Multi-Objective Control Strategies and Prognostic-Based Lifetime Extension of Utility-Scale Wind Turbines

Von der Fakultät für Ingenieurwissenschaften,
Abteilung Maschinenbau und Verfahrenstechnik
der
Universität Duisburg-Essen
zur Erlangung des akademischen Grades
eines
Doktors der Ingenieurwissenschaften
Dr.-Ing.
genehmigte Dissertation

von

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Tag der mündlichen Prüfung: 22. August 2016

To
my wife and my children

Acknowledgements

The results presented in this thesis are part of the findings for my doctoral research at the Chair of Dynamics and Control (SRS) at the University of Duisburg-Essen. First and foremost, I would like to sincerely thank Univ.-Prof. Dr.-Ing. Dirk Söffker for offering me an opportunity to carry out my research at the Chair of Dynamics and Control as well as guiding and giving me valuable advice throughout my research period. Second, I am indebted to Univ.-Prof. Dr.-Ing. Tamara Nestorović from the Ruhr-Universität Bochum for accepting to review my thesis as the second examiner.

This work could not have been accomplished without the support of research collaboration between the Ministry of Higher Education, Science and Technology of Kenya (MOHEST) and the German Academic Exchange Service (DAAD). I would also like to thank the administration of Jomo Kenyatta University of Agriculture and Technology (JKUAT) for granting me the study leave for the entire period of my research.

Special thanks to all my colleagues at the Chair of Dynamics and Control (SRS) at University of Duisburg-Essen for their support, encouragement, and making my stay in Germany to be cheerful one. Likewise, I thank all my fellow compatriots and by extension people from east Africa whom I interacted during my stay in Germany.

I would like to extend my sincere gratitude to my wife for her great sacrifice, unwavering love, prayers, and encouragement throughout my research journey. I owe resolute gratitude to my children, who despite losing pretty of playing time with their daddy, always afforded something to encourage me everyday. Last but not least, I would like to acknowledge my parents for the sacrifices they made for me and instilling good moral values in me.

Duisburg, September 2016 Jackson G. Njiri

Kurzfassung

Windenergie wird zunehmend als erneuerbare Energiequellen attraktiv, da Wind nachhaltig genutzt werden kann. In vielen Ländern gibt es umfangreiche Anstrengungen, die Produktion von elektrischer Energie aus Wind zu steigern. Im Vergleich zu anderen erneuerbaren Energiequellen wie Sonne, Gezeiten, Wasserkraft o.ä. ist die Energiegewinnung aus Wind technologisch ausgereifter, daher ist die Energiegewinnung aus Wind stärker gewachsen ist als andere Technologien. Windkraft verursacht weniger nachteilige Auswirkungen auf die Umwelt als konventionelle Energiequellen. Aufgrund der vergleichsweise hohen Investitions-, Betriebs- und Wartungskosten sind trotz einer weltweit starken Verbreitung von Windenergieanlagen die Produktionskosten von Windenergie im Vergleich mit anderen alternativen Energiequell-en hoch.

Um die wachsende Nachfrage nach Windkraft zu befriedigen, werden Windkraftanlagen in Größe und Leistung zunehmend skaliert. Bei zunehmender Größe dominieren die strukturellen Lasten der Turbine. Dies führt vermehrt zu Materialermüdung und Ausfällen. Ein weiterer Schwerpunkt in der Entwicklung von Windtecholo-gie ist die Forderung nach Senkung der Produktionskosten, um einen Wettbewerbsvorteil gegenüber anderen alternativen Energiequellen zu schaffen. Im Bereich der Steuerung können niedrigere Produktionskosten durch den Betrieb der Windturbine am/oder in der Nähe der optimalen Energieeffizienz im Teillastbetrieb erreicht werden. Dies erhöht die Zuverlässigkeit durch Verringerung des Verschleißes und die erzeugte Nennleistung auf ihrem Nennwert im hohen Windregime. Häufig ist es schwierig, einen Steueralgorithmus zu realisieren, der sowohl Effizienz als auch Zuverlässigkeit gewährleistet, da diese beiden Ziele widersprechen.

In dieser Arbeit werden Mehrzielsteuerungsstrategien sowohl für den Teillastbereich als auch für hohe Windgeschwindigkeitsbereiche vorgestellt. Im Bereich geringer Windgeschwindigkeiten ist eine Steuerungsstrategie so zu konzipieren, dass die Stromerzeugung sowie die strukturelle Belastung im Sinne einer Balance zwischen maximalen Stromproduktion und verlängerter Lebensdauer der Windturbine optimal ist. Für den Bereich hoher Windgeschwindigkeiten wird ein multivariates Steuerungsverfahren vorgeschlagen, um das Verhältnis von Leistung/Geschwindigkeit und struktureller Lastreduzierung zu optimieren. Es wird ein Regler zur Einzelblattverstellung entworfen, um sowohl die unausgewogene Strukturlasten als auch durch die Variation des Windgeschwindigkeit verursachte Rotorscheibe, vertikale Windscherung und Gierversatz fehler zu reduzieren.

Um die Zuverlässigkeit der Windturbine zu gewährleisten, ist ein Online-Schadensbewertungsmodell in den Hauptwindturbinenregelkreis integriert, so dass die Windturbine entsprechend ihres aktuellen Verschleißzustandes betrieben wird. In Abhängigkeit von der akkumulierten Schadenshöhe werden Regler zur Einzelblattverstellung mit unterschiedlichen Lastreduktionen und Kompromissen bei der Stromerzeugung

eingesetzt, um zwischen den beiden Zielen verlängerte Lebensdauer und Leistungsregelung einen geeigneten Kompromiss zu erzielten. Aufgrund der Herausforderungen die mit Offshore-Windpark Standorten verbunden sind, ist diese Art von prognosebasierter Regelung im Windturbinenbetrieb vor allem im Offshore-Einsatz vorteilhaft. Insbesondere im Kontext outputbasierter Vertragsformen z.B. power purchase agreement (PPA) kann dieser Ansatz zur Optimierung der Wartungsplanung genutzt werden.

Die Ergebnisse zeigen, dass die vorgeschlagenen Strategien die Auflast auf Windturbinen reduzieren kann ohne sich auf andere Ziele wie die Leistungsoptimierung und Leistung/Drehzahlregelung auszuwirken. Es konnte außerdem gezeigt werden, dass eine prognostisch basierte Steuerung effektiv die Lebensdauer von Windenergieanalagen verlängern kann, ohne das Ziel der Leistungsregelung einzuschränken.

Abstract

Wind energy is one of the rapidly growing renewable sources of energy due to the fact that wind is abundantly available and unlikely to be exhausted like fossil fuel. Additionally, there are deliberate effort to sensitize many countries to develop polices that support production of electrical power from wind. Maturity of wind energy technology has made power production from wind grow significantly compared to other renewable energy sources such as solar, tidal, hydro among others. Like many other renewable energy sources, production of power from wind has less adverse effects on the environment. Despite the growth of global cumulative installed wind capacity, its cost of production is still higher compared to other alternative energy sources due to high initial investment cost and high operation and maintenance (O&M) costs.

To meet the growing demand of wind power, wind turbines are being scaled up both in size and power rating. However, as the size increases, the structural loads of the turbine become more dominant, causing increased fatigue stress on the turbine components and consequent loss of functionality before the end of lifetime. Another area of focus in wind power production is lowering its production cost; hence, making it more competitive compared to other alternative power sources. From the control point of view, low production cost of wind energy can be achieved by operating wind turbine at/or near the optimum power efficiency during partial load regime, regulating generated power to its rated value in the high wind regime as well as mitigating structural loads so as to guarantee extended lifetime. Often, it is difficult to realize a control algorithm that can effectively guarantee both efficiency and reliability because these two aspects involve conflicting objective. Therefore, it is important to optimize the trade-off between these competing control objectives.

In this thesis, multi-objective control strategies for both the partial load region and high wind speed region are presented. During low wind speed, a control strategy that optimizes power production as well as mitigating structural load is designed to balance between power production maximization and extended lifetime of wind turbine. On the other hand, a multivariate control method to balance between power/speed regulation and structural load reduction is proposed for high wind speed region. More specifically, an individual blade pitch controller is designed to eliminate the unbalanced deterministic structural loads across rotor disc caused by variation in wind speed, vertical wind shear, and yaw misalignment error.

To guarantee reliability in wind turbine, an online damage evaluation model is also integrated into the main wind turbine control loop such that wind turbine is operated accordance to its structural health status in order to tolerate fault or to extend its service lifetime by a given period of time. Depending on the accumulated damage level, individual pitch controllers with different degrees of load reduction and power production compromise are employed to balance between extended lifetime

and power regulation objective. This kind of prognostic-based control is useful in wind turbine operation, especially in offshore application due to challenges associated with offshore wind farm sites. Additionally, in wind farms that are managed through output-based contracts such as power purchase agreement (PPA), this approach can be utilized to optimize maintenance scheduling to avoid unscheduled downtime.

The results demonstrated that the proposed multi-objective control strategies can reduce structural load on wind turbine without adversely affecting other objectives of power optimization and power/speed regulation. It has also be shown that a prognostic-based control can be effectively used to extend the lifetime of wind turbine without sacrificing the objective of power regulation.

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Nomenclature

Symbols

$\beta_1, \beta_2, \beta_3$	Individual blade pitch angle
β_{opt}	Optimum pitch angle during low wind speed region
τ_g	Electrical generator torque
λ	Tip speed ratio
λ_*	Optimum tip speed ratio during low wind speed region
Ω	Rotor rotational speed
Ω_e	Rotor rotational speed error
K_p	PI controller proportional gain
K_i	PI controller integral gain
K_a	PI controller anti-winding gain
v	Wind speed
ρ	Air density
R	Rotor radius
C_p	Power coefficient
τ_{aero}	Aerodynamic torque
$\underline{q}$	The DOF used in a linear model
Ψ	Generator variable speed mode DOF
τ	Tower fore-aft deflection mode DOF
$\zeta_1, \zeta_2, \zeta_3$	First flapwise bending modes DOFs for blades 1, 2, and 3
M	Mass matrix containing inertia and mass components
f	Nonlinear function relating DOFs and input variables
$\underline{u}$	Control input vector for a nonlinear wind turbine model
$\underline{u}_d$	Unknown wind input to a nonlinear wind turbine model
v_h	Hub height wind speed
h	Hub height
z_h	Vertical distance from from hub center
m	Vertical wind shear exponent power law
$T_c(\psi)$	Control input vector transformation matrix from fixed coordinate to rotating coordinate system
$T_o(\psi)$	Output measurement vector transformation matrix from fixed coordinate to rotating coordinate system
$T_s(\psi)$	System state vector transformation matrix from fixed coordinate to rotating coordinate system
Δu_{IPC}	Perturbed individual pitch controller control input
w	Exogenous input to the system
$F_l(G, K)$	Linear fractional transformation
$\|\|.\|\|_\infty$	$\mathcal{H}_\infty$ norm
J_{LQR}	Quadratic performance index

Q	States weighing matrix
R	Control input weighing matrix

Abbreviations

EKF	Extended Kalman Filter
FDI	Fault Detection and Isolation
KF	Kalman Filter
LMI	Linear Matrix Inequality
LQR	Linear Quadratic Regulator
LTR	Loop Transfer Recovery
MIMO	Multi-Input Multi-Output
PI-Observer	Proportional-Integral-Observer
SHM	Structural Health Monitoring
FAST	Fatigue, Aerodynamics, Structures, and Turbulence
NREL	National Renewable Energy Laboratory
MBC	Multi-blade coordinate transformation
LTI	Linear time invariant
SISO	Single-Input Single-Output
WECS	Wind energy conversion system
FRP	Faber-reinforced plastic
LQG	Linear Quadratic Gaussian
DFIG	Doubly-fed induction generator
CPC	Collective pitch controller
IPC	Individual pitch controller
HHC	Higher harmonic controller
DAC	Disturbance accommodating controller
SDAC	Stochastic disturbance accommodating controller
MRAC	Model reference accommodating controller
RMF	Residual mode filter
MISO	Multi-Input Single-Output
LMI	Linear matrix inequalities
MPC	Model predictive control
LIDAR	Light Detection And Ranging
MPPT	Maximum power point tracking
TSR	Tip speed ratio
P&O	Perturbed and Observation
PSF	Power signal feedback
TLC	Total life cycle
DTC	Disturbance tracking control
ADTC	Adaptive disturbance tracking control
O&M	Operation and maintenance

CBM	Condition-based maintenance
IFC	Individual flap control
AALC	Active aerodynamic load control
DTEF	Deformable trailing edge flaps
OTC	Optimal torque control
MBD	Multi-body dynamics
DEL	Damage equivalent load
AKF	Augmented kalman Filter
SHMP	Structural Health Monitoring and Prognostic
COE	Cost of energy
AOE	Annual operating expenses
FCR	Fixed cost rates
ICC	Initial capital cost
AEP_{net}	Net annual energy production
RUL	Remaining useful life
PHM	Prognostic and health management
PPA	Power purchase agreement
DCF	Discounted cash flow

1 Introduction

As the demand of producing electricity from wind energy increases, it is important to develop technologies that guarantees reliability, safety, and cost effectiveness. In the last few decades, power production from wind energy has increased sharply due to associated benefits in comparison to fossil fuel. The main focus is to make wind power production more competitive as compared to other alternative power sources. Some of the new trends in wind energy harvesting that are being adopted to make the cost of wind power more competitive include upscaling of turbines' power rating and employment of advanced control methods. However, there are inherent challenges in wind energy harvesting partly resulting from variability of wind speed and nonlinearities. In this thesis, some of challenges related to variability of turbine speed/power and structural load reduction are addressed. In this chapter, a brief overview of wind energy production, advancement in wind energy installations, and the trends thereof are discussed. Then, the motivation and statement definition as well as objectives of the research are also outlined. Some of the ideas and aspects discussed in this chapter have also been highlighted in [NS16, NBS16a, NLS15].

