POLITECNICO DI MILANO
Faculty of Engineering
Masters of Science in Automation and Control Engineering
Department of Engineering and Informatics

LQG CONTROL OF WiNd TuRbiNe

Supervisor: Prof. Marco Lovera

Master's Thesis of:

Usman Shahzad
Matricola no. 769342

Academic Year: 2012-2013

Acknowledgements

I would like to sincerely thank my research advisor, Prof. Marco Lovera for being a patient mentor over the course of my degree completion. His guidance and constant support helped me to stay motivated. I learnt a great deal from him about scientific writing and problem solving in the area of control system.

Last but not least I wish to avail this opportunity and express a sense of gratitude and love to my beloved parents and friends for their manual support, strength, help and for everything especially my beloved sister Farah for giving me moral support during my stay in Italy. The love and support given by them all has been a real source of strength and comfort throughout my work.

USMAN SHAHZAD

TABLE OF CONTENTS

CHAPTER

Nomenclature

WS	[m/s]	-	Instantaneous wind speed
T_r	[N.m]	-	Mechanical torque from rotor
ω_r	[rad/s]	-	Rotational speed of Rotor
ω_g	[rad/s]	-	Angular speed for generator shaft
T_e	[rad/s]	-	Electrical Torque from generator
P_g	[watt]	-	Power generated
C_p	[-]	-	Performance co-efficient
λ	[-]	-	Tip-Speed Ratio
R	[m]	-	Radius
V_{wind}	[m/s]	-	Wind Speed
P_w	[watt]	-	Power available in the wind for turbine
J_T	[Kg.m^2]	-	Rotational Inertia
ρ	[Kg/m^3]	-	Air density
C_q	[-]	-	Torque Co-efficient
β	[-]	-	Blade-pitch Angle

Acronyms

ARE	Algebraic Riccati Equation
CAE	Computer-Aided Engineering
CART	Control Advanced Research Turbine
FAST	Fatigue, Aerodynamic, Structure, Turbulence
HAWT	Horizontal-axis Wind Turbine
LQG	Linear Quadratic Gaussian
LQR	Linear Quadratic Regulator
LTP	Linear Time Periodic
NREL	National Renewable Energy Laboratory
PID	Proportional Integral Derivative

LIST OF FIGURES

LIST OF GRAPHS

LIST OF DIAGRAMS

Abstract

Wind energy is one of the fastest growing renewable energies in the world. The generation of power from wind turbines is non-polluting; it doesn’t produce any by-products.

In the early developments, researchers worked on fixed-speed wind turbines. But nowadays, large number of variable-speed wind turbines is getting installed in wind farms and manufactures are focusing on variable speed wind turbines. Hence controllers are getting their attention to provide their services for non-linear systems such as variable-speed wind turbines.

This thesis describes a control technique and its implementation to the system in order to optimize the system’s performance. The system is controlled by the class of state feedback and output feedback controllers to generate the constant speed of wind turbine irrespective of wind inflow. In the high wind speed region, the wind turbine is controlled using Linear Quadratic Gaussian (LQG) controller to maintain the uniform motion of wind turbine. The unusual behavior of turbine tackled by the controller and imposed to the system to move uniformly in one direction at high speed operation by maintaining the constant rotation. By doing so, we can produce smooth electrical curve without any considerable fluctuation up to the nominal value.

The controller implemented on the models which are linearized and time variant extracted by the FAST code.

Keywords: *Wind Turbines, LQG controller, Multivariable System*

Chapter 1

INTRODUCTION

1.1 Work Motivation

Wind energy is one of the fastest growing renewable energies in the world. The generation of wind power is clean and non-polluting; it does not produce any byproducts harmful to the environment.

Nowadays, modeling is the basic tool for analysis, such as optimization, project, design and control. Wind energy conversion systems are very different in nature from conventional generators and therefore dynamic studies must be addressed in order to integrate wind power into the power system. According to [1], in the case of power systems with classical sources of energy analysis, the modeling is relatively simple because the models of objects and controllers are well known and even standardized; the data are available. But in the case of wind turbine modeling, researchers meet problems related to the lack of data and lack of control-system structures due to strong competition between wind turbine manufacturers. This leads to the situation in which many researchers model the wind energy conversion systems in relatively simple form, almost neglecting the control systems, which significantly influence the reliability of the analytical results.

Classical techniques such as proportional (P), integral (PI) and derivative (PID) controllers are typically used to regulate wind power. But by assuming the wind turbine operating in steady state conditions, most of the previous work regarding wind turbine control does not take into consideration the dynamical aspects of the wind and the turbine, which have strong non-linear characteristics [2]. Advances in wind turbine technology made necessary the design of more powerful control systems, to improve wind turbines behavior and make them more profitable and reliable [3]. However, as stated in [2] "Controlling modern turbines to minimize the cost of wind energy is a complex task, and much research remains to be done to improve controllers". An interesting characteristic of wind energy systems is that wind speed determines the point of operation; it simply defines the available amount of energy that can be converted into electricity. The wind cannot be controlled; in other words the system is driven by noise, which makes wind turbine systems essentially different from most other systems. This explains the need for robust controller design [4]. On the other hand, theoretically, the electrical output from a wind turbine should be smooth and non-fluctuating [5]. But electricity generated from wind farms can be highly variable on different time scales: from hour-to-hour, daily and seasonally. This represents a considerable challenge when incorporating wind power into a grid system, since in order to maintain grid stability energy supply and demand must remain in balance.

1.2 Work Objective

The main objective of this work is to contribute to the topic of wind energy systems. Designing the controller for the models developed by FAST code, an aeroelastic Computer-aided Engineering tool for horizontal axis wind turbines [23]. The model is periodic and linearized, about its operating point, which is extracted from non-linear wind turbine model by FAST.
The scientific objectives of this research include the following:

- Designing a LQG controller to keep constant the speed of wind turbine irrespective of wind inflow. The only control variable to whom we are concern is blade pitch angle for a variable speed wind turbine
- Simulation of the overall wind energy system in MATLAB.

As anticipated above that PI/PID techniques don't give considerable results for dynamic time variant system so we inclined our self towards Linear Quadratic Gaussian Controllers (LQG).

The LQG controllers basically connect the Kalman estimator with the optimal state-feedback gain designed. More detail about LQG controller is given in the Chapter 3.

1.3 Wind Turbine Developments and Types of Wind Turbines

1.3.1 Wind Turbine History

Wind-powered machines have been used by humans for thousands of years. Until the 20th century wind power was used to provide mechanical power to pump water or to grind grain. The earliest recorded windmills are vertical-axis mills and were used in Afghanistan in the seventh century BC. Horizontal-axis windmills are found in historical documents from Persia, Tibet and China around 1000 AD. From Persia and the Middle-East, the horizontal-axis windmill spread across Europe in the 12th century, where windmill performance was constantly improved; by the 19th century a considerable part of the power used in the industry in Europe was based on wind energy. Industrialization then led to a gradual decline in windmills, as the use of fluctuating wind energy was substituted by fossil fuel fired engines which provided a more consistent power source [6]. In the 1970s, with the first oil price shock, the modern era of wind turbine generators began, focusing in producing electricity instead of mechanical energy.

In recent years there has been a growing interest in wind energy power systems because of the environmental benefits and the economic benefits of fuel savings [7]. The wind is a clean source and it will never run out. Wind energy technology is developing fast; turbines are becoming cheaper and more powerful, bringing the cost of renewably-generated electricity down [8]; The cost of generating electricity from wind has fallen almost 90% since the 1980s [9]. Nowadays, wind energy is one of the most important sustainable energy resources and has become an acceptable alternative for electrical energy generation by fossil or nuclear power plants [4].

1.3.2 State-of-the-art Technologies

1.3.2.1 Definition of Wind Turbines:

A wind turbine is a machine for converting the kinetic energy in the wind into mechanical energy. If the mechanical energy is used directly by machinery, such as a pump or grinding stones, the machine is called a windmill. If the mechanical energy is then converted to electricity, the machine is called a wind generator. Utility-scale turbines range in size from 100 kilowatts to several megawatts [10].

1.3.2.2 Horizontal-axis and Vertical-axis Wind Turbines:

Wind turbines can further be classified into horizontal-axis or vertical-axis. The earliest windmills in antiquity rotated about a vertical axis and they were driven by drag. Modern vertical-axis turbines use vertical symmetrical airfoils and the driving force is produced by lift developed by the blade in the moving air stream. The only vertical-axis turbine which has been manufactured commercially at any volume is the Darrieus machine, named after the French engineer Georges Darrieus who patented the design in 1931. The conventional Darrieus turbine has curved blades connected at the top and at the bottom and rotates like an “egg whisk” [11], as illustrated in Figure 1.1.

Figure 1.1 Vertical-axis Wind Turbine [12]

Vertical-axis wind turbines have the advantages that no tower is needed, they operate independently of the wind direction (a yawning mechanism is not needed) and heavy gearboxes and generators can be installed at ground level. But they have many disadvantages: they are not self-starting, the torque fluctuates with each revolution as the blades move into and away from the wind, and speed regulation in high winds can be difficult. Vertical-axis turbines were developed and commercially produced in the 1970s until the end of the 1980s. But since the end of the 1980s the research and production of vertical-axis wind turbines has practically stopped worldwide [6].

At present, horizontal-axis wind turbines dominate the market; Figure 1.2 illustrates the different configuration between a horizontal-axis and a vertical axis turbine.

