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# Multivariable Control for Load Mitigation of Wind Turbine

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# MULTIVARIABLE CONTROL FOR LOAD MITIGATION OG WIND TURBINE

BY
RAJA MUHAMMAD IMRAN

PH.D.AFHANDLING, 2016

AALBORG UNIVERSITY
DENMARK

# Multivariable Control for Load Mitigation of Wind Turbine

Ph.D. Dissertation

Raja Muhammad Imran

Dissertation submitted June 17, 2016.

Thesis submitted: June 17, 2016

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# Abstract

Wind turbine is a nonlinear system used to convert wind's kinetic energy into electricity. Turbulence nature of wind produce fluctuation in output power and highly varying load of structural components (i.e., rotor blade, tower, gearbox etc. ) which could reduce their life time. There are mainly two region of control determined by wind speed. For above-rate wind speed (Region II), typically generator torque is controlled to maximize the captured power by tracking the maximum power coefficient. For above-rated wind speed (Region III), generator speed is regulated at its rated value and fatigue of the components are mitigated using collective pitch control (CPC) or individual pitch control (IPC) for variable speed wind turbine. There are three types of loads acting on wind turbine. Steady aerodynamic loads are associated with mean wind speed and centrifugal forces on the blades. The fatigue life of the onshore wind turbine is generally defined on the basis of random fluctuating loads and its main source is turbulence. Periodic aerodynamic loads are generated due to wind shear, tower shadow, wake effect, rotor rotation and off-axis wind. These periodic loads add flickers as 1p, 3p, 6p etc., (p is the rotor rotational frequency) for three bladed wind turbine. The control of wind turbines is a challenging task with multiple objectives like structural fatigue, slip in the generator and power production.

The main contribution of this thesis is to develop a multivariable control to reduce fatigue of drive-train, rotor and tower for above rated wind speed. Proportional–integral (PI), linear-quadratic-Gaussian (LQG) and disturbance accommodation control (DAC) control schemes are used to mitigate the effect of turbulent wind. Wind turbines installed in the cold climate areas has an icing on its rotor blade which might change its aerodynamics. We have performed an experiment to analyze the aerodynamic changes occur due to the ice accumulated on the rotor blades of wind turbine. Three small scale model of the NREL's 5MW rotor blade with same profile and simulated different icing effect are printed with 3D printer are tested in a Wind Tunnel. Power coefficient curves generated from the test results are compared to see the aerodynamic changes due to icing effect.

Moreover, DAC control strategies are developed to mitigate loads gen-

erated by wind shear and tower shadow effect using CPC of wind turbine. Multivariable disturbance accommodated observer based control (DOBC) is developed and tested on FAST code model of NREL's 5 MW wind turbine with multiobjective control to reduce loads on drive train and tower, regulation in output power using individual blade pitch control. Then linear multivariable disturbance observer based controllers are developed at two operating point and a novel scheme is presented to switch between two controller in a smooth way. A glitch free gain-scheduling algorithm based on the interpolation of parameters such that closed loop system remain stable throughout the interpolation for DOBC is presented and tested on wind turbine for above rated wind speed.

# Resumé

Vindmølle er en ikke-lineært system anvendes til at konvertere vindens kinetiske energi til elektricitet. Turbulens natur vind producere udsving i udgangseffekt og stærkt varierende belastning af strukturelle komponenter (dvs. vinge, tårn, gearkasse etc.), som kan reducere deres levetid. Der er primært to region af kontrol bestemmes af vindhastigheden. For ovennævnte sats vindhastighed (Region II), typisk generator moment styres til at maksimere det opfangede effekt ved at spore den maksimale effekt koefficient. For overrated vindhastighed (Region III), er generator hastighed reguleret på den nominelle værdi og træthed i komponenter er afbødes ved hjælp af kollektiv pitch kontrol (CPC) eller individuel pitch kontrol (IPC) til variabel hastighed vindmølle. Der er tre typer af belastninger, der virker på vindmølle. Steady aerodynamiske belastninger er forbundet med betyde vindhastighed og centrifugale kræfter på vingerne. Udmattelseslevetiden den onshore vindmølle er generelt defineret på grundlag af tilfældige svingende belastninger og dens vigtigste kilde er turbulens. Periodiske aerodynamiske belastninger genereres på grund wind shear, tårn skygge, wake effekt, rotor rotation og off-akse vind. Disse periodiske belastninger tilføje flimmer som 1p, 3p, 6p etc., (p er den rotor rotationsfrekvens) for trebladet vindmølle. Styringen af vindmøller er en udfordrende opgave med mange mål som strukturel træthed, glide i generatoren og elproduktionen.

Det vigtigste bidrag med denne afhandling er at udvikle en multivariabel kontrol at reducere træthed i drive-tog, rotor og tårn for ovennævnte bedømt vindhastighed. Proportional-integral (PI), lineær-kvadratisk-Gauss (LQG) og forstyrrelser overnatning kontrol (DAC) kontrol ordninger anvendes til at afbøde virkningen af turbulent vind. Vindmøller installeret i det kolde klima områder har en glasur på dens rotorblad, som kan ændre sine aerodynamik. Vi har udføres et eksperiment for at analysere de aerodynamiske ændringer forekomme på grund til akkumuleret på rotorbladene af vindmøllens is. tre små skalamodel af NREL s 5 MW rotorblad med samme profil og simuleret forskellige glasur effekt udskrives med $3D$-printer er testet i en vindtunnel. Power koefficient kurver genereret fra testresultaterne sammenlignes for at se de aerodynamiske ændringer som følge af tilisning effekt.

Desuden er DAC kontrolstrategier udviklet til at mindske belastninger genereret af vind shear og tårn skygge effekt ved hjælp CPC vindmølle. Multivariable forstyrrelse indkvarteret observatør baseret kontrol (DOBC) er udviklet og testet på FAST kode model af NREL s 5 MW vindmølle med multiobjective kontrol for at reducere belastninger på drev toget og tårnet, regulering i udgangseffekt anvender individuel bladvinkelregulering kontrol. Så lineær multivariable forstyrrelse observatør baserede controllere er udviklet på to driftspunkt og en roman ordning præsenteres for at skifte mellem to controller i en jævn måde. En glitch gratis gain-planlægning algoritme baseret på interpolationen af parametre, således at lukket kredsløb forblive stabil hele interpolation for DOBC præsenteres og testet på vindmølle for ovennævnte bedømt vindhastighed. 1

# Contents

# Thesis Details

**Thesis Title:** Multivariable Control for Load Mitigation of Wind Turbine
**Ph.D. Student:** Raja Muhammad Imran
**Supervisors:** Assoc. Prof. D. M. Akbar Hussain, Aalborg University, Denmark
Assoc. Prof. Mohsen Soltani, Aalborg University, Denmark

The main body of this thesis consist of the following papers.

[A] Raja M. Imran , D. M. Akbar Hussain, and Zhe Chen , "LQG Controller Design for Pitch Regulated Variable Speed Wind Turbine," *IEEE International Energy Conference (ENERGYCON)*, Dubrovnik Croatia, 2014.

[B] Raja M. Imran , D. M. Akbar Hussain, and Mohsen Soltani , "DAC with LQR Control Design for Pitch Regulated Variable Speed Wind Turbine," *IEEE International Telecommunications Energy Conference (INTELEC)*, Vancouver, BC, Canada, 2014.

[C] Raja M. Imran , D. M. Akbar Hussain, and Mohsen Soltani , "DAC to Mitigate the Effect of Periodic Disturbances on Drive Train using Collective Pitch for Variable Speed Wind Turbine," *IEEE International Conference on Industrial Technology (ICIT)*, Seville, Spain, 2015.

[D] Raja M. Imran , D. M. Akbar Hussain, and Mohsen Soltani , "An Experimental Analysis of the Effect of Icing on Wind Turbine Rotor Blade," *IEEE PES T&D Conference and Exposition*, Dallas, USA, 2016.

[E] Raja M. Imran , D. M. Akbar Hussain, Mohsen Soltani, Raja M. Rafaq " Optimal Tuning of Multivariable Disturbance-Observer-Based Control for Flicker Mitigation Using IPC of Wind Turbine," Submitted to *Journal of IET Renewable Power Generation* , 2016.

[F] Raja M. Imran, D. M. Akbar Hussain, Bhawani Shanker Chowdhry, Raja M. Irfan " Bumpless Transfer of Parametrized Disturbance Accommodated Controller for Wind Turbine," Submitted to *Journal of Energies*, 2016.

In addition to the main papers, the following publications have also been made.

[1] D. M. Akbar Hussain, Raja M. Imran and Ghulam Mustafa Shoro, "Harmonic Detection at Initialization With Kalman Filter," *6th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops( ICUMT)*, St. Petersburg, Russian Federation, 2014.

[2] D. M. Akbar Hussain, Ghulam Mustafa Shoro and Raja M. Imran , "Detection of Harmonic Occurring using Kalman Filtering," *IEEE PES Transmission Distribution Conference Exposition*, Chicago, United States, 2014.

[3] D. M. Akbar Hussain, Raja M. Imran and Ghulam Mustafa Shoro, "A Novel Technique to Obtain the Health of a PV Panel," *6th IEEE PES Asia-Pacific Power and Energy Engineering Conference (IEEE PES APPEEC )*, Hong Kong, 2014.

