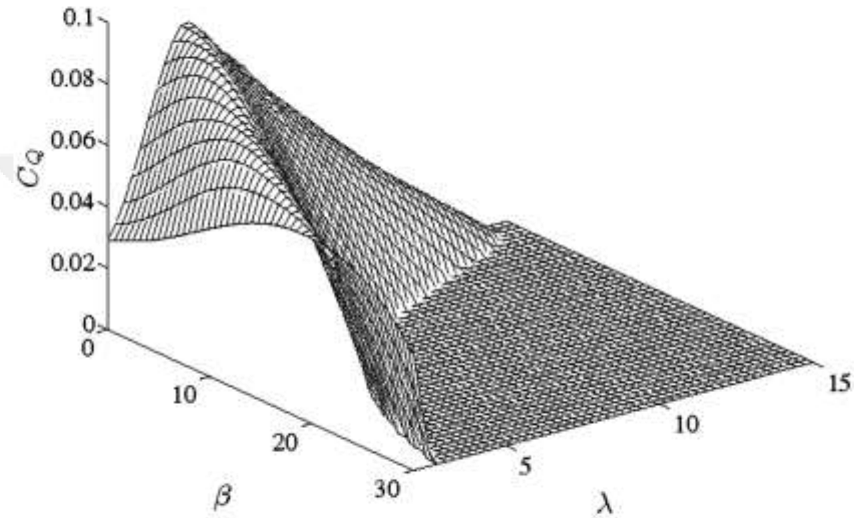

Figure 2.6 Typical changes of C_Q

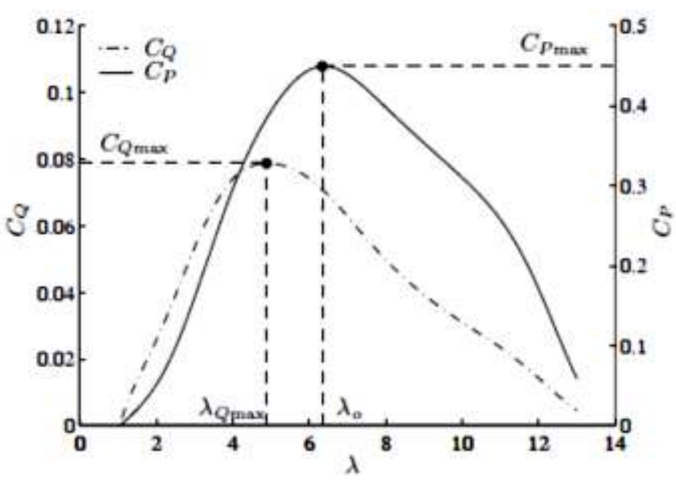

Figure 2.7 Typical changes of C_Q and C_p for the fixed pitch wind turbine

Therefore, fixed speed wind turbines will operate with maximum efficiency just for a unique wind speed, whereas variable-speed turbines can potentially work with maximum efficiency over a wide range of wind speeds at least up to rated power.

2.5 Wind Turbine Configurations

As mentioned in the literature above, by varying the speed of the rotor blades and the pitch angles of the blades the control of a wind turbine is made achievable. Generally, there are four different types of wind turbine configurations, each having its advantages as well as disadvantages. The description of the configurations are as follows.

2.5.1 Fixed Speed and Fixed Pitch (FS-FP)

The Fixed Speed and Fixed Pitch was a prominent configuration for the wind turbines for so many years but in the present times it is not commonly used in the commercializing wind turbines. In FS-FP the electrical output of the generator is directly attached to the power grid due of which the generator speed is locked to the power grid frequency due to which it is called fixed speed. When the maximum speed of wind exceeds a certain limit the turbine blades start to stall and consequently decelerate the wind turbine down preventing it from damage and sheer wind force affects. As the blades pitch angle is not controlled due to its fixed pitch mechanism the stall effect of the turbine is due to how the blades are designed. The advantage of the FS-FP turbines is that they are accessible to construct and have lower cost because of less equipment requirements for control actions. The disadvantage of this configuration is that these turbines deliver rather poor performance overall and the lack optimal conversion efficiency.

2.5.2 Fixed Speed – Variable Pitch (FS-VP)

FS-VP is commonly used in the middle-sized to large power wind turbines. As the wind turbine has a fixed speed the maximal power conversional change is achievable at a certain wind speed. Therefore, when the wind speeds are below the rated values it is not possible for conversion efficiency optimization. The FS-VP wind turbines are normally functioned to operate with a fixed pitch in the time they are running under the rate wind speeds. When the turbine is operating at wind speeds above the rated values, the power is conditioned and restricted by the control action of the blade pitch angle which provides a more optimal conversion efficiency as the wind speeds surpass the rated values.

2.5.3 Variable Speed – Fixed Pitch (VS-FP)

The Variable Speed – Fixed Pitch configuration it is currently acknowledged in the commercialization of wind turbines, particularly for the ones installed in the places with wind speeds that are low. The advantage of having the ability of controlling the speed of the turbine gives much optimal conversion efficiency especially at low wind speeds. The maximal conversion efficiency of the Variable Speed – Fixed Pitch setup is specified in the time the tip speed ratio λ is always equivalent to the optimal tip speed ratio λ_o. It can be analyzed from the equation 2.11 that the value of R is constant and V and Ω are variables. So to have λ equivalent to λ_o the value of Ω should be varied in a proportional form to the value of V. With the turbines variable speed configuration it cannot be connected in direct form to the power grid due to the discrepancy with the line frequency. Consequently, this requires additional hardware installations on the wind turbine for its suitable operation.

2.5.4 Variable Speed – Variable Pitch (VS-VP)

VS-VP are more common the commercial wind turbine market. In this type of configuration the turbine is normally set to operate with the variable speed and fixed pitch below the rated wind speeds and have variable pitch above the rated wind speeds. This allows the wind turbine for the maximum conversion efficiency and a wider range of operation but it requires complex control systems.

2.6 Maximum Power Point Tracking (MPPT) Control

The amount of power output from a WECS depends upon the accuracy with which the peak power points are tracked by the MPPT controller of the WECS control system irrespective of the type of generator used. The maximum power extraction algorithms researched so far can be classified into three main control methods, namely tip speed ratio (TSR) control, power signal feedback (PSF) control and the perturbation and observation (P&O) or hill-climb search (HCS) control. (Jogendra Singh, 2011)

2.6.1 Tip speed ratio (TSR) control

The TSR control method regulates the rotational speed of the generator in order to maintain the TSR to an optimum value at which power extracted is maximum. This method requires both the wind speed and the turbine speed to be measured or estimated in addition to requiring the knowledge of optimum TSR of the turbine in order for the system to be able extract maximum possible power. Fig. 2.9 shows the block diagram of a WECS with TSR control.

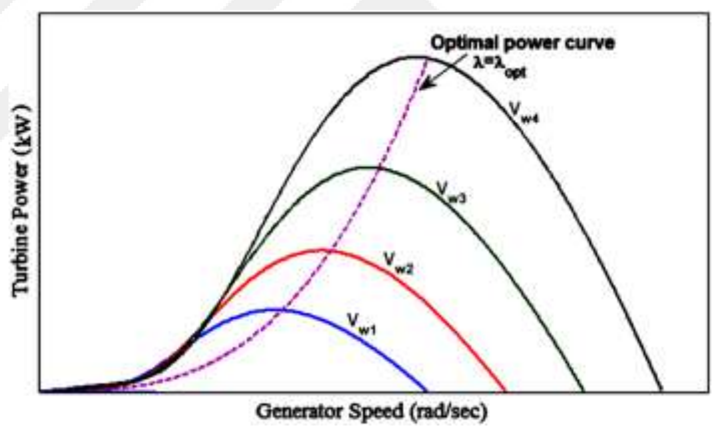

Figure 2.8 Characteristics of turbine power as a function of the rotor speed for a series of wind speeds

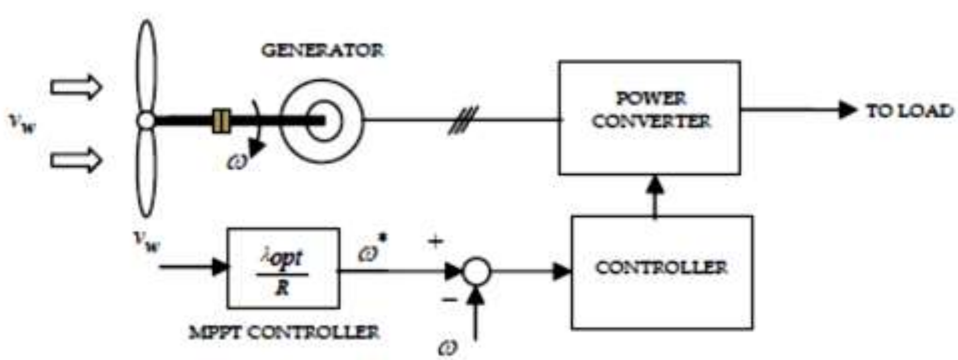

Figure 2.9 The block diagram of a WECS with TSR control

2.6.2 Power signal feedback (PSF) control

In PSF control, it is required to have the knowledge of the wind turbine's maximum power curve, and track this curve through its control mechanisms. The maximum power curves need to be obtained via simulations or off-line experiment on individual wind turbines. In this method, reference power is generated either using a recorded maximum power curve or using the mechanical power equation of the wind turbine where wind speed or the rotor speed is used as the input. Fig. 2.10 shows the block diagram of a WECS with PSF controller for maximum power extraction.