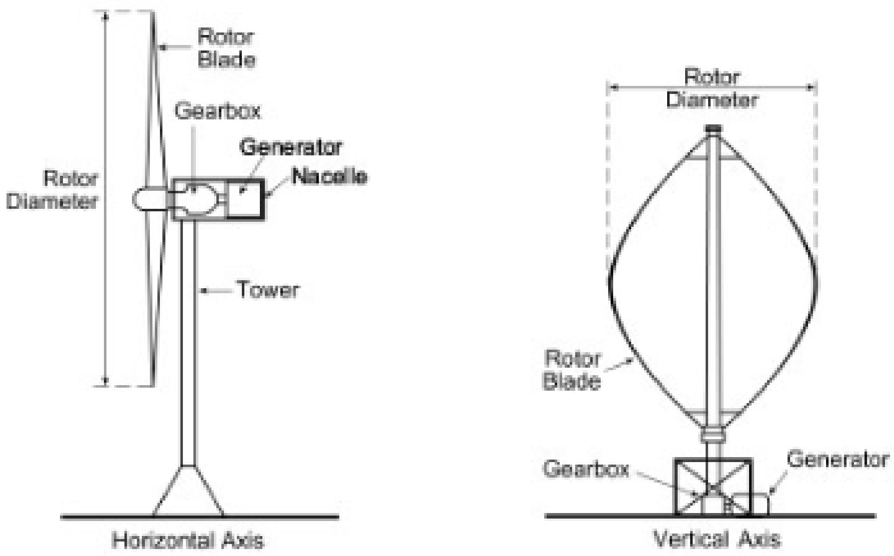

Figure 1.2 Horizontal-axis and Vertical-axis Wind turbines [13]

1.3.2.3 Variable-Speed and Constant-Speed Wind Turbines:

A final distinction is whether the rotor is allowed to run at variable speed or constrained to operate at *constant speed*. In the early 1970s wind turbines usually operated at constant speed. That means that regardless of the wind speed, the wind turbine's rotor speed is fixed. Constant speed wind turbines allow the use of simple generators whose speed is fixed by the frequency of the electrical network. For variable speed wind turbines, a power electronic frequency converter is required in order to connect the variable-frequency output of the wind turbine to the fixed frequency of the electrical system. Although the power electronics needed for variable speed wind turbines are more expensive, this type of turbines can spend more time operating at maximum aerodynamic efficiency than constant speed turbines [2]. This can be seen clearly if the performance coefficient, C_p of a wind turbine is plotted against the tip speed ratio λ.

The tip speed ratio λ, is defined as the ratio between the speed of the tips of the blades of a wind turbine and the speed of the wind

$$\lambda = \frac{v_{tip}}{v_{wind}} = \frac{\omega R}{V} \qquad (1.1)$$

Whereas, ω is the blades angular velocity (rad/s), R the rotor radius (m) and υ the wind speed (m/s).

The coefficient of performance, Cp, is defined as the fraction of energy extracted by the wind turbine of the total energy that would have flowed through the area swept by the rotor if the turbine had not been there

$$C_p = \frac{P_{EXTRACTED}}{P_{WIND}} \qquad (1.2)$$

The coefficient of performance C_p has a theoretical optimum of 0.59. Only a portion of the power in the wind can be converted to useful energy by a wind turbine. The power available for a wind turbine is equal to the change in kinetic energy of the air as it passes through the rotor. This maximum theoretical C_p was first formulated in 1919 by Betz and applies to all types of wind turbines. It is conventional to plot the variation of the performance coefficient C_p against the tip speed ratio λ rather than against the wind velocity, as this creates a dimensionless graph. A typical C_p vs. λ curve is shown in Figure 1.3.

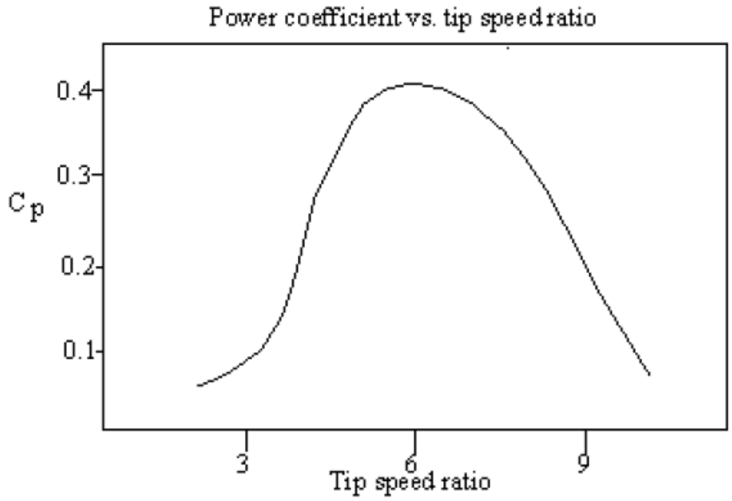

Figure 1.3 C_p vs. λ for a typical wind turbine [16]

This curve illustrates that the maximum value of C_p is only reached for a specific λ (approximately 6 in this example). For a fixed-speed wind turbine, where ω is constant, this corresponds to a particular wind speed. For all other wind speeds the efficiency of the turbine is reduced [14]. The aim of variable-speed wind turbines is to always run at optimal efficiency, keeping constant the particular λ that corresponds to the maximum C_p, by adapting the blades velocity to the wind speed changes. Hence, variable speed wind turbines are designed to operate at optimum energy efficiency, regardless of the wind speed. On the other hand, due to the fixed-speed operation for constant speed turbines, all fluctuations in the wind speed are transmitted as fluctuations in the mechanical torque and then as fluctuations in the electrical power grid [17]. This, together with the increased energy capture obtained by using a variable-speed wind turbine provides enough benefit to make the power electronics (frequency converter) cost effective [2]. Therefore, the wind industry trend is to design and construct variable-speed wind turbines.

1.3.3 Power Control and Wind Turbine Power output

1.3.3.1 Power Control

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

$$P_w = \rho Av\frac{1}{2}v^2 = \frac{1}{2}\rho Av^3 \qquad (1.3)$$

Where ρ is the air density (kg/m3), A is the area (m2) and v is the wind speed (m/s), and
P_w *is* the power of the wind (watts or J/s).

From equation (1.3), the power available from the wind is a function of the cube of the wind speed. That means that a doubling of the wind speed gives eight times the power output from the turbine. Therefore, turbines have to be designed to support higher wind loads than those from which they can generate electricity, to prevent them from damage. Wind turbines reach the highest efficiency at a wind speed between 10 and 15m/s. above this wind speed, the power output of the rotor must be controlled to reduce driving forces on the rotor blades as well as the load on the whole wind turbine structure [6]. High winds occur only for short periods and hence have little influence in terms of energy production but, if not controlled, they would dominate the design and cost of the drive train and the generator [11].

Accordingly, all wind turbines are designed with a type of power control. There are different ways to control aerodynamic forces on the turbine rotor and therefore limit the power in high winds in order to avoid damage to the wind turbine [17].

1.3.3.2 Wind turbine power output

The figure 1.4 below shows a sketch how the power output from a wind turbine varies with the wind speed.

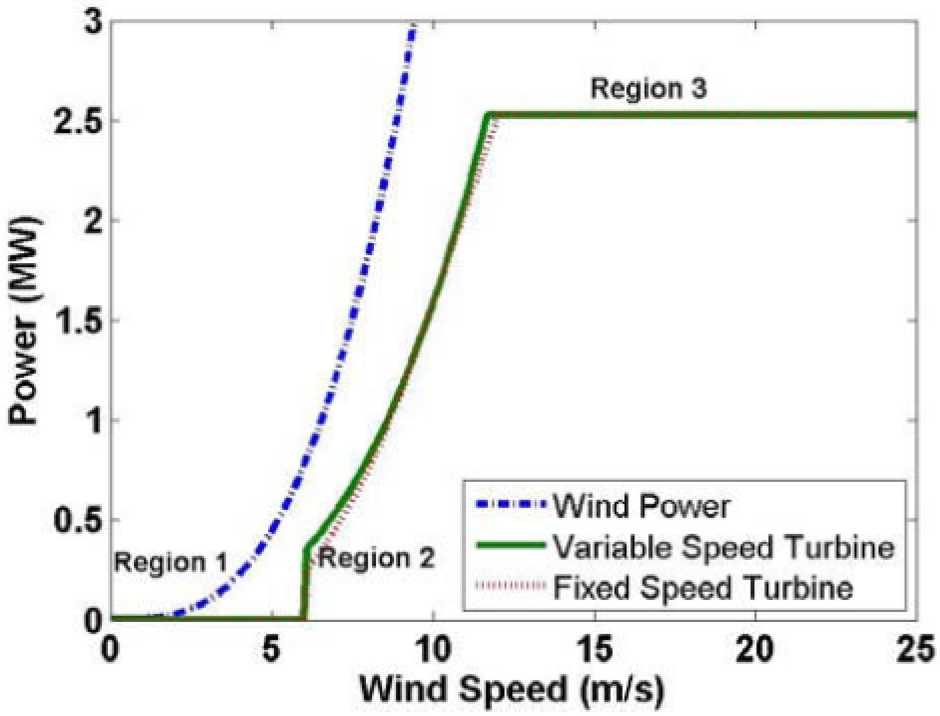

Figure 1.4: Curve between Power (kw) and Wind Speed (m/s) [15]

Basically, the turbine curve can be distributed in three different regions i.e. 1) cut-in wind speed, 2) Rated-wind speed and 3) cut-out wind speed or storm protection shutdown

1.3.3.2.1 Cut-in Wind Speed

At very low wind speed, there is insufficient torque exerted by the wind on the turbine blades to make them rotate. However, as the speed increases, the wind turbine will begin to rotate and generate electrical power. The speed at which the turbine first starts to rotate and generate power is called the cut-in speed and is typically between 3 and 4 meter per second [15].

1.3.3.2.2 Rated output Power and rate output wind speed

As the wind speed rises above the cut-in speed, the level of electrical output power rises rapidly as shown in figure 1.4. However, typically somewhere between 10 and 15 meters per second, the power output reaches the limit that the electrical generator is capable of. This limit to the generator output is called the ***rated power output*** and the wind speed at which it is reached is called ***the rated output wind speed***. At higher wind speeds, the design of the turbine is arranged to limit the power to this maximum level and there is no further rise in the output power. How this is done varies from design to design but typically with large turbines, it is done by adjusting the blade angles so as to keep the power at the constant level [15].

1.3.3.2.3 Cut-out speed or storm protection shut-down

As the speed increases above the rate output wind speed, the forces on the turbine structure continue to rise and, at some point, there is a risk of damage to the rotor. As a result, a braking system is employed to bring the rotor to a standstill. This is called the cut-out speed and usually around 25 meters per second as shown in the figure 1.4 above [15].