1.1 Overview of wind power generation

Owing to the growing environmental concerns, focus has shifted to generating power from renewable energy sources such as hydro, tidal, wind, bio-, and solar which do not emit greenhouse gases. Among these renewable energy sources, wind energy has attracted a lot of attention due to its abundance and advancement of supporting technologies among other factors [NS16]. Unlike the fossil fuels which are scarce, expensive, and have negative impact on the environment, wind energy is clean and unlikely to be exhausted with time. In essence wind energy can also be described as an indirect form of solar energy resulting from from pressure difference due to uneven heating of the earth surface. Wind energy is harnessed by wind turbines which converts wind kinetic energy into mechanical energy and finally into electrical energy.

Due to the rising demand in wind energy, the global installed wind turbines capacity have been on a steady increase for the last few decades. In fact, according to the global wind energy council (GWEC)'s projections [STR14], if robust policies are embraced to address climate changes the global total installed capacity could hit nearly 2000GW mark by 2030, accounting for about 19% of the global electricity supply. It is further envisaged that wind power could account for 25-30% of the global electricity demand by 2050. According to the international energy agency (IEA) wind annual report of 2015 [Ahl15], the current installed wind power accounts for only 5% of the world's electricity demand.

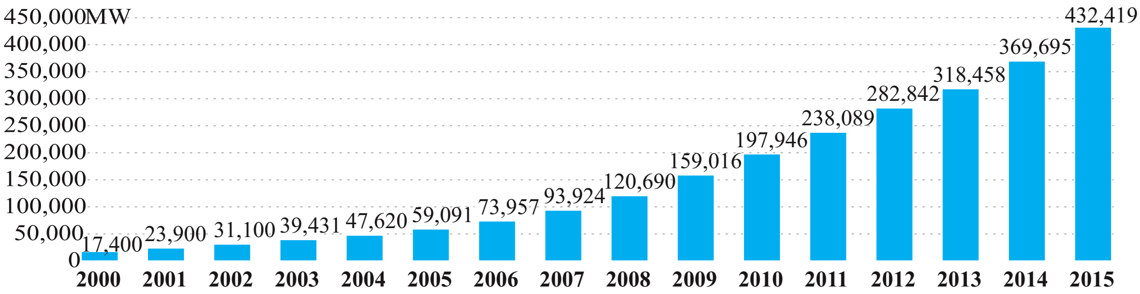


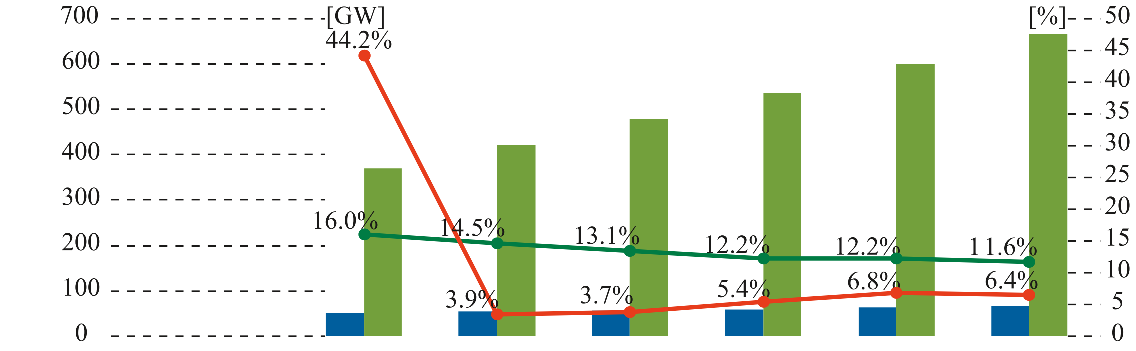
Figure 1.1: Global cumulative installed wind capacity 2000 $\sim$ 2015 [STR14]

As illustrated in Fig. 1.1, global annual installed wind capacity has increased almost 25 times from 2000 to 2015, with the global wind power installation standing at $432,419$ MW as of 2015. Notably, the sharp increment in the world installed wind power was registered in the last 1 decade. In spite of increasing global installed wind turbine capacity and favorable future projections [STR14], the cost of wind power is still high compared with other conventional power sources due to high initial capital investment and high operation and maintenance (O&M) costs among other factors.

In Fig. 1.2 the world wind energy forecast for the period between 2014 and 2019 is shown. As depicted, the cumulative capacity is projected to increase steadily during this period. On the other hand, cumulative growth rate is predicted to slow down from 16.0% in 2014 to 11.6% in 2019. One of the reasons for a steady positive increase in the world's cumulative wind power capacity is heightened awareness for the need to employ emission free technologies in order to mitigate the effects of green house gases. The decrease in cumulative growth rate is partly attributed to adoption of different energy policies and international political commitment towards achieving climate goals by the main countries leading in wind power production. In some cases, the slow growth rate could be due to interference with the supply chain of the main components for wind turbine manufacturing such as raw material for making the permanent magnets of Megawatt turbines.

To understand how wind energy is converted to electrical power, it is important to know how main subsystems in the turbine interact and relate with each other. As illustrated in Fig. 1.3, the main components of a horizontal-axis wind turbine are: rotor (comprising of blades and hub), nacelle, and tower. Nacelle houses the drivetrain, generator, and some actuation mechanisms. The figure depicts physical dimensions of a typical commercial utility-scale wind turbine. As noted in [Wil11], typical utility-scale wind turbines have rotor diameter in the range of 57 to 99 m and tower heights ranging from 45 m to 105 m, with 1.5 MW (80 meter tower) being the most widely installed land-based turbine. In Fig. 1.4, a detailed block diagram showing interaction between various subsystems of a wind energy conversion system is illustrated.

Aerodynamic subsystem converts kinetic energy from a three dimensional wind field



	2014	2015	2016	2017	2018	2019
Cumulative [GW]	369.6	423.1	478.6	357.1	599.6	666.1
Cumulative growth rate [%]	16.0%	14.5%	13.1%	12.2%	12.2%	11.6%
Annual installed capacity [GW]	51.5	53.5	55.5	58.5	62.5	66.5
Annual installed growth rate [%]	44.2%	3.9%	3.7%	5.4%	6.8%	6.4%

Figure 1.2: Wind energy world market forecast for 2014-2019 [STR14]

into aerodynamic torque that is fed into drivetrain module. Then, the drivetrain module converts low-speed-high-torque on the rotor side to a high-speed-low-torque on the generator side. To make sure that aerodynamic torque (which varies according to wind speed) does not exceed the limits, blade pitch control system is employed. The generator subsystem takes generator speed Ω_g as the input to convert mechanical torque into electrical power. Depending on the amount of available wind speed, torque controller is either used to maintain generator torque at the rated value during high wind speed or it is used to optimize power capture during low wind speed regime by varying generator torque τ_g. In utility-scale wind energy conversion

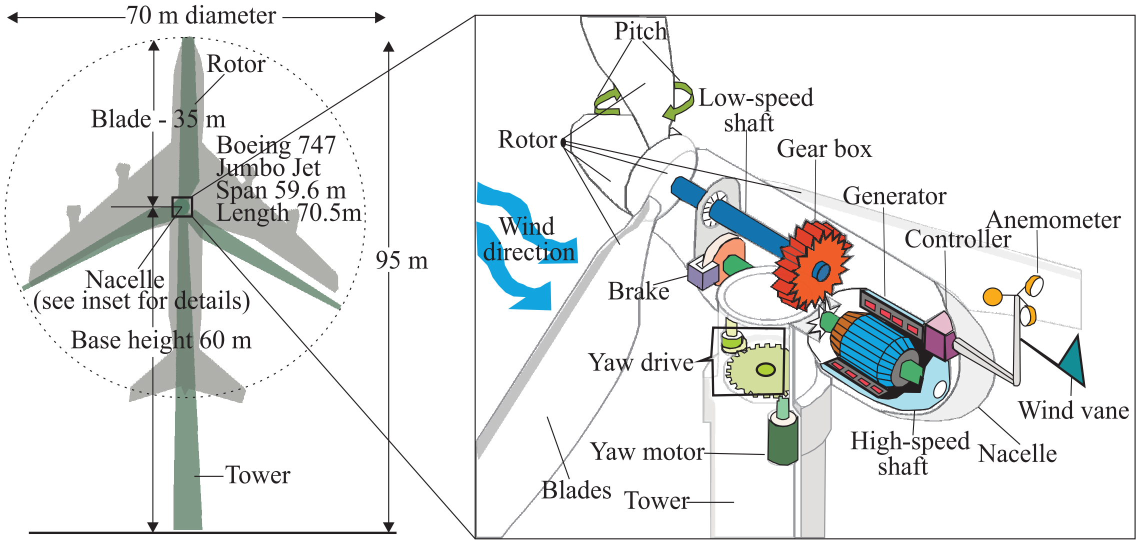


Figure 1.3: Wind turbine main components of a HAWT [Wil11]

system (WECS), squirrel cage induction generator (SCIG), doubly-fed induction generator (DFIG), and permanent magnet synchronous generator (PMSG) are the most commonly used in converting mechanical torque to electrical power. It is important to note the unique interaction between aerodynamic subsystem and tower dynamics; during wind turbine operation, thrust force F_{aero} on the rotor causes tower to deflect in fore-aft direction causing interference on the effective wind speed which in turn affects the aerodynamic torque as well as the overall output power.

Although wind turbine can either be constructed as a fixed or variable turbine [PM00], the variable-speed are the most common in utility-scale turbines. These turbines are designed in a way to support grid integration by guaranteeing grid stability and ensuring that power is injected into the grid at the right frequency and voltage. Despite the variation of incoming wind speed, variable-speed wind turbines can effectively support smooth grid integration if suitable supporting technology is employed. This can be made possible by employing power electronic converters as well as auxiliary energy storage system (ESS) on the grid side of wind turbine. They are a number of ESS available, but their choice largely depends on the application and the cost [ZWH+15]. Although the use converters and auxiliary ESS make variable-speed wind turbine relatively expensive compared to fixed speed turbines, variable-speed wind turbines are operated at around the optimum power point most of the time regardless of variations of incoming wind speed, making them being preferred in most of utility-scale turbines.

Wind turbine installations can be broadly classified into two categories: the onshore and offshore applications. Although offshore turbines have high initial installation cost and high maintenance cost, they are slowing gaining popularity as compared to onshore wind turbines [Win12] due to greater energy potential associated with availability and higher wind speeds in offshore wind farm sites. Additionally, there

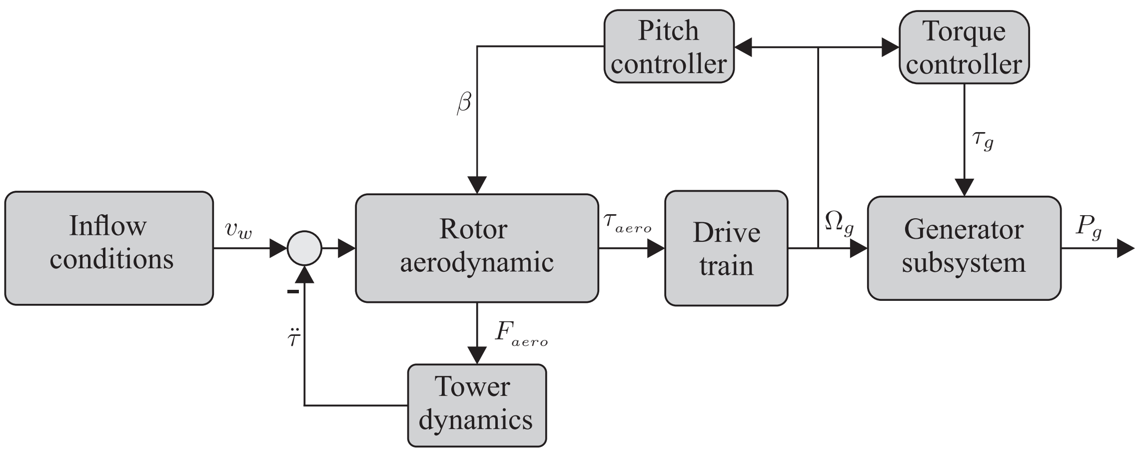


Figure 1.4: Generalized block diagram of a wind energy conversion system [BDBM07]

is less interference with human settlements caused by acoustic noise and negative impact on landscape aesthetic. It is worthwhile to note that due to some of advancements in wind energy industries, there are prospects of manufacturing wind turbines of even higher wattage and bigger sizes in offshore sites.

High O&M costs in offshore applications is partly due to the fact that offshore wind farms are normally located in remote areas far away from coastline, making it logistically difficult to access turbine during maintenance routines. Likewise, offshore wind turbines are more prone to breakdowns as compared to land-based turbines since they are subjected to harsher operation conditions which include saline marine environment as well as high velocity winds. Nonetheless, employing robust Structural Health Monitoring and Prognosis (SHMP) techniques in conjunction with appropriate control strategies, especially in offshore wind farms can significantly reduce the O&M costs. Similarly, most of the onshore wind farm sites are normally located in remote areas far away from urban centers where electricity demand is high. This leading to construction of expensive transmission and distribution lines which further contributes to high cost of wind power.

During wind power harvesting, it is crucial to monitor the health status of turbine such that the fault can be precisely detected, located, and its propagation trend established. Another important aspect in wind turbine management is the integration of prognostic strategies in its operation so as to determine the remaining useful lifetime (RUL) before the lose functionality. Closely related to SHMP is the predictive maintenance scheme which is based on the health condition of a given component. Unlike the time-based maintenance strategy, predictive maintenance optimizes the planning and scheduling of upcoming maintenance activities. The SHMP strategies allows for monitoring of health status of wind turbine components and help to plan for the appropriate maintenance action before failure can occur. Application of SHMP in wind turbines can allow for enough lead time to schedule for maintenance, especially in offshore application due to logistic challenges related to accessing these sites.