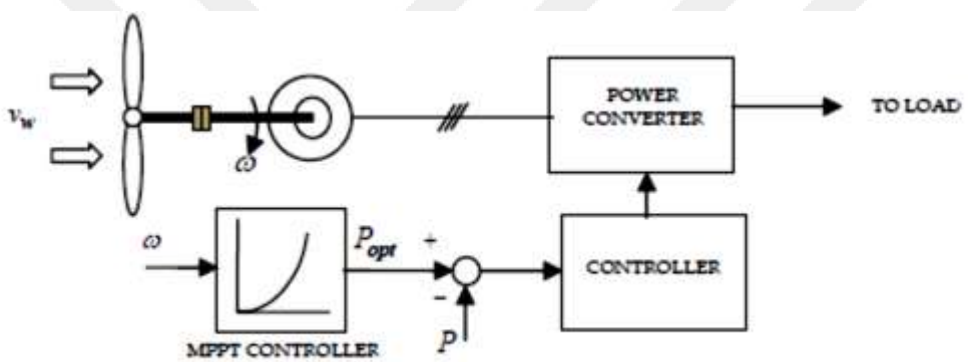

Figure 2.10 Power signal feedback control

2.6.3 Perturbation and Observation (P&O) control

The perturbation and observation (P&O) or HCS control algorithm continuously searches for the peak power of the wind turbine. It can overcome some of the common problems normally associated with the other two methods. The tracking algorithm, depending upon the location of the operating point and relation between the changes in power and speed, computes the desired optimum signal in order to drive the system to the point of maximum power. Fig. 2.11 shows the principle of HCS control and Fig. 2.12 shows a WECS with HCS controller for tracking maximum power points.

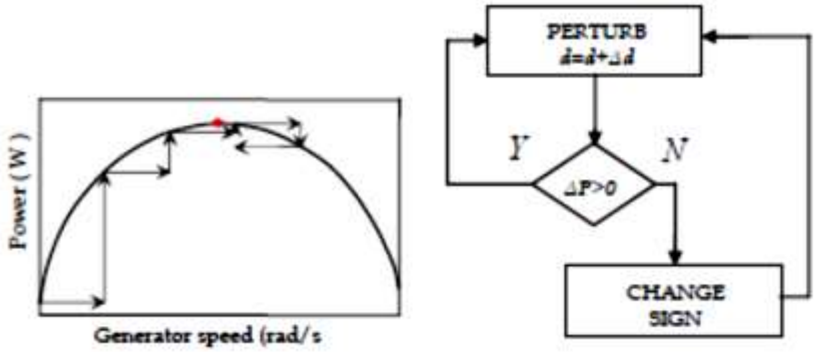

Figure 2.11 HCS Control Principle.

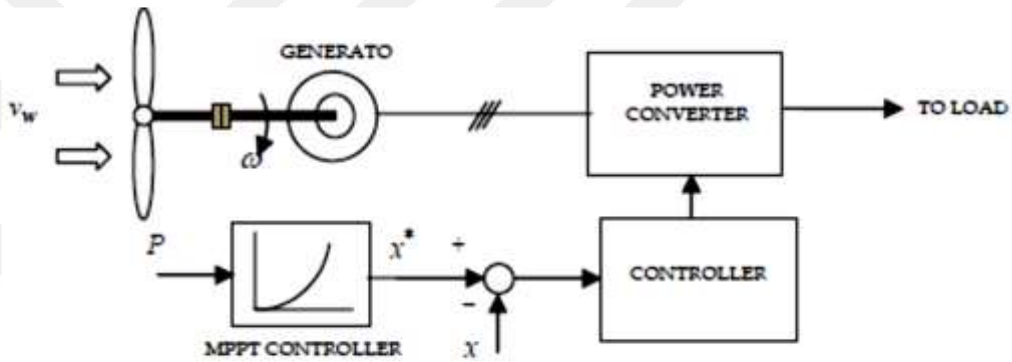

Figure 2.12 WECS with hill climb search control

3 MODELING OF SMALL SCALE WIND TURBINE

In this chapter the procedure of developing a mathematic model of the system is explained which defines the physical components of the whole system. The aim is to find a state space model of the system, by means of which a modern control system can be designed for the fixed speed, variable pitch wind turbine configuration. The initial portion analyses the elements that are required to be modeled. The parameters and the values for the modeling of the small scale wind turbine are mentioned in Appendix A.

3.1 Wind Energy Conversion Systems (WECS)

The primary objective is to achieve a control oriented model for the whole system. Therefore, the WECS is classified in four principal functional sections, which are: aerodynamic, mechanical, electrical and pitch servo subsystems, (Anaya-Lara et al., 2009).

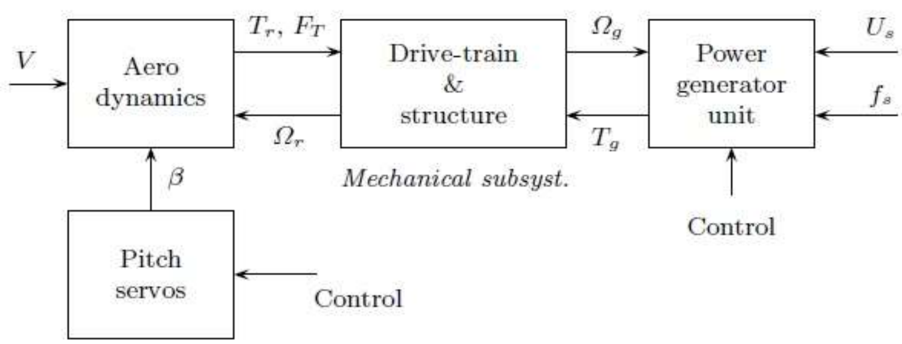

Figure 3.1 Subsystem block diagram of WECS

The aerodynamic subsystem is dedicated to the conversion of the extracted wind energy into mechanical energy. The mechanical has a dual function: the first is achieved by the drive train by transferring the torque from the motor to the electrical generator and the second one is to maintain the turbine rotor and other components in height while enduring the trust force. The electrical accomplishes conversion of mechanical power at the shaft of generator into electricity. And, the pitch servo contains an electromechanical or hydraulic system which turns the blades to modify its pitch angle.

3.2 Mechanical Modeling

The mechanical model explains the forces and the torque which affect the various parts of the mechanical system. The following figure 3.2 demonstrations different parts of the system that are interlinked with each other.

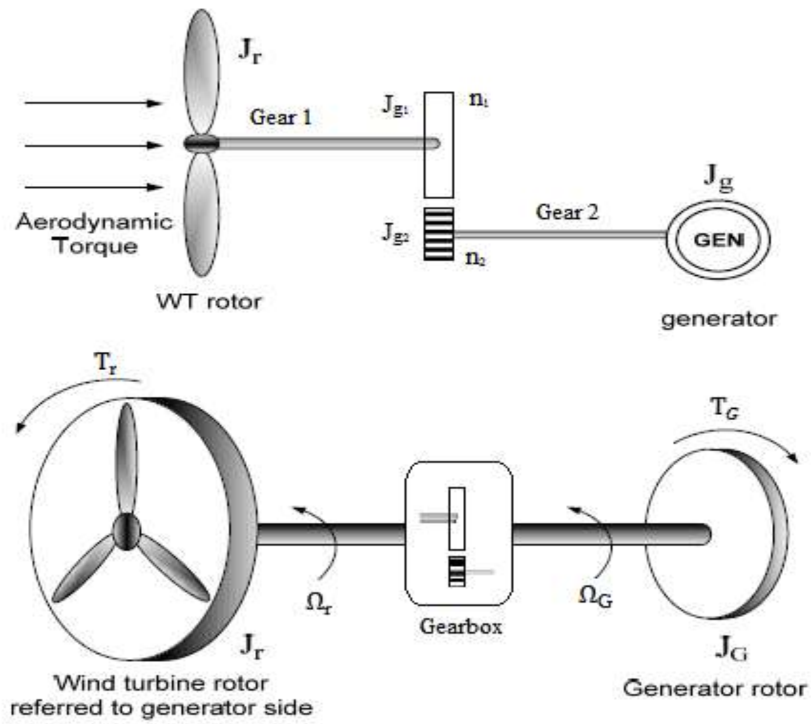

Figure 3.2 Mechanical Model of the system

Where:

J_r Is inertia of the rotor $(kg.m^2)$

J_G Inertia of the generator $(kg.m^2)$

J_{g1} Inertia of gear 1$(kg.m^2)$

J_{g2} Inertia of gear 2 $(kg.m^2)$

n_1 Relative size of gear 1

n_2 Relative size of gear 2

T_r Force provided by the rotor (Nm)

T_G Counterforce provided by the generator (Nm)

Ω_r Angular velocity of the rotor (rad/s)

Ω_G Angular velocity of the generator (rad/s)

3.2.1 Gears

The inertia experienced from the gears is cumulated to the inertia of the generator. Assuming the gears are just affected by the viscous friction that is going to be cumulated with the generators friction, then the gear radio is expressed:

$$\frac{n_2}{n_1} = N \tag{3.1}$$

According to these deductions we can realize the torque and the angular velocity is changed from one axe to another by a multiplication with the gear ratio. The time of inertia on the second axis is experienced on the first axis as J^2/N^2 and conversely.