Chapter 2

Problem Statement and Mathematical Modeling

2.1 Problem Statement

The wind turbine is a device for conversion of kinetic energy in the wind into electricity [18]. Although there are many different configurations of wind turbines systems they all work in the same way. The available power originates from the mass of the moving air, referred to as the wind speed. The transformation to mechanical torque is done by aerodynamically forces acting on the rotors blades, the actuator disc. The wind turbine shaft then transports the power to the generator which is connected to the electrical grid. Usually there is a gearbox between the slowly rotating turbine shaft and the more rapidly rotating generator shaft. This is described by the model shown in Figure 2.1

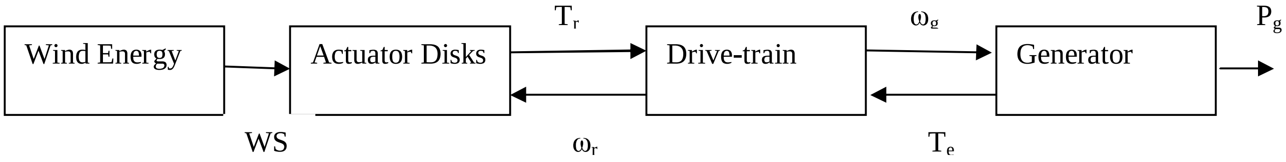

Figure 2.1: Block diagram scheme for the functioning of wind turbine

The differential heating of the earth’s atmosphere is the driven mechanism for wind. Various atmospheric phenomenon, such as nocturnal low-level jet, sea breezes, frontal passages, mountain and valley flows, affect the wind inflow across a wind turbine’s rotor plane [19]. Given the large rotor plane and the variability of the wind, hundreds of sensors would be required to characterize the spatial variation of the wind speed encountering the entire span of each blade.

Due to the fact of change in wind speed, we need to take care of the rotational speed of wind turbine which will further take care of the output energy. Using of controllers instead of sensors for the dynamic behavior of system is a good practice.

2.1.1 Turbine Control Loops:

In designing controllers for wind turbines, it is often assumed as in equation (1.3) that the wind speed is uniform across the rotor plane. However, as shown by the instantaneous wind field in figure 2.2, the wind input may vary in space and time over the rotor plane. The deviations of the wind speed from the nominal wind speed across the rotor plane can be considered disturbances for control design.

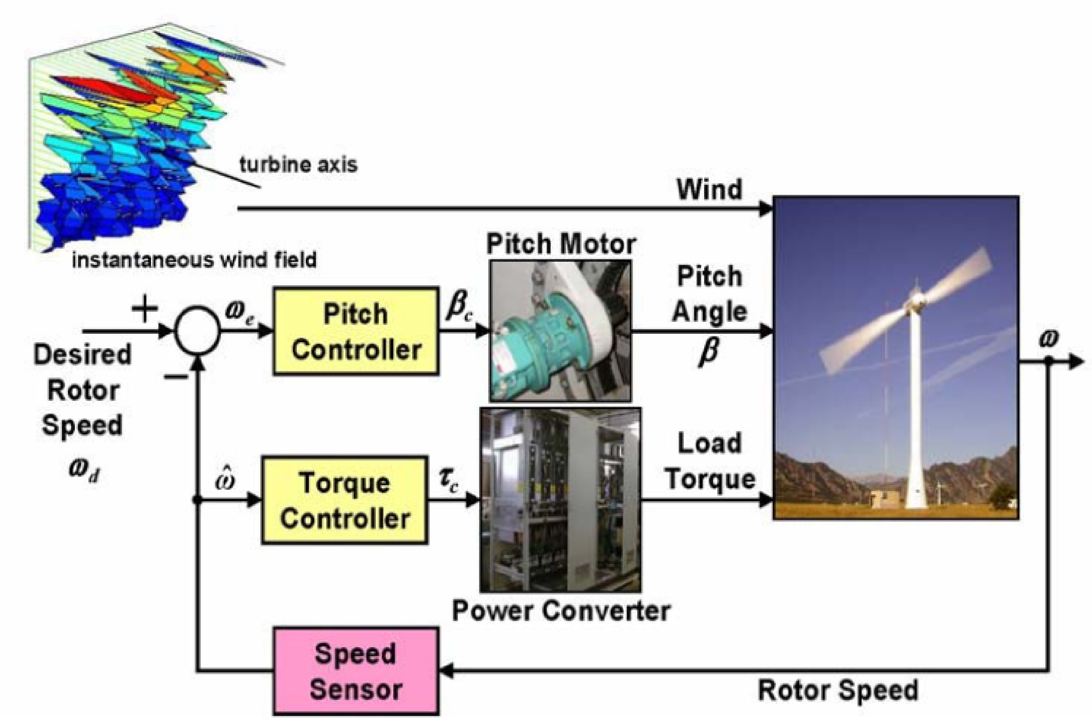

Figure 2.2 Wind turbine control feedback loops [20]

Referring to the figure above, the wind speed varies across the rotor plane; wind speed point measurements convey only a small part of the information about the wind inflow. The desired rotor speed get in to the pitch and torque controller and these controllers provides the new input to the pitch motor and power converter respectively. Then further it is imposed to the wind turbines. Hence, rotor speed is the only measurement required for the baseline generator torque and blade-pitch controllers [20] and we will mainly focus on Pitch controller

In order to tackle the variability of wind and to prevent the wind turbine it is required to change the pitch angle of the turbine on run time i.e. to keep the rated speed of wind turbine constant while change wind and decreases the speed of turbine to avoid damage to the turbine. By doing so, as per stated in [21], we can control,

- To alleviate the transient loads throughout the wind turbine.
- To regulate and smooth the power generated
- To maximize the energy capture

Maximizing energy capture relates to the variable speed operation regime. Power regulation is performed in above-rated wind speed conditions in region 3 as shown in fig. 1.4, which is the focus of this research. Competing specifications of maintaining constant rotational speed while minimizing actuator motion, the control objectives of this study, dominate this design as well.

2.2 Dynamic Modeling

Modeling is a basic tool for analysis, such as optimization, project, design and control. Wind energy conversion systems are somehow different in nature from usual generators which are normally available, and therefore special attention must be carry out to integrate wind power into the power system. Models utilized for steady-state analysis are extremely simple, while the dynamic models for wind energy conversion systems are not easy to develop. Dynamic modeling is needed for various types of analysis related to system dynamics: stability, control system and optimization.

When only the rotor speed is of interest, the fundamental dynamics of this variable-speed wind turbine are captured with the following simple mathematical model:

$$J_{T\dot{\omega}_T} = \tau_{aero} - \tau_{load} \qquad (2.1)$$

Or,

$$\dot{\omega}_T = \frac{1}{J_T}\tau_{aero} - \tau_{load} \qquad (2.2)$$

Whereas, ω is the rotor velocity, J_T is the rotational inertia of the turbine, τ_{aero} is the aerodynamic torque, and τ_{load} is the electrical load.

As stated in the previous chapter, the tip-speed ration of the tangential speed of the blade tip to wind speed is given as:

$$\lambda = \frac{\omega R}{V} \qquad (2.3)$$

Where R is the rotor radius, the instantaneous wind speed v is time varying, and the rotor angular velocity ω, most commonly known as the rotor speed, is time varying for variable-speed turbine.

As the generator moment of inertia of a direct-drive turbine is generally several orders of magnitude less than J_T, it has been neglected. The aerodynamic torque, τ_{aero}, is represented by:

$$\tau_{aero} = \frac{1}{2}\rho A R c_q(\lambda, \beta) v^2 \tag{2.4}$$

The air density, ρ, swept area of the rotor, A, and rotor radius, R, are constant. The torque coefficient, c_q , is a highly non-linear function of tip-speed ratio, λ, and blade-pitch angle, β as illustrated in figure 2.3. The tip-speed ratio is defined as the ratio of the blade tip speed to the prevailing wind speed. The surface presented in Figure 2.3 shows only positive values of cq because the turbine operates most often in this region [22]

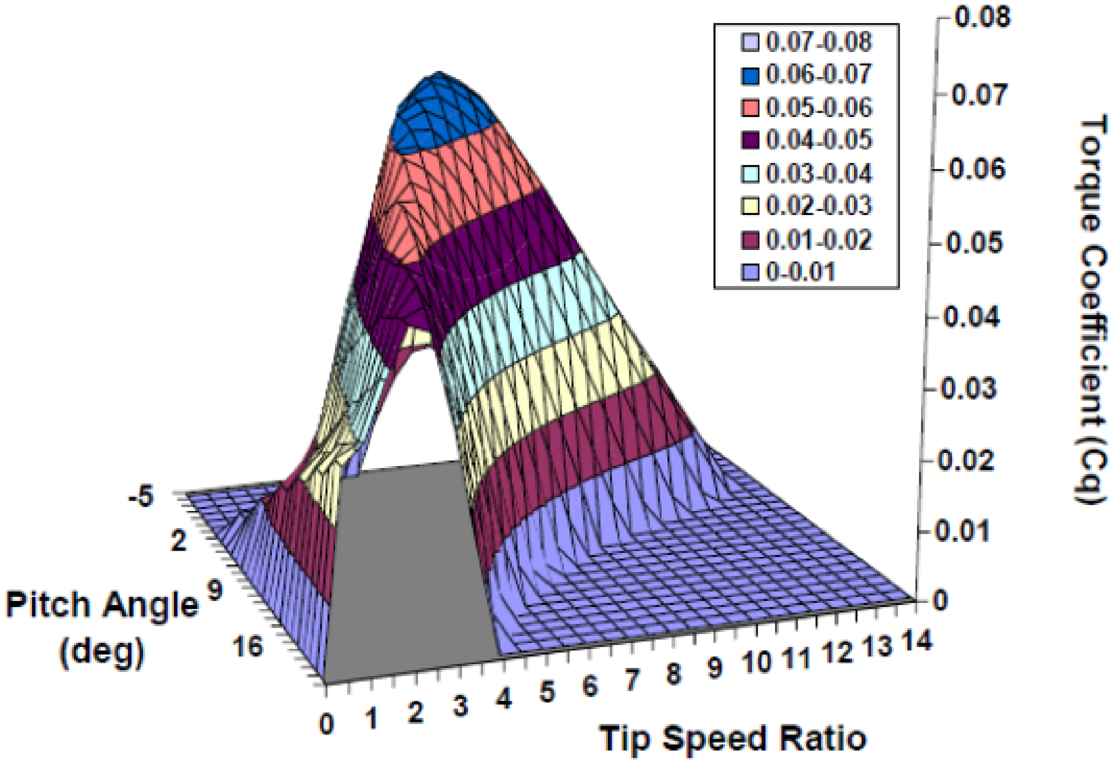

Figure 2.3: Torque coefficient surface as a function of tip-speed ratio and blade-pitch angle. All negative Cq values have been set to zero [22]