To develop appropriate control schemes to realize given objectives, it is important to have a general knowhow of wind turbine control hierarchy in a wind farm. This requires a clear understanding of how different control levels interact and influence each other from the individual turbine level to the distribution point (grid integration). As notes in [JPBF05], wind farms are controlled at four levels, namely: farm level control, supervisory control, operational control level, and subsystem control level. Wind farm control deal with the integration of turbines of a given wind farm to the main grid system such that the prescribed power quality system, stability as well as reliability requirements are met. On the other hand, supervisory control level is responsible for monitoring the structural health status of individual wind turbine to aid into decision making with respect to operation and maintenance scheduling. At the same time, supervisory control level monitors the speeds of the prevailing wind and give alerts on when to turn on wind turbine to start power generation or to stop to avoid damage due to excessive wind. Operational control level is responsible of achieving specific operational goals of optimizing power capture during low wind speed region, regulation of power/speed during high wind speed region, and/or mitigation of structural loads. Subsystem control level is responsible of controlling pitching and yawing actuation system as well as controlling the converter firing system. Dynamics at this control level are considered to be fast enough such that control goals can be effected in operational control level without degrading the performance.

1.2 Motivation and problem statement

The most significant difficulties in generating electrical energy using fossil fuel resources are their high cost, scarcity and negative environmental impact. Thus, renewable energy sources, which are produced from natural resources such as water, solar, tides, and wind among others, are the most promising in resolving the energy crisis since they are unlikely to be depleted. Among all these renewable energy sources, wind energy is the most developed renewable technologies in the world.

More often than not wind turbines operate in environment where wind speeds are not steady i.e., wind speeds are sometime lower or higher than the rated speed. To guarantee the reliability and efficiency, there is need to install control systems to coordinate all the operations of wind turbines. As the wind turbine blades experience wind gusts and turbulence, high power torque variations can be delivered to the drivetrain. This results in an increased stress on wind turbine components especially gearbox as the torque is transmitted along the drivetrain.

Nowadays, the trend is to manufacture wind turbines with higher rating and upscaled size in order to meet the increasing demand of wind power. This is due to the fact that the power captured by wind turbines is proportional to the area swept by rotor and and cubic of the incoming wind speed. As shown in Fig. 1.5, wind turbine power and size have been gradually increasing since 1980s, with 20 MW turbine being the envisaged future utility-scale wind turbine. As depicted in this figure, the prospects of developing land-based turbine with more than 3 MW are limited. This could be attributed to the limited wind speeds in onshore wind farm sites to drive massive turbines. On the contrary, the prospects of upscaling the size/wattage of the offshore wind turbines are promising provided that the appropriate measures to tackle challenges associated with offshore sites are employed.

As the trend of constructing turbines with larger size and power rating continues, deliberate efforts are being made to reduce structural weight by fabricating rotor blades and tower using lighter and stronger materials such as fiber reinforced composites or concrete reinforced composites. Due to lighter structural members, challenges are

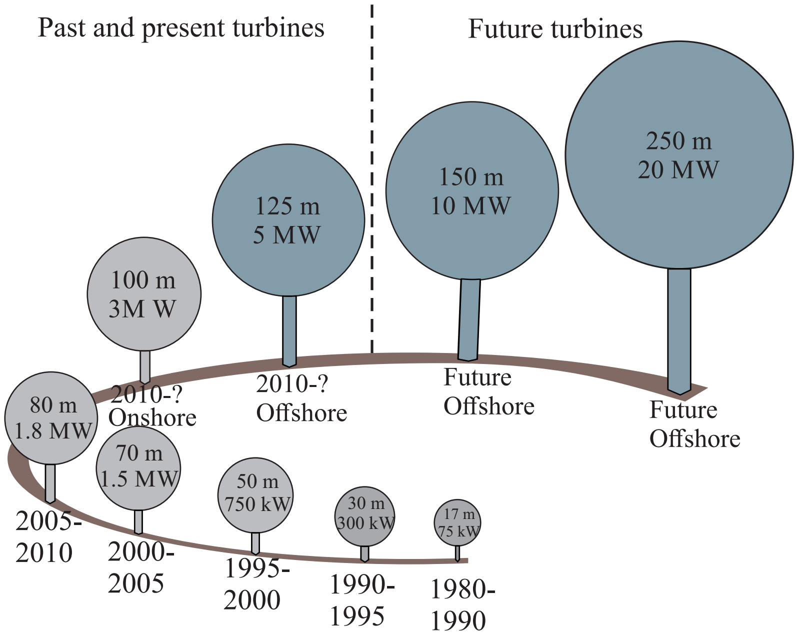


Figure 1.5: Size growth of commercial wind turbines [KMA09]

emerging regarding flexibilities and fatigue loads. If the dynamics due to flexibility are not properly considered during controller design, induced vibrations, resonance, or even permanent failure before the end of service life can occur. It is therefore inevitable to come up with control schemes that actively damp the vibration in large wind turbines, which are inherently flexible, without adversely affecting the core objective of maximizing the power production. Moreover, dynamics of different subsystems in wind turbine are highly coupled, further complicating controller design process. For instance, rotor blade dynamics are highly coupled to tower dynamics such that they have to be considered together during control design to avoid occurrence of instability.

Although a lot of research have been done to develop new advanced control strategies, majority of commercial wind turbines in the field are still installed with the classical proportional-integral-derivative (PID) controllers and standard generator torque controller. This is attributed to the fact that most of the advanced control methods have not been tested in the field making it hard to win the confidence of turbine manufacturers to invest in new technologies. The PID controller, which is a single input and single output (SISO) controller, is primarily used to regulate speed/power during high wind speed region and generator torque controller is used to optimize power capture during low wind speed region.

For the modern wind turbines with multiple control inputs and multiple measured outputs, SISO-based controllers are not efficient to adequately realize the operational objectives, especially in large wind turbines. For example multiple control loops must be used together to damp several flexible turbine modes and if such control approaches are not designed with utmost care, these control loops might interfere with each other causing the turbine to become unstable. Normally, individual loops are decoupled using appropriate filters by limiting control bandwidth so as to avoid overlapping with each other. As a matter of fact, the potential to destabilize wind turbines increases as the turbines become larger, more flexible, and when the degree of coupling between flexible modes increases.

To address the inherent flaws of the standards control methods, this thesis proposes multi-variable control design to provide a unifying strategy of coupling inputs and outputs of a MIMO system as well as offering a trade off between competing objectives. The MIMO control strategy offers a systematic and centralized approach in controller design; hence, avoiding the instances of instability occasioned by inference between difference control loops. Moreover, a MIMO controller offers a viable solution to reconcile the control objectives that have conflicting interests such as power/speed regulation and structural load reduction. The MIMO controllers are designed in a way that tightly coupled modes are decoupled to avoid resonance vibrations and instability during operation.

As wind turbine technologies mature, it is important to integrate Structural Health Monitoring and Prognostic (SHMP) tools in the management of wind power harvesting. The growing interest in this paradigm is motivated by the need to employ best operations and maintenance practices that would lead to reduction of wind power production cost. In wind turbine application, the prognostic tools can be integrated into maintenance planning and scheduling, especially in offshore wind farms such that maintenance is based on the health status of the turbine. This research proposes a novel prognostic-based control strategy geared towards extending the operation lifetime. The prognostic model is integrated into the main control loop such that the structural load reduction strategy is employed based on the health status of the turbine. This scheme can be employed to maximize power production in wind turbine as well scheduling the appropriate maintenance and also helping in planning the operations and inventory.

1.3 The scope and objectives

Since the challenges related to structural loads in wind turbines become more noticeable as the size increases, the scope of this thesis is limited to Mega-scale wind turbines. More specifically, a fictitious land-based windPACT 1.5 MW developed by National Renewable Energy Laboratory (NREL) is chosen as an application example to realize the set out objectives. This model represents a variable-speed, variable-pitch horizontal-axis wind turbine which can be operated to capture the optimum wind power irrespective of wind speed variations.

The main objective of this research is to develop multi-objective control schemes to guarantee the reliability and improve performance with respect to power maximization and speed regulation in wind energy conversion system, both in partial load region and high wind speed region. To achieve the principal objective the following specific objectives are identified

1. To develop a control scheme to optimize a trade-off between power maximization and load reduction in low wind speed region.
2. To design a muti-variable control strategy for mitigating structural loads and regulating power/speed in high wind speed region.
3. To integrate a damage evaluation model into wind turbine control loop to come up with a health status-based operation scheme to extend wind turbine lifetime.

1.4 Thesis organization

In this thesis, lifetime extension algorithm and multi-objective control strategies in wind turbine applications are discussed. First, a multivariant controller to optimize a trade-off between structural loads reduction and speed/power regulation in high wind speed region is discussed. Second, a controller to balance between power maximization and structural load mitigation is proposed for partial load region. Lastly a framework that combines structural load reduction and online fatigue load evaluation is designed to extend the lifetime of wind turbine.

This thesis is based on scientific papers that have been published as journal papers [NS16, NBS16a] or in the proceedings of international conferences [NLS14, NLS15, NS15, BNRS15]. In chapter 2, a state-of-the-art, trends and challenges in wind turbines control are discussed. The chapter starts by pointing out the challenges that exist in wind energy production. Then these challenges are discussed with respect to standard control methods and advance control strategies that are being developed to tackle these challenges. The trend in wind turbine application in terms of operation and control, new materials development, and upscaling of size and power to meeting the rising demand is also discussed. Distinctions between onshore and offshore applications is made with respect to material requirements, control requirement and potential of yielding higher power. Lastly, the prospects of adopting permanent magnet direct drive for large wind turbines are reviewed against cost, sustainability, and impact of the environment.

The details of the wind turbine model used in this thesis are discussed in chapter 3. The challenges associated with development of a comprehensive wind turbine model are outlined. Then, existing wind turbine models are compared in terms of computation effort and easiness of extracting control oriented models (linearization). The details of how to obtain linear models from a nonlinear aeroelastic wind turbine model are give. Moreover, the causes of inherent periodicity in wind turbines are identified and how they are accounted for during control design process through multiblade transformation is explain in details.

A multivariant controller for regulating speed/power fluctuations and minimizing structural load during high wind speed region is considered in chapter 4. In this scheme, individual blade pitch control is employed to reduce structural load on rotor blades while maintaining speed/power fluctuation within allowable range. To evaluate the performance, the results are compared against that of a standard collective pitch controller (baseline PI controller).

In chapter 5, design process of multi-object controller for partial load region is discussed. The control strategy balances between two opposing objectives of maximizing power generation and mitigation of induced structural loads. The results are compared to that of a standard baseline torque controller to determine the performance with respect to power optimization and load reduction.

In chapter 6, a frame work to integrate an online damage evaluation model into wind turbine control loop is introduced. The scheme proposes a novel operational paradigm in wind turbines that balance between lifetime extension and power regulation objective. Depending on the health status of the wind turbine rotor blade, load mitigation controllers with different gains are employed to balance between load reduction and power regulation. The possibilities of integrating this scheme into predictive maintenance method is also discussed. Finally, the summary of the whole thesis, conclusions, and suggestions for future work are outlined in chapter 7.

2 Literature Review and Theoretical Background

Before discussing the multi-objective control strategies employed in this thesis, it is important examine various control methods that have been proposed in the literature. The aim of this chapter is to identify the existing research gap to avoid duplication of knowledge. A review of various control strategies that are used in wind turbine systems, both in low and high wind speed regions focusing primarily on multi-objective control schemes is carried out. Emerging trends that are likely to influence the current or future wind energy production, either positively or negatively, are also discussed. It is important to note that the literature survey discussed in this chapter has already been published as a scientific paper [NS16].

2.1 Introduction

Wind energy is one of the most rapidly growing renewable sources of energy due to the fact that it has little negative impact on environment. To meet the growing demand, wind turbines are being scaled up both in size and power rating. However, as the size increases, the structural loads of the turbine become more dominant, causing increased fatigue stress on the turbine components which can lead to early failure. Another area of focus in wind energy is lowering production cost to give it a competitive edge over other alternative power sources. From the control point of view, low production cost of wind energy can be achieved by operating the wind turbine at/or near the optimum power efficiency during partial load regime, guaranteeing reliability by reducing fatigue loads, and regulating generated power at its rated value in the high wind regime. Often, it is difficult to realize a control algorithm that can guarantee both efficiency and reliability because these two aspects involve conflicting objectives.

The WECS can be considered as a complex, nonlinear system consisting of different subsystems working in a coordinated way to convert wind kinetic energy into electrical power. Hence, it is important to have a know-how across different disciplines constituting wind harvesting system and these include aerodynamics, mechanical, and electrical systems. For a given wind turbine, the main aim is to effectively and efficiently produce wind power as well as guaranteeing safety and reliability.

Wind turbines are classified into two main configurations, but due to the obvious advantages, majority of modern utility-scale wind turbines produced today have three blades with horizontal-axis configuration [PJ09, Hau05]. For instance, the entire rotor can be placed atop tall tower where it is able to capture higher velocity winds. Other advantages include; improved power capture efficiency, use of yaw mechanism to position rotor to face the direction of wind flow, easy installation and maintenance.

As noted in [GY14], wind turbines can either be manufactured with a fixed-pitch or variable-pitch blades. Although, fixed-pitch turbines are initially less expensive, their inability to adjust pitch angle make them less popular in the realm of large wind turbines where structural loads are more pronounced. Moreover, wind turbines can also be variable-speed or fixed-speed [PM00]. Variable-speed turbines can also be operated around their optimum power efficiency, but this requires the use of additional power electronic processing unit to couple them to grid system. The use of converters guarantee that the power generated meets certain performance requirements before it is connected to the main grid. On the other hand, fixed speed wind turbine are simple and robust, but they are not popular with Megawatt-scale turbines due to ineffectiveness in extracting energy from wind and induction of mechanical stress in drive-train during variable wind speed. Furthermore, generator speed of the fixed-speed wind turbines is fully dependent on the grid frequency making them undesirable candidates for variable-speed operations. As a matter of fact majority of Mega utility-scale wind turbines that are manufactured nowadays are variable-speed, variable-pitch, and horizontal-axis turbines.

Nowadays, most of utility-scale wind turbines are installed with individual blade actuation mechanism to control each blade independently. Furthermore, they are also equipped with several sensors on blades as well as on tower and nacelle, making them inherently multi-input multi-output (MIMO) systems. For this reason, standard single-input single output (SISO) controllers that are used in majority of utility-scale wind turbines are rendered ineffective in controlling such systems [LPW09b]. The additional measurements can also be used for monitoring the health status of various components in turbine and in condition-based maintenance (CBM) [RZH+07].