Therefore, the two gear's free body diagrams will not be made. The gear ratio of the small scale wind turbine is $N = \frac{1}{11}$

From the following figure 2.3, two free body diagrams are presented which shows the following equations:

$$J_r \,.\, \dot{\Omega}_r = T_r - \frac{1}{N} \,.\, T_r \tag{3.2}$$

$$J_G \,.\, \dot{\Omega}_G = N \,.\, T_r - T_G \tag{3.3}$$

$$\Omega_r = N \,.\, \Omega_G \tag{3.4}$$

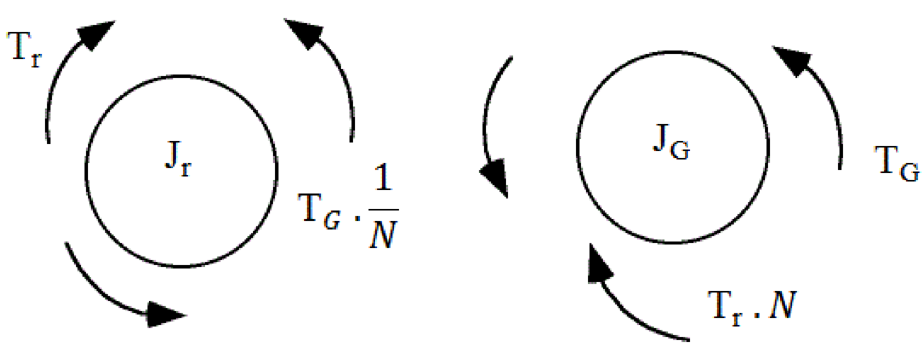

Figure 3.3 Rotor and Generator free body diagrams with effect of different forces acting on them

The T_r force is mentioned in the equation 2.20, in which the $C_Q$relies on λ *and* β. The torque T_G from the generator could be divided into two different torques, the one is the load torque T_L delivered by the control and the other is the friction torque T_f from the whole system. The equation for T_G can be written as $T_G = T_L + T_f$. The frictional and load torque can be written as follows:

$$T_L = K_G \,.\, I \tag{3.5}$$

$$T_f = B \,.\, \Omega_G \tag{3.6}$$

Where:

K_G Is the constant of generators torque, describes how current is converted into torque inside the generator. (Nm/A)

I Current passing through the coils of the generator (A)

B Viscous friction coefficient of the system (Nm/ rad/s)

Conversely, the generator is assisting the rotation when voltage signal is exerted and thus the equation 3.5 becomes

$$T_G = -K_G \,.\, I \tag{3.7}$$

Now the equation 3.7 can be merged with the equation 3.8 and 3.9 to make the mechanical equation for the generator. The Laplace transform of the equation is also calculated and expressed as follows:

$$J_G \,.\, \dot{\Omega}_G = N \,.\, T_r + K_G \,.\, I - B \,.\, \Omega_G \tag{3.8}$$

$$J_G \,.\, s \,.\, \Omega_G = N \,.\, T_r + K_G \,.\, I - B \,.\, \Omega_G \tag{3.9}$$

The inertia in the system model is the total inertia J_{tot}, expressed:

$$J_{tot} = J_G + J_r \,.\, N^2 \tag{3.10}$$

Therefore, the mechanical equation of the generator results in:

$$J_{tot} \,.\, s \,.\, \Omega_G = N \,.\, T_r + K_G \,.\, I - B \,.\, \Omega_G \tag{3.11}$$

3.3 Electrical Modeling

The corresponding electrical circuit diagram is shown in the figure 3.4 which demonstrates the generator through a controllable load. The assumption is made that the load produces a voltage on the terminals of the generator which consequently produces a force that acts against the rotors force. As observed on the electrical circuit diagram, following are the devised equations and mentioned in Laplace transform as well:

$$U_L\ (t) = I\ (t). R_G + \dot{I}(t)\ .\ L_G + \mathrm{U}_{emf}(t) \tag{3.12}$$

$$U_L\ (t) = I\ (t). R_G + \dot{I}(t)\ .\ L_G + K_G\ .\Omega_G(t) \tag{3.13}$$

$$U_L\ (s) = I\ (s). R_G + s\ .\ I\ (s)\ .\ L_G + K_G\ .\Omega_G(s) \tag{3.14}$$

Where:

U_L Is the load voltage (V)

R_G Generator terminal resistance (Ω)

L_G Generator inductance (H)

U_{emf} Backwards electromotive force (V)

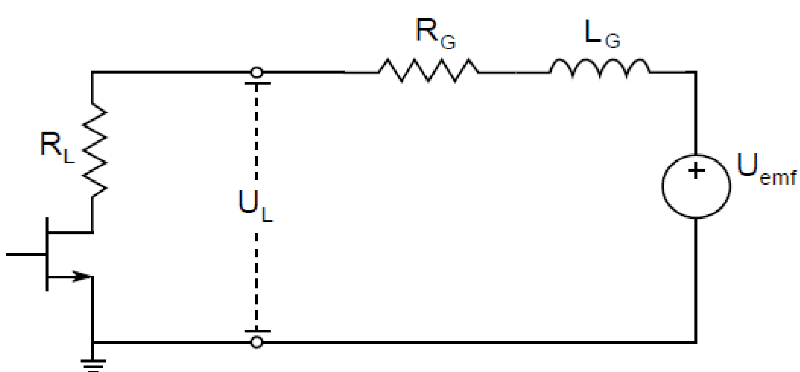

Figure 3.4 Electrical circuit diagram of the generator with variable load

The influence of L_G is disregarded and taken out from the equation 3.13. There the new equation 3.14 becomes:

$$U_L\ (s) = I\ (s). R_G + K_G\ .\Omega_G(s) \tag{3.15}$$

3.4 Pitch Subsystem Modeling

The pitch actuator system controls the force T_r from the rotor by varying the blade angles. The pitching system of the small scale wind turbine is a collaborative system where the blades altogether are pitches simultaneously to the equivalent angle.

The system is considered to be a type 1 system which demonstrates that the steady state error is absent if the reference input is a step. The output signal and the derivative of the output signal, both have saturations which explains that on the time that the servo is working outside the saturation regions of the system grows to nonlinearity. (Anaya-Lara et al., 2009). And expressed in the figure 3.5 below:

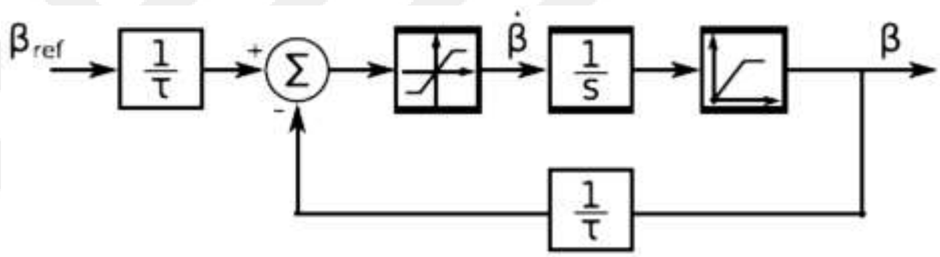

Figure 3.5 Pitch servo system

The servomechanism is considered that it functions comprised in a little region which is 1-2 degree step at a time and it constantly turns to the reference position. The dynamic behavior of the pitch actuator working in the region of linearity is explained by the differential equation:

$$\dot{\beta} = -\frac{1}{\tau} . \beta + \frac{1}{\tau} . \beta_{ref} \tag{3.16}$$

Where:

τ Is the servomechanism time constant (s)

By changing the pitch angle β and thus T_r then consequently the velocity of the generator Ω_G with would be changed feedback signal.

3.5 State Space Representation of the System

The state space representation of the system is given in the table 3.2 with the states that are required to be controlled in accordance with the input and output of the system.

Table 3.1 The states, Input and Outputs of the State Space system

States	Input	Output
Generator Angular Velocity Ω_G	Generator voltage at its terminals U_L	Generator Angular Velocity Ω_G
Pitch β	Pitch β_{ref}	

The state space representation of the system is derived from the equation 3.11 and 3.16 and cumulated in the equation 3.17 which is formulated and expressed in terms of I as follows:

$$I = \frac{U_L - K_G . \Omega_G}{R_G} \tag{3.17}$$

Putting it into the mechanical differential equation of the generator, equation 3.11, we have:

$$\dot{\Omega} = \frac{K_G}{J_{tot}} . I - \frac{B}{J_{tot}} . \Omega_G + \frac{N . T_r}{J_{tot}}$$

$$\dot{\Omega} = \frac{K_G}{R_G . J_{tot}} . U_L - \frac{{K_G}^2 + B . R_G}{R_G . J_{tot}} . \Omega_G + \frac{N . T_r}{J_{tot}} \tag{3.18}$$

The whole system model is acquired by interconnecting the models of the individual subsystems (Anaya-Lara et al., 2009). Since the T_r is the non-linear function of the wind speed, rotor speed and the angle of pitch, it is linearized about a precise functioning region. We perform it in order to design a linear state space control system that functions in the operating region. The operating points are listed in the table in Appendix A and the linearization is carried out according to the references in (Anaya-Lara et al., 2009).

The operating point is set in order that the model linearized on the time that its functioning in the region III in figure 2.1. The linearization is performed by partly separating the equation 2.20 in correspondence with $\overline{\Omega_G}$ and $\bar{\beta}$ which effects in the gradient at the operating point.

$$\widehat{T_r}|_{(\bar{V},\overline{\Omega_G},\bar{\beta})} = \frac{\partial T_r}{\partial \Omega_G}|_{(\bar{V},\overline{\Omega_G},\bar{\beta})} . \widehat{\Omega_G} + \frac{\partial T_r}{\partial \beta}|_{(\bar{V},\overline{\Omega_G},\bar{\beta})} . \hat{\beta}$$

$$\widehat{T_r}|_{(\bar{V},\overline{\Omega_G},\bar{\beta})} = B_r . \widehat{\Omega_G} + K_\beta . \hat{\beta} \tag{3.19}$$

These coefficients values are listed in the Appendix A and further used in the in MATLAB/Simulink environment for carrying out simulation analysis

We have the following equation 3.24 after replacing T_r with $\widehat{T_r}$, we have:

$$\dot{\Omega} = \frac{\mathrm{K}_G}{\mathrm{R}_G . \mathrm{J}_{tot}} . \widehat{\mathrm{U}_L} - \frac{\mathrm{K}_G{}^2 + (B - N . \mathrm{B}_G). \mathrm{R}_G}{\mathrm{R}_G . \mathrm{J}_{tot}} . \widehat{\Omega_G} + \frac{N . \mathrm{T}_r}{\mathrm{J}_{tot}} . \hat{\beta} \tag{3.20}$$