Also the relationship between the power coefficient C_p and the tip-speed ratio λ is a turbine-specific nonlinear function but usually has a downward parabolic shape. Torque co-efficient C_q is related with the power co-efficient C_p as,

$$C_p(\lambda,\beta) = \lambda . C_q(\lambda,\beta) \tag{2.5}$$

And hence the aerodynamic torque is then given as:

$$\tau_{aero} = \frac{1}{2\lambda}\rho ARC_p(\lambda,\beta)\nu^2 \tag{2.6}$$

Linearizing τ_{aero} around the operating point $(\omega_{op,}\ \beta_{op},\ \upsilon_{op})$ yields

$$\tau_{aero} \backsimeq \tau_{aero_{op}} + \Gamma_\omega \delta\omega + \Gamma_\beta \delta\beta + \Gamma_\upsilon \delta\upsilon \tag{2.7}$$

Whereas, $\Gamma_\omega = \frac{\partial\tau_{aero}}{\partial\omega}|_{\omega=\omega op}$, $\Gamma_\beta = \frac{\partial\tau_{aero}}{\partial\beta}|_{\beta=\beta op}$ and $\Gamma_\upsilon = \frac{\partial\tau_{aero}}{\partial\upsilon}|_{\upsilon=\upsilon op}$

A pitch controller can be designed based on the pitch-angle perturbation $\delta\beta$ to regulate rotor speed, where the perturbed wind speed $\delta\upsilon$ is the disturbance.

Referring to figure 1.4, region 3 control is typically performed by means of pitch control loop such as the one shown in figure 6. On utility-scale wind turbines, Region 3 control is typically performed via a separate pitch control loop, it basically regulates the rotor speed, as shown in Fig. 2.2. In Region 3, the primary purpose is to limit the turbine power so that safe electrical and mechanical loads are not exceeded. Power limitation can be achieved by pitching the blades or by yawing the turbine out of the wind, both of which can reduce the aerodynamic torque below what is theoretically available from an increase in wind speed [20]. If the power and rotor speed are held constant, the aerodynamic torque τ_{aero} must also be constant even as wind speed varies. It is desirable to produce as much power as the turbine can safely produce, the limit of which is known as the turbine's rated power

Power limitation through speed regulation is the ultimate purpose for the controller, it is important to recognize the relationship between the power coefficient and the torque coefficient. Power extracted from the wind is shown in the following equation:

$$P = o.5\,\rho A C_p(\lambda, \beta) v^3 \qquad (2.8)$$

2.2.1 Torque Control:

Various kind of torque controllers are used by the wind industry. A standard torque controller used on Control Advance Research Turbine (CART3) sets the generator torque τ_{load} [20] in equation (2.2) as

$$\tau_{load} = K\omega^2 \qquad (2.9)$$

Where K is given by

$$K = \frac{1}{2}\rho\pi R^5 \frac{C_{p_{max}}}{\lambda_*^3} \qquad (2.10)$$

And λ_* is the tip-speed ratio at the maximum power coefficient$C_{p_{max}}$.

The torque control given by (2.9) and (2.10) can be shown to achieve $C_{p_{max}}$ to analyze the closed-loop system, we combine from equation (2.1) to (2.10) to obtain

$$\dot{\omega_T} = \frac{1}{2J_T}\rho\pi R^5 \omega^2 \left(\frac{C_p}{\lambda^3} - \frac{C_{p_{max}}}{\lambda_*^3}\right) \qquad (2.11)$$

It follows from (2.11) that, if $C_p < ({C_{p_{max}}}/{\lambda_*^3})\lambda^3$, then $\dot{\omega}_T<0$. On the other hand, if $C_p > ({C_{p_{max}}}/{\lambda_*^3})\lambda^3$, then $\dot{\omega}_T>0$. Thus, the control law given by (2.9) and (2.10) causes the turbine to accelerate toward the desired setpoint λ_* when the rotor speed is too slow and decelerate when the rotor speed is too fast. The representation in (2.11) is shown graphically in figure 2.4.

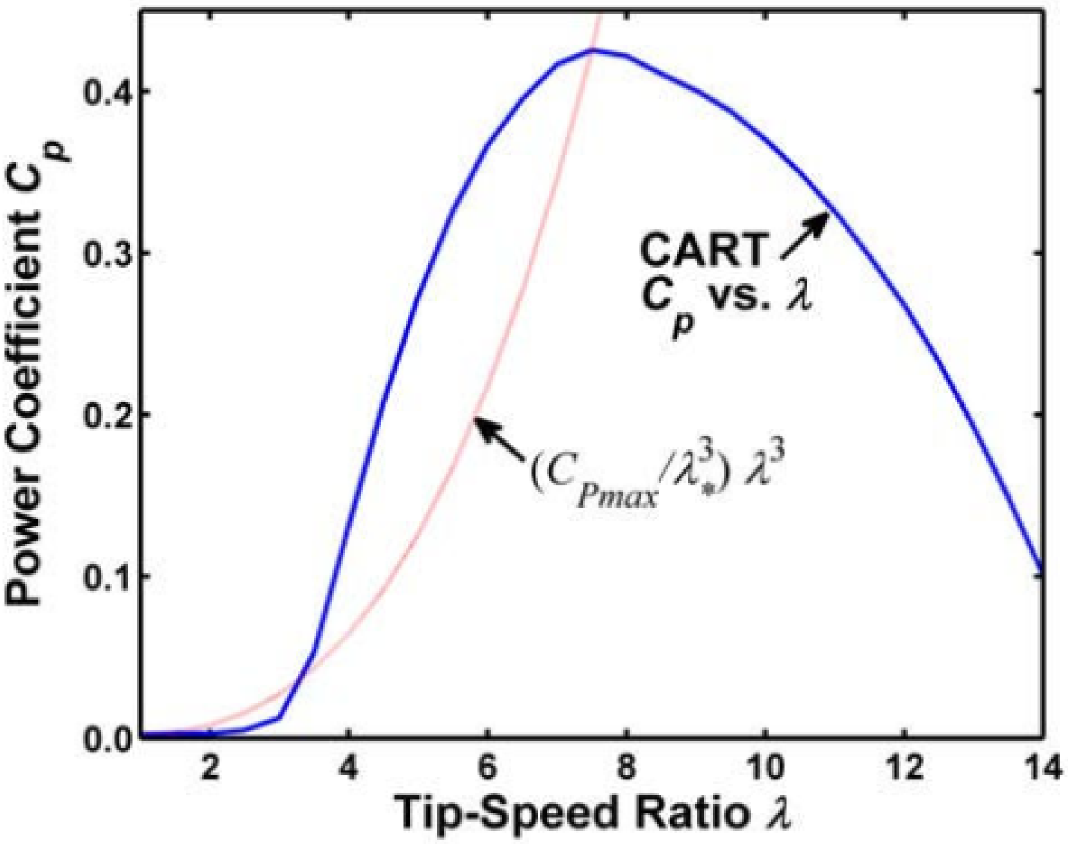

Figure 2.4: Plot of C_p versus λ for CART3. The blade pitch angle is fixed at β= -0.75°. the turbine accelerates towards the optimal tip-speed ratio λ_* when the red dashed curve representing (2.11) is less than the blue solid curve and decelerates when the opposite is true [20]

2.2.2 Simulation Models:

The Models for the wind turbine that has been used for the simulations are produced by FAST. FAST (Fatigue, Aerodynamics, Structure, and Turbulence) is basically an aeroelastic Computational-Aided Engineering (CAE) tool, developed and sponsored by NREL (National Renewable Energy Laboratory), used the model of three-bladed horizontal axis wind turbine (HAWT). FAST code is comprehensive aeroelastic simulator capable of anticipating both extreme and fatigue loads of two and three-bladed horizontal axis wind turbine [23].

The model contains numbers of degree of freedoms (DOFs). FAST extracted these models which are then linearized from non-linear aeroelastic wind turbine models. The linearization has been done in two steps. In the first step, it computed periodic steady state operating point condition for the DOFs and then in the next step, numerically linearized the FAST model about this operating point to form periodic state matrices. The code is designed for onshore Horizontal axis wind turbines [23]. For further detail about the mechanical structure and its behavior consult the reference.