Unlike SISO controllers, MIMO controllers can realize multiple objectives such as elimination of structural loads and regulation of generated power at the same time. This is becoming an attractive control strategy since wind turbine maintenance cost can be lowered as well as extending operational life time. In recent years, a number of control strategies have been proposed to mitigate structural load on wind turbines and these include mitigation of loads in rotor blades [SZW06, ZS07], minimization of tower deflection [NKL13, KMK13, HG15], and reduction of drive-train vibrations [FWW11, BMC00].

2.2 Fundamentals of wind energy generation

To have a comprehensive understanding of advanced wind turbine control system, it is crucial to have a know-how of its basic operations as well as knowing the fundamentals of standard control methods employed in wind energy conversion system and the existing challenges thereof.

2.2.1 Wind turbine basics

The maximum extractable power by wind turbines is limited to 59.3% of the available wind power [Bet66]. This limit is referred to as Betz limit, which gives the maximum achievable aerodynamic efficiency in wind turbines.

The power extracted by wind turbine P_a is expressed as

$$P_a = C_p(\lambda, \beta)P_w = \frac{1}{2}\rho\pi R^2 C_p(\lambda, \beta)v^3, \tag{2.1}$$

where ρ denotes air density, R is the rotor radius, v represents wind speed before interacting with turbine, and $C_p(\lambda, \beta)$ is aerodynamic efficiency which is a nonlinear function of the tip-speed-ratio (TSR), λ and blade pitch angle β. The TSR is defined as

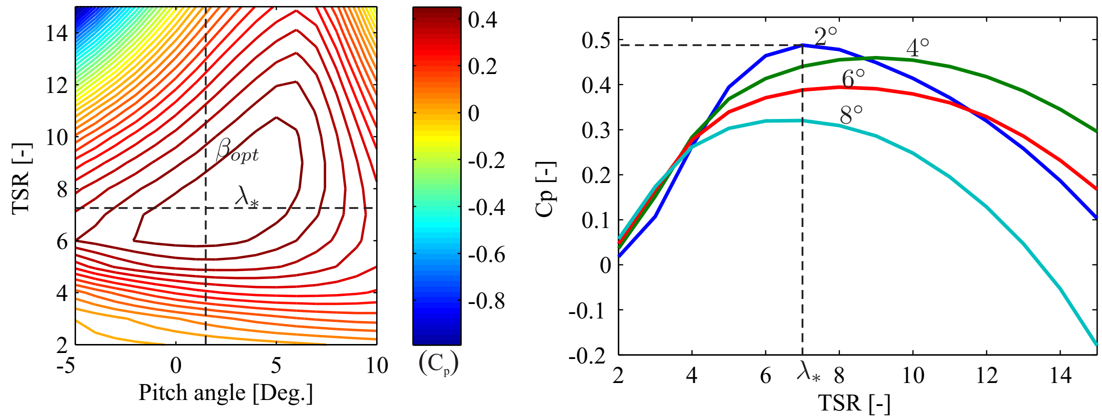
$$\lambda = \frac{\Omega R}{v}, \tag{2.2}$$

where Ω denotes the angular rotor speed, R is the rotor radius and v is the incoming wind speed. For any wind speed there exist a rotor speed for which the value $C_p(\lambda, \beta)$ is maximum and this value corresponds to optimum tip-speed-ratio λ_*. This is illustrated in Fig. 2.1, which represents a typical TSR-β-C_p curve for a fictitious NREL, WindPACK 1.5 MW wind turbine model. Figure 2.1(a) shows a three dimensional plot of TSR-β-C_p, while Fig. 2.1(b) depicts the maximum C_p corresponding to a given TSR for a particular blade pitch angle. Specifically, this wind turbine model has a maximum power coefficient of 0.488 at TSR of 7 and optimum blade pitch angle of $2°$.

2.2.2 Standard control methods and control hierarchy

The wind Energy conversion system (WECS) control hierarchy has three distinct levels; namely, supervisory control, operational control, and subsystem control [JPBF05]. The high-level or supervisory control is charged with turbine's starting-up and shutting-down procedures. The operational or turbine-level control is concerned with how specific control objectives are realized during the operation of wind turbine. The subsystem controls are responsible for various actuation mechanisms like pitching, yawing, and generator power electronic unit. Subsystem controls are usually considered as a black box since they are commanded by other control systems higher in the hierarchy [PJ11]. The scope of this chapter is limited to the review of turbine-level control strategies that realize specific operational goals.

Sa as to have an in-depth understanding of operational goals, the variable-speed wind turbine power curve can be used to distinguish the operational zones and the related control objectives thereof. As illustrated in Fig. 2.2, three distinct operation



(a) (b)

Figure 2.1: Tip speed ratio, pitch angle power coefficient curve for NREL Wind-PACT 1.5 MW Turbine [NS16]

regions in variable-speed wind turbines can be identified: below the cut-in speed region (region I), the region between the cut-in wind speed and below the rated wind speed (region II), and the region above the rated wind speed (region III). Another important zone for control design is the transition region from partial wind to above rated wind speed. As noted in [PJ09], the control objective changes depending on the prevailing wind conditions. The primary control goal in region II is to maximize the amount of power extracted by wind turbine, while in region III the objective is to limit the amount of power produced to avoid damage caused by exceeding mechanical and electrical limits. The transition region is designed to ensure that the turbine reaches the rated power at the rated speed.

To realize the two mainstream objectives of maximum power extraction and regulation of generated power, most of the installed wind turbines use proportional-integral, a collective blade pitch controller, and a torque controller. As shown in Fig. 2.3, rotor speed Ω is used as the only measured variable to generate either the demanded collective blade pitch angle β_{com} or demanded generator torque τ_g depending on the operational objectives to be realized.

Generator torque control

When wind speed is greater than cut-in speed, but lower than the rated value, standard generator torque controller is utilized to maximize generated power. This is achieved by operating the turbine at/or near the optimum power efficiency $C_{p_{max}}(\lambda, \beta)$

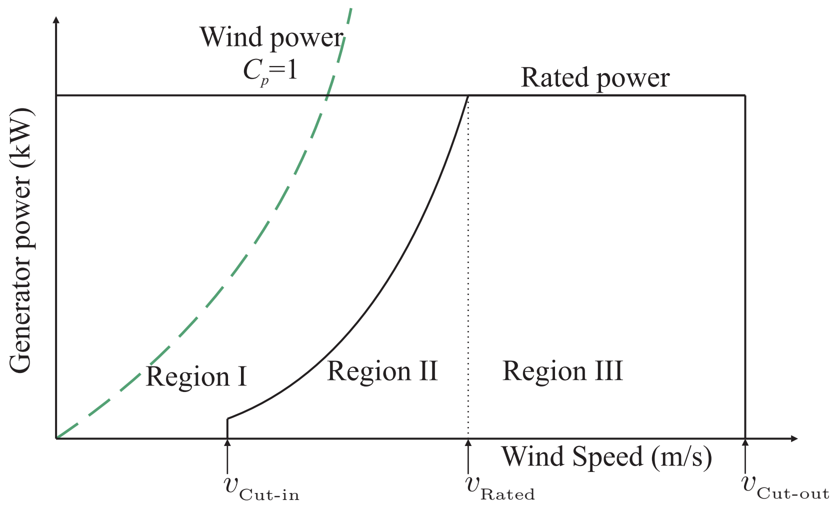


Figure 2.2: Generalized variable-speed wind turbine power curve [NS16]

by accelerating or decelerating rotor in order to track the speed of incoming wind. The turbine is operated at a constant tip-speed-ratio (TSR) λ_*, to yields maximum power. Normally, the rotor blades are pitched at optimum pitch angle β_{opt} to generate the highest possible lift.

The standard generator controller is expressed as

$$\tau_g = K_T \Omega^2, \tag{2.3}$$

where K_T is given by

$$K_T = \frac{1}{2}\rho\pi R^5 \frac{C_{p_{max}}(\beta_{opt}, \lambda_*)}{\lambda_*^3}. \tag{2.4}$$

Here, λ_* is the optimum tip-speed-ratio that corresponds to the maximum power coefficient $C_{p_{max}}$. It is clear from a simplified one-mass wind turbine model

$$J_r\dot{\Omega} = \tau_{aero} - \tau_g \tag{2.5}$$

that generator torque τ_g balances out with aerodynamic torque τ_{aero} at steady state, otherwise the rotor either accelerates or decelerates to maintain a constant TSR that yields the maximum power. This control method is popular and simple to implement. As outlined in [Joh07b], no accurate method for determining the constant gain K_T exists. Even when K_T is assumed to be accurately approximated either numerically or experimentally, wind speed varies spatially forcing the turbine to operate sub-optimally. It has been further observed that when the rotor speed is strictly tracking the speed of incoming wind in region II, very high mechanical stresses are induced in the drive-train due to torque variation. This in turn can cause severe excitation of poorly damped modes in the turbine [WF08].

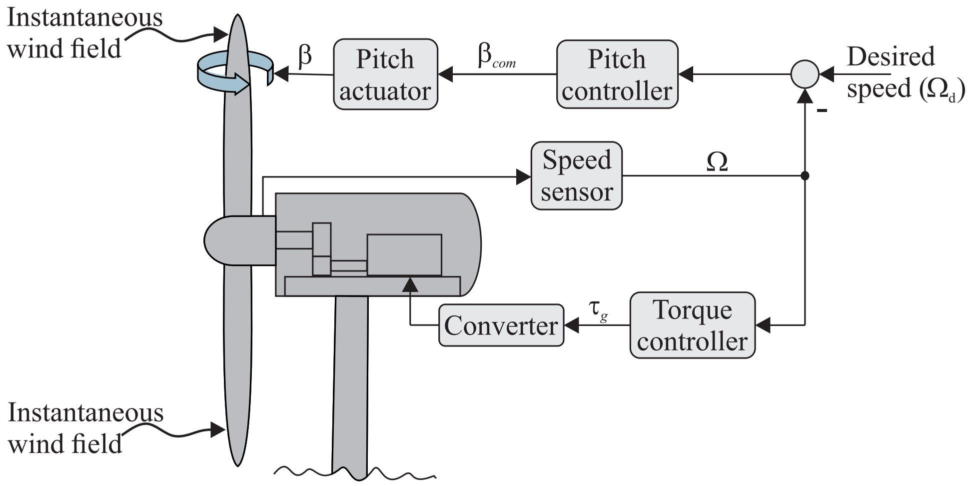


Figure 2.3: Wind turbine standard control loops [NS16]

Standard collective pitch control

In region III, the main objectives is to regulate generated power around the rated value as well as limiting structural loads to avoid violation of mechanical and electrical constraints of the wind turbine system. In the standard traditional control scheme, this is achieved by holding generator torque constant, while deploying collective pitch control to regulate the generator speed to the rated value. Most of the commercial wind turbines use proportional-integral (PI) collective blade-pitch control controller [HK12] to regulate rotor speed above-rated wind speed regime given by

$$\beta_c(t) = K_p \Omega_e(t) + K_i \int_0^t \Omega_e(\tau) d\tau, \tag{2.6}$$

where $\Omega_e = \Omega_d - \Omega$ is the rotor speed error, Ω_d represents the desired rotor speed while K_p and K_i denote proportional and integral control constants, respectively. In most cases, a standard gain-scheduling type PI controller is employed to cope with nonlinearities caused by the pitch actuation mechanism and the deviation of operation point from the control design point. Likewise, anti-wind up and saturation limits are deployed to avoid problems related to integration of negative speed error which might be occasioned by gusty winds.

One of the major drawbacks of this control method is that all blades are assumed to have similar physical properties and are subjected to the same amount of aerodynamic load during operation which is seldom the case. As a consequence, the rotor disc is always acted upon by unbalanced loads which cause induced stresses that might lead to eventual failure.

2.2.3 Structural loads in wind turbines

As wind turbines grow in size and output power rating, the adverse effects of structural loads become more and more pronounced, especially those induced by aerodynamic and gravitational forces. If not mitigated, structural loads can cause undesirable performance or even lead to early failure of the whole wind turbine system. It is therefore imperative to know how structural loads interact and/or influence wind turbine power generation and affect its life time.

Normally, wind turbines are subjected to intermittently variable wind profile which changes in both direction and magnitude, resulting into asymmetrical aerodynamic loads that vary spatially across the rotor disk. Incidentally, unbalanced aerodynamic loads are the main cause of the structural loads in wind turbines. Another cause of induced structural loads is gyroscopic effect which come about as a result of combined action of rotor rotation, blade pitching, and nacelle yawing. Like asymmetrical aerodynamic loads, gyroscopic forces can cause cyclic stress to the hub or induce cracks in blades. It is worth noting that the aforementioned loads act simultaneously during power generation, making it difficult to determine the contribution of each class of load to the overall structural load in wind turbine system. In large wind turbines, cyclic loads are the major cause of fatigue stress which, if not mitigated, may lead to premature failure of turbine [SZW06].

For a 3-bladed turbine, rotor blades are 120° out of phase with each other, meaning that at any given azimuth position, each blade is subjected to unequal aerodynamic forces because of vertical wind shear. Indeed, each blade samples different aerodynamic forces for every cycle since the approaching wind varies in both speed and direction. Since wind exhibits turbulent behaviors, the resulting unbalanced loads have stochastic properties.

Vertical wind shear is another main cause of asymmetrical loads across the rotor. It is described as a change in horizontal wind speed and/or direction with altitude as shown in Fig. 2.4(a). Additionally, rotor load imbalance can be caused by the tower shadow which makes the wind speed to reduce as it approaches the turbine tower. Normally, the effects of tower shadow are more pronounced in upwind horizontal-axis wind turbine configuration compared to downwind configuration. The structural loads emanating from vertical wind shear and tower shadow are said to be deterministic in nature since they occur in a periodic manner for every rotor revolution. Since the wind turbine is influenced by the loads that have both deterministic and stochastic properties, it is difficult to effectively predict its dynamic response.