This thesis has been submitted for assessment in partial fulfillment of the PhD degree. The thesis is based on the submitted or published scientific papers which are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty. The thesis is not in its present form acceptable for open publication but only in limited and closed circulation as copyright may not be ensured.

# Preface

This thesis is submitted in partial fulfillment of the requirements for the Doctor of Philosophy at the Department of Energy Technology, Aalborg University, Denmark. The work has been supervised by Associate Professor Dil Muhammad Akbar Hussain and Associate Professor Mohsen Soltani from the department of Energy Technology Aalborg University Denmark. Thesis deals with multivariable control to mitigate load of wind turbine. Although main focus is on the application but a number of theoretical contributions are also presented.

Firstly, my sincere gratitude to my supervisors, Assoc. Prof. Dil Muhammad Akbar Hussain and Assoc. Prof. Mohsen Soltani from Department of Energy Technology Aalborg University Denmark, who have supported me throughout my thesis with their advice, patience and knowledge whilst giving me enough freedom to work in my own way. All faculty and staff members were extremely helpful whenever they were needed.

I am grateful to my mother for her uninterrupted support and prayers. I feel sorry that I cannot share this great moment with my late father. I keep praying for both of you that "O Allah! Forgive me and my parents as they have brought me up from my childhood". Words fail me to express my appreciation to my wife whose dedication, love and persistent support has taken the load off my shoulder and during first year of study my daughter "Adn Imran" was born. I am thankful to my brothers and my sisters for their love and support during my stay abroad.

Thesis consists of a summary report and six research papers, written during the period April 2013 to April 2016. Four of the research papers are published in international peer-reviewed scientific conferences and two are submitted to international peer-reviewed scientific journals.

Raja Muhammad Imran
Aalborg University, July 25, 2016

# Part I

# Thesis Frame Work and Background

# 1 Introduction

## 1.1 Background and Motivation

Renewable energy sources-biomass, wind, solar, hydro and geothermal- are clean sources of energy with lower environmental impact than non-renewable energy sources- coal, petroleum, natural gas, propylene and Uranium. Electricity generation is the leading cause of air pollution comes from coal, nuclear, and other non-renewable power plants. Whereas renewable energy sources are domestic sources of energy provides increased energy independence and energy supply security at the national level. These sources can be used to produce electricity without producing carbon dioxide which is the leading cause of global climate change and never runs out. Electricity generating from renewable energy offers significant public health benefits. The air and water pollution emitted by coal and natural gas plants are creating health issues like breathing problems, neurological damage, heart attacks, and cancer. By the replacement of fossil fuels with renewable energy has been reducing premature mortality and overall healthcare costs [1]. Renewable energy is providing affordable electricity and costs of renewable energy technologies have reduced steadily e.g., the average price of a solar panel has descended about 60 percent since 2011 [2] and electricity generation cost from wind reduced to more than 20 percent between 2010 and 2012 and more than 80 percent since 1980 [3]. Wind power generation has been expended quickly in United states and generation from wind may reach to 20% of total electricity by 2030 [4] [13]. According to the European Wind Energy Association Report [5] wind power was the energy technology with the highest installation rate with 43.7% and Solar PV was second with 29.7% of all new installations in 2014 as shown in Fig . 1

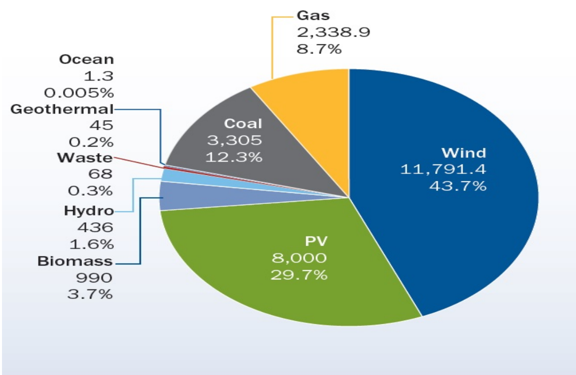


**Fig. 1:** Share of New Power Capacity Installed in EU(MW) [5]

Wind energy is an important source of renewable energy and deliver power with minimal impact on environment. A system that converts wind into the useful work is called wind energy conversion system (WECS) and today the most common is the wind turbine. Wind turbine can be divided into two categories on the basis of their axis of rotation; horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT). HAWT have advantages over VAWT and wind turbine technology started from the fixed-speed then moved to variable-speed operation to increase the extracted power below rated wind speed. Aerodynamic control in combination with power electronics is used to regulate torque, rotational speed and power of wind turbine. Wind turbine control's main objective is to maximize power and reduce its transient, steady, cyclic and stochastic loads. It can be operated in different modes which are defined on the basis of rotational speed, power and wind speed. Wind turbine starts rotating at cut-in wind speed ($V_{cut-in}$), it deliver rated power at rated wind speed ($V_{rated}$) and turbine shutdown to avoid damage at cut-out wind speed ($V_{cut-out}$). For National Renewable Energy Laboratory (NREL)'s 5MW wind turbine [6]; power available to the turbine, extracted power and regions of control are shown in Fig. 2.

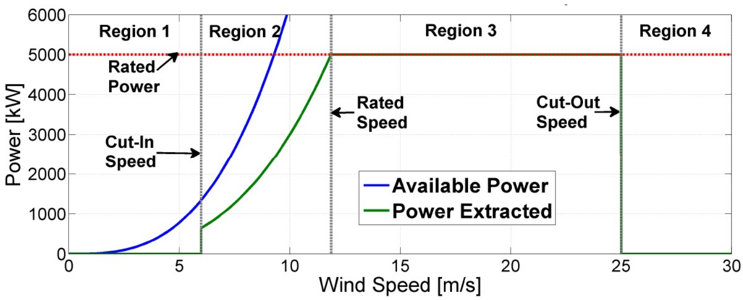


**Fig. 2:** NREL's 5 MW Wind Turbine Power Curve [7]

Wind turbine typically have four region of control. Region 1 is from the start up to cut-in wind speed when generator starts producing power. Region 2 (Below-rated wind speed) is from the above cut-in wind speed to rated wind speed and control objective is to capture as much power as possible by maximizing aerodynamic efficiency. Region 3 (Above-rated wind speed) is from above rated wind speed to cut-out wind speed where the control objective is the regulation of rotor speed and reduction of loads on its components. Region 4 starts from the cut-out wind speed when wind turbine shuts down to avoid damage due to high wind. Advanced control algorithms have become necessary to meet multiple objectives such as maximum power, speed regulation, blade load mitigation, and mode stabilization. The control objectives of wind turbine vary over the entire wind speed regions and hence arise the need of developing an intelligent control system that can maximize not only the wind energy captured but also extend the lifetime of wind turbine components.

In Region 2, typically blade pitch angle is kept constant and generator torque is controlled to keep tip-speed ratio (TSR) at its optimal value to maximize output power of the wind turbine. In Region 3, generator torque is kept constant and blade pitch angle is controlled to regulate the generator speed at its rated value and to reduce structural loads. As modern wind turbines are larger in size, so its components are very expensive and large fatigue of component may result their failure [12]. Various types of loads acting on wind turbine with their sources [8] [9] [10] are summarized in Fig.3.

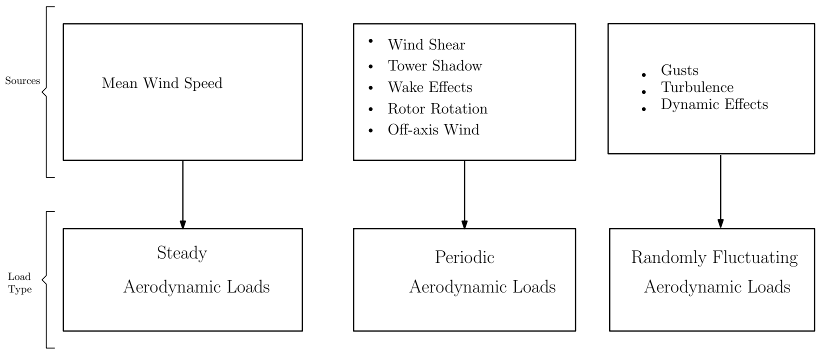


**Fig. 3:** Loads on Wind Turbine

- Steady Loads are due to mean wind speed, centrifugal forces on the blades and weight of the machine on tower.The steady aerodynamic loads contributes to the long-term power production estimations.

- Periodic or Cyclic loads are generated due to the rotation of the rotor. The basic cyclic load are at blade roots due to the gravitation force. As wind speed varies with the height of the rotor is called wind shear. When wind turbine rotor blade passed from the tower then wind speed acting on rotor will be decelerated which is known as tower shadow. Additionally, constant off-axis winds will also cause similar periodically changing load on the turbine and the blades.

- Random variation of the wind speed in time and space around a mean value is known as turbulence which is the main source of fluctuating aerodynamic loads. Fatigue life of the onshore wind turbine is generally defined on the basis of loads due to the turbulence. Sudden increase in wind speed which lasts from 3 to 20 sec and imposes high loads on the blades of the wind turbine is called a gust [10]. Wind gusts acting on the whole area of the blade and partial gusts acting on part of the rotor area of the blade can trigger aerodynamic states which may result airfoils stall and generate extreme load changes.