The dynamic system has 10 state variables ($\dot{x}_i$), and hence this is the 10th order system. The names of the state variables are;

i. 1st Tower Fore-Aft Bending Mode Tip Displacement (m)
ii. Rotor Position (rad)
iii. Blade1 1st Flapwise Bending Mode Tip Displacement (m)
iv. Blade2 1st Flapwise Bending Mode Tip Displacement (m)
v. Blade3 1st Flapwise Bending Mode Tip Displacement (m)
vi. 1st Tower Fore-Aft Bending Mode Tip Velocity (m/s)
vii. Rotor Speed (rad/s)
viii. Blade1 1st Flapwise Bending Mode Tip Displacement (m/s)
ix. Blade2 1st Flapwise Bending Mode Tip Displacement (m/s)
x. Blade3 1st Flapwise Bending Mode Tip Displacement (m/s)

And the system has 5 inputs (u_i) named as;

1. Horizontal Hub-height Wind Speed (m/s)
2. Electrical Generator Torque (N.m)
3. Blade1 Pitch Angle (rad)
4. Blade2 Pitch Angle (rad)
5. Blade3 Pitch Angle (rad)

So there are 7 output states (y_i) which are given as;

1. Rotor Speed (rpm)
2. Blade1 Flapwise Root Bending Moment (kN.m)
3. Blade2 Flapwise Root Bending Moment (kN.m)
4. Blade3 Flapwise Root Bending Moment (kN.m)
5. Tower Base Fore-Aft Bending Moment (kN.m)
6. Tower Bade Side-to-Side Bending Moment (kN.m)
7. Drivetrain Low Speed Shaft Torque (kN.m)

Hence by summarizing all we have,

$$\dot{x}(t) = A(t)x(t) + B(t)u(t)$$
$$y(t) = C(t)x(t) + D(t)u(t)$$

$x(.)$ is called the "state vector", $x(t) \in \mathbb{R}^n$
$y(.)$ is called the "output vector", $y(t) \in \mathbb{R}^q$
$u(.)$ is called the "input (or control) vector", $u(t) \in \mathbb{R}^p$
$A(.)$ is the "state (or system) matrix", $\dim[A(.)] = n \times n$
$B(.)$ is the "input matrix",$\dim[B(.)] = n \times p$
$C(.)$ is the "output matrix", $\dim[C(.)] = q \times n$
$D(.)$ is the " feedforward matrix", $\dim[D(.)] = q \times p$

Whereas in our model;

$$n = 10; \qquad p = 5; \qquad q = 7$$

Chapter 3

Controller Design and Methodology

This chapter will discuss the control strategies and methodology that have adopted to implement the controller on the models which are extracted by FAST code.

As the model is structured as interconnected subsystems models i.e an aerodynamics, a mechanical, electrical, dampers and so on but the dominant part for the wind turbine is lie in mechanical subsystem. Also the mechanical structure that FAST code used is the combination of rigid and flexible joints, so the amount of these joints determines the order of the model. Hence, the number of degree of freedoms increases and so the order of the model increases too.

As stated in chapter 2, the energy from the wind is not constant due to inflow of wind and the power of wind turbine is proportional to the cube of the wind speed i.e. ($P = \frac{1}{2}\rho A v^3$), which causes to fluctuate the generated power. Generally, the electrical power should be non-fluctuating. So to conquer this problem, a blade pitch control approach should be developed. With this control, the power captured from the wind power can be controlled by a pitch actuator.

As the wind speed increases, the power generated by the wind turbine also increases. Once we achieve the maximum rated power, the pitch angle is increased to reduce the power coefficient and so the aerodynamic power pitch angle is a controlled variable.

3.1 LQG Approach

The models that we are using contains number of degree of freedoms which in turns means we are dealing with Multiple input and Multiple output (MIMO) system. The models are linear time periodic too so the classical techniques such as Proportional (P), Proportional-Integrator (PI) are not sufficient. Special attention should be turned towards the class of state-feedback controllers. These classes of controllers are inherently suited for MIMO systems. A particular design technique which is suitable for Linear Time Periodic (LTP) MIMO system is LQG (Linear Quadratic Gaussian) design, that provides stable closed-loop system and allows us to tune it in intuitive manner. The control problem is stated as quadratic minimization problem.

3.1.1 LQG Controller Design

The implication of LQG design provides a reliable design procedure that assures the stability for the linearized closed-loop system model. Figure 3.1 shows the block diagram for the system that is implied by the state feedback controller.

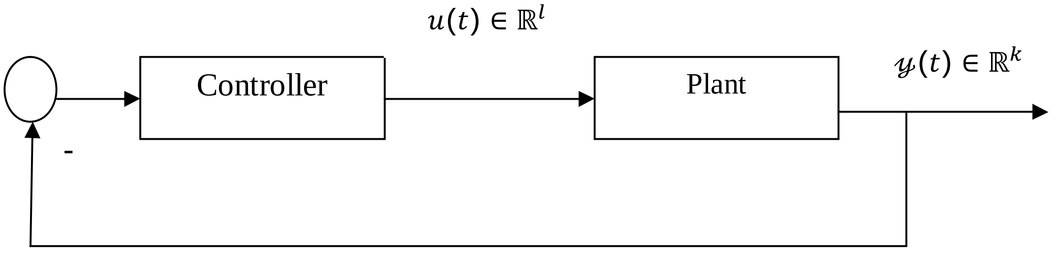

Figure 3.1: Linear quadratic regulation (LQR) feedback configuration

In the figure above the state space of the plant is given as:

$$\dot{x}(t) = A(t)x + B(t)u \qquad (3.1)$$

$$y(t) = C(t)x$$

Whereas, A(.) is time periodic state matrix.

The combined controller including an LQR (optimal linear quadratic regulator) and Kalman estimation is usually called the Linear Quadratic Gaussian (LQG) controller.

Linear Quadratic Gaussian (LQG) controller shows good performance and robustness in the design applied to wind turbines. Typically, in LQG method, it is necessary to select weighting matrices in order to solve the Algebraic Riccati Equations and get the possible best solution by connecting Kalman estimation and optimal state-feedback. Hence the LQG design is the combination of linear optimal gain and the state estimators. LQG is generally not robust, but it t always gives a good results when the model of the system is reasonably accurate [24].

LQG design is performed in two major steps first is to determine the state-feedback $u = -Kx$ that minimizes the quadratic cost function:

$$J(u) = \int_0^\infty (x^T Qx + u^T Ru + 2x^T Nu)dt \qquad (3.2)$$

Whereas J(u) is the cost function that will be reduced by the state-feedback. Also Q>0 and R>0 are the weighting matrices. It is well known that the state-feedback gain K is given as:

$$K = R^{-1}(B^T S + N^T) \qquad (3.3)$$

And S≥0 is the solution of the associated Riccati Equation:

$$A^T S + SA - (SB + N)R^{-1}(B^T S + N^T) + Q = 0 \qquad (3.4)$$

Q, R, and N are the weighting matrices discussed in the next section.

In the next step it is required to design a kalman filter. Kalman state estimator estimates the states for the given Plant model shown below and the process and measurement noise covariance data.

$$\dot{x} = Ax + Bu + Gw \qquad \text{(State equation)}$$

$$y = Cx + Du + Hw + v \qquad \text{(Measurement noise)}$$

With inputs u, white process noise w, and white measurement noise v.

The optimal solution is the filter with equation:

$$\hat{\hat{x}} = A\hat{x} + Bu + \dot{L}(y - C\hat{x} - Du)$$

$$L = P_f C^T W^{-1}$$

Whereas P_f is the positive semi-definite solution of the Riccati Equation.

$$P_f A^T + AP_f - P_f - C^T W^{-1} C P_f + MVM^T = 0$$

Figure 3.2 depicted the clear picture of about kalman filter.

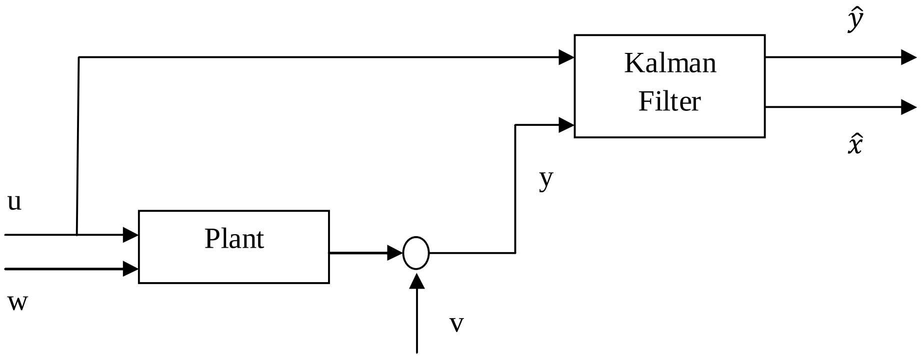

Figure 3.2 Kalman Estimator

By combining the kalman estimator that is calculated by kalman filter and the state-feedback by LQR, we can get the LQG controller as shown in figure 3.3

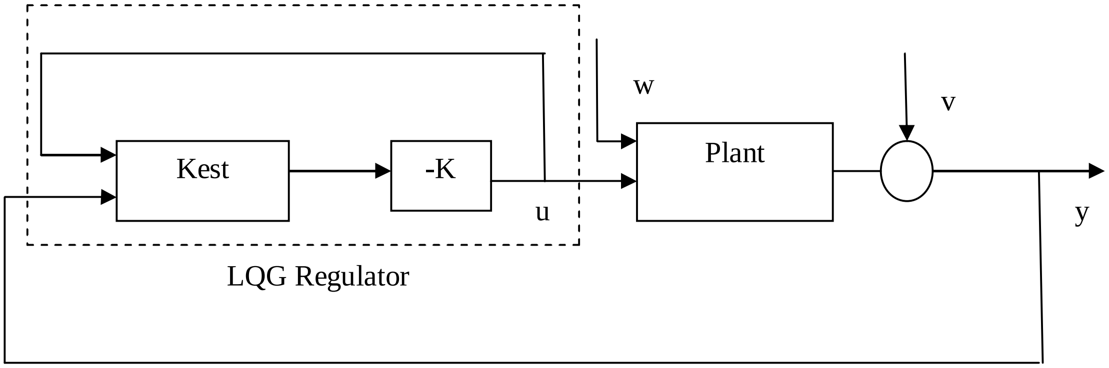

Figure 3.3: Dynamic LQG regulator with the Plant

3.1.2 Controller Implementation

In order to implement the controller lets recall that the Plant with the multiple inputs and multiple outputs and the state equation for this plant is given as,

$$\dot{x} = Ax + Bu \qquad (3.5)$$

$$y = Cx \qquad (3.6)$$

And the estimated states from the regulator is given as,

$$\dot{\hat{x}} = A_e\hat{x} + B_e y \qquad (3.7)$$

$$u = C_e\hat{x} \qquad (3.8)$$

By arranging the equations we get,

$$\dot{\bar{x}} = \bar{A}\bar{x} \qquad (3.9)$$

Whereas,

$$\dot{\bar{x}}=\begin{bmatrix}\dot{x}\\ \dot{\hat{x}}\end{bmatrix} \quad , \quad \bar{A}=\begin{bmatrix}A & BC_e\\ B_eC & A_e\end{bmatrix} \quad \text{and} \quad \bar{x}=\begin{bmatrix}x\\ \hat{x}\end{bmatrix}$$

Now, by solving the above differential equation we can observe the rotor speed and position of the wind turbines. The results are shown in the chapter 4.