In the realm of large wind turbines, structural load mitigation is attracting a lot of attention, with most of the reported work focusing on mitigation of once per revolution (1p) loads using independent blade pitch controller [JPP10, Bos03]. However, only a few attempts have been made to minimize higher harmonic loads [Bos05]. It is usually presumed that fatigue damage is mainly contributed by 1p deterministic

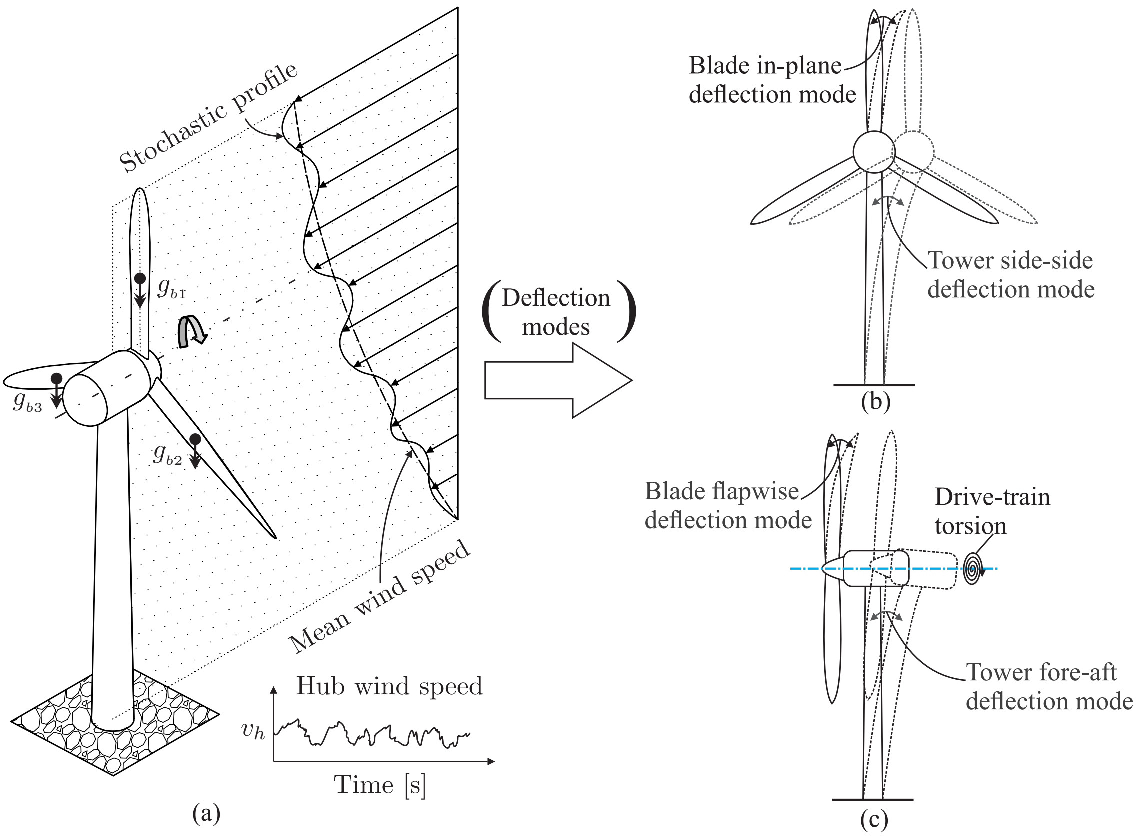


Figure 2.4: Tower and rotor blade deflection modes in wind turbines [NS16]

loads on rotor blades and 3p harmonic loads on the fixed structure, which might not be absolutely correct in large wind turbines.

The rotor blades, tower and drive train bending modes considered in regulation of structural loads are shown in Fig. 2.4(b)-(c). Here, the tower has fore-aft and side-side deflection modes, while the blade has flap-wise and in-plane deflection modes. Additionally, the drive-train is usually subjected to varying torsional stresses during generation of wind energy due to fluctuating wind speed.

In addition to the two mainstream objectives of power maximization and regulation of generated power/speed, mitigation of structural loads in wind turbines has attracted a lot of attention in the recent past. In the literature, most of the control strategies have been developed to handle only a particular kind of deflection mode while disregarding the others, majority focusing on flap-wise deflection mode [JPP10, Bos03, SZW06, NLS15]. Other authors have reported control methods that mitigate loads on turbine tower [KMK13, HG15] and drive-train deflection [FWW11, BMC00]. From the aforementioned discussion, it can be concluded that it is important to consider structural load reduction from a global point of view rather than accomplishing localized solutions for specific turbine parts. This can be achieved by designing multi-objective control strategies capable of reconciling different opposing control requirements.

2.2.4 Material-related aspects related to structural loads

Material consideration for various components in wind turbine plays an important role in determining the overall cost, performance, and structural load endurance in wind turbine systems. The suitable selection of materials in wind turbine harvesting systems is strongly affected by the location. Depending on the location (onshore, offshore, location related-wind profiles and properties), wind turbines are subjected to different operation conditions. This and also turbine dimensions strongly effect the materials choice because parts with special attributes are required as the turbine grows in size. Furthermore, it is inevitable to make material consideration with respect to all major components in wind turbine rather than focusing only on few components that are considered to be highly susceptible to failure. Generally, the development of new materials and manufacturing technologies are geared towards lowering the cost of producing wind power and investments into such developments should be viewed in terms of long term benefits since the initial investment capital might be higher than the existing ones. For instance, components made from materials of superior quality are likely to be costly, but on the other hand a materials-based extended lifetime (leading also to reduced maintenance cost) changes the cost, especially in the case maintenance cost are weighted higher (offshore applications).

Special attention should be paid to offshore wind turbines due to harsh environmental conditions they operate under. Normally, they are subjected to higher velocity winds and exposed to saline marine environment, making them more susceptible to corrosion [SHW12]. As a result, the components for such turbines should have high mechanical strength, high fatigue strength as well as high corrosion resistance. Stringent material requirements, installation of offshore wind turbines is more capital intensive.

The rotor, which consists of blades and hub, is one of the most expensive component in wind turbine system, roughly accounting for 20% of the total wind turbine cost [MJ12a]. Rotor blades are more susceptible to damage due to intermittently varying aerodynamic loads and to different weather conditions. As stated in [VK11], rotor blades should possess the following qualities: high mechanical strength to handle extreme aerodynamic loads, high fatigue resistant, high stiffness strength to avoid collision with tower, and light in weight. Mostly, blades are manufactured using fiber-reinforced plastic (FRP) due to improved strength-to-weight ratio, with glass, carbon, and aramid fibers being the most commonly used [DSDK13]. The choice of these fibers as a reinforcement material primarily depend on the cost and the application requirements such as strength, stiffness, and corrosion resistant among others. As outlined in [MJ11], glass fibers have high tensile strength and impact resistant, but low modulus strength making them unsuitable for large wind turbines applications. On the other hand, carbon fibers are preferred for high performance applications because they exhibit excellent resistance, although they have less impact resistance and poor inter-laminar properties as compared ro glass fiber. Aramid fibers have high strength-to-weight-ratio and good impact resistance, making them suitable for applications that require high toughness and high modulus strength. To take the advantages of superior properties of glass and carbon fibers, hybrid composite made of glass and carbon can be used to enhance the mechanical properties [MJD14]. It should be mentioned that the overall strength of any composite is strongly influenced by the volume of fiber content, with stiffness increasing proportionally up maximum (about 65%) then start deteriorating [SSLC12].

Likewise, the type of laminate material is crucial in determining load carrying capacity as well as the cost of fiber-reinforced composites blades. Epoxy, vinyl ester, and polyester resins are the commonly used laminate materials in wind turbine blades. As example, epoxy resin has strong advantages in comparsion to polyester and vinyl ester, but related to the cost it shows strong disadvantages. All resins are prone to degradation due to moisture absorption, but the rate of epoxy degradation is slower compared with polyester and vinyl ester, making them more suitable in offshore wind turbine application [RHV12], while glass, carbon, and aramid fiber-reinforced polymer have been considered as suitable alternative choices for manufacturing wind turbine blades. According to [DSDK13] their production is highly based on petroleum-based resources and is negatively weighted by the authors. This has necessitated exploration on the suitability of using naturally occurring fibers as a substitute of petroleum-based fibers [SJYH15].

For wind turbine tower, material choice should be geared towards performance characteristics, ease of manufacturing and transporting so as reduce installation and manufacturing costs [LKP13]. It is imperative to note that material for offshore applications should be durable and have high corrosion resistance. Steel/concrete composite and fiber-reinforced composite have been proposed as an alternative solutions to building large wind turbine towers [QOP12].

Gearboxes are used to transfer mechanical power from rotor to generator. During wind power production, gearboxes are subjected to varying mechanical stresses which might lead to fatigue damage. Therefore, the choice of material is critical in determining the service life of a gearbox. As delineated in [Boz09], some of innovative material development processes used to enhance gear properties (increased wear and corrosion resistance and micro hardening) are: ultra-dispersed diamond power (UDDP), novel coating and surface treatment such as high velocity oxygen fuel (HVOF), and physical vapor deposition (PVD) process. Gearboxes are among the most expensive components in wind turbines, the manufacturers often include significant overhead costs to cover warranties due to their high failure rates and high maintenance cost [MB07]. Direct drivetrain are to replace geared drivetrains, also leading to effects of minimizing maintenance cost [Wil11].

In the construction of wind turbine foundation, durability and related cost are the main factors that influence material choice, especially in offshore applications. The construction cost of offshore foundation constitutes a sizable portion of the overall cost of wind turbine and a trade-off between cost and performance requirements must be carefully considered in material selection. In fact, the construction cost increases with the distance from shore and increase in water depth [BYS11]. As water depth increases, the foundation diameter is enlarged to preserve the required stiffness, resulting into increased material and installation cost [HF14].

2.3 Advanced control methods

Nowadays, the focus in wind energy has shifted to lowering its production cost, improving the quality of generated power, safety, and reliability. However, to tackle these challenges, researchers have proposed various innovative control strategies to address the deficits of the standard control methods. Most of these advanced control algorithms are concerned with optimization and quality improvement of generated power, speed/power regulation, and/or reduction of structural load in wind turbines. This section discusses various advanced control methods that are employed in wind energy production.

2.3.1 Power/speed regulation and load mitigation problem

As mentioned, load mitigation is becoming increasingly important among the Mega-scale utility wind turbines. This is motivated by the need to guarantee reliability and to ensure that the quality of output power is not compromised. To reduce fatigue load emanating from asymmetric loads in the rotor disk, blades are normally manipulated independently using independent blade pitch controller (IPC).

Classical methods

In the literature, several classical control methods have been proposed to address the objective of regulating speed/power as well as mitigation of the structural loads. As pointed out in [ZCCZ11], asymmetrical loads across rotor disk cause blades to be excited by a dominant once per revolution 1p harmonic load in addition to other higher order harmonic flap-wise load spectra i.e., 2p, 3p, 4p, etc., whose frequencies depend on rotor rotational speed. On the other hand, non-rotating parts of the turbine are dominantly influenced by 3p harmonic load components plus their higher order integral multiples.

Since wind turbines are inherently MIMO systems with measurements being taken from both the fixed and rotating structural members, it is important to design a

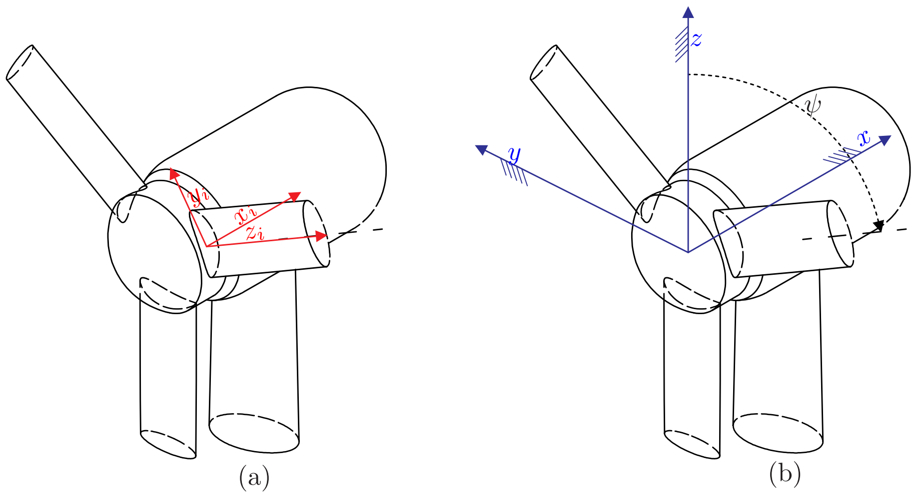


Figure 2.5: Rotating and fixed coordinate of reference [NS16]

controller with all state variables expressed with respect to a fixed coordinate system rather than in a mixed coordinate system. This can be achieved by transforming all dynamics of system model expressed with respect to rotating rotor to a fixed coordinate system. In literature, Multi-blade coordinate (MBC) transformation [Bir10], also referred to as Coleman transformation is used to map all dynamic variables into a fixed coordinate system. As shown in Fig. 2.5, variables expressed with reference to rotating coordinate system x_i y_i z_i are mapped into a fixed coordinate system x y z. The fixed coordinate system is usually referred to as collective, cosine-cyclic, and sine-cyclic coordinates, respectively [Bir08].

Most of the reported work on individual pitch controller concentrates on reduction of 1p harmonic rotor blade load [Gao12, Bos03, ZCCZ11]. Coleman transformation is normally used to express the root blade bending moments with respect to a fixed direct- and quadrature- orthogonal axes. Then two independent PI-control loops are designed to suppress loads on these two axes. Finally to generate the corresponding demanded individual pitch angle, inverse Coleman transformation is carried out. In [Bos03], an alternative solution is discussed, where an LQG controller is used to generate the pitch angle for each blade instead of designing multiple PI-control loops.

An individual pitch controller is applied to a doubly fed induction generator (DFIG) wind power system to mitigate 1p harmonic loads on the rotor blades and 3p harmonic loads on the fixed structure of wind turbine is reported in [ZCCZ11]. To realize this goal, bending moments on the rotating rotor blades were transformed into fixed d-q coordinate axes moments (yaw and tilt bending moments) using Coleman transformation. Then two standard PI controllers were designed to regulate d-and q-moments. Since 1p harmonic load is the main source of fatigue loads on the rotor blades, a low pass filter was used to mitigate higher order harmonics from being transmitted to the fixed structure of the turbine. The results showed improvement in load reduction as compared to a collective pitch controller (CPC).