## 1.2 State of the Art

Various linear and nonlinear control strategies have been used to meet multiple objectives of wind turbine [12] . Nonlinear control techniques are concerned with the analysis and design of nonlinear systems [18]. As we know that nonlinear technique have more mathematically intensive so controller will take longer time than linear system which has less computation. Nonlinear system can be divided into linear system in a limited range of operation and then a gain scheduling [19] or adaptive [20] control scheme can be used to solve the problem. Bossanyi reviewed [21] [22] some recent developments in control algorithms for pitch control and generator torque control for variable speed turbines. He discussed that in addition to improving the control design, it is also possible to add some additional sensors to achieve its objectives effectively. These additional actuators are implementing individual pitch controllers for each blade and then control performance can be improved by making trade-off between energy capture and loads. Then by adding the accelerometer and load sensors [23] [24] independent blade pitch is implemented to achieve its objectives more effectively. Advanced controller design strategies can provide an explicit mathematical formulation for controller design with multiple objectives including load reduction and are used on commercial turbines to a limited extent.

Classical control theory (also know as conventional control theory) deals only with single-input, single-output (SISO) systems and most widely used industrial controller is the Proportional-Integral-Derivative (PID); it has been used to regulate generator speed by controlling rotor blade pitch for full load operation of wind turbine [12]. A trade-off study between minimization of the deviation of the rotor speed from desired speed with actuator dynamics for constant power production using PID controller is illustrated [25] and optimal operating conditions are determined. Commonly PI controller is used to adjust rotor speed above the rated wind speed. Since wind turbine is highly nonlinear, so one set of parameter may not provide good performance. Therefore an expert PID controller based on a tracking differentiation is presented [27] to restrain the overshoot of rotor speed and provide better performance as compared to PI control. Also a self tuning PID control [26] using reinforcement learning in an adaptive way by taking benefit of the model free learning and new type of integral control action was used.

Modern control theory [28] is based on time-domain analysis of differential equation systems and can handle multiple-input, multiple-output (MIMO) systems. Linear Quadratic Gaussian (LQG) is a linear control design based on state-space model of the system and is used for the power regulation in the high wind speed [29] for variable speed wind turbines using collective blade pitch [11] [12]. The simulation result showed that the LQG controller has good power regulation as compared to PI control. General formulation of the LQG [30] with the design procedures for the Controls Advanced Research Turbine (CART) and pole placement technique for LQR design [31] to make closed loop stable for wind turbine. However better performance was achieved using optimal control theory [32] [33] to minimize quadratic cost function and can also be used to a multivariable systems. MIMO LQR controller was designed [34] for a horizontal variable speed wind turbine with focus on optimality of the trade-off between the wind energy conversion maximization and the minimization of the fatigue in the mechanical structure for above rated wind speeds. Then a wind-scheduling LQR with online wind speed estimation is designed for a multi-MW size wind turbine [35] by linearizing wind turbine along the operating point trajectory.

Disturbance Accommodation Control (DAC) is model based control approach to reject disturbance from a linear system and is used to reduce loads on wind turbine by controlling the rotor blade pitch [12] [13]. Alan D. Wright [36] used modern state-space control for two-bladed wind turbine based on the DAC method to provides damping in several low-damped flexible modes of the turbine and to regulate turbine speed. These modern controls designs have effectively mitigated tower fore-aft motion, drive-train shaft torsion moments, and blade root flap bending moments as compared to classical control. Also tested multi-input multi-output (MIMO) control method [37] based on state-space models to meet multiple objectives. He has prepared report about the design, testing through simulation and field testing of advanced wind turbine and showed that load mitigating potential of the advanced state-space controllers is better than as compared to the classical control. Cyclic aerodynamic loads are generated due to periodic disturbances are mitigated using generator torque control [38] and then these harmonics are mitigated using individual pitch control [39] strategy for wind turbine with Doubly Fed Induction Generator (DFIG) to reduce fatigue of components [13]. For two bladed Control Advanced Turbine (CART2), flickers are mitigated using DAC caused by wind shear and tower shadow effects [40]. A mathematical time domain modeling of the torque oscillations for three-bladed horizontal-axis upwind turbines caused by periodic effects are discussed in [41] [42] [43] [44]. Composite controller based on disturbance tracking theory(DTC) is designed for region 2 operations using IPC [46] and then optimal control theory is used to design DAC [47] to meet multiple objectives of wind turbine. Also periodic DAC techniques [45] is used to regulate rotor speed at above-rated wind speeds while mitigating cyclic blade root loads using individual blade pitch for a two-bladed downwind machine. This periodic controller shows a potential in reducing blade loads without sacrificing rotor speed regulation.

Modern control systems have the capability to handle MIMO system in efficient manner. Multivariable control algorithm [51] [52] has been used for the tuning of individual control loops; PI is used to generate demanded collective pitch angle for regulating generator speed and IPC is used to reduce structural load. Boukhezzar used a multivariable control strategy by combining a nonlinear state feedback torque control with a linear blade pitch angle control for the above-rated power operating condition of wind turbine [48] and overall instantaneous control input is the combination of collective pitch angle and perturbed IPC pitch angle demand input. MIMO systems are represented by transfer matrix and robust control has been also used to design the controller with uncertainties [53] [54]. Multivariable pitch controller with $H_\infty$ norm minimization for collective and cyclic pitch has been used [49] with objective to reduce load and power regulation. It has actively increased damping of the first axial tower bending mode and reduced 1p fluctuations in blade root bending moments. Multi-Objective mixed $H_2/H_\infty$ control design on the basis of linear model with pole placement constraint is used [50] to mitigate unwanted oscillations in the drive train, tower and generator rotational speeds at its rated values. Observer-based controllers play an important role to handle multivariable systems due to their wide use in industry because process variables that are not directly accessible by measurements can be estimated for feedback. Any controller with estimator can be formulated as observer based controller and practical appeal of observer based control is that they allow a simplified implementation of gain scheduling with an explicit separated estimation/control structure [55]. An observer-based output feedback control for uncertain systems [56] using LQR optimization is used to minimize the energy while variable structure control law is used for robustness to uncertainty. Disturbance-observer based control (DOBC) have been researched in various industrial sectors are reviewed of linear and nonlinear systems [57].

Operation of wind turbines at different wind speeds require some kind of gain scheduling, so linear parameter varying control (LPV) of robust control is applied [58] for both partial load and full load conditions. Gain scheduling strategy for multivariable controller [59] which interpolates between unstable controllers based on $\mu$ synthesis is used. One important step is the gain scheduling of linear controllers such that the controller coefficients are scheduled with the current value of the exogenous or endogenous scheduling signal. A safe bumpless transfer has been proposed [60] between two observer-based controllers for linear multivariable system by the interpolation of covariance to keep the closed loop system stable and bumpless transfer with integral action [61] based on the Youla-Kucera parametrization is used for wind turbine. LPV design methods are investigated [62] and gain-scheduling (GS) control techniques to floating offshore wind turbines on barge platforms.

Modeling and controller performance evaluation are presented for both low and high wind speed cases [63], [64] [65].

## 1.3 Objectives and Contributions

The objective of this thesis is the analysis and design of a multivariable control for load mitigation using CPC or IPC of large scale wind turbine for full load operation to regulate output power and to reduce the fatigue of the components. The objectives of the wind turbine control are quite preemptively as follows.

- Improvements in cost-effectiveness and reliability of wind turbine.
- Regulate the output power under the effect of aerodynamic loads.
- Mitigate loads on wind turbine components to increase life and reduce failure.
- Harmonic Mitigation because of frequencies which may cause resonance in the mechanical structure.
- Mitigation of tower oscillations in side-to-side and fore-aft directions.
- Aerodynamic analysis to see effect of ice/dirt accumulation on rotor blade of wind turbine to reduce th failure .
- Maintain safe turbine operation

The contributions to achieve the above objectives are listed as follows:

- In Paper A; LQG control scheme is developed based on three-state linear model of wind turbine to regulate generator speed and mitigate the effect of turbulent wind in the presence of sensor noise. Numerical linearization technique is used for the generation of linear model, plant and measurement noises are considered as Gaussian noise. Two-bladed Control Advanced Research Turbine (CART2) used as research object and developed controller is tested on linear model. The proposed controller provide better mitigation to turbulent wind in the presence of measurement noise as compared to PID control.
- In Paper B; DAC control strategy is developed to reduce periodic disturbances using CPC for full load operation of wind turbine. It is tested on National Renewable Energy Laboratories (NREL) 5MW three-blade wind turbine. The proposed controller shows good regulation of generator speed, reduced fatigue of gearbox, robustness to parametric uncertainties and stability.

- In Paper C; Multivariable DAC is presented to mitigate the effect of periodic aerodynamic loads caused by wind shear and tower shadow effect using CPC of wind turbine. Wind profile with periodic effects is presented for the simulation and tested on NREL's 5MW nonlinear model with actuator dynamics. It can be concluded from the results that proposed control has good regulation of output power, better mitigation to turbulent wind and to flickers generated due wind shear and tower shadow using collective pitch control.

- In Paper D; Wind turbine installed in the cold climate areas has an icing on its rotor blade which might change its aerodynamics. This paper is about wind tunnel experiment to see the aerodynamic changes occur due to effect of ice accumulated on the rotor blades of wind turbine. The results showed that maximum Cp value is reduced with the increase of ice accumulation which will result less power production and more fatigue of the components of the wind turbine. As the blade with ice on lead edge shows different characteristics than the blade with ice on lead-trail edge Ice, so control should be able to monitor theses changes and adapt accordingly.