3.1.3 Controller Tuning

As mentioned above, the weights in the LQ design correspond to a weighting of the variances. A common starting point, for the weights when doing LQ design, is to use identify matrices as per according to the dimension of the system. Weights equal to the inverse of the square of the variable's nominal value.

Thus for LQ controller, we can write as:

$$Q=\begin{pmatrix}1 & \cdots & 0\\ \vdots & \ddots & \vdots\\ 0 & \cdots & 1\end{pmatrix} \qquad \text{And} \qquad R=\varrho.\begin{pmatrix}1 & \cdots & 0\\ \vdots & \ddots & \vdots\\ 0 & \cdots & 1\end{pmatrix}$$

Whereas ϱ is a scalar multiple and we can tune Q and R as per our requirement. The results are shown in chapter 4.

Hence, it should be clear that the LQG design procedure allows a controller which is optimal in the sense depicted by the designer through the cost function. The designer still need to adjust the weights by hand to obtain a controller which would be comprehensively optimal in the sense as described above.

3.2 Augmentation Using Integral action

Another simple way is to integrate the error between the reference signal and the output signal, augmenting the system with the reference error integration state and minimize the augmented state in the controller cost function. This kind of LQ controller called LQI controller where we there is an integration of the reference error. The LQI approach is like the integral part of a traditional PI/PID controller. Figure 3.4 shows the clear picture of such design implemented with our system.

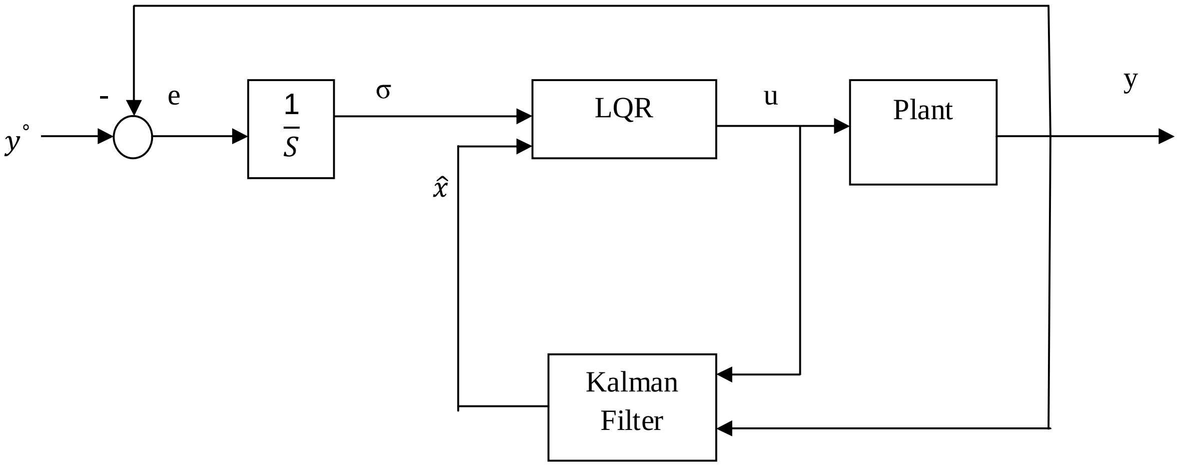

Figure 3.4: optimal control with Integral action

For a given system, the state equations are given as,

$$\dot{x} = Ax + Bu$$

$$y = Cx$$

$$e = y - y^{\circ}$$

And by introducing the integral action

$$\dot{\sigma} = e = Cx - y^{\circ}$$

Hence by combining these equations leads to the augmented system description which is given as below:

$$\dot{x}_{aug} = A_{aug}x_{aug} + B_{aug}u + \begin{pmatrix} 0 \\ -I \end{pmatrix} y^{\circ}$$

$$y_{aug} = C_{aug}x_{aug}$$

Whereas,

$$A_{aug} = \begin{pmatrix} A & 0 \\ C & 0 \end{pmatrix}\ , B_{aug} = \begin{pmatrix} B \\ 0 \end{pmatrix},\ C_{aug} = \begin{pmatrix} C \\ 0 \end{pmatrix} \text{ and } x_{aug} = \begin{pmatrix} x \\ \sigma \end{pmatrix}$$

As you can see we introduced integral action to our model and imposed the reference speed of the rotor y°. Now by implementing the LQR controller to the augmented system we will be able to get the state-feedback for this augmented model and then implementing the controller to the system.

Whereas, the optimal control for the augmented system is realized as,

$$u = -K\hat{x} - K_i\sigma$$

Chapter 4

Simulation and Results

In this chapter the simulations done on horizontal-axis wind turbines (HAWT) are presented. The simulation work done on MATLA and we realized our system by two ways. First we investigate with the time invariant models by taking the mean of the models over one period of time. Secondly we compare this time invariant models with the time variant strategy.

4.1 Time Invariant Model.

As mentioned in chapter 2, we are working in region 3 where the wind speed is between 11 m/s to 25 m/s and it can rotate the wind turbine at its maximum power. Initially, the model is implemented by taking the mean of the model for a single period of time just to investigate the behavior of the model. In order to do that it was essential to compare the true model with the estimated model and the estimation was done by using the kalman filter. As shown in figure 4.1 the response of the true model in which the rotor speed is investigated.

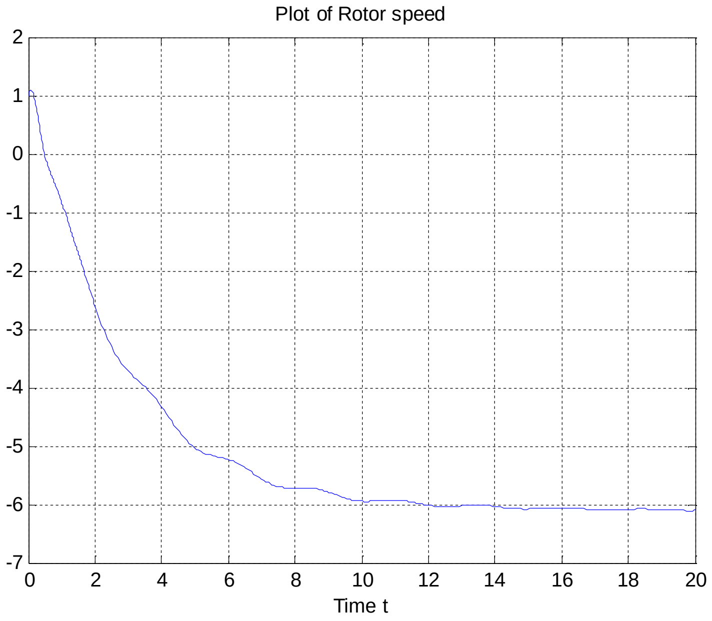

Figure 4.1: True model response over single period of time

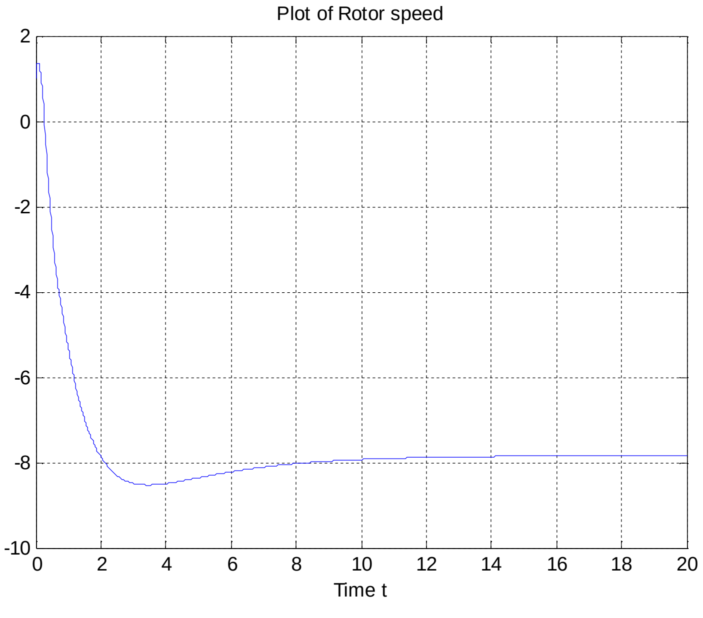

Figure 4.2 Estimated model response over single period of time

We can see that the estimated response follows the true model to some extent.

4.1.1 Closed Loop Response

After designing the controller as mentioned in chapter 3, our next task was to implement it on the model of wind turbine. As stated in previous chapter that the choice was to choose between PI/PID or LQG and we go for LQG due to its inherent stability, flexibility and comprehensiveness. After implemented the controller it is supposed that the wind turbine should get to zero as the LQG controller imposed the states of the system. The result is shown in figure 4.3. By adjusting the weight of LQG controller as discussed in chapter 3 the settling time is getting shorter and the wind turbine gets stop as the wind speed is one of the state of the model.