Now we can use the matrix notation for the system which is described as follows

$$\dot{x}(t) = A. x(t) + B. u(t)$$

$$y(t) = C. x(t) + D. u(t) \tag{3.21}$$

$$\hat{\dot{x}} = \begin{bmatrix} -\frac{K_G^2 + (B - B_r.N).R_G}{J_{tot}.R_G} & \frac{N.K_\beta}{J_{tot}} \\ 0 & -\frac{1}{\tau} \end{bmatrix} . \begin{bmatrix} \widehat{\Omega_G} \\ \beta \end{bmatrix} + \begin{bmatrix} \frac{K_G}{J_{tot}.R_G} & 0 \\ 0 & \frac{1}{\tau} \end{bmatrix} . \begin{bmatrix} \widehat{U_L} \\ \beta_{ref} \end{bmatrix} \tag{3.22}$$

$$\hat{y} = [1 \quad 0]. \begin{bmatrix} \widehat{\Omega_G} \\ \beta \end{bmatrix} \tag{3.23}$$

4 OBSERVER BASED STATE SPACE CONTROL

The present chapter explains the observer based state space controller's design and execution, intended for wind turbines which small to medium sized in their construction. Initially the control system and the control schemes are presented, subsequently the state feedback with integral control is illustrated and furthermore the observer based control system is designed. The design of the controller is accomplished with the convenience of state space modeling of the dynamical system as analyzed in chapter 3. The conventional design and scheme is illustrated in Figure 4.1.The comprehensive state feedback diagram is designed using references from Ogata (2010) and Bertelsen et al (2011). Additionally the figure shows the complete model of the state space controller along with the feedback paths. It is important to note that by utilizing this modern controlling system approach the output power of the SSWT is maintained constant. The control system simulations are carried out in the MATLAB/Simulink environment to validate the proposed control scheme for the small scale wind turbine.

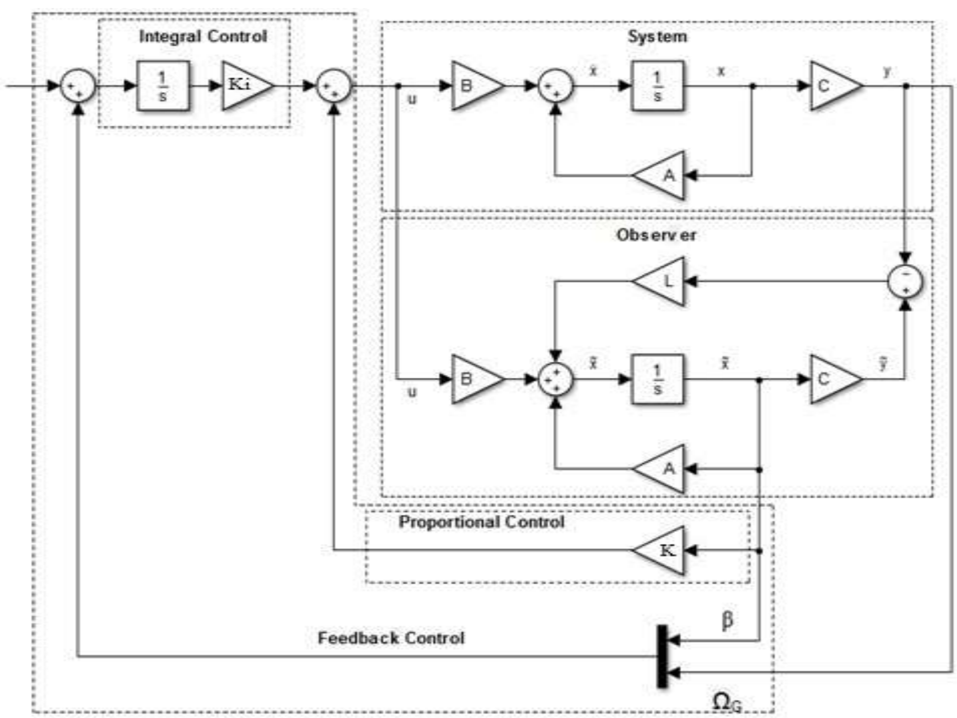

Figure 4.1 Outline of the state space feedback system

4.1.1 The System

A small-scale wind turbine represents the system. The turbine can be directed and controlled by:

- Exerting voltages to the generator terminals (U_L), and by
- Modifying the pitch angle of the blades (β).

The input consists of these signals that are gathered and accumulated into the *vector u* (input column). The row *vector y* indicates the angular velocity of the generator (Ω_G) that corresponds to the output of the system. The obtained matrices A, B, C and D describes the system. The procedure to obtain the state space model is explained in chapter 3 and from there it is stated as below.

$$\dot{x}(t) = A.x(t) + B.u(t)$$

$$y(t) = C.x(t) + D.u(t) \tag{4.1}$$

$$\dot{\hat{x}} = \begin{bmatrix} -\frac{K_G^2+(B-B_r.N).R_G}{J_{tot}.R_G} & \frac{N.K_\beta}{J_{tot}} \\ 0 & -\frac{1}{\tau} \end{bmatrix} . \begin{bmatrix} \widehat{\Omega_G} \\ \beta \end{bmatrix} + \begin{bmatrix} \frac{K_G}{J_{tot}.R_G} & 0 \\ 0 & \frac{1}{\tau} \end{bmatrix} . \begin{bmatrix} \widehat{U_L} \\ \beta_{ref} \end{bmatrix} \tag{4.2}$$

$$\hat{y} = \begin{bmatrix} 1 & 0 \end{bmatrix} . \begin{bmatrix} \widehat{\Omega_G} \\ \beta \end{bmatrix} \tag{4.3}$$

4.1.2 The Feedback Control

The feedback control is constructed by: an integral control and a proportional control. The states of the observer are feedback via the matrix K with the design and control effect of the proportional control. It is used the matrix K_I in view of the fact that in the system is not possible to calculate and determine all the states. The aim is to behold the system convergence at a stabilized point of operation determined and directed by the reference *vector r*.

Due to the nature of the proportional controller which experiences a steady state error, for that reason an integral controller is required, so it is made possible that the system converges to the references set in the *vector r*. The integral control matrix K_I it is hence utilized to control the integrated error between the output and the reference.

Furthermore, the observers estimated state can possibly experience some deviation, which consequently generates inconvenient steady state error, therefore output signal Ω_G is applied for feedback to the integral controller.

4.1.3 The State Observer/Estimator

Since measuring all the states of the real system it is not attainable, the state observer is a requirement for the feedback control. Thus, with the utilization of the observer it is feasible to achieve in the system the feedback to all the states. Additionally, to avoid the model uncertainties, the observer gain matrix L is feedback with the error between the measured output and the estimated output. The observer estimated states are represented by $\tilde{x}$.

4.2 Feedback Control Scheme & Design

Is assumed that a continuous time system can be controlled at time t0 if it is possible by utilizing a control vector that is not limited to make the system to transfer to any other state in a finite interval of time from any initial state x(t0). (An assertion that is similar is used for a discrete system). As stated by Bertelsen et al (2011):

"The system is controllable if and only if the rank of the controllability matrix 'C' equals the number of states 'n' in the system".

It must be verified that the modeled system is controllable before a controller is designed. The controllability matrix rank is 2 (for SSWT) that is equivalent to the number of states. Therefore, the system is said to be controllable. To determine rank of the controllability matrix, MATLAB has been used, utilizing the following command: *ctrb and rank*.

4.2.1 Pole Placement Approach for Feedback Controller

The Pole Selection, according to the paper: "Feedback Control Systems" elaborated by the MIT, can have two different approaches:

- *"To use time-domain specifications to locate dominant poles:* also known as the dominant second order pole placement, as stated by Ogata (2010): "it is such a system where the closed-loop transfer function possesses two poles" where for a higher order system, the two dominant closed-loop poles are selected and the other poles are chosen to have real parts to such extent that they are damped enough, hence the system will imitate a second-order system, and

- *The Linear Quadratic Regulator (LQR):* that is to place the pole locations in order that the closed-loop system optimizes the cost function".

The above mentioned pole place approach is used in the thesis and is explained as follows:

4.3 Linear Quadratic Regulator (LQR)

This method has the benefit that presents a systematic procedure of computing the state feedback control gain matrix (Ogata, 2010).

As referenced above the LQR, optimizes the cost function:

$$J_{LQR} = \int_0^\infty [x(t)^T Q x(t) + u(t)^T R u(t)] dt \quad (4.5)$$

Where:

J_{LQR} Is the Performance Index

$x^T Q x$ State Cost with weight Q

$u^T R u$ Control Cost with weight R

One reasonable simple method to start the LQR design iteration is suggested by Bryson's rule (Bryson and Ho, 1969 as seen in Franklin, Powell and Emami-Naeini, 2002). A balance amid state deviance and control effort emerges with the selection of the states weighthing matrix Q and the control signal weighting matrix R and the depreciation of the performance index J. State deviation being the difference amongst the reference output and the actual output whereas extent of output actuators require to supply is termed as control effort.(Bertelsen et al, 2011). Practically, to attain adequate values of x and u is to firstly select the diagonal matrices, Q and R:

$$Q_{ii} = \frac{1}{(maximum\ acceptable\ value\ of\ [x_i^2])}$$

$$R_{ii} = \frac{1}{(maximum\ acceptable\ value\ of\ [u_i^2])}$$

Subsequently, the weighting matrices are altered during succeeding and successive iterations for attaining an adequate trade-off amongst performance and the control effort.

Where:

Q_{ii} *Q* Matrix at row i^{th} *row* and i^{th} column

R_{ii} *R* Matrix at i^{th} row and i^{th} *column*

x_i The state vector's *i*'th element

u_i The input vector's *i*'th element

On the Bryson's Rule, the entries of *Q* and *R*, are ought to be thought of as a measure of the amount of treatment the given state or input acknowledges and receives from the controller. Therefore a small number signifies that the control action from the controller must be aggressive and a large number signifies that the control action from the controller must be gentle. According to Hespanja (2005), although Brysons's rule generally provides decent outcomes, often it is just the initial point to a trial-and-error strategy and design technique intended for attaining necessary and required properties for the closed-loop system.