- In Paper E; Multivariable Disturbance Observer Based Control (DOBC) is presented to mitigate the periodic aerodynamic loads of wind turbine. These periodic loads are caused by wind shear and tower shadow add flickers as 1p, 3p, 6p etc., (p is the rotor rotational frequency) for three bladed wind turbine. We have developed a novel DOBC to mitigate the flickers using IPC and linear state space model of wind turbine with tower dynamics is also presented. The proposed controller performance is compared with PI and DAC with collective pitch control. The degradation in the performance of the controller as moving away from the operating point is assessed by applying step changing wind for Region III. Furthermore, a comparison of power spectral density of generator speed, drive-train torsion and tower fore-aft moment shows better mitigation to the flickers by applying turbulent wind. It can inferred from the comparison of results that presented control strategy have good regulation of output power, mitigation 1p, 3p and 6p flicker and reduced fatigue of components as compared as compared to PI and DAC.

- In Paper F; This paper has presented a systematic method for designing a parametrized DAC for full load operations of wind turbine. The presented control strategy is designed using LPV design method which provides bumpless transition between different DAC controllers. We have presented and discussed issues for the smooth transfer of DAC controllers and tested on the wind turbine for full load operation. The proposed method for obtaining a stable design has been used for the design of an LPV controller for above rated wind speed condition of wind turbines. By the comparison of the results generated from the simulation studies of presented parametrized controller and DAC controller designed at mid wind speed, it has been concluded that the parametrized DAC controller achieves better performance by a decrease in pitching activity and reducing fatigue of the drive train without affecting the produced power.

## 1.4 Outline of the Thesis

The organization of the thesis is shown in fig. 4 and is as follows:

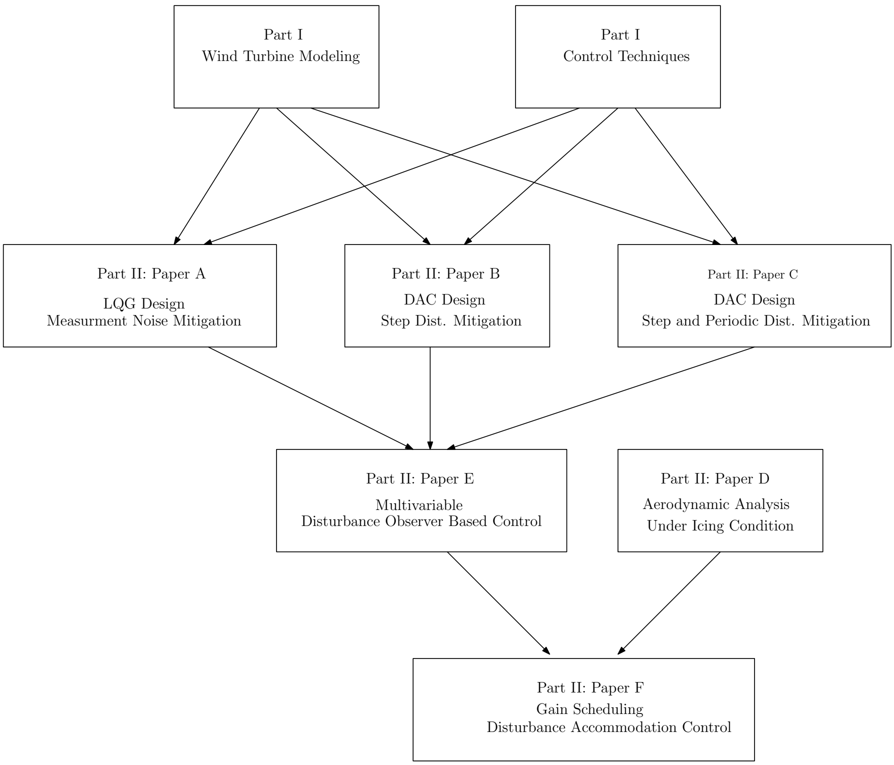


**Fig. 4:** Structure of the Thesis

- Part I: Introduction
- Part II: Papers

- **Paper A: LQG Controller Design for Pitch Regulated Variable Speed Wind Turbine**, (Raja M. Imran , D. M. Akbar Hussain, and Zhe Chen). In the Proceeding of IEEE International Energy Conference (ENERGYCON), Dubrovnik Croatia, 2014.
- **Paper B: DAC with LQR Control Design for Pitch Regulated Variable Speed Wind Turbine**, (Raja M. Imran , D. M. Akbar Hussain, and Mohsen Soltani). In the Proceeding of IEEE International Telecommunications Energy Conference (INTELEC), Vancouver, BC, Canada, 2014.
- **Paper C: DAC to Mitigate the Effect of Periodic Disturbances on Drive Train using Collective Pitch for Variable Speed Wind Turbine**, (Raja M. Imran , D. M. Akbar Hussain, and Mohsen Soltani).In the Proceeding of IEEE International Conference on Industrial Technology (ICIT), Seville, Spain, 2015.
- **Paper D: An Experimental Analysis of the Effect of Icing on Wind Turbine Rotor Blade**, (Raja M. Imran , D. M. Akbar Hussain, and Mohsen Soltani). In the Proceeding of IEEE PES TD Conference and Exposition, Dallas, USA, 2016.
- **Paper E: Optimal Tuning of Multivariable Disturbance-Observer-Based Control for Flicker Mitigation Using IPC of Wind Turbine**, (Raja M. Imran , D. M. Akbar Hussain, Mohsen Soltani, Raja M. Rafaq). Submitted to Journal of IET Renewable Power Generation .
- **Paper F: Bumpless Transfer of Parametrized Disturbance Accommodated Controller for Wind Turbine**, (Raja M. Imran, D. M. Akbar Hussain, Bhawani Shanker Chowdhry, Raja M. Irfan). Submitted to Journal of Energies.

# 2 Wind Turbine Modeling

## 2.1 Introduction

We have used two wind turbine models; linear model and FAST code model. As for control design we need a simplified model, we have considered reduced order two-mass model of wind turbine. This reduce order model is linearized using numerical and first principle linearization techniques to get three-state and five-state model. Then control techniques are developed on the basis of these linear models and simulation are performed on nonlinear FAST code model of wind turbine.

## 2.2 Wind Energy Conversion System (WECS)

A WECS consists of rotor blades, gearbox, generator and tower. The interaction of these subsystem [19] is shown in Fig.5

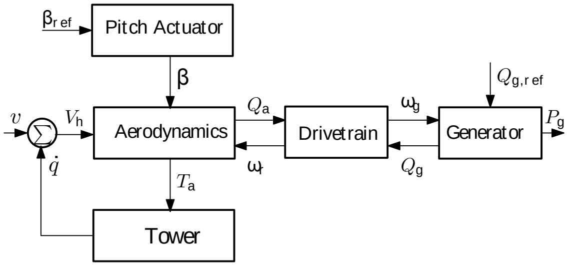


**Fig. 5:** Wind Turbine Subsystem Interconnection [15]

### 2.2.1 Aerodynamics

Available power [11] [12] [13] [14] is

$$P_{wind} = \frac{1}{2}\rho A\ v^3 \tag{1}$$

Harvested power [11] [12] [13] [14] is

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

$v$ is wind speed, $A$ is rotor swept area and $\rho$ is air density. $\lambda$ is tip speed ratio. $\beta$, $R$, $\omega_r$ are blade pitch angle, length and angular rotational speed of rotor blade respectively.
Aerodynamic torque exerted by rotor on drive-train is $Q_a$ and $T_a$ is the thrust force on the nacelle of the wind turbine [15] [19] can be written as

$$Q_a(t) = \frac{1}{2}\rho\pi R^2\ \frac{v^3(t)}{w_r(t)} C_p(\lambda(t), \beta(t)) \tag{3}$$

$$T_a(t) = \frac{1}{2}\rho\pi R^2 C_T(\lambda(t), \beta(t))\ v^2(t) \tag{4}$$

$$\lambda(t) = \frac{w_r(t)\ R}{v(t)} \tag{5}$$

$C_p(\lambda, \beta)$ is power coefficient and $C_T(\lambda, \beta)$ is thrust coefficient of the rotor of wind turbine.

### 2.2.2 Drive-train

The two-mass model of the drive train is used and dynamic equation [12] [13] are

$$J_g\dot{w}_g(t) = -\frac{B_{dt}}{{N_g}^2}\omega_g(t) + \frac{B_{dt}}{N_g}\omega_r(t) + \frac{K_{dt}}{N_g}\theta(t) - Q_g(t) \tag{6}$$

$$J_r\dot{w}_r(t) = \frac{B_{dt}}{N_g}\omega_g(t) - B_{dt}\omega_r(t) - K_{dt}\theta(t) + Q_a(t) \tag{7}$$

$$\dot{\theta}(t) = \omega_r(t) - \frac{1}{N_g}\omega_g(t) \tag{8}$$

$J_r$ is combined inertia of rotor and shaft, $J_g$ is combined inertia of high speed, drive-train and generator. $K_{dt}$ is drive-train stiffness and $B_{dt}$ is drive-train damping coefficient. $Q_g$ is the generator torque, $\omega_g$ is generator speed, $N_g$ is the gear ratio and $\theta$ is the drive-train torsion.