A study aimed at offering reconciliation between two competing objectives of reducing tower deflection and speed regulation in a two bladed wind turbine is explored in [PBP12]. This is achieved through a combination of IPC and CPC control schemes. It was observed that CPC influenced blade aerodynamic torque and employing it to damp tower oscillation could lead to interference with the rotor speed control objective. On the contrary, IPC can reduce tower vibrations by allowing higher aerodynamic rotor loads for just a brief moment. Hence, by combining these two control approaches a trade-off between these two opposing objectives was realized. The reported results indicates improved trade-off between tower deflection reduction and rotor speed regulation when a combination of collective and individual pitch controller is used as compared with CPC or IPC independently.

Individual pitch control can also be utilized to reduce wind turbine torque fluctuation as demonstrated in [DPLC13]. This is achieved by the reduction of blade edge-wise bending moments which in turn minimizes rotor torque variation. The adjustment of individual pitch angles is based on multi-stage dynamic weight distributions which are evaluated depending on the rotor azimuth position, influence of tower shadow, and vertical wind shear. The performance of this control method was evaluated against a single neuron PID controller. This control approach does not only minimize torque variation but also smooths the fluctuation in the flap-wise bending moments, the yaw bending moments, and the tilt bending moments

The minimization of rotor tilt and yaw bending moments so as to suppress both the low frequency 1p harmonics on blades and 3p harmonics on fixed turbine structure is discussed in [SKW+09b]. To achieve this, a 2 degrees-of-freedom IPC controller comprising of a multi-variable LQG and feed-forward disturbance controller was proposed. A simplified form of Multi-blade coordinate (MBC) transformation similar to that reported in [Bos03] is used to convert all quantities defined in rotating coordinate system to a fictitious fixed direct- and quadrature-axes (d-q coordinates). This led to an exploitation of a well-developed linear control theory to reduce the structural loads. The results demonstrated a significant reduction in both tilt and yaw bending moments when feed-forward control loop was introduced.

As stated in [PN12], a fusion of two controllers is used to realize a trade-off between speed regulation and load reduction: Collective pitch control is used for speed regulation while individual pitch controller is used for structural load reduction. Both controllers are based on LQR control technique with integral action (LQRI) to cancel steady-state errors for step wind disturbances, and employ Kalman filter to estimate both system states and wind speed. Again, Coleman transformation is applied to convert linear time varying model into linear time invariant wind turbine model in order to design a linear controller. A feed-forward control loop is added to compensate for variation in wind speed. Results indicate improved rotor speed regulation as well as reduction in d- and q-bending moments which in turn reduces $1p$ rotor blade harmonics.

In [SSCA13, SSKA10], a multi-variable $\ell 1$-optimal control scheme is used to minimize blade root bending moment while maintaining a constant rotor speed during high wind speed regime. To achieve this goal, two decoupled LTI models were derived using Coleman transformation to design CPC and IPC based on $\ell 1$-optimal control theory. It was noted that a multi disturbance model like the one described in [FAS] was not suitable for designing an $\ell 1$ controller, and some modifications to decouple irrelevant mode intersections were required. Blade root out-of-plane bending moment and low speed shaft bending moment are greatly reduced while tower fore-aft bending moment was slightly reduced.

A proportional resonant individual pitch controller for mitigating blade root blade, tilt, and yaw bending moments is examined in [ZCC13]. Unlike other load reduction control strategies in wind turbines, this method does not require measurement of blade azimuth angle or carrying out multiple complex Coleman transformations between rotational coordinate frame to fixed coordinate frame. Here, individual blade bending moments are converted into two orthogonal α- and β-axes using Clarke transformation, and then two proportional resonant (PR) controllers are used to reduce transformed bending moments in these two new axes. The transfer function of PR controller depends on bandwidth of resonant peaks and the harmonic of blade root bending moment that has to be minimized. Simulation results indicate that proposed PR-based individual pitch controller can effectively alleviate structural load in wind turbine. However, the influence of load mitigation on torque variation and generated power was not reported.

According to [van06], higher harmonic loads can also contribute significantly to fatigue loads in larger wind turbines. So, it is necessary to mitigate higher harmonic structural load, especially in Mega-scale wind turbines. In literature, a number of higher harmonic controllers (HHC) [van06, Bos05, BCRN13, PJB15], with applications to wind turbines, have been investigated. Normally, individual HHC loops connected in parallel are designed to minimize higher harmonic loads in the rotor which in turn reduce 3p harmonic and its integral multiple structural loads on the fixed structure.

Most of the structural load reduction controllers in wind turbines that have been reported rely on blade load measurements. To avoid direct measurements of these loads, control methods based on the computation of structural aerodynamic loads using inflow conditions have been explored in [LMK05, JPP10, Gao12]. Normally, pitot tubes are used to measure inflow conditions. In [JPP10, TNP08], local inflow measurements on each blade were used to compute blade bending moments for designing an individual pitch controller. It was assumed that all blades were physically and aerodynamically similar since the properties of a single blade were used to compute future loading of all other blades.

A cyclic blade pitching control method for mitigating the slow varying rotor tilt and yaw moments is proposed in [LMK05]. Here, pitch angles were adjusted depending on measured local inflow angle and relative velocity on each of the rotor blades. Compared with collective pitch controller, individual pitch controller greatly reduced blade tilt and yaw bending at the tower top. Nevertheless, in this contribution, it was not demonstrated how the compromise between structural load reduction and power regulation was achieved.

Disturbance observer-based controllers

Since not all system states are available for measurement and due to the fact that the dynamics of the incoming wind are unknown, it is reasonable to use few output measurements to estimate unknown system and disturbance states. More specifically, wind speed variation, nonlinearities, and other unmodeled dynamics can be estimated and compensated for using a suitable observer in conjunction with an appropriate control scheme. Next, various variations of disturbance observer-based controllers applied to wind turbine systems are discussed.

The idea of estimating and compensating for disturbance was first proposed in 1976 by Johnson [Joh76] and has since then been referred to as disturbance accommodating controller (DAC). A fixed gain DAC has been applied successfully in regulating rotational speed of turbine rotor [SRB00]. Later, the idea of compensating for persistent wind variations was extended to multi-variable control design methods [SB02, SZW06, NS09], followed by the introduction of periodic gain DAC to mitigate asymmetrical loads across rotor disk [SB03, SRB00, Joh07a].

In [SB01], the performance of a periodic gain controller for regulating generator speed in a two-bladed, variable-speed, horizontal axis wind turbine was investigated. In comparison with a constant gain controller, the periodic gain controller had marginal performance improvement with respect to speed regulation. In a different study [SB02], a similar conclusion was drawn when a fixed gain collective pitch DAC and a collective periodic DAC were compared in speed regulation.

A periodic disturbance accommodating controller for regulating rotor speed and mitigation of cyclic rotor blade loads is proposed in [SB03]. This controller was applied to a two-bladed downwind turbine, where blades were manipulated individually to realize these two objectives simultaneously. The algorithm utilized a periodic state estimator to reconstruct system and disturbance states using rotor speed and rotor azimuth position as the only measurement signals. Compared to the fixed gain controllers, periodic gain controller has better performance with regards to load reduction. Unlike the approach reported in [SB02], where marginal performance improvement was registered with regard to speed regulation, IPC periodic disturbance accommodating controller offers a reasonable trade-off between speed regulation and structural load reduction.

To effectively compensate for unknown disturbances in any controlled system, it is important to accurately estimate them. This is normally realized using disturbance observers. In which case the determination of the optimum gain is essential for achieve good results. While high gains are necessary for reasonable disturbance estimation, extremely high gains cause the disturbance observer to become sensitive to measurement noises and unmodeled dynamics [SYM95]. One of the strategies for determining the optimum observer gain is discussed in [LS12], where the gains are on-line adapted.

A stochastic disturbance accommodating controller (SDAC) for stabilizing a system with unmodeled dynamics and unknown exogenous disturbance is presented in [GD13]. This approach uses an Augmented Kalman Estimator in the feedback loop to estimate the system and disturbance states using noisy output measurement. The results indicate good performance with reference to speed regulation and damping of drive-train vibration.

In [CKC14], SDAC is used for output power regulation and structural loads reduction in wind turbine. This control method is motivated by the fact that wind turbine is normally influenced by aerodynamic loads with statistical properties. In this study, it was assumed that wind turbine was excited by both wave and stochastic process noises in addition to measurement noise. The controller mitigated 1p harmonic loads while maintaining a generator speed around the rated value.

In order to compensate for adverse effects resulting from the model uncertainties and unknown exogenous disturbances, a linear stochastic disturbance accommodating (SDAC) controller is proposed in [GSC08]. Unlike the traditional DAC which treat external disturbances as a waveform with unknown magnitude, the SDAC considers disturbances as composed of both the waveform and stochastic components. This control method also uses the Augmented Kalman Filter to estimate both the system states and the disturbance (unknown inputs). Then the appropriate controller was designed to compensate for disturbances and stabilize the closed-loop system. Additionally, the stochastic stability analysis revealed that weighting gains for the Kalman filter must be lower-bounded to guarantee closed-loop stability. Similar work is reported in [GSC09], where the focus is on studying the stability and on-line adaption of process noise covariance matrices of SDAC so as to stabilize the closed-loop system.

A control strategy to suppress wind turbine tower vibration is presented in [HG15], where a disturbance observer-based controller was used to attenuate the disturbance at the top of the tower. Compared with proportional derivative (PD) controller, this control strategy had better performance in terms of dampening tower top deflection.

An adaptive collective blade pitch controller for regulating generator speed and disturbance rejection during high wind speed region is discussed in [FBW09, FBW10]. In [FBW09], a modified direct model reference accommodating controller (MRAC) with an ability to cancel the disturbance on the output is presented. While in [FBW10], the turbine model is augmented with Residual Mode Filter (RMF) to compensate for modes in the system that might violate the requirements of the Almost Strict Positive Real (ASPR) plant for adaptive control design is discussed. Compared to the standard collective blade pitch PI-controller, the results indicate improved performance with respect to generator speed regulation for both step and turbulent wind inflow.

In another study, a supervisory control strategy to mitigate structural loads in wind turbine is discussed in [SJB15]. This strategy is based on model predictive control, where a trade-off between structural load minimization and tracking of the maximum power is realized. It was observed that a significant reduction in rotor thrust dominant loads could lead to an increased low-speed shaft torsion moment, causing fatigue failure in drive-train system.

Multi-variant robust control

Robust control schemes have also been applied to wind turbines to mitigate adverse effects of variability of wind speed, with $\mathcal{H}_2$ and $\mathcal{H}_\infty$ being the most reported in the literature. As pointed out in [RMFB05], $\mathcal{H}_2$ controller is more appropriate in applications where disturbance rejection and noise suppression are crucial whereas $\mathcal{H}_\infty$ controller is suitable when the robustness to plant uncertainties is important. In both $\mathcal{H}_2$ and $\mathcal{H}_\infty$ control schemes, the task is to achieve stabilization while guaranteeing certain performance requirements such as disturbance attenuation, bandwidth limitation, and robust tracking problem.

A multivariate $\mathcal{H}_2$-based control strategy for minimization of structural load is proposed in [TNP10]. In this study, a multi-blade coordinate transformation was applied to the nominal wind turbine model. Then the resulting model was augmented with a stochastic wind model to design an observer-based independent blade pitch controller so as to estimate and compensate for wind speed variability. In comparison to collective pitch controller, the results of a multi-variant controller indicate improved performance regarding the reduction in yaw and tilt moments.

In [GC10], an $\mathcal{H}_\infty$-based individual blade pitch control for minimization of first axial tower bending mode as well as 1p fluctuations in blade bending moment is proposed. Since blade, rotor speed, and axial tower deflection modes are highly coupled, a multi-variable controller based on $\mathcal{H}_\infty$ design is proposed to stabilize the wind turbine while reconciling the conflicting requirements of structural load reduction and speed regulation. Again, d-q transformation was carried out to convert from mixed coordinate system to fixed coordinate system. The results indicated a significant reduction in structural loads, although at the sacrifice of the time required to settle to the reference rotor speed.

In another study, a $\mathcal{H}_\infty$-based multi-variable, multi-objective control strategy for regulating generator speed and reducing both the drive-train and tower loads during high wind speed is discussed in [CPAE+12]. These objectives were realized by designing two robust $\mathcal{H}_\infty$ multi-input single-output (MISO) control loops: One for generating a collective pitch angle and the other for determining generator torque signal. The two controllers were actualized by solving a $\mathcal{H}_\infty$ mixed sensitivity problem where notch filters were included in the control dynamics to achieve these objectives. Compared to standard pitch controller, the proposed strategy offered a compromise between speed regulation and load reduction.

A multi-objective control scheme for regulating generator speed and minimizing structural load reduction is described in [HEFS12]. This control scheme comprises of a linear matrix inequality-based collective pitch controller for generator speed regulation and an individual pitch controller for alleviating once per revolution frequency fatigue load on the rotor blades. The linear matrix inequalities (LMI) technique was applied to incorporate the constraints that satisfy the requirements of perfect speed regulation, efficient disturbance rejection, and allowance of permissible actuator usage. The strategy offers a reasonable trade-off between speed regulation and load reduction.

Multiobjective and model-predictive approaches

In [FJT13], an LQG controller with capability of determining the optimal weighting matrices is proposed to regulate generator angular speed, active and reactive power for a DFIG wind turbine system. Instead of using a trial-and-error method to evaluate suitable weighting matrices for both the Kalman filter gain and state feedback gain, a Genetic Algorithm (GA) was used to automatically search for the optimal weighting matrices that can satisfy the required performance specifications.

An independent pitch controller based on fuzzy logic is proposed in [PM13]. This control scheme aims at mitigating 1p harmonic loads on rotor blades without adversely affecting the quality of generated power. Similar to [Bos03], individual blade bending moments were transformed into yaw and tilt moments using Coleman transformation. Then PI-fuzzy controllers were designed to minimize tilt and yaw bending moments. The results indicate that an acceptable compromise between load mitigation and power regulation can be realized using this control approach.