Application:

Taking as a reference Ogata (2010), to apply the two integral terms into a feedback law where the matrices of the system are A & B having 2x2 dimension and taking in consideration that these matrices have to be extended for determining the integral gain matrix, so that:

$$u(t) = F.x(t) + F_I \, . x_I \tag{4.6}$$

Where:

$$x_I(t) = \int_0^t y(\tau) - r(\tau) d\tau \tag{4.7}$$

Or:

$$\dot{x}_I = y(t) - r(t) \tag{4.8}$$

The new state space equations, using the integral states are:

$$\dot{x}(t) = A.x(t) + B.u(t) \tag{4.9}$$

$$\dot{x}_I = y - r \tag{4.10}$$

$$y = Cx \tag{4.11}$$

The extended state space model of the system can be expressed as follows:

$$\begin{bmatrix} \dot{x} \\ \dot{x}_I \end{bmatrix} = \begin{bmatrix} A & 0 \\ -C & 0 \end{bmatrix} \begin{bmatrix} x \\ x_I \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u + \begin{bmatrix} 0 \\ I \end{bmatrix} - r \tag{4.12}$$

$$y = \begin{bmatrix} C & 0 \end{bmatrix} \begin{bmatrix} x \\ x_I \end{bmatrix} \tag{4.13}$$

Consequently, the model expands: the Q matrix obtains a dimension of 4 x 4 as a result of the incorporation of the two extra integral states. The R matrix consists of a 2 x 2 dimension, as there are two inputs. By using the MATLAB command lqr ( ), the solution for optimal control is found. The values for the feedback matrix given by the before mentioned command is:

$$Je = -lqr(A_e, B_e, Q, R) \tag{4.14}$$

Where:

$$A_e = \begin{bmatrix} A & 0 \\ C & 0 \end{bmatrix} \tag{4.15}$$

$$B_e = \begin{bmatrix} B \\ 0 \end{bmatrix} \tag{4.16}$$

The Q and R matrix values are found in MATLAB. These values are mentioned in the Appendix A.

Subsequently, utilizing the values from appendix A table the two matrices are:

$$Q = \begin{bmatrix} \frac{1}{\Omega_{Gmax}^2} & 0 & 0 & 0 \\ 0 & \frac{1}{\beta_{max}^2} & 0 & 0 \\ 0 & 0 & \frac{1}{\Omega_{G,I}^2} & 0 \\ 0 & 0 & 0 & \frac{1}{\beta_I^2} \end{bmatrix} \tag{4.17}$$

$$R = \begin{bmatrix} \frac{1}{U_{Lmax}} & 0 \\ 0 & \frac{1}{\beta_{refmax}} \end{bmatrix} \tag{4.18}$$

The resulting Je matrix, derived from the calibrated values of Q and R, includes elements from the matrix K which the state feedback matrix and the matrix K_I which is the integral control gain.

The matrix K which the state feedback matrix and the matrix K_I which is the integral control gain are obtained using the matrix Je.

Therefore, the delineation and design of the state feedback controller completed.

4.4 Observer Design

The observer design can assist us to measure and estimate the values of the quanitites that we do not know and perform a remarkable role in decreasing the complexity and total cost of the overall system. Adding a lot of sensors to the system increase cost to the system and expand the complexity of the system. In the real wind turbines the pitch angle of the blades does not have a sensor that can measure it. Though, the other state of the system, the rotational velocity is measured with the help of the sensor. Thus an observer based control system is designed for estimating the unavailable state and make the possibility for the state feedback. (ogata)

To make this achievable, the observer is placed in parallel to the actual system, hence both have the same input, u. The outputs, y and $\tilde{y}$, are estimated and analogized by a deduction, where the difference is feed through L, the observer gain, and then summed with the the observer's derivative of the states, $\dot{\tilde{x}}$ (Ogata, 2010).

4.4.1 Observability

A system needs to be validated for observability to make certain that is possible to design an observer. The process is calculated by determining if it is plausible to make an approximation of the states that we do not know using the states that are obtainable. Using the Observability Matrix (as seen in Equation 4.20) we can test this process.

$$O = \begin{bmatrix} C \\ CA \\ \vdots \\ CA^{n-1} \end{bmatrix} \qquad (4.19)$$

The observability matrix is found by using MATLAB command obsv.

Consequently, it can be stated that the model used to outline the wind turbine is observable as rank of O is equal to the A matrix dimension.

4.4.2 The Design of Observer Gain

The Equation 4.21 explains the dynamics presented by applying the observer. It is obtianed by examining the observer error, e which is defined as The estimation error or observation error is the difference between the measured output and the estimated output.

$$e = x - \tilde{x}$$

$$\dot{e} = \dot{x} - \dot{\tilde{x}}$$

$$= (A.x + B.u) + A.\tilde{x} + B.u + L(y - C\tilde{x})$$

$$= A(x - \tilde{x}) - L(Cx - C\tilde{x})$$

$$= (A - LC)(x - \tilde{x})$$

$$\dot{e} = (A - LC)e \qquad (4.20)$$

We must designate the poles of A - LC to be located in the left half plane, in order to make the observer stable the gain L (it is delineated in a way that it places the poles where we wanted).

Observer Canonical Form

The system is then changed to an Observable Canonical Form to prove that what was previously explained it is achievable. In order to change the system, "*T*" is instituted and used to modify *A* and *C*, such that:

$$A_o = T^{-}AT \qquad (4.22)$$

$$C_o = CT \qquad (4.23)$$

Where *T*:

$$t_2 = O^{-}\begin{bmatrix}0\\1\end{bmatrix} \qquad (4.24)$$

$$t_1 = At_2 \qquad (4.25)$$

$$T = [t_1 \quad t_2] \qquad (4.26)$$

Same form is additionally utilized to assess L_O that by using *T* which could be changed to *L*, that is the real observer gain.

We can observe the actual simplicity that means using the canonical form by writing the $A_O + L_O C_O$ matrix, as:

$$A_o + L_o C_o = \begin{bmatrix} a_1 & I \\ a_2 & 0 \end{bmatrix} + \begin{bmatrix} l_1 \\ l_2 \end{bmatrix} [1 \quad 0]$$

$$= \begin{bmatrix} a_1 + l_1 & I \\ a_2 + l_2 & 0 \end{bmatrix} \quad (4.27)$$

Selecting an appropriate value of L_O can transform any of the observer's poles, if we use this matrix's formula, so that:

$$\det(sI - (A_o + L_o C_o)) = s^2 - (a_1 + l_1) \,.\, s - a_2 + l_2 \quad (4.28)$$

It is changed back to the form utilized in the real feedback with the values of L_O stated directly from the selected poles:

$$L = T L_o \quad (4.29)$$

For the calculations it is utilized the function available in MATLAB, called place ( ), as seen below:

$$L' = -place(A', C', Po) \quad (4.30)$$

Where:

P_o Is the vector that includes the selected poles

4.4.3 Selecting Observer Poles

As stated by Franklin, Powell and Emami-Naeini (2002), the poles can be selected voluntarily by general or approximate principle or "as a rule of thumb" to place them from 4 to 6 times further out than the controller poles. This signifies that the controller poles will largely direct the response of the system (that has been previously delineated to perform such response). The saturation of the input, and conceivably the states, restricts the physical system, unlike the mathematical model of the observer. As well, the observer is not restricted as the physical system when is needed to cause a faster response.

Same authors noted that the bandwidth of the observer becomes higher, thus causing more sensor noise to pass on. Supported by Bertelsen et al (2011), furthermore asserting that this noise is therefore conveyed through the observer and utilized by the controller in the state feedback to drive the physical system and in the worst-case scenario it can cause lack of stability in the system.

4.5 The Reference Signal

The states of the SSWT that have to be under control are the pitching angle of the blades β along with that is the angular velocity of the generator Ω_G, as we want to preserve a fixed power output. In order to achieve this, a reference signal is inserted as observed in the subsequent equation:

$$-r + C.x = -\begin{bmatrix}\Omega_{Gref} \\ \beta_{ref}\end{bmatrix} + \begin{bmatrix}\Omega_G \\ \beta\end{bmatrix} \quad (4.31)$$

β state which is estimated (%)

Ω_G state which is measured (rad/s)

The reference signal is used before the input to the integrator. Additionally, the integral control which exists amongst the reference signal and the feedback signal, removes and eradicates the steady state error.

Therefore, so the system to avoid a steady state error:

$$\begin{bmatrix}\Omega_{Gref} \\ \beta_{ref}\end{bmatrix} = \begin{bmatrix}\Omega_G \\ \beta\end{bmatrix} \quad (4.32)$$

Hence, we can observe through the examination of these equations that the SSWT's pitch angle of the blades β and the angular velocity will advance towards and approximate the stated reference signal.

5 SIMULATION OF THE MODEL IN MATLAB/SIMULINK

In this chapter the observer based feedback control of the model is simulated in the MATLAB/Simulink environment. The state space control system is constructed for affirming a constant speed and torque by pitching the blades of the turbine achieving greater efficiency at varying wind speeds and enhanced operation of the wind turbine. The results are analyzed and discussed in this chapter.

5.1 Modeling and Simulation

Modeling and simulation are inseparable processes that include complicated activities, mainly the elaboration of models that represent real processes, it also include the experimentation of the models to acquire behavioral information of the modeled system. Thus, modeling is mainly about the relations between real dynamic processes and its models and simulation the relations between the simulation tool and the model.

After understanding the necessary concepts and control strategies in the above chapters, an observer based control system has been designed in the MATLAB/Simulink environment.