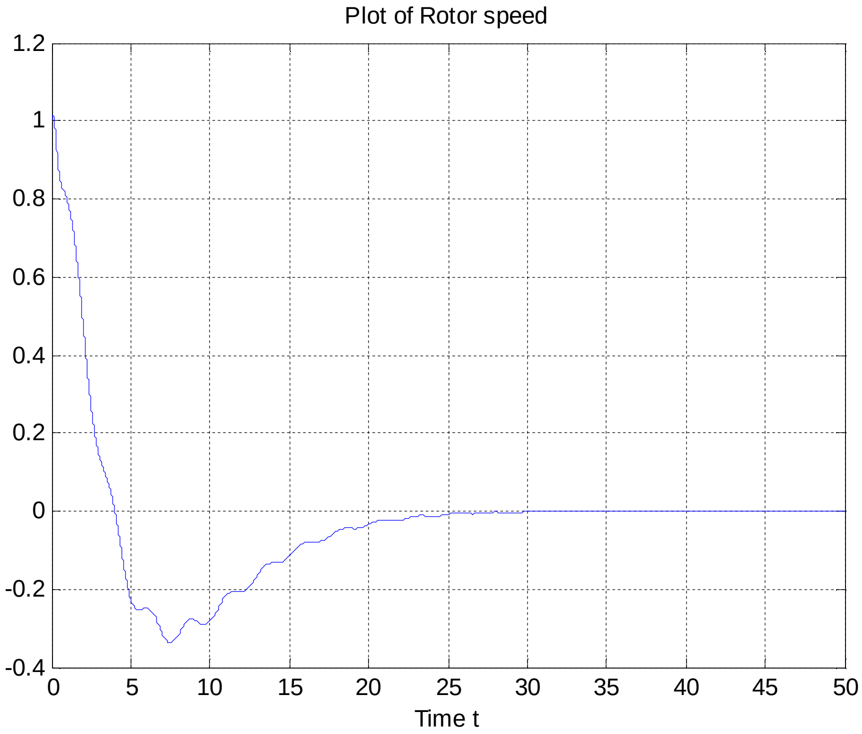

Figure 4.3: Angular speed of the Rotor after implementing LQG controller

As the response in above figure tells us the story that by adjusting the weight of state feedback controller we got a smooth curve after some settling time. This is why we chose LQG controller because the controller is inherently suited for such kind of systems. Also it provides stable closed-loop system and allows us to tune it in intuitive manner as shown in figure above that just by adjusting the weights the system gets more stable.

4.1.2 Integral action Response

Now if we introduce the integral action to our model and design an augmented system using reference value the system behaves more adequately. In order to do so first we analyze our system by considering time invariant system as shown in figure 4.4. In time invariant system, we took the mean of our overall state space system and imposed the state feedback controller and close the loop. In the figure we can observe that the system follows the reference output speed and hence approaches to reference value which sets to 5 rad/sec.

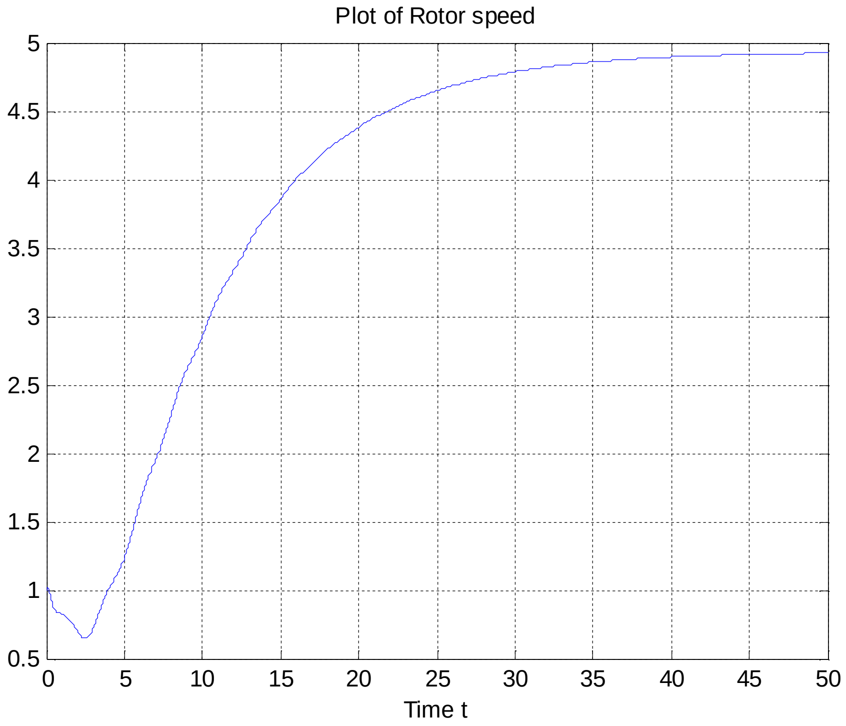

Figure 4.4: Angular Speed with integral action over single period of time

4.2 Linear Time Variant (LTV) Model Response

Now after investigating the time invariant response, it is essential to look at the response of the system that varies with the time. On the similar, as we have done with the time invariant system, we will see the system response. As can be seen the response of the rotor speed with the true model and the estimated one in figure 4.5 and figure 4.6 respectively. Estimation is done by kalman filter

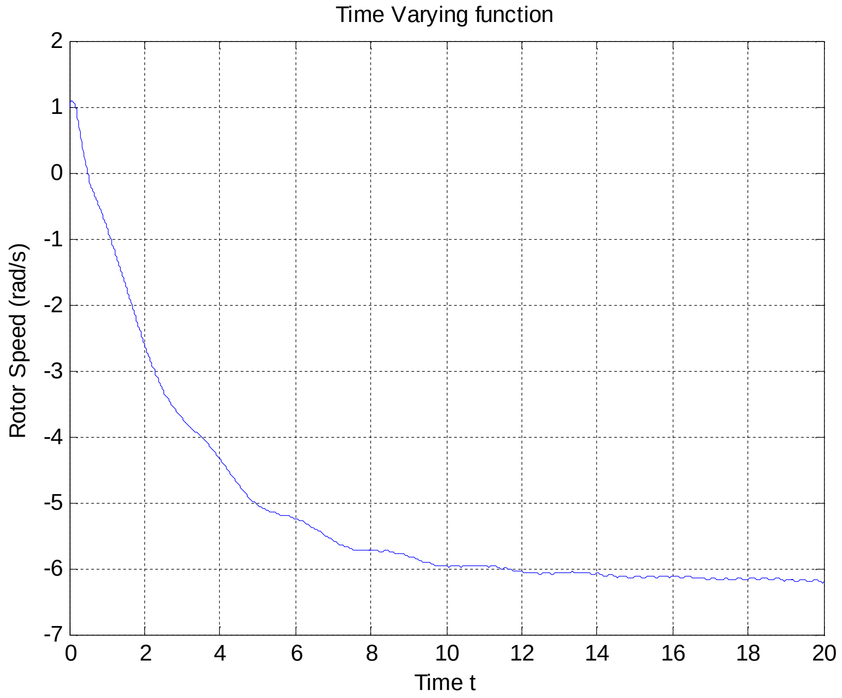

Figure 4.5: True model response for time varying system

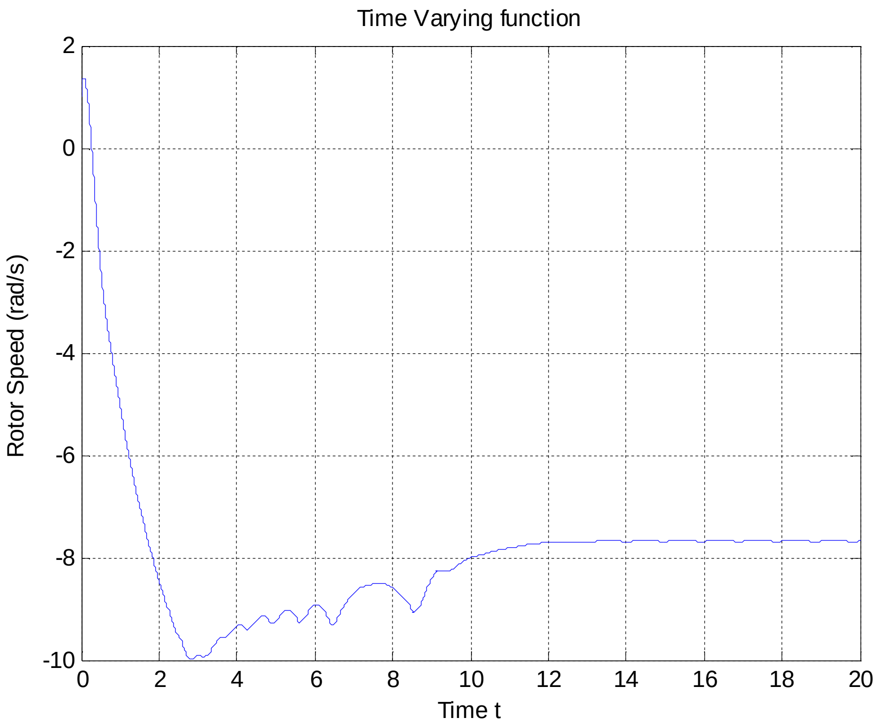

Figure 4.6: Estimated model response for time varying System.

4.2.1 Closed Loop Response for LTV system

For the time variant system the closed loop response is shown in figure 4.7. The controller imposed the state of the system to zero.