A multi-variable control method is presented in [BLSH07], where a combination of nonlinear dynamic state feedback torque controller and a linear blade pitch controller is used to achieve the objectives of regulating output electric power and controlling rotor rotational speed. This control strategy satisfies both rotor speed and electrical generator power regulation goals. However, the variation of structural load which is an important aspect in large wind turbines was not considered.

In a different study, a MIMO nonlinear model predictive controller for a floating wind turbine is presented in [RSS+14]. The goal of this controller is to mitigate structural loads by minimizing yawing and pitching moments on the rotor. A model predictive strategy was employed to predict optimal future control input trajectory using the current measurement information as well as input/output constraints. The results indicate that the control approach is promising in reduction of rotor blade load of floating wind turbine.

Other similar work has been reported in [MSPN13a], where model predictive controller (MPC) together with a feed-forward disturbance controller was used to minimize structural loads on wind turbine structure. To develop a control algorithm that could operate in both partial and full load regimes, the whole operation envelop was subdivided into a number of finite sub-regions, where linearized models were used to capture localized dynamics within each sub-region. Here, upstream wind speed measured using LIDAR was then used as the gain scheduling variable to switch between the operating regions. In this case, prior knowledge of approaching wind speed was beneficial in MPC control design since the gain scheduling variable was known for the entire prediction horizon.

A model predictive-based IPC is proposed in [MSPN13b] to regulate rotational speed while minimizing the effect of asymmetric load across rotor disk. Individual blade pitch angles are adjusted depending on the speed of incoming wind to reduce the blade root bending moment's fluctuations. To account for model uncertainties and variation of operation point, a linear control strategy together with a model that predicts effective wind speed were used for gain scheduling. The operating points were evaluated in accordance with LIDAR measurements, both for current and predicted operating point. In this study, it was observed that LIDAR measurements can significantly improve the performance of wind turbine, but error in computing wind propagation time can severely degrade the performance of the controller. Compared with standard PI controller, this control approach allowed for a trade-off between speed/power regulation and structural load reduction. However, it led to increase in pitch actuation duty cycle (ADC).

A multi-variable model predictive controller (MMPC) for realizing multiple objectives in both partial and full load regions of a variable-speed wind turbine is discussed in [SMW10]. The controller aims at maximization and smoothening of generated power, mitigation of drive-train vibrations as well as reduction of pitching actuator activities. To cover the whole operation region, a number of linear models, each representing localized dynamics of a given sub-region were defined and appropriate switching mechanism to switch between sub-regions was also designed. During low wind regime, it was observed that MMPC had better generator speed tracking and higher aerodynamic efficiency compared to standard control method. Similarly, during above the rated speed region, the power fluctuation was considerably reduced in comparison with the standard collective pitch PI controller. Nonetheless, this led to increased fluctuations in generator speed.

As specified in [WF08], reduction of drive-train mode vibration can be realized by using small perturbed generator torque signal on the nominal value, especially in high wind speed region. However, generator torque control cannot effectively alleviate asymmetric rotor loads.

A multi-variable feed-forward/feedback controller for improving blade root bending moment reduction is reported in [LPW09a]. This control approach is based on the fact that either the full knowledge of incoming wind is known beforehand or the measurement by LIDAR system is possible. Results indicated improved performance with respect to blade load reduction. However, dynamics of actuation were not explicitly considered during controller design leading to high pitching rates. The two methods used for designing feed-forward controller were gain-scheduled model-inverse and gain-scheduled shaped compensator.

The use of disturbance feed-forward controller in conjunction with a standard feedback blade pitch controller is proposed in [DPW+10]. The focus is to reduce fatigue loads on wind turbines without significant compromise on power regulation. The study concluded that when the wind turbine is under influence of stochastic wind field, a significant structural load reduction could be realized without affecting the quality of generated power, if an additional feed-forward control loop is applied. This control configuration was implemented and tested on a real 3-bladed wind turbine as reported in [SFF+13]. The findings from this study pointed out that the use of a feed-forward control loop in conjunction with a feedback speed control loop could be utilized to further reject wind speed variations at low frequencies.

2.3.2 Power optimization control problem

Another important goal in wind turbine is to maximize power extraction efficiency during low wind speed region. To tackle this problem, controllers are usually designed to track the maximum aerodynamic efficiency when the wind speed is below the rated value, although it is difficult to accurately determine the maximum power coefficient since it is a nonlinear function of tip-speed-ratio and blade pitch angle. Even in circumstances where its nearly optimum value can be approximated, blade aerodynamic properties are likely to change with time due to aging and corrosion, leading to sub-optimal operation. As shown in Fig. 2.1, for a given blade pitch angle, there is a maximum value for power coefficient C_p that corresponds to the optimal tip-speed-ratio λ_*. Next, in this section a number of control methods for maximizing power extraction in wind turbines are discussed. Some of these control methods assume prior knowledge of optimum operation conditions, either computed through empirical data from experiments or using theoretical models like blade element momentum theory. Others control approaches assume that optimal TSR and blade pitch angle are unknown; hence, an on-line optimization solution to maximize generated power is usually sought.

As outlined in [AYTS12,TO11], Maximum Power Point Tracking (MPPT) methods can be summarized as follow: Tip Speed Ratio (TSR) control, Optimal Torque (OT) control, power signal feedback (PSF) control, and Perturbation and Observation (P&O) control. Most of these MPPT methods usually require a priori knowledge of the optimum power coefficient [BKA09]. However, in strict sense a perfect estimate cannot be achieved either by analytical methods or through experiments. In majority of MPPT control algorithms, pitch angle is normally held constant at a predefined optimal value and the optimal power coefficient is solely determined by tip-speed ratio [ST12, EAF13]. Despite the performance improvement in comparison with the fixed gain control methods, some of these power maximization control schemes have other shortcomings. For instance, the tip speed ratio control method utilizes wind as an input to compute the optimum value of the TSR; however, it is hard to accurately determine the effective wind speed from direct measurements [OBS07]. On the contrary P&O method does not require prior knowledge of wind turbine characteristic curve rather a hill-climb search method is used to locate the local optimum power coefficient. However, this approach is bound to fail when used in large wind turbines under the influence of rapidly varying wind speed due to large inertial loads on turbine rotor [JSL12]. Likewise, sliding mode approaches and extremum seeking control [PJJ08] take a lot of time to converge to the optimal operating conditions [YHD13]. As a result, this might not give favorable results if the rate of wind speed fluctuation is very high. In [BAAB08, BAAB09], a sliding mode controller based on MPPT algorithm is used to maximize captured power by tracking the optimum aerodynamic torque. This strategy is formulated to guarantee stability despite parameter uncertainties and model inaccuracies. Additionally, this control approach is designed in such a way that no induced mechanical stresses are transmitted to the drive-train system. The obtained results indicated good convergence of both the rotor speed and torque.

A nonlinear sliding mode control method for power production optimization on a variable speed wind turbine that is fitted with a DFIG is proposed in [BM08]. The control system consist of two cascaded controllers: a DFIG controller for tracking both the generator torque and rotor flux, and another control loop for tracking optimal rotor speed to maximize power capture. Although improved performance in terms of optimal torque and flux tracking was obtained, zero error tracking was not realized. This control method offers a trade-off between perfect reference tracking and escalation of chatter in drive-train.

A nonlinear cascaded controller for variable speed wind turbine that is equipped with a DFIG is demonstrated in [BS09]. Here, the aim was to optimize output generated power while avoiding induction of strong transient loads in drive-train. This was achieved by tracking optimal reference rotor speed generated using estimated aerodynamic torque and estimated effective wind speed. Compared with standard partial load control strategy, the proposed nonlinear controller led to improved power extraction efficiency while maintaining drive-train transient loads within acceptable range.

Unlike other control methods, which optimize power by manipulating generator torque only, optimal direct shooting control approach and Lyapunov-based controllers [EPVF13] can use both the generator torque and blade pitch angle to attain the local maximum of the power coefficient. Application of multi-input multi-output optimal direct shooting control to maximize the aerodynamic power efficiency in partial load operation region has been presented in [YHD13]. The effectiveness of the proposed algorithm was evaluated against the standard single-input single-output (SISO) torque feedback controller, where a noticeable improvement in tracking $C_{p_{max}}$ was observed. The requirement of prior knowledge of effective speed of incoming wind is the major weakness of this method. Furthermore, the influence of torque variation in drive-train was not investigated.

A Lyapunov-based control approach for maximizing generated power in partial load regime is studied in [HHWS10]. In this scheme common blade-pitch angle (β_{com}) and tip-speed-ratio (TSR) are varied to ensure that the turbine operates at optimum condition for maximum power extraction. The results indicated reasonable convergence to a predefined optimal value despite the variation of the incoming wind.

A robust control scheme for power capture optimization during low wind speed is described in [ISDW08, ISD+10, HHWS10], where Lyapunov-based approach is used to determine the trajectory of the desired rotor speed that corresponds to maximum power point for any given wind speed. Unlike MPPT methods, where optimum power point is assumed to be known, this approach searches for the best combination of blade pitch angle and tip-speed-ratio that lead to optimum power extraction.

Alternative control strategies where generator torque and blade pitch are both used to achieve various control objectives have also been reported in the literature. As discussed in [MTG11], torque controller is used for track incoming wind trajectory to extract as much power as possible from wind whereas pitch controller is used for regulating the electrical power to the rated value. Both of these control loops are based on a SISO control configuration, thus limited in handling a multi-objective control problem.

In an effort to minimize uncertainties related to determination of the gain K_T corresponding to the maximum power coefficient $C_{p_{max}}$, adaptation torque control methods have been proposed in [JPBF05, Joh07b, JFBP04]. Here, a highly intuitive adaption gain was used to maximize power extraction in wind turbines during partial load region. The gain was adapted using large time steps in order to average out high frequency wind variation and sluggish turbine response to gust wind. Compared to the standard torque control, the proposed adaptive control method gives better performance in power maximization. Another variation of adaptive control scheme for computing optimum aerodynamic efficiency is proposed in [JF07]. Unlike other adaptive controllers used in partial load region, where a constant optimum blade pitch angle is assumed, this control method also varies pitch angles by small increments to enhance the efficiency of power extraction.

Other examples of advanced control algorithms for maximizing power extraction have been reported. For example, an adaptive disturbance tracking control (ADTC) is applied to track the optimum tip-speed ratio (TSR) so as to maximize power generation during low wind speeds [BMF13]. In essence, this control method aims at regulating rotor speed so as to track the incoming wind speed, hence keeping TSR at its optimum value. A low order wind turbine model augmented with wind disturbance model was used to estimate incoming wind speed for use in ADTC algorithm. Other similar work has been reported in [BLMF11], where ADTC with different tracking ratios is used for smooth transition from low wind speed to high wind speed region. The transition region ensured that turbine reached its rated generator torque at its rated rotor speed.

2.3.3 Power optimization and load reduction control methods

While power optimization is crucial in low wind speed region, care must be taken not to induce undesirable torsional vibration on the drive-train. Therefore, reconciliation between these two conflicting requirements is required. This section explores different control methods that have been proposed in the literature to deal with this challenge. Most of the studies on maximization of power extraction during low wind regime have not investigated negative consequences of tracking the optimum power on the reliability of drive-train system. For instance, mechanical fatigue tresses are induced in drive-train by large generator torque variations during maximum power point tracking. To overcome this challenge, studies to reconcile the competing objective of maximizing power extraction and reduction of induced mechanical loads in drive-train have been proposed. In [MCBC05], an optimal control framework for variable-speed fixed-pitch wind turbine is discussed. In this study, wind speed was divided into a slowly varying component and rapidly varying component in order to determine the average position of operation point as well as generating high frequency variations around this point. A PI-controller was then designed to keep wind turbine system around the desired operation point, and a Linear Quadratic Gaussian (LQG) controller was used to compromise between maximization of wind power and minimization of generator torque variation. Simulation showed good control performance in wind power maximization. However, this optimization method assumed known optimum operating point.

Linear and nonlinear control strategies based on a two-mass nonlinear wind turbine model and a wind speed estimator is presented in [BS10]. The focus was to optimize power capturing and reduce drive-train load is realized at the same time. To realize this, Kalman filter in conjunction with Newton algorithm was used to estimate aerodynamic torque and effective wind speed using generator torque and generator speed as the only measurement variables. Then, the estimated torque and wind speed were used to calculate optimum reference rotor speed for tracking maximum power. Comparing the performance of both control methods, nonlinear controllers outperformed the linear controller, especially during high turbulent winds.

In a different study, a composite linear state space controller consisting of a disturbance tracking controller and an independent blade pitch controller [Sto03] was developed to realize the goal of optimizing energy capture and reducing structural load on the rotor blades at the same time. The disturbance tracking controller was employed to optimize energy capture in low wind speed region despite persistent wind disturbances whereas independent blade pitch controller was used to minimize blade root fatigue loads. To avoid the interference with torque controller, independent pitch controller was designed so as not to actively regulate the rotor speed. A single-state control model like the one described in [BLK98] was used to design a torque controller based on disturbance tracking theory (DTC) to maintain an optimum tip-speed-ratio for maximum power generation during low speed region. The results indicated that the proposed control method can reduce the structural load without sacrificing power optimization objective.

A multi-variable control strategy for regulating the speed and electrical power is proposed in [LBS06]. To realize these two goals, a combination of nonlinear dynamic state feedback controller and linear pitch controller was used. A trade-off between speed regulation and power control was achieved by constraining power tracking error and pitch controller to regulate the rotor speed. To improve on the torque control response, small perturbed signals from a variable-pitch control were used. The results indicated improved performance in rotor speed and power regulation while maintaining loads within acceptable limits. It is important to consider advanced control strategies, either model-based or model-free, to trade off between maximizing energy production and guaranteeing the extended life time of the structural members.

2.3.4 Emerging trends and issues affecting wind turbine control

This section outlines technological developments and social economic issues that are likely to positively or negatively impact on wind power production. While it is important to explore enabling technologies that can lead to lowering wind energy production cost, sustainability and environmental impact assessment need to be considered before deploying such technologies.