For designing the observer-based feedback control system in MATLAB/Simulink the small scale wind turbine parameters (listed in appendix A) are plugged into the MATLAB environment. The MATLAB codes and scripts are generated for achieving the control action. The MATLAB codes and scripts are listed in the appendix B.

5.2 Observer-Based State Feedback Controller Design

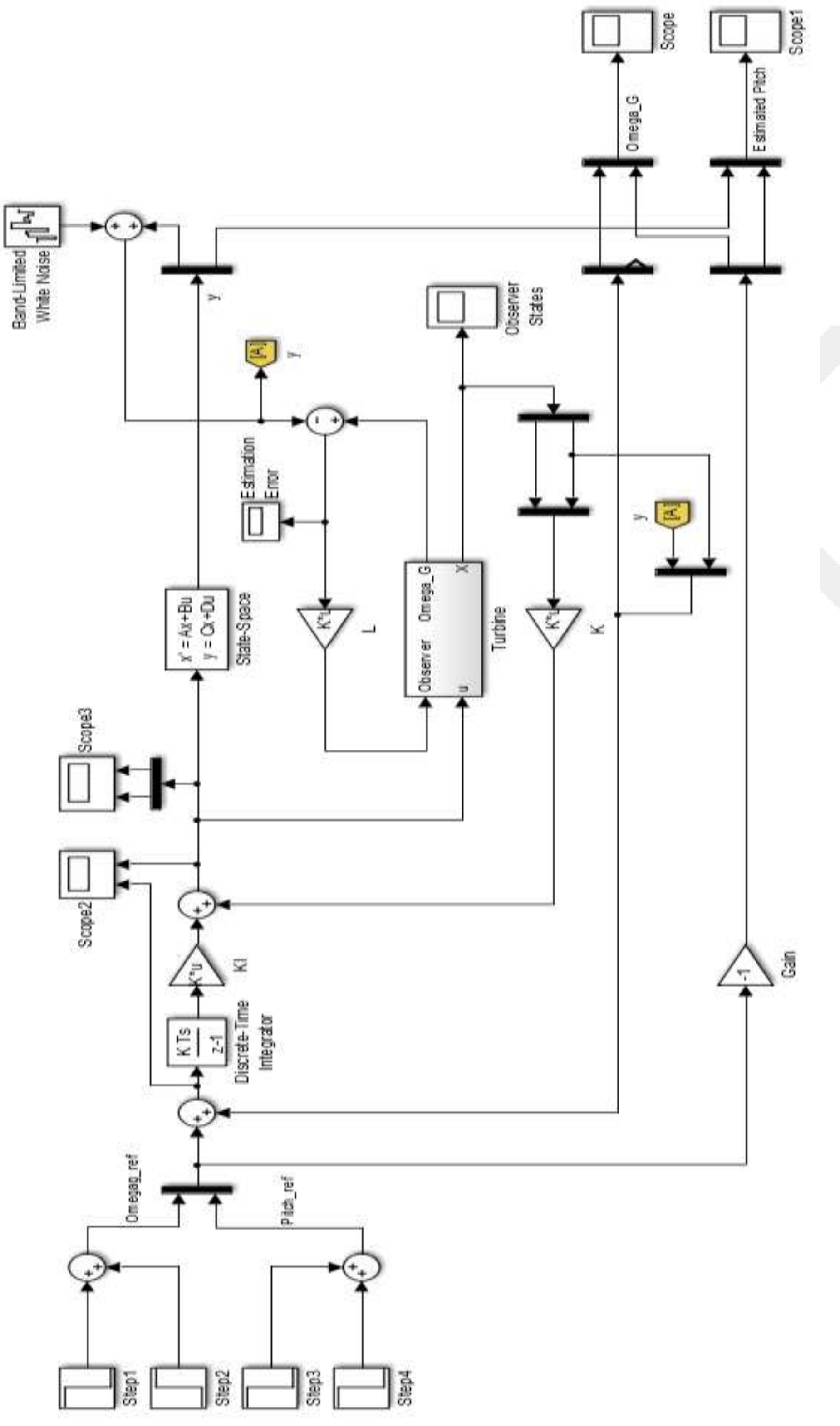

Figure 5.1 Model of the observer-based feedback control system in Simulink

The complete state space observer control is shown in the figure 5.1 and is implemented in the MATLAB/Simulink.

The simulation is carried out in the Simulink environment of MATLAB.

In order to perceive the amount of variation occurred in the pitch and the speed and its affects to be known. The step inputs are used as reference for the simulation purposes.

The measured output Ω_G from the plant can be seen in the figure 5.2

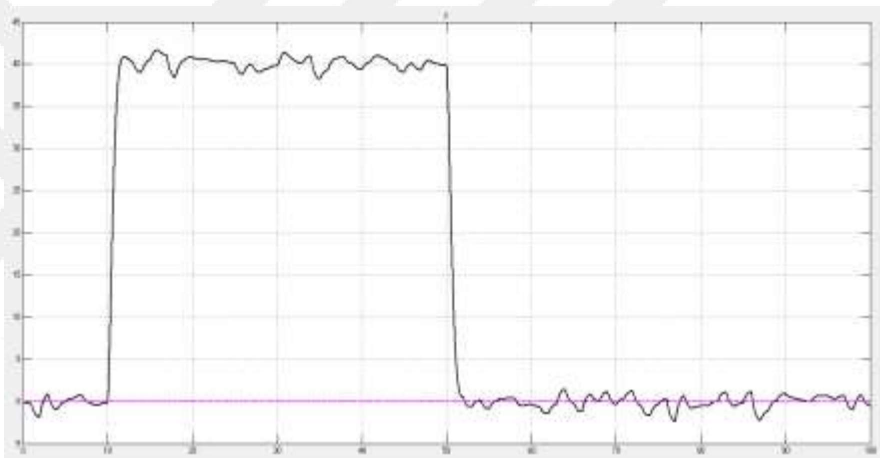

Figure 5.2 Measured output Ω_G from the actual system

The output $\widetilde{\Omega_G}$ from the state observer can be seen in the figure 5.3

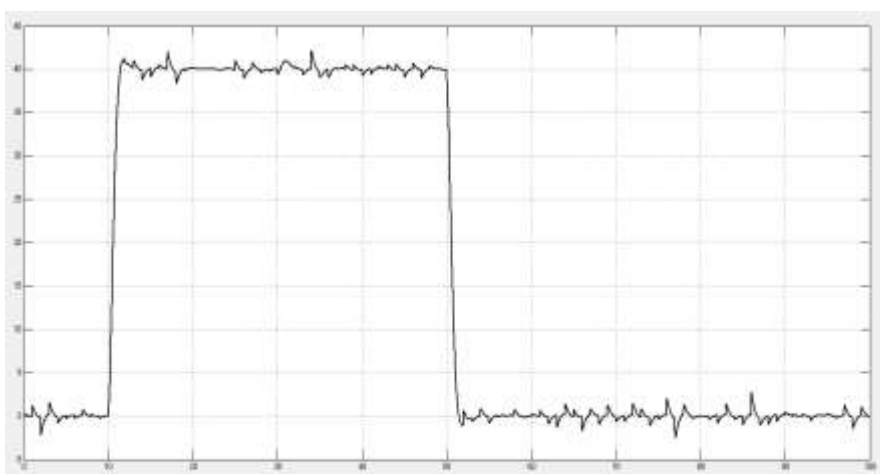

Figure 5.3 Estimated output $\widehat{\Omega_G}$ from the state observer

We can see from the both figures 5.2 and 5.3 that the observer has reconstructed the state vector of the plant since the mathematical model of the observer is similar that of the plant but with the exception that it contains an another term which comprises of the estimation error to regulate for the discrepancies in the A & B matrices. The estimation error or observer error is checked and shown in the figure 5.6 which is the difference between the measured output and the estimated output.

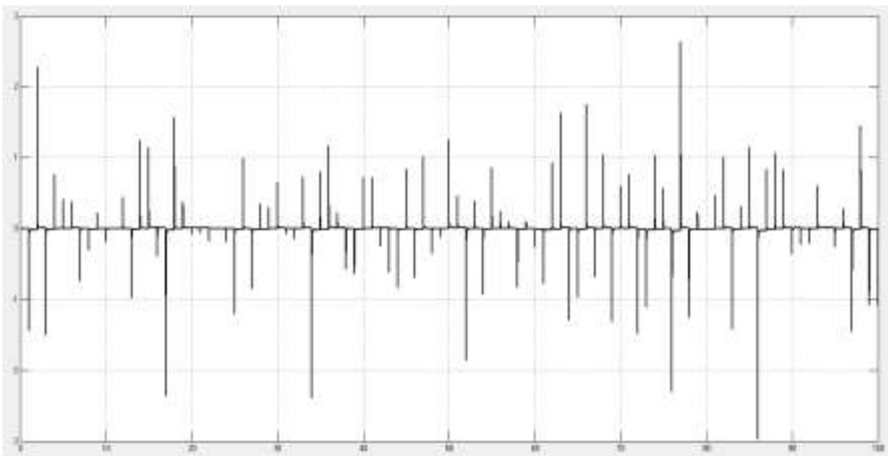

Figure 5.4 Estimation/Observer Error

As we can see from the figure 5.4, that estimation error difference between the state of the plant and the estimated state of the observer tends to fade as time approaches infinity

$$e\ (\infty) = 0\ as\ t \rightarrow \infty$$

The desired system response with the addition reference signals is simulated in MATLAB/Simulink and the output can be seen in the following figures 5.5 and 5.6.