### 2.2.3 Tower

The tower is modeled as a mass-spring-damper system [15] [19] can be represented as

$$M_t\ddot{q}_t = T_a(t) - B_t\dot{q}_t(t) - K_tq_t(t) \tag{9}$$

The relative wind speed is $v(t) = V_h(t) - \dot{q}(t)$, $V_h$ is the absolute wind speed measured at hub height and $q(t)$ is the fore-aft bending displacement of the tower. $M_t$ is the model mass of the first fore-aft bending mode, $B_t$ is structural damping coefficient and $K_t$ is the stiffness coefficient of the tower.

### 2.2.4 Pitch Actuator

The pitch actuator dynamics [15] [19] is

$$\dot{\beta}(t) = -\frac{1}{\tau}\beta + \frac{1}{\tau}\beta_{ref} \tag{10}$$

$\beta_{ref}$ is the commanded pitch angle and $\tau$ is the time constant for the pitch actuator.

### 2.2.5 Generator

The generator dynamics [15] [19] can be represented as

$$\dot{Q}_g(t) = -\frac{1}{\tau_g}Q_g + \frac{1}{\tau_g}Q_{g,ref} \tag{11}$$

$$\dot{P}_g(t) = \eta_g \omega_g(t) Q_g(t) \tag{12}$$

$Q_{g,ref}$ is the commanded generator torque, $\tau_g$ is the time constant for the generator, $\eta_g$ is the efficiency of the generator and $P_g$ is the output power.

## 2.3 Linearization

### 2.3.1 Three-State Model

Aerodynamic torque acting on the drive train can be written by equation 3. Drive train dynamics is represented by equations 6, 7 and 8. Three-state linear model [11] [12] [13] of wind turbine using numerical linearizaiton [17] can be written as

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \end{bmatrix} = \underbrace{\begin{bmatrix} -\frac{B_{dt}}{J_g N_g^2} & \frac{B_{dt}}{J_g N_g} & \frac{K_{dt}}{J_g N_g} \\ \frac{B_{dt}}{J_r N_g} & \frac{Q_{aw}}{J_r} - \frac{B_{dt}}{J_r} & -\frac{K_{dt}}{J_r} \\ -\frac{1}{N_g} & 1 & 0 \end{bmatrix}}_{A} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

$$+ \underbrace{\begin{bmatrix} 0 \\ \frac{Q_{a\beta}}{J_r} \\ 0 \end{bmatrix}}_{B} u + \underbrace{\begin{bmatrix} 0 \\ \frac{Q_{av}}{J_r} \\ 0 \end{bmatrix}}_{B_d} u_d \tag{13}$$

$$y = \underbrace{\begin{bmatrix} 1 & 0 & 0 \end{bmatrix}}_{C} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \underbrace{\begin{bmatrix} 0 \end{bmatrix}}_{D} u$$

(14)

Where $Q_{av}$, $Q_{a\beta}$, $Q_{aw}$ are partial derivatives of the aerodynamic torque with respect to wind speed, pitch angle and rotor speed calculated at the operating point respectively. $x1$ is the generator speed, $x2$ is the rotor speed and $x3$ is the drive-train torsion perturbation from the operating point. $A$ is state transition, $B$ is control input, $B_d$ is disturbance input, $C$ is measured state and $D$ is output gain matrix of the plant.

### 2.3.2 Five-State Model

We have generated five-state linear model of wind turbine with tower dynamics using first principle method [17] by linearizing torque and thrust force at the operating point $\bar{\zeta}$ for above-rated wind speed condition

$$Q_a(t) \approx Q_{a\bar{\zeta}} + Q_{av}\delta v + Q_{aw}\delta w_r + Q_{a\beta}\delta\beta \tag{15}$$

$$T_a(t) \approx T_{a\bar{\zeta}} + T_{av}\delta v + T_{aw}\delta w_r + T_{a\beta}\delta\beta \tag{16}$$

where $\delta v$, $\delta w_r$, $\delta\beta$ are perturbation of wind speed, generator speed and pitch angle from $\bar{\zeta}$ respectively. $Q_{a\bar{\zeta}}$ is the torque and $T_{a\bar{\zeta}}$ is the thrust at the operating point. Five-state linear model with tower dynamics [15] can be represented as

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \\ \dot{x_4} \\ \dot{x_5} \end{bmatrix} = \underbrace{\begin{bmatrix} -\frac{B_{dt}}{J_g N_g^2} & \frac{B_{dt}}{J_g N_g} & \frac{K_{dt}}{J_g N_g} & 0 & 0 \\ \frac{B_{dt}}{J_r N_g} & \frac{Q_{aw}}{J_r} - \frac{B_{dt}}{J_r} & -\frac{K_{dt}}{J_r} & 0 & 0 \\ -\frac{1}{N_g} & 1 & 0 & 0 & 0 \\ 0 & T_{aw}/M_t & 0 & -K_t/M_t & -B_t/M_t \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}}_{A} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} + \underbrace{\begin{bmatrix} 0 & -1/J_g \\ \frac{Q_{ab}}{J_r} & 0 \\ 0 & 0 \\ T_{ab}/M_t & 0 \\ 0 & 0 \end{bmatrix}}_{B} u + \underbrace{\begin{bmatrix} 0 \\ \frac{Q_{av}}{J_r} \\ 0 \\ T_{av}/M_t \\ 0 \end{bmatrix}}_{Bd} u_d \tag{17}$$

$$y = \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \end{bmatrix}}_{C} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} + \underbrace{\begin{bmatrix} 0 \end{bmatrix}}_{D} u$$

(18)

Where the sensitivity coefficients are

$$Q_{av} = \frac{\partial Q_a}{\partial v}|_{\bar{\zeta}} = \frac{1}{2}\frac{\rho\pi R^2 v^2}{\omega_r}\left(3C_p + v\frac{\partial C_p}{\partial \lambda}\frac{\partial \lambda}{\partial v}\right), \quad T_{av} = \frac{\partial T_a}{\partial v}|_{\bar{\zeta}} = \frac{1}{2}\frac{\rho\pi R^2 v}{\omega_r}\left(2C_T + v\frac{\partial C_T}{\partial \lambda}\frac{\partial \lambda}{\partial v}\right)$$

$$Q_{a\beta} = \frac{\partial Q_a}{\partial \beta}|_{\bar{\zeta}} = \frac{1}{2}\frac{\rho\pi R^2 v^3}{\omega_r}\left(\frac{\partial C_p}{\partial \beta}\right), \quad T_{a\beta} = \frac{\partial T_a}{\partial \beta}|_{\bar{\zeta}} = \frac{1}{2}\rho\pi R^2 v^2\left(\frac{\partial C_T}{\partial \beta}\right)$$

$$Q_{a\omega} = \frac{\partial Q_a}{\partial \omega_r}|_{\bar{\zeta}} = \frac{1}{2}\frac{\rho\pi R^2 v^3}{\omega_r}\left(\frac{\partial C_p}{\partial \lambda}\frac{\partial \lambda}{\partial \omega_r} - \frac{C_p}{\omega_r}\right), \quad T_{a\omega} = \frac{\partial T_a}{\partial \omega_r}|_{\bar{\zeta}} = \frac{1}{2}\rho\pi R^2 v^2\left(\frac{\partial C_T}{\partial \lambda}\frac{\partial \lambda}{\partial \omega_r}\right)$$

$x = \begin{bmatrix} w_g(t) & w_r(t) & \theta(t) & \dot{q}(t) & q(t) \end{bmatrix}$ is the state matrix, $u = \begin{bmatrix} \beta & Q_g \end{bmatrix}$ is the input matrix, $u_d$ is the disturbance and $y$ is the output.

## 2.4 FAST Code

This model is used for the simulation of wind turbine wind collective and individual pitch control. The FAST code was first developed at Oregon State University [66] and validated [67] at the National Renewable Energy Laboratory (NREL). It can model the dynamic response of both two and three bladed, horizontal - axis wind turbines. For two-bladed turbines, 15 degrees of freedom (DOFs) are used to describe the turbine dynamics. For NREL's 5-MW three bladed wind turbine, it incorporates 16 DOFs; one edgewise bending-mode for each blade and two flapwise , generator speed, drive shaft torsional, nacelle-yaw-actuator, two side-to-side bending-mode and two fore-aft bending-mode in the tower. This makes debugging and interpreting results very straightforward. Linear models can be extracted from FAST based on just a subset of the total modeling DOF contained in FAST. The DOF can be switched on or off and same can be used in closed-loop simulation. The effects of un-modeled modes can be studied by switching on those DOF in simulation, which are neglected in the linear model used for control design. Aerodynamic loads are also modeled in Fast code and TurbSim is used to generate 3D wind profile for the simulation.

# 3 Control Techniques

## 3.1 Introduction

In this section we will give a short description of the control techniques developed for the wind turbine. First of all classical PI control is used to regulate generator speed for above-rated wind speed condition using collective pitch. Modern control LQG, DAC and multivariable DOBC are developed to meet multiple control objectives using collective and individual blade pitch of wind turbine. Then a gain scheduling DOBC with bumpless transfer is proposed for above-rated wind speed condition of wind turbine.