To make wind energy more competitive compared to other energy sources, the turbine total life cycle (TLC) cost has to be lowered. This involves reduction of both initial investment cost and operation and maintenance (O&M) cost. These two classes of costs contribute separately to the TLC cost. For instance, initial investment cost can be drastically reduced if efficient manufacturing technologies for mass production are embraced in addition to using high quality and cheap alternative materials to manufacture various turbine components. A good example is to replace fiber reinforced plastic (FRP) rotor blades with hydroformed steel blades as proposed in [DPT^{+}14]. In this study, it was noted steel has a recycling rate of 90%, making it an attractive substitute for manufacturing cheap blades. Although FRP has a number of advantages over steel, it is more susceptible to aging, more expensive, and problematic in recycling. On one hand the use of steel can reduce the manufacturing cost of rotor blade, but on the other hand, weight might present challenges in designing controllers due to high inertial loads.

Maintenance and operational cost can be reduced by employing suitable control strategies in combination with appropriate health condition monitoring methods. This aims at extending the operational life time of critical parts of wind turbine as well as indicating when a certain part is due to replacement. As a result, condition-based maintenance (CBM) [TJWD11] can be used to reduce unnecessary downtimes by carrying out maintenance only when it is necessary rather than on a scheduled basis. Among all wind turbine subsystems, the gearbox is one of the most expensive component and most susceptible to failure [LLD^{+}12]. Any attempt to reduce the failure rate of wind turbine gearbox will significantly lower O&M costs and overall production of wind power. To avoid the problems associated with gearbox failure, some researchers have proposed direct-drive instead of geared-drive system, especially in utility-scale wind turbines.

While permanent magnet direct-drive systems are compact and robust, sustainability of its future production cannot be guaranteed because a rare earth metal, Neodymium, is required to make its permanent magnet [Wil11]. Neodymium is an expensive and a scarce rare earth metal which is likely to be depleted over time if its demand keeps on growing. Additionally, its extraction has very adverse effects on environment and this can be a setback in producing environmental friendly power. The fact that 90% of the world total Neodymium production is produced by only a few countries and political influences makes it even more expensive [iNE14]. These restrictions and political interference may hamper future prospects of manufacturing Mega-scale permanent magnet wind turbine generators. In a different study, ferrite permanent magnet generator was studied as possible substitute for Neodymium permanent magnet generator [ESEL14], however, it was concluded that the resulting generator would be too heavy because a large magnet volume would be required to attain the same air gap flux density and voltage as Neodymium-based generator.

In recent past, the use of light detection and ranging (LIDAR) sensor in wind turbine control application has been investigated. As noted in [HHW06], this measurement technology has been in existence since 1970s, but its wide spread use has been hampered by high cost. This sensor measures the upwind speed before it interacts

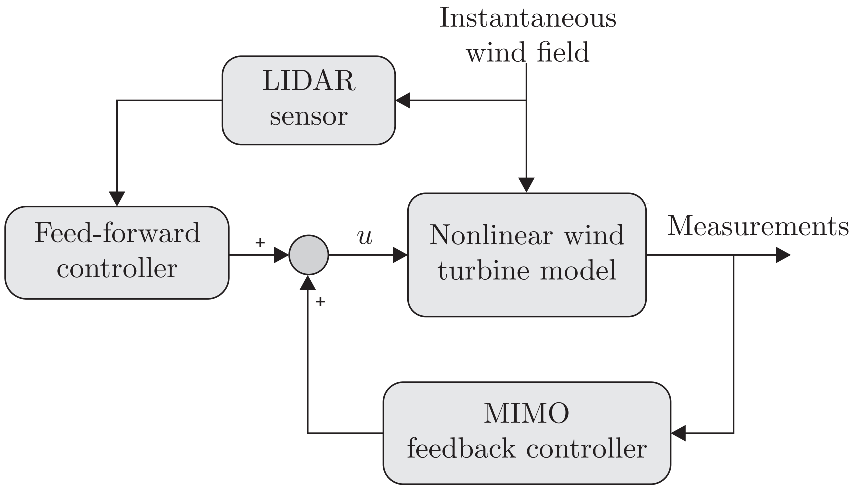


Figure 2.6: Wind turbine control system with a LIDAR feed-forward loop [NS16]

with the turbine, hence allowing time for the turbine to respond to control output signal since the dynamics of incoming wind are faster than that of the turbine itself. This is very beneficial in large wind turbine where blades are massive; pitch actuation can be activated ahead of time to effectively minimize asymmetrical loads on the rotor blade. It is important to mention that this technology is still an active area of research, especially in Mega-scale wind turbines due to high inertial loads.

In Fig. 2.6, it is illustrated that a LIDAR system can be integrated into wind turbine control loop to realize desired performance. The upstream wind speed is measured using LIDAR system and the variation from nominal speed is compensated using the feed-forward controller. A multi-variable controller is used in the feedback loop to realize the objectives related to power/speed regulation and structural load reduction. This kind of control scheme can be desirable for large wind turbines that are subjected to rapidly varying wind speeds due to their slow reaction time.

As mentioned before, structural loads increase as the turbine grows in size. More specifically, it has been noted in [SC12] that blade root edge-wise stresses emanating from gravitational force increase as the blade size increases in size. On the contrary, flap-wise stresses due to aerodynamic loads are independent of blade size. Another challenge related to large wind turbines is slow pitching dynamic response due to massive inertial forces of the blades. To overcome the problems related to slow dynamic response of blade pitching due to large size and increased weight, a number of investigations combining active aerodynamic control devices and full span blade pitch control have been reported. In the literature, trailing edge flaps and micro tabs are the most used active aerodynamic control devices. As pointed in [DCZB07, YZX12], trailing edge flaps can be classified as rigid or deformable, with deformable trailing edge flap (DTEF) being most preferred. In comparison with individual pitch control, it has been observed in [LK09] that individual flap control (IFC) is more effective in mitigating high frequency loads in addition to reduction rate of pitching.

It has been further noted in [YZX12, LK09] that active aerodynamic control devices have a potential of minimizing fluctuation of generator power in addition to damping tower deflection.

In a different study, the performance of a combined active aerodynamic load control (AALC) and IPC scheme on fatigue load reduction was investigated in [WBR+09]. The individual pitch controller similar to that described in [Bos03] was used together with AALC based on proportional derivative (PD) feedback design. The PD controller employed blade tip deflection as the feedback signal and was used to actuate flaps in all the three blades. When active aerodynamic load controller was deployed, the results depicted significant improvement on root blade flap-wise moments reduction. Though the scheme did not explicitly investigate the variation of generated output power, the improvement on flap-wise bending moment reduction did not adversely affect other important turbine component such as drive-train and tower deflection.

Other issues likely to influence current and future production of wind power are social economic- and cultural-related [LRA11]. Before any wind farm installation, a site with prerequisite climatic conditions has to be identified and acquired. This may sometime involve displacement of human population leading to conflicts. Setting up wind turbine installations near residential areas may cause interference due to emission of acoustic noise. Another challenge of onshore wind farm is disturbance of natural ecology and natural habitat. It has been concluded in [SHHM10] that offshore wind turbines offer greater potential in scaling up the power production capacity. This is due to availability and higher wind speeds in offshore wind farm sites. In addition, there is less interference with human settlements caused by acoustic noise and negative impact on landscape aesthetic. It is worth noting that due to some of advancements in wind energy industries; there are prospects of manufacturing wind turbines of even higher wattage and bigger sizes in offshore sites.

2.4 Discussion and evaluation

It is evident from literature survey that the focus of wind energy research has been on the reduction of its production cost, enhancement of safety and reliability, and improvement of the quality of produced power. From the control point of view, this can be realized by designing control strategies that can handle multiple objective problems for the whole operation range, i.e., during the partial and above the rated speed regions. More precisely, it is important to consider the power maximization against load reduction in the drive-train during partial load region and speed/power regulation against load mitigation during high wind speed region.

Different control approaches can be used to mitigate structural loads on different wind turbine subsystems. For example, IPC can mitigate rotor blade load and damp the side-side tower deflections. On the other hand, collective pitch control can minimize tower fore-aft deflection as well as regulating rotor speed during high wind speed. Additionally, generator torque controller can be utilized to minimize tower side-side deflection and drive-train torsional vibration. To reduce structural loads on different subsystems simultaneously, it is important to fuse more than one control approach; however, care must be taken to avoid them from interfering with each other by using appropriate filters.

Table 2.1 summarizes and compares various control methods used for power optimization in partial load region. The main challenge in this region is to compute the optimal operation point which in most cases is approximated. Since the aerodynamic properties are bound to change the wind turbine ages, the operating point is likely to change. Moreover, the turbine is influenced by variable wind speed make it very to operate a optimum point that is determined under steady state conditions.

Some of power the maximization methods cannot be used in Mega-scale wind turbines because of large inertial loads, especially those that require manipulation of both pitch angle and generator torque to reach the optimum operation point [HHWS10]. On the other hand, adaptive control methods can be effectively used in large wind turbine to track maximum power provided that the gain is adapted using large time steps to accommodate high variations in wind speed and slow response due to large inertia forces.

Strict tracking of maximum power curve can cause the induction of undesirable mechanical stresses on the drive-train system, which can cause fatigue failure if not checked [WF08]. To reconcile these two contradicting requirements, independent pitch control and optimization algorithms can be used simultaneously to minimize induced mechanical load without significantly interfering with power maximization objective. More specifically, adaptive control method can be fused with IPC to achieve these two objectives at the same time. In this control configuration, IPC must be designed in such a way that it does not regulate generator speed hence, avoiding performance degradation. It is worth mentioning that employing IPC results into increased pitching activities, and thus care must be taken not to violate the limits of the pitch actuators.

In Table 2.2, different control methods developed for high wind speed region to regulate speed/power and mitigate structural loads are given. Most of these methods are based on linear control theory, meaning that they are only effective around a given operation point. Therefore, measures must be taken to compensate for uncertainties resulting from the change of operation point due to variation of incoming wind speed. Although the PI gain scheduling controller is simple to design and more robust, it has limitations in handling multi-objective problems since as it is a single-input single-output controller.

Linear quadratic methods can offer an optimal solution by trading-off opposing requirements by minimizing a given cost function. In most cases, full system state

Table 2.1: Comparison of control methods in low wind speed region

Control method	References	Manipulated variables	Short description
Tip Speed Ratio (TSR)	[AYTS12 , BKA09]	Torque	Known optimal operation point is assumed. Wind speed measurement is required.
Power Signal Feedback (PSF)	[TO11 , EAF13]	Torque	Requires the knowledge of the wind turbine's maximum power curve. Wind speed measurement is not required.
Optimal Torque Control (OTC)	[AYTS12 , BKA09]	Torque	Requires the knowledge of turbine optimal characteristic curve. The reference torque is always proportional to the square of rotor speed.
Perturbed and Observation (P&O)	[ST12 , JSL12]	Torque	Does not require knowledge of optimum point characteristic curve. Suitable for low inertia wind turbine systems.
Adaptive Disturbance Tracking Controller (ADTC)	[BMF13 , BLMF11]	Torque	Based on linear model and tracks optimum TSR for a given speed.
Adaptive controller	[JPBL05 , Joh07b]	Torque	Adapts the control gain depending on incoming wind speed.
Sliding mode	[BAAB08 , BAAB09]	Torque/Pitch	Does not guarantee finite-time convergence of the tracking errors. Leads to performance degradation if wind speed is rapidly changing.
Extremum seeking	[PJJ08]	Torque/Pitch	Take time to converge to optimal solution. Leads to performance degradation if wind speed is rapidly changing.

information is required to design this class of controllers, but not all states are available for measurements. This has necessitated the need to design observers to reconstruct unknown states. Observers can be designed using linear quadratic methods, $\mathcal{H}_\infty$, pole placement among others. In literature, LQG has been applied in regulating generator speed and reducing of structural loads, where it is assumed that wind turbine is influenced by disturbances and noise that have stochastic properties. Due to these strict requirements, LQG controllers are restricted in terms of applications. Another problem associated with LQG controller is poor gain margins which are improved using loop transfer recovery (LTR). To reduce the steady state error, the standard LQR controller is normally modified to include an integral action.

Another control structure that has attracted a lot of attention in wind turbine applications is disturbance accommodating controller (DAC). This is due to its ability

Table 2.2: Comparison of control methods in high wind speed region

Control method	References	Gain	Pitching	Short description
PI-controller (gain scheduling)	[WF08]	Variable	Collective	Simple to design and robust. SISO controller.
Linear Quadratic Gaussian (LQG)	[Bos03, SKW+09b, FJT13]	Fixed	Individual	Kalman filter is used to estimate system states. Loop transfer recovery is used to improve stability margins.
$\mathcal{H}_2/\mathcal{H}_\infty$	[RMFB05, TNP10, GC10]	Fixed	Individual	Used to reject unknown disturbance and suppression of measurement noise.
Linear Quadratic Regulator with Integral action (LQRI)	[PN12]	Fixed	Individual	An additional integral action is used to cancel steady state error.
Disturbance Accommodating Controller (DAC)	[SZW06, SB02, NS09]	Fixed	Individual	Estimate system and disturbance states. Assumes measurement signal are noise free.
Stochastic Disturbance Accommodating Controller (SDAC)	[GD13, CKC14, GSC08]	Fixed	Individual	Estimation of system and disturbance states using measurements with noise.
Periodic Disturbance Accommodating Controller (PDAC)	[SRB00, SB03]	Periodic	Individual	Uses periodic model and is complex to design. Azimuth position is used to vary the gain.
Model predictive control (MPC)	[MSPN13a, MSPN13b]	Variable	Individual	On-line optimization as well as input and output constraints handling.

to estimate system and disturbance states as well as compensating for unknown disturbances. In wind turbine application, the variation of incoming wind from its nominal value is considered as disturbance. Majority of the reported work in wind turbine application, compensate for unknown disturbances using static disturbance rejection method which assumes that disturbances influence the turbine through the same channel as the manipulated variables, resulting to poor performance when this condition is violated. On the contrary, dynamic disturbance rejection method can offer an effective means of compensating for unknown disturbances, nonlinearities, and uncertainties due to unmodeled dynamics.

As pointed out, wind comprises of deterministic and stochastic properties and the combined effect of these two properties is responsible for