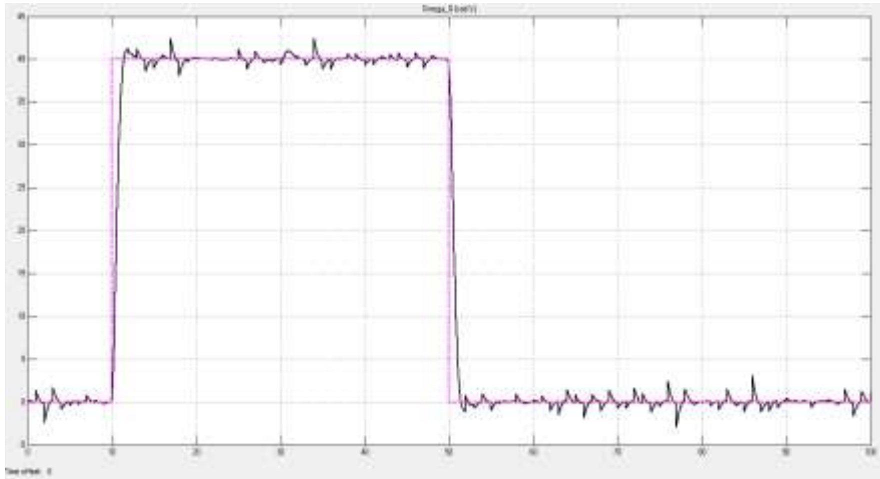

Figure 5.5 Tracking performance of the Generator Speed Control

It is evident from the figure 5.5 that the simulated output Ω_G is following the reference signal trajectory i.e. Ω_{Gref} and which validates the model.

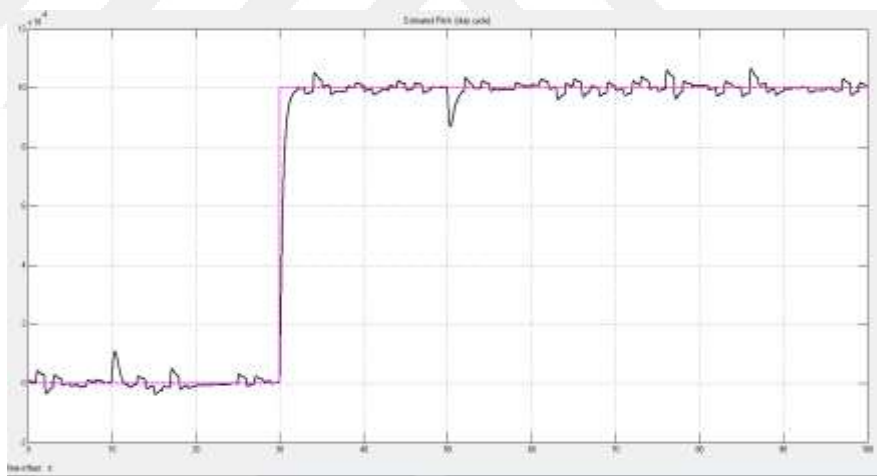

Figure 5.6 Tracking performance of the estimated Pitch control

In the figure 5.6, we can see the observer has successfully estimated the state which being the pitch β, and the pitch control successfully follows the reference signal's trajectory i.e. β_{ref}

We can conclude from the chapter 4, section 4.4 that,

$$\begin{bmatrix} \Omega_{Gref} \\ \beta_{ref} \end{bmatrix} \approx \begin{bmatrix} \Omega_G \\ \beta \end{bmatrix}$$

From the figure 5.5 and 5.6, it can be seen that the velocity control and the pitch control follow the trajectory of the reference signal and the overall response of the controller is quite satisfactory. With the help of the observer based control the missing state being the pitch of the turbine is estimated and controlled.

White Noise is added into the plant's feedback signal in order to mimic a real system response on the simulation which is carried out. The purpose is to you analyze the response of the observer controller whether it can handle the discrepancies and irregularities between the estimated output of the system and the actual output of the system. In the figure 5.7 and 5.8 are the response of the states when exposed to noise signals

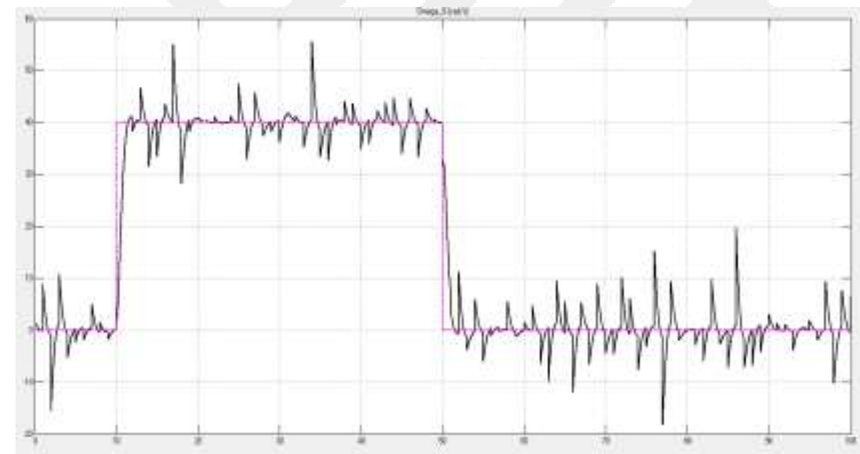

Figure 5.7 Generator speed control. The response of the controller with noise

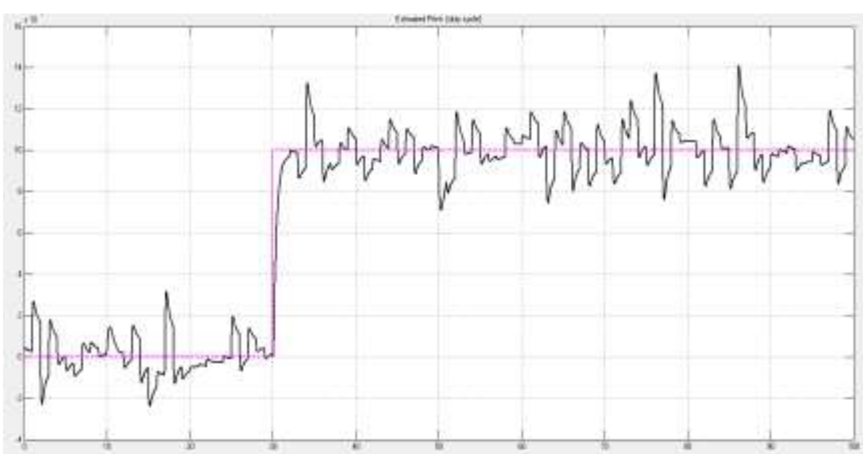

Figure 5.8 Estimated Pitch Control. The response of the controller with noise

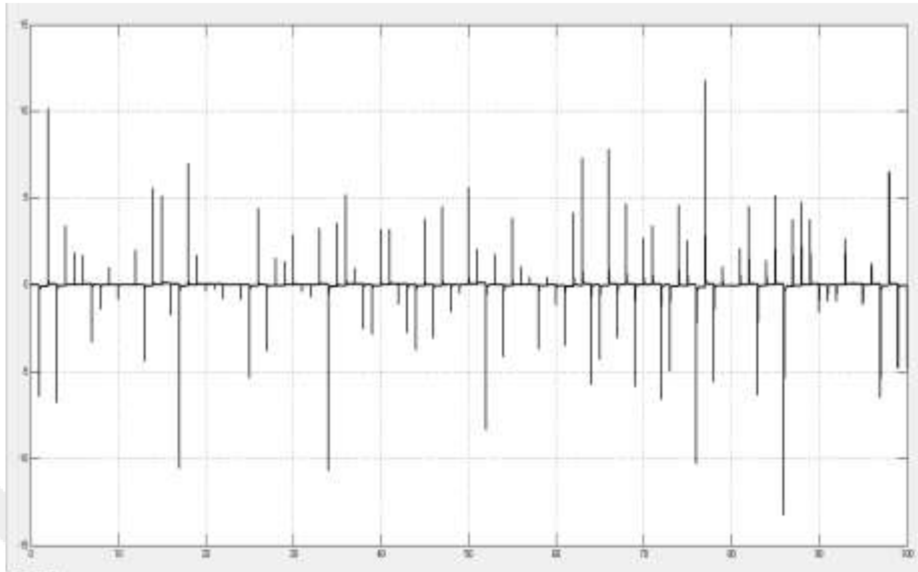

Figure 5.9 Estimation error with noise signals

$$e\,(\infty) \cong 0 \; as \; t \rightarrow \infty$$

It can be seen from the figure 5.7 and 5.8 that with the inclusion of noise in the system, the system experiences fluctuations and disturbances which can be conceived as in real systems and a similar response of the controller to disturbances and noise. In fig 5.9 the estimation error approaches to zero but with noise. In order to overcome this issue the controller must be tuned to enhance the response of the physical system, when real physical systems are considered.

6 CONCLUSION AND FUTURE WORK

The scope of this thesis was to develop an understanding about the system theory, modern control systems and observer based design of dynamic systems and integrate these concepts with designing a small scale wind turbine system to achieve control actions for enhanced performance of the wind turbine system. A fixed speed variable pitch configuration wind turbine was used and a state space feedback control was designed to maintain a constant speed of generator by varying the pitch of the blades.

The wind energy conversion system comprising of blades, mechanical and electrical parts and pitch control mechanism were modeled and a state space representation of the system was obtained. The state feedback with integral control action was designed followed with design of observer and observer gain matrix L. As all the states of a system cannot be measured, the proportional control was designed to feed the states of the observer via the state feedback gain matrix K. The proportional controller experiences steady state error. Therefore, an integral control action was added to make the system converge to the references set in r which was achieved successfully. The error between the output and the reference was integrated and later controlled via integral control matrix K_I . With the complexity involved and unavailability of sensors for measuring the actual pitch of the blades, state observer was used to estimate the missing state and made the feedback conceivable. The inaccuracies in the system were compensated by the estimation error.