## 3.2 Classical Proportional-Integral (PI) Control

The most widely used industrial controller is the PI because of its simplicity and robustness to model inaccuracies. It is based on classical control theory for single-input-single-output (SISO) systems and is used as baseline for the performance analysis of modern control designs. For full load operation of wind turbine, PI controller K(s) used to regulate generator speed using CPC of wind turbine can be written as

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

$K_p$ and $K_i$ are proportional and integral gains. Let G(s) is the transfer function of wind turbine and Act(s) is the pitch actuator dynamics.

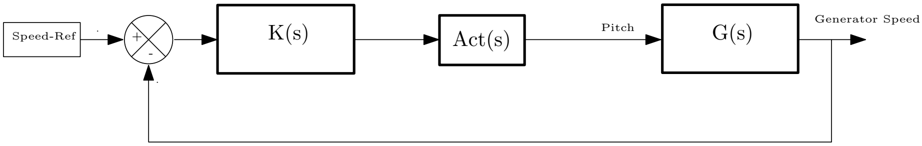


**Fig. 6:** Closed-loop System with PI Control

## 3.3 Linear Quadratic Gaussian (LQG)

LQG is a optimization controller based on linear state space model of system with quadratic cost function. It is a superposition of Linear Quadratic Regulator(LQR) and Linear Quadratic Estimator(LQE).
State space equation of the plant [11] is

$$\dot{x} = Ax(t) + Bu(t) + B_d\xi(t) \tag{19}$$

$$y(t) = Cx(t) + Du(t) + \mu(t) \tag{20}$$

$\xi$ is plant and $\mu$ is the measurement white Gaussian noise.

Feedback law [11] is

$$u = -K_f\ \hat{x}(t) \tag{21}$$

Then dynamics of closed loop system with LQG controller [11] is shown in Fig. F.2 and can be represented as

$$\begin{bmatrix} \dot{x}(t) \\ \dot{e}(t) \end{bmatrix} = \begin{bmatrix} A - BK_f & BK_f \\ 0 & A - BK_k \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix} + \begin{bmatrix} B_d & 0 \\ B_d & -K_k \end{bmatrix} \begin{bmatrix} \xi(t) \\ \mu(t) \end{bmatrix} \tag{22}$$

$$y(t) = \begin{bmatrix} C & 0 \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix} + \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} \xi(t) \\ \mu(t) \end{bmatrix} \tag{23}$$

$K_f$ is full state feedback matrix, $K_k$ is kalman gain matrix, $\hat{x}(t)$ is the estimated states of the plant and $e(t)$ is the error between the estimated and measured states of the plant.

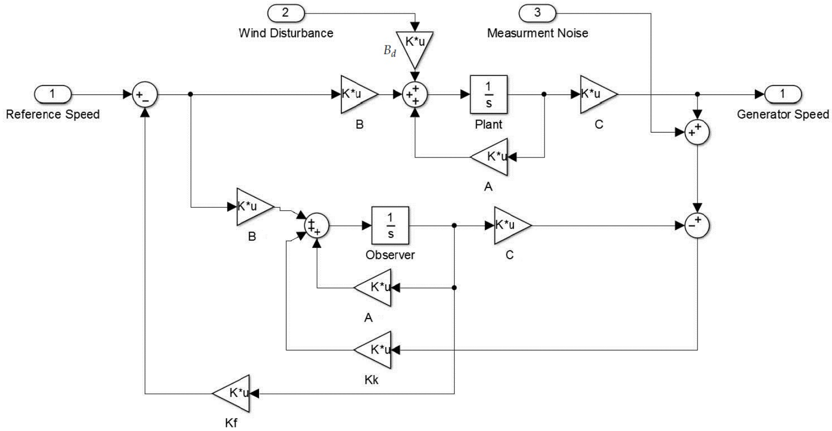


**Fig. 7:** Structure of LQG Control for Wind Turbine [11]

## 3.4 Disturbance Accommodation Control (DAC)

DAC theory is used to solve multi-objective problem using optimal control. DAC is the superposition of state feedback and disturbance feedback to reject the effect of known disturbance.
Wind turbine linear state-space model [12] [13] is

$$\dot{x} = Ax(t) + Bu(t) + B_d u_d(t) \tag{24}$$

$$y(t) = Cx(t) \tag{25}$$

Feedback control law [12] [13] is

$$u = -(K_{fx}\,\hat{x}(t) + K_{fd}\,\hat{z}_d(t)) \tag{26}$$

Then closed loop system with DAC [12] can be represented as

$$\begin{bmatrix} \dot{x} \\ \dot{z}_d \\ \dot{\hat{x}} \\ \dot{\hat{z}}_d \end{bmatrix} = \begin{bmatrix} A & 0 & -BK_{fx} & -BK_{fd} \\ 0 & F & 0 & 0 \\ K_{ox}C & 0 & A - BK_{fx} - K_{ox}C & B_d\theta - BK_{fd} \\ K_{od}C & 0 & -K_{od}C & F \end{bmatrix} \begin{bmatrix} x \\ z_d \\ \hat{x} \\ \hat{z}_d \end{bmatrix} + \begin{bmatrix} B_d \\ 0 \\ 0 \\ 0 \end{bmatrix} u_d \tag{27}$$

Let

$$\overline{A} = \begin{bmatrix} A & B_d\theta \\ 0 & F \end{bmatrix}, \overline{C} = \begin{bmatrix} C & 0 \end{bmatrix}, K_o = \begin{bmatrix} K_{ox} \\ K_{od} \end{bmatrix}, K_f = \begin{bmatrix} K_{fx} & K_{fd} \end{bmatrix}$$

Also

$$e(t) = \begin{bmatrix} e_x(t) & e_d(t) \end{bmatrix}$$

where $\quad e_x(t) = x(t) - \hat{x}(t), \quad e_d(t) = z_d(t) - \hat{z}_d(t)$

Then dynamic of system with DAC [13] is shown in Fig.8 and can also be written as

$$\begin{bmatrix} \dot{x} \\ \dot{e} \end{bmatrix} = \begin{bmatrix} A + BK_{fx} & BK_f \\ 0 & \overline{A} - K_0\overline{C} \end{bmatrix} \begin{bmatrix} x \\ e \end{bmatrix} + \begin{bmatrix} BK_{fd} + B_d\theta \\ 0 \end{bmatrix} z_d \tag{28}$$

Where $F$ is state and $\theta$ is the output matrix of known disturbance waveform. $x$ is the state of the plant, $z_d$ is state of the disturbance, $\hat{z}_d$ is estimated state of the disturbance and $\hat{x}$ is estimated state of the plant. $K_{fx}$ is state feedback matrix, $K_{fd}$ is disturbance feedback matrix, $K_{ox}$ is kalman state estimation matrix, $K_{od}$ is kalman disturbance estimation matrix.

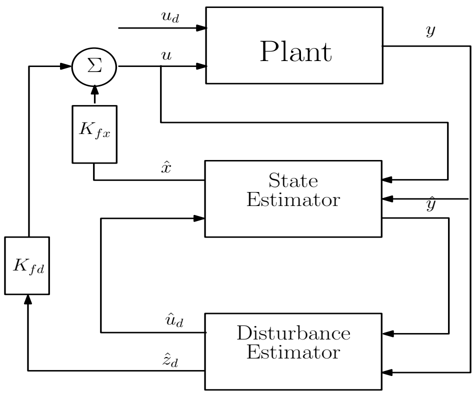


**Fig. 8:** Structure of DAC Control [13]

## 3.5 Disturbance Observer Based Control (DOBC)

Let the open loop system is

$$\dot{x} = Ax(t) + Bu(t) \tag{29}$$

$$y(t) = Cx(t) + Du(t) \tag{30}$$

It can also be represented as

$$G(s) = \left[\begin{array}{c|c} A & B \\ \hline C & D \end{array}\right] \tag{31}$$

Disturbance accommodated observer based control [15] can be represented as

$$u = K(s)\, y \tag{32}$$

where

$$K(s) = \left[\begin{array}{cc|c} A - BK_x - L_xC + L_xDK_x & B_d\theta - BK_d + L_xDK_d & L_x \\ L_dDK_x - L_dC & L_dDK_d + F & L_d \\ \hline -K_x & -K_d & 0 \end{array}\right] \tag{33}$$

$K_x$ is state feedback matrix, $L_x$ is kalman state estimation matrix, $K_d$ is disturbance feedback matrix, $L_d$ is kalman disturbance estimation matrix.