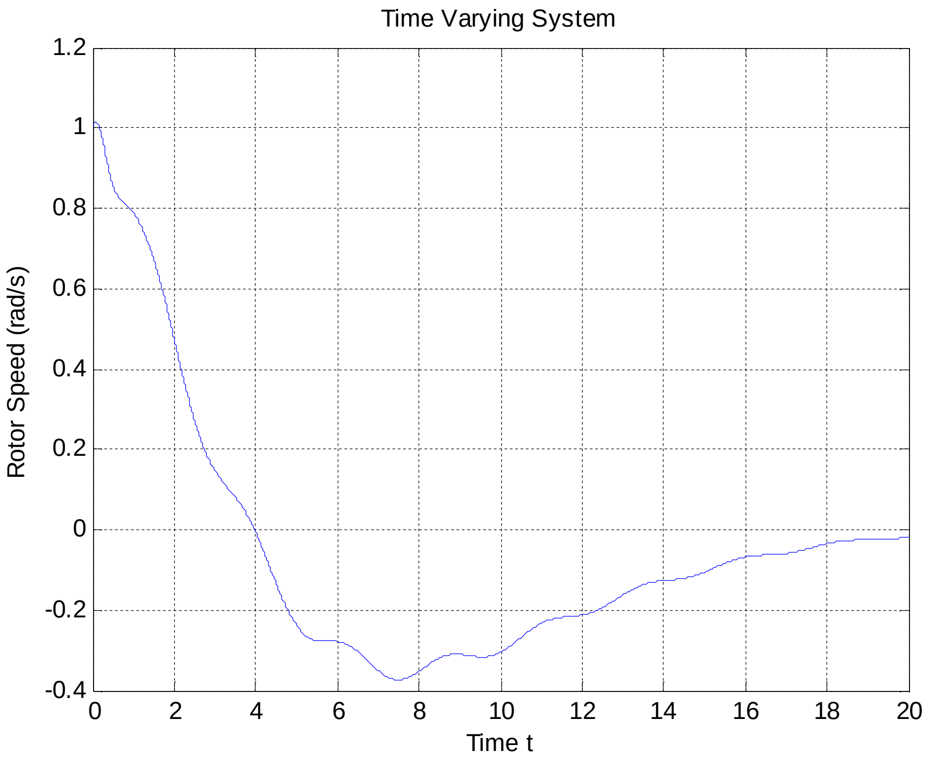

Figure 4.7:Angular Speed of the rotor after implementing LQG Controller

4.2.2 Integral Action for LTV System

By taking the reference value 10 rad/sec the response of the rotor speed for the time varying system is shown in figure 4.8

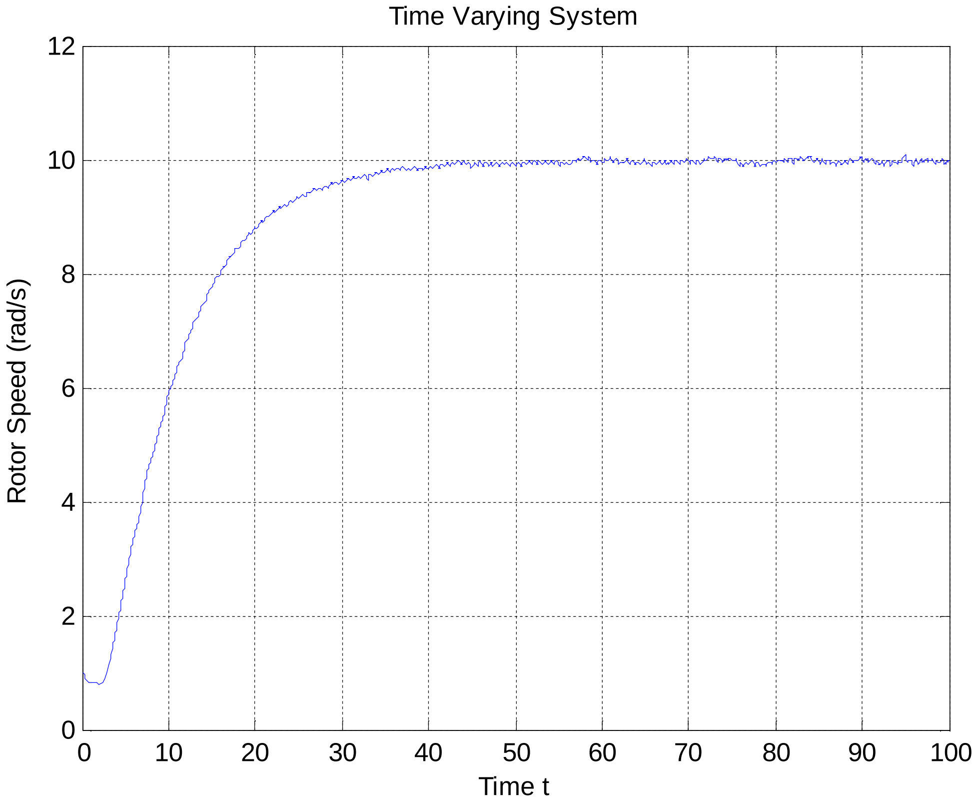

Figure 4.8: Linear Time varying Response using Integral action

So we can see that by using an integral action over the error signal between the reference speed of the rotor and the feedback measured speed the system behaves adequately and so the rotor speed follows the reference speed. This is what we were concerned about to realized the rotor speed that is varying on each and every time interval and after some settling time it attains the reference speed.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

This thesis describes the wind turbine system from control engineering point of view. Using the presented model, the wind turbine is simulated in MATLAB first with the time invariant model by taking the mean of overall models, that were extracted by the FAST code, over single period of time and then with the time varying models.

The control system design of a complex dynamic system modeled by FAST code has been successfully performed. Since the wind turbine is fairly complex system, keen attention required for the chosen and the designing of the controller. The control system design demanded the class of state-feedback and output-feedback controller after assuring that the system is controllable and observable as per the requirement of LQG controller.

The LQG controller design was presented for horizontal-axis variable speed wind turbines. The unusual behavior of turbine tackled by the controller and imposed the system to move uniformly in one direction at high speed operation region i.e. region 3 by maintaining the constant rotation, we can produce smooth electrical power without any considerable fluctuation up to the nominal value.

The obtained results demonstrated that this type of controller ensures good performance especially for such kind of complex MIMO time variant systems.

It is clear from the graphs shown in chapter 4 that the controller stabilizes the system. As we have seen that by using an integral action over the signal which is the difference between the reference speed of the rotor and the feedback measured speed, the system behaves adequately and so the rotor speed follows the reference speed. Finally, the response of the time variant system is compared with the time invariant system. The system behaves more efficiently with time varying system and the settling time gets closer as compare to time invariant system.

5.2 Future Work

The results obtained during this investigation are encouraging. The possible benefits of LQG control for wind energy systems were examined; it appears that this kind of control method allows for smooth wind turbine operation. On the other hand, a comparison of this control method with classical PI controllers would be worthy to demonstrate if the performance of PI controller over LQG controller is considerable good enough as compare to LQG controller approach.

Furthermore, an experimental real-time implementation on an actual turbine would be very valuable. Moreover, this study is limited to the available data and further justifications of the model with other wind turbines, and different disturbances would be worthwhile. For instance, this study can be better by taking into account wind gusts and other practical problems. Further research includes modeling and control of a group of interconnected wind turbines or wind farm. Since this work is a first attempt to develop an explicit controller for a wind turbine, the design of classical controller is recommended as future work.

REFERENCES:

[1]. Lubosny, Z. (2003) *Wind Turbine Operation in Electric Power Systems.* Springer, Germany.

[2]. Balas, M. Fingersh, L. Johnson, K. Pao, L. (2006) Control of Variable-Speed Wind Turbines: standard and adaptive techniques for maximizing energy capture. *IEEE Control Systems Magazine,*

[3]. Boukhezzar, B. Siguerdidjane, H. (2005) Nonlinear Control of Variable Speed Wind Turbines without wind speed measurement. *IEEE Conference on Decision and Control*.

[4]. Bongers, P. Van Baars, G. (1992) Wind turbine control design and implementation based on experimental models. *IEEE.*

[5]. Butterfield, C. Muljadi, E. (2001) Pitch-Controlled Variable-Speed Wind Turbine Generation. *IEEE Transactions on Industry Applications*.

[6]. Ackermann, T. Söder (2000) Wind energy technology and current status: a review. *Renewable and Sustainable Energy Reviews.*

[7]. Fujita, H. Funabashi, T Sekine, H. Senjyu, T. Sakamoto, R Urasaki, N. (2006) Output Power Levelling of Wind Turbine Generator for All Operating Regions by Pitch Angle Control. *IEEE Transactions on Energy Conversion*.

[8]. British Wind Energy Association (2006) *The technology of turbines*. [Online] Available from: www.bwea.com/ref/tech.html [Accessed in October 2006].

[9]. Karrari, M. Malik, O. Rosehart, W. (2005) Comprehensive Control Strategy for a Variable Speed Cage Machine Wind Generation Unit. *IEEE Transactions on Energy Conversion*.

[10]. EERE (2007) *Wind Power*. [Online] Available from:www1.eere.energy.gov/windandhydro/wind_how.html

[11]. Harrison, R. Hau, E. Snel, H. (2000) *Large Wind Turbines*. Wiley, England.

[12]. Wind-Works (2007) [Online] Available from: www.windworks. org/photos/PhotosVAWTs.html

[13]. Scottish Executive (2007) [Online] Available from: www.scotland.gov.uk

[14]. Jenkins, N. Walker, J. (1997) *Wind Energy Technology*. Wiley, England.

[15]. Wind Power Program, NREL. Available on www.wind-power-program.com.

[16]. De Montfort University (2007) *Wind Energy Training Course*. [Online] Available from: www.iesd.dmu.ac.uk/wind_energy/m32extex.html

[17]. Ackermann, T. (ed). (2005) *Wind Power in Power Systems*. Wiley, England.

[18]. J. F. Manwell, J. G. McGowan and A. L. Rogers, "Wind Energy Explained", John Wiley and Sons LTD, Chichester, England, 2002.

[19].

[20]. Lucy Y. Pao and Kathryn E. Johnson "Control of Wind turbines Approaches, Challenges, and Recent Developments"

[21]. Leithead, W.E., de la Salle, S., Reardon, D., 1990, "Wind turbine control objectives and design," European Community Wind Energy Conference, H.S. Stephens, Bedford, United Kingdom, Vol. xvi+771, pp. 510-515

[22]. M.M. Hand, July 1999, "Variable-Speed wind Turbine Controller Systematic Design Methodology: A Comparison of Non-Linear and Linear Model-Based Designs"

[23]. NREL information portal available on: http://wind.nrel.gov/designcodes/simulators/fast/

[24]. "Multivariable Feedback Design" by J.M. Maciejowski (Addison Wesley, 1989)

VITA

Usman Shahzad was born in February, 1989, in Islamabad, Pakistan. He graduated with his Bachelor of Sciences in Computer Engineering from COMSATS Institute of Information Technology, Islamabad, Pakistan in 2010 and got Campus Silver Medal. He is presently enrolled in Masters Program in Automation and Control Systems at Politecnico di Milano, Milan, Italy and is expected to graduate in December 2012. His research interests includes Automation, Process controlling, Controls Theory and Signals and Systems.