The outputs of the controller were obtained by simulating the controller in MATLAB/Simulink and the results were examined. The velocity control and the pitch control tracking performance was good and resulted in satisfactory conclusion.

$$\Omega_G \approx \Omega_{Gref} \; t \rightarrow \infty$$

$$\beta \approx \beta_{ref} \; t \rightarrow \infty$$

Furthermore, Disturbances were added on the feedback signal from the plant to understand the performance of observer and it coped up with the differences between the estimated output of the plant and the actual output. The white noise or disturbances were also added in order to mimic the effects of real physical system with the controller. Despite the added disturbances, the controller performance was observed to be good and satisfactory results were obtained.

It can be concluded that the proposed, observer-based state feedback controller can be utilized with practical real time application of small scale wind turbine and play a vital role in enhancing the overall system performance.

Future work, can be the practical implementation of the designed observer-based feedback control system with physical wind turbine.

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RESUME

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Education

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2008-2012	Bachelor of Science, Electronic Eng. (CGPA: 3.93/4) Dawood UET, Karachi, Pakistan (www.duet.edu.pk)
2004-2006	Pre-Engineering, Higher Secondary School, (Grade B) Forman Christian College, Lahore, Pakistan (fccollege.edu.pk)

Experience

Jun 2015-Jul 2015	Production Management Intern Coca-Cola Içecek, İzmir, Turkey
Jun 2012-Jul 2012	Engineering Management Intern Pakistan State Oil (PSO), Karachi, Pakistan
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Aug 2010-Sep 2010	Intern Pakistan International Airlines, Karachi, Pakistan

Hobbies and Interests

- R&D, Innovation, New Technologies, Renewable energy
- Traveling and exploring the world
- Digital photography
- Helping people
- Fitness & Sports

APPENDICIES

Appendix A : Parameters of the SSWT

Appendix B : MATLAB commands & scripts

Appendix A

A.1 Torque Coefficient of wind Turbine C_Q

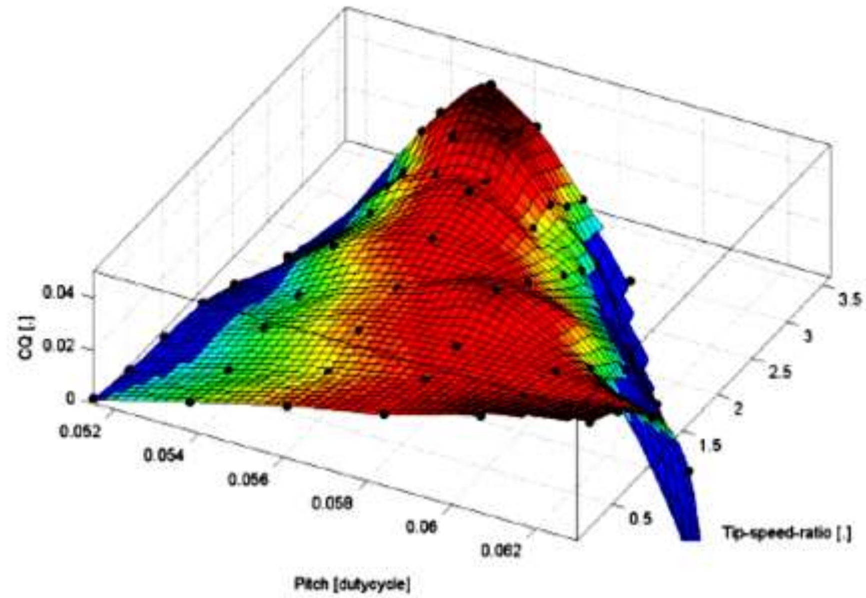

Figure A.1 Graph of the measured points and the interpolated surface for C_Q

A.2 Linearization

Since T_r is a function with non-linearity of both wind speed, rotor speed and pitch angle, it is linearized around a specific operating point. This is performed to make is possible to design a linear state space controller that works in the operating point. The chosen operating points are mentioned as follows:

Table A.1 Operating point for the linearization of the torque obtained by the rotor.

Property	Symbol	Value	Unit
Wind speed	V	4.5	m/s
Rotor speed	$\dot{\Omega}_r$	28	rad/s
Generator speed	$\dot{\Omega}_G$	308	rad/s
Tip-speed-ratio	λ	3.11	-
Pitch angle	β	5.47	% duty cycle

The value of coefficients B_r are K_β are found using the measured CQ curve as can be and resulted in the following linear relation Br = 0.773e-3 and K_β 38:4.

A.3 Wind Turbine Parameters

Table A.2 Small scale wind turbine parameters

Data of the wind turbine		
Description	**Value**	**Unit**
Blade length	0.5	m
Blade weight	0.111	kg
Generator power	15	W
Height	1.2	m
Total weight	19.5	kg
Gear ratio	1:11	
Pitch mode	Collective	-

A.4 Generator/Motor & Gear Parameters

Table A.2 Small scale wind turbine parameters

Property	**Symbol**	**Value**	**Unit**
Torque constant	K	$38.2.10^{-3}$	Nm/A
Terminal resistance	R_G	7.19	Ω
Terminal inductance	L_G	$1.04.10^{-3}$	H
Gear ratio	N	1 : 11	-
Generator inertia	J_G	$4.4.10^{-6}$	kg.m^2
Inertia of generator and gears	J_{GG}	$12.6.10^{-6}$	kg.m^2
Inertia of blades	J_r	186.10^{-6}	kg.m^2
Total inertia of system	J_{tot}	199.10^{-6}	kg.m^2
Viscous friction coefficient	B	$42.4.10^{-6}$	Nm/rad/s

A.5 Q & R matrices selection

Table A.3 The values for the Q and R matrices is obtained by the following list. All values arechosen with regards to the operating point,

	***Q* and *R* Matrices' Values:**
$\boldsymbol{\Omega_{Gmax}}$	17.5, that is the maximum speed-deviation of the generator compared to the operating point, in [rad/s]
$\boldsymbol{\beta_{max}}$	0.008, that is the maximum deviation of the pitch-servo duty cycle compared to the operating point, in [%]
$\boldsymbol{\Omega_{G,I}}$	1, that is a guess of the integral part that influence Ω_G
$\boldsymbol{\beta_I}$	1, that is a guess of the integral part that influence β
$\mathbf{U}_{\boldsymbol{Lmax}}$	8, that is the maximum load voltage on the generator compared to the operating point, in [V]
$\boldsymbol{\beta_{refmax}}$	0.004, that is the maximum allowable pitch-servo duty cycle compared to the operating point, in [%]

All the values are selected considering the operating point, which is: Ω_G= 308rad/s, β = 0.0547, V = 4.5 m/s.

Appendix B

```
clc; clear all; close all;
%% Parameters for wind turbine model

% System paramaters
Jg = 12.6*10^-6;         % inertia for motor rotor, gears and hub
Bg = 42.4*10^-6;         % Viscose friction constant

% Generator/(DC Motor) parameters
Jg = 4.4*10^-6;          % Rotor inertia [kg*cm^2]
Rg = 7.19;               % Motor resistance [ohm]
Lg = 1.04*10^-3;         % Motor ind    nce [H]
Kg = 38.2*10^-3;         % Torque co    nt [Nm/A]
Tc = 9.18*10^-6;         % Coulomb friction

% Applied load parameters
RL = 1;                  % load resistance [Ohm]

% Construction parameters
Jw = 0.0089;           % Inertia of wings (all three)
Rw = 0.50;               % Length of wing [m]
Jr = Jw*3;

% Gear ratio
N = 1/11;

% Wind parameters
rho = 1.2;               % Density at 23 degrees celcius
V = 2;                   % Windspeed

% Total inertia
Jtot = 199*10^(-6);       % The tota    ertia of the system
% Operating point
Omega_rbar = 28;
V_bar = 4.5;
```

```
Beta_bar = 0.0547;

% Br
Br = 7.73*10^-4;
k_rb = 38.44;

%% State space controller
% System matrices

A = [(-(Kg^2+Bg*Rg-N*Rg*Br)/(Rg*Jtot)) N*k_rb/Jtot; 0 -1/tau];
B = [Kg/(Rg*Jtot) 0; 0 1/tau];
C = [1 0];
C1 = [1 0; 0 1];
D = [0 0];D1 = [0 0; 0 0];

sysOL = ss(A,B,C,D);
% Controllability and Observability
Cc = [B A*B]        % Controllability matrix
rank(Cc)
Oc = [C; C*A]       % Observerbaility matrix
rank(Oc)

% PI controller
Ae = [A [0 0; 0 0]; C1 [0 0; 0 0]];
Be = [B; [0 0; 0 0]];
Ce = [C1 [0 0; 0 0]];

% Q and R matrices
% Max state values
OmegaG_max = 17.5;      % rad/sec
beta_max = 0.005;       % Pitch

% Max controller output value
UL_max = 8;
beta_refmax = 0.004;
```

```
% Q matrix
q11 = 1/(OmegaG_max^2);
q22 = 1/(beta_max^2);
q33 = 0.0008*325;          % Integral of Omega_G (guess)
q44 = 500000*325;          % Integral of beta (guess)
Q = [q11 0 0 0; 0 q22 0 0; 0 0 q33 0; 0 0 0 q44]
Q = Q/325

% R Matrix
r11 = 1/(UL_max^2);
r22 = 1/(beta_refmax^2);
R = [r11 0; 0 r22]

% Optimal control
Fe = -lqr(Ae,Be,Q,R);
F = Fe(:,1:2);
FI = Fe(:,3:4);

% Observer design
% controller poles
pc = eig(A+B*F)

% observerpoles 4 times the controller poles
po = 4*[pc(1) pc(2)]
L= -place(A',C',po)'

% Closed loop
Acl = [A B*F B*FI; -L*C A+B*F+L*C B*FI; C1 [0 0 0 0; 0 0 0 0]];
Bcl = [zeros(1,4) 1 -1]';
Ccl = [C1 [0 0 0 0; 0 0 0 0]];
Dcl = [0;0];

sysCL = ss(Acl,Bcl,Ccl,Dcl)
```