So closed loop system with disturbance accommodated observer based control is

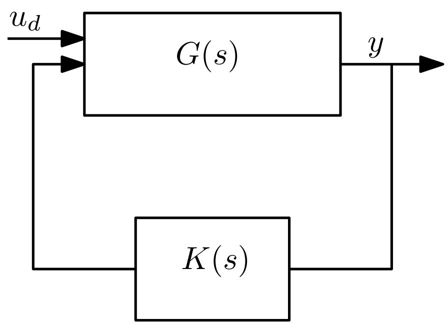


**Fig. 9:** Closed-loop system with DOBC [15]

## 3.6 Bumpless Transfer of DAC Controllers

Let $G_0(s)$ and $G_1(s)$ be the detectable and stablizable linearized plant of $G(s)$ at two operating points and is scheduled [59] as

$$G_\gamma(s) = (1 - \gamma)G_o(s) - \gamma G_1(s) \tag{34}$$

Let $K_0(s)$ and $K_1(s)$ are DAC controllers tuned at operating points to satisfy the desired performance. $L_{x0}$ , $L_{d0}$, $K_{x0}$ and $K_{d0}$ are the plant state estimation, disturbance state estimation, plant state feedback and disturbance feedback matrices respectively for the first controller. $L_{x1}$ , $L_{d1}$, $K_{x1}$ and $K_{d1}$ are the plant state estimation, disturbance state estimation, plant state feedback and disturbance feedback matrices respectively for the second controller.

$$K_d(\gamma) = (1 - \gamma)K_{d0} - \gamma K_{d1} \tag{35}$$

$$K_x(\gamma){=}(1-\gamma)K_{x0}-\gamma K_{x1} \tag{36}$$

$$L_d(\gamma){=}(1-\gamma)L_{d0}-\gamma L_{d1} \tag{37}$$

$$L_x(\gamma){=}(1-\gamma)L_{x0}-\gamma L_{x1} \tag{38}$$

Then $K_\gamma(s)$ is the family of internally stable disturbance accommodated observer based controllers [16] can be represented as

$$A_{11}(\gamma) = A(\gamma) - B(\gamma)K_x(\gamma) - L_x(\gamma)C(\gamma) + L_x(\gamma)D(\gamma)K_x(\gamma) \tag{39}$$

$$A_{12}(\gamma) = B_d(\gamma)\theta - B(\gamma)K_d(\gamma) + L_x(\gamma)D(\gamma)K_d(\gamma) \tag{40}$$

$$A_{21}(\gamma) = L_d(\gamma)D(\gamma)K_x(\gamma) - L_d(\gamma)C(\gamma) \tag{41}$$

$$A_{21}(\gamma) = L_d(\gamma)D(\gamma)K_d(\gamma) + F \tag{42}$$

$$K_\gamma(s){=}\left[\begin{array}{cc|c} A_{11}(\gamma) & A_{12}(\gamma) & L_x \\ A_{21}(\gamma) & A_{22}(\gamma) & L_d \\ \hline -K_x & -K_d & 0 \end{array}\right] \tag{43}$$

Where $\gamma\epsilon(0,1)$ is the scheduling parameter.

$A(\gamma)$ is interpolated state transition, $B(\gamma)$ is interpolated control input, $B_d(\gamma)$ is interpolated disturbance input, $C(\gamma)$ is interpolated measured, $D(\gamma)$ is the interpolated output matrices of $G_\gamma(s)$ between the operating points.

# 4 Conclusion and Future Work

Multivariable linear control techniques are developed to reduce fatigue of wind turbine components- drivetrain, tower, rotor blade and regulate output power in the presence of aerodynamic loads and sensor noise for full load operation using rotor bloade pitch control. Wind turbine linearization is performed using numerical method and three state linear model of wind turbine is presented. A systematic design methodology for the LQG control using optimal control theory is developed for NREL's CART2 wind turbine using CPC to get better speed regulation and mitigation of turbulent wind in the presence of sensor measurement noise. DAC with optimal control theory make

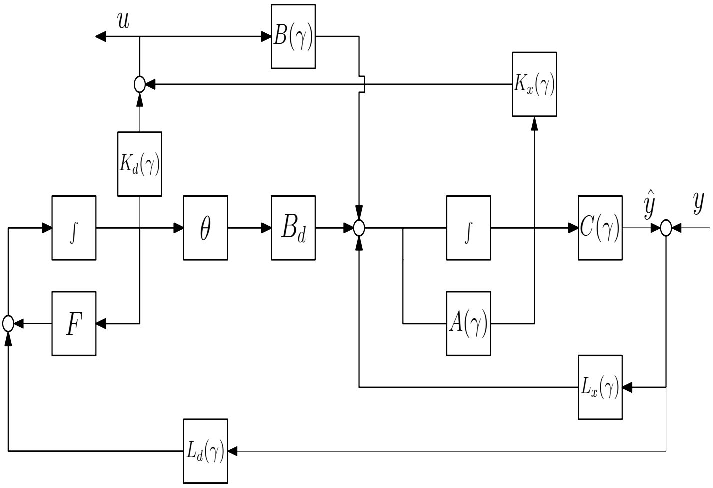


**Fig. 10:** Parametrized DAC Structure [16]

system disturbance free, therefore it is designed to meet multiple control objectives of wind turbine i.e., less fluctuation in output power, better stability and reduced loads on drive train. Wind profile is modeled with wind shear and tower shadow effect then tested on NREL's 5MW for step mitigation in the presence of actuator dynamics. DAC is designed with extended disturbance states to mitigate step wind as well as periodic aerodynamic loads and tested on FAST code model of wind turbine. It can be inferred from the results that it shows better mitigation to turbulent wind, wind shear and tower shadow effects, less power fluctuation and filtered well 3p harmonics using CPC. Wind tunnel experimental is performed to investigate the effect of icing on rotor blade of wind turbine. Three small scale models of the wind turbine rotor blade with same profile with different icing effects are tested. Power coefficient curves generated from the experiment are compared and analyzed to see the aerodynamic changes. It is observed that there should be some mechanism which should adopt with these changes to get more efficiency from the wind turbine.

Multivariable disturbance accommodated observer based control strategy is proposed using individual blade pitch control (IPC) of wind turbine to reduce fatigue of component under wind shear and tower shadow effect. IPC control showed less fluctuation in output power, reduced loads on gearbox and tower in the presence of wind shear and tower shadow effects as compared to the PI and DAC with CPC. Five-state linear model with tower dynamics using first principle linearization is presented and disturbance is modeled for 1p, 3p and 6p flicker mitigation. Multivariable DOBC is tuned using Bryson's rule to meet multiple objectives -power regulation, tower and drive train fatigue reduction under the effect of periodic aerodynamic loads using IPC. A parametrized DAC is presented for above rated wind speed condition. Linear Time Invariant DAC controllers are tuned at different operating points to get desired performance and then bumpless transfer between the controllers is described by interpolation method. Its simulation results for full load operation of wind turbine showed that parametrized controller scheduling with operating point has better fatigue reduction of components and regulation of output power as compared to fixed gain DAC.

DAC is based on linear model of the plant and disturbance, so DAC can be developed with extended states of the wind turbine linear model with side-side moments and also disturbance modeled for 3p,6p, 9p flicker mitigation. Model uncertainties can be handled using robust or adaptive control which may shows better performance of the controller under the icing condition.

# References

[1] Machol, Ben, and Sarah Rizk. "Economic value of US fossil fuel electricity health impacts." Environment international 52 (2013): 75-80.

[2] Solar Energy Industries Association. "Solar Market Insight Report 2012 Q3." Solar Energy Industries Association, SEIA (2012).

[3] American Wind Energy Association. "Federal production tax credit for wind energy." Fact Sheet (2013).

[4] Lindenberg, Steve, ed. 20 % Wind Energy By 2030: Increasing Wind Energy¿ s Contribution to US Electricity Supply. DIANE Publishing, 2009.

[5] Corbetta, Giorgio, I. Pineda, and J. Wilkes. "Wind in power–2013 European statistics." European Wind Energy Association (2014).

[6] Butterfield, Sandy, Walter Musial, and George Scott. "Definition of a 5-MW reference wind turbine for offshore system development." (2009).

[7] Aho, Jarmo, et al. "A tutorial of wind turbine control for supporting grid frequency through active power control." American Control Conference (ACC), 2012. IEEE, 2012.

[8] Manwell, James F., Jon G. McGowan, and Anthony L. Rogers. Wind energy explained: theory, design and application. John Wiley Sons, 2010.

[9] Burton, Tony, et al. Wind energy handbook. John Wiley Sons, 2001.

[10] Matha, Denis. Model Development and Loads Analysis of an Offshore Wind Turbine on a Tension Leg Platform with a Comparison to Other Floating Turbine Concepts: April 2009. No. NREL/SR-500-45891. National Renewable Energy Laboratory (NREL), Golden, CO., 2010.

[11] Imran, Raja M., D. M. Akbar Hussain, and Zhe Chen. "LQG controller design for pitch regulated variable speed wind turbine." Energy Conference (ENERGYCON), 2014 IEEE International. IEEE, 2014.

[12] Imran, Raja M., D. M. Akbar Hussain, and Mohsen Soltani. "DAC with LQR control design for pitch regulated variable speed wind turbine." Telecommunications Energy Conference (INTELEC), 2014 IEEE 36th International. IEEE, 2014.

[13] Imran, Raja M., D. M. Akbar Hussain, and Mohsen Soltani. "DAC to mitigate the effect of periodic disturbances on drive train using collective pitch for variable speed wind turbine." Industrial Technology (ICIT), 2015 IEEE International Conference on. IEEE, 2015.

[14] Raja M. Imran, D.M. Akbar Hussain and Mohsen Soltani,"An Experimental Analysis of the Effect of Icing on Wind Turbine Rotor Blades," IEEE PES T&D Conference and Exposition, Dallas Texas USA, 2-5 May 2016.

[15] Raja M. Imran , D. M. Akbar Hussain, Mohsen Soltani, Raja M. Rafaq , " Optimal Tuning of Multivariable Disturbance-Observer-Based Control for Flicker Mitigation Using IPC of Wind Turbine," Submitted to *Journal of IET Renewable Power Generation* , 2016.

[16] Raja M. Imran, D. M. Akbar Hussain, Bhawani Shanker Chowdhry, Raja M. Irfan, " Bumpless Transfer of Parametrized Disturbance Accommodated Controller for Wind Turbine," Submitted to *Journal of Energies*, 2016.

[17] Mahmood Mirzaei,"Wind Turbine Control: Robust Model Based Approach." PhD diss., Technical University of Denmark, 2012.

[18] Khalil, Hassan K., and J. W. Grizzle. Nonlinear systems. Vol. 3. New Jersey: Prentice hall, 1996.

[19] Bianchi, Fernando D., Hernan De Battista, and Ricardo J. Mantz. Wind turbine control systems: principles, modelling and gain scheduling design. Springer Science Business Media, 2006.

[20] Åström, Karl J., and Björn Wittenmark. Adaptive control. Courier Corporation, 2013.

[21] Bossanyi, E. A. "The design of closed loop controllers for wind turbines." Wind energy 3.3 (2000): 149-163.

[22] Bossanyi, E. "Developments in closed loop controller design for wind turbines." 2000 ASME Wind Energy Symposium, 19 th, AIAA, Aerospace Sciences Meeting and Exhibit, 38 th, Reno, NV. 2000.

[23] Bossanyi, E. A. "Wind turbine control for load reduction." Wind energy 6.3 (2003): 229-244.

[24] Bossanyi, E. A. "Individual blade pitch control for load reduction." Wind energy 6.2 (2003): 119-128.

[25] Hand, M. Maureen, and Mark J. Balas. Systematic approach for PID controller design for pitch-regulated, variable-speed wind turbines. National Renewable Energy Laboratory, 1997.

[26] Kim, Jin-Sung, Jonghyun Jeon, and Hoon Heo. "Design of adaptive PID for pitch control of large wind turbine generator." Environment and Electrical Engineering (EEEIC), 2011 10th International Conference on. IEEE, 2011.

[27] Anjun, Xia, et al. "Pitch control of large scale wind turbine based on expert PID control." Electronics, Communications and Control (ICECC), 2011 International Conference on. IEEE, 2011.

[28] Ogata, Katsuhiko. Modern control engineering. Prentice Hall PTR, 2001.

[29] Yao, Xingjia, et al. "Pitch regulated LQG controller design for variable speed wind turbine." Mechatronics and Automation, 2009. ICMA 2009. International Conference on. IEEE, 2009.

[30] Kalbat, Abdulrahman. "Linear Quadratic Gaussian (LQG) control of Wind turbines." Electric Power and Energy Conversion Systems (EPECS), 2013 3rd International Conference on. IEEE, 2013.

[31] Y. Kim, C. Yixuan, "Pole Placement for Wind Turbine," Department of Engineering, The University of Michigan MI 48502, USA 2013.

[32] Bryson, Arthur Earl. Applied optimal control: optimization, estimation and control. CRC Press, 1975.

[33] Anderson, Brian DO, and John B. Moore. Optimal control: linear quadratic methods. Courier Corporation, 2007.

[34] Pintea, Andreea, et al. "Optimal control of variable speed wind turbines." Control Automation (MED), 2011 19th Mediterranean Conference on. IEEE, 2011.

[35] Pham, Trung-Kien, et al. "LQR control for a Multi-MW wind turbine." World Academy of Science, Engineering and Technology 62 (2012).

[36] A. D. Wright,"Modern Control Design for Flexible Wind Turbines", PhD thesis, University of Colorado, 2003.

[37] Wright, A. D., and L. J. Fingersh. "Advanced control design for wind turbines." Part I: Control Design, Implementation, and Initial Tests, National Renewable Energy Lab., USA (2008).

[38] Zhang, Yunqian, et al. "Flicker mitigation strategy for a doubly fed induction generator by torque control." Renewable Power Generation, IET 8.2 (2014): 91-99.

[39] Zhang, Yunqian, et al. "Flicker mitigation by individual pitch control of variable speed wind turbines with DFIG." Energy Conversion, IEEE Transactions on 29.1 (2014): 20-28.

[40] Wright, Alan Duane. Modern control design for flexible wind turbines. Golden, CO, USA: National Renewable Energy Laboratory, 2004.

[41] De Kooning, Jeroen DM, et al. "Shaft speed ripples in wind turbines caused by tower shadow and wind shear." Renewable Power Generation, IET 8.2 (2014): 195-202.

[42] Das, Swagata, Neeraj Karnik, and Surya Santoso. "Time-domain modeling of tower shadow and wind shear in wind turbines." ISRN Renewable Energy 2011 (2011).

[43] Burlibasa, A. "Wind speed modelling for large wind turbines: Interacting with tower and blades dynamics." System Theory, Control and Computing (ICSTCC), 2012 16th International Conference on. IEEE, 2012.

[44] Dolan, Dale SL, and Peter W. Lehn. "Simulation model of wind turbine 3p torque oscillations due to wind shear and tower shadow." Power Systems Conference and Exposition, 2006. PSCE'06. 2006 IEEE PES. IEEE, 2006.

[45] Stol, Karl A., and Mark J. Balas. "Periodic disturbance accommodating control for blade load mitigation in wind turbines." Journal of Solar Energy Engineering 125.4 (2003): 379-385.

[46] Stol, Karl A. "Disturbance tracking and blade load control of wind turbines in variable-speed operation." ASME 2003 Wind Energy Symposium. American Society of Mechanical Engineers, 2003.

[47] Li, Jianlin, et al. "Disturbance accommodating LQR method based pitch control strategy for wind turbines." Intelligent Information Technology Application, 2008. IITA'08. Second International Symposium on. Vol. 1. IEEE, 2008.

[48] Boukhezzar, Boubekeur, et al. "Multivariable control strategy for variable speed, variable pitch wind turbines." Renewable Energy 32.8 (2007): 1273-1287.

[49] Geyler, M., and P. Caselitz. "Robust multivariable pitch control design for load reduction on large wind turbines." Journal of solar energy engineering 130.3 (2008): 031014.

[50] M.Z. de la Hoz, F. Pozo, "Advances on Analysis and Control of Vibrations: Theory and Applications ,"Publisher; InTech, ISBN 978-953-51-0699-9, 2012.

[51] Johansson, Karl H., et al. "Multivariable controller tuning." American Control Conference, 1998. Proceedings of the 1998. Vol. 6. IEEE, 1998.

[52] Njiri, Jackson G., Yan Liu, and Dirk Söffker. "Multivariable control of large variable-speed wind turbines for generator power regulation and load reduction." IFAC-PapersOnLine 48.1 (2015): 544-549.

[53] Zhou, Kemin, John Comstock Doyle, and Keith Glover. Robust and optimal control. Vol. 40. New Jersey: Prentice hall, 1996.

[54] Gu, Da-Wei, Petko Petkov, and Mihail M. Konstantinov. Robust control design with MATLAB®. Springer Science Business Media, 2005.

[55] Alazard, Daniel, and Pierre Apkarian. "Exact observer-based structures for arbitrary compensators." International Journal of Robust and Nonlinear Control 9.2 (1999): 101-118.

[56] Muhammad Nizam, Kamarudin, Md Rozali Sahazati, and Husain Abdul Rashid. "Observer-based output feedback control with linear quadratic performance." (2012).

[57] Chen, Wen-Hua, et al. "Disturbance observer-based control and related methods: An overview." IEEE Transaction on Industrial Electronics, Vol. 63, No. 2, February 2016,

[58] Østergaard, Kasper Zinck, Jakob Stoustrup, and Per Brath. "Linear parameter varying control of wind turbines covering both partial load and full load conditions." International Journal of Robust and Nonlinear Control 19.1 (2009): 92-116.

[59] Hangstrup, Mads E., et al. "Gain-scheduled control of a fossil-fired power plant boiler." Control Applications, 1999. Proceedings of the 1999 IEEE International Conference on. Vol. 2. IEEE, 1999.

[60] Stoustrup, Jakob, and Mohammad Komareji. "A parameterization of observer-based controllers: Bumpless transfer by covariance interpolation." Proc. American Control Conf., St. Louis, MO, USA. 2009.

[61] Niss, Michael Odgaard Kuch, et al. "A Youla-Kucera approach to gain-scheduling with application to wind turbine control." CCA/ISIC. 2009.

[62] Østergaard, Kasper Zinck. Robust, gain-scheduled control of wind turbines. PhD diss., Automation and Control, Department of Electronic Systems, Aalborg University, 2008.

[63] Bagherieh, Omid. "Gain-scheduling control of floating offshore wind turbines on barge platforms." Electronic Theses and Dissertations (ETDs) 2008+ (2013).

[64] Shirazi, Farzad A., Karolos M. Grigoriadis, and Daniel Viassolo. "Wind turbine linear parameter varying control using fast code." ASME 2012 5th Annual Dynamic Systems and Control Conference joint with the JSME 2012 11th Motion and Vibration Conference. American Society of Mechanical Engineers, 2012.

[65] Bu, Yiming. Switching linear parameter-varying control of a variable-speed wind turbine. California State University, Long Beach, 2015.

[66] J.M. Jonkman, and M.L. Buhl., “FAST User’s Guide", Golden, CO: National Renewable Energy Laboratory, NREL/EL-500-38230, 2005.

[67] Buhl Jr., M.L., Wright, AD. Pierce, K.G,”Wind Turbine Design Codes: A Comparison of the Structural Response”, Proc. ASME Wind Energy Symposium, 38th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 2000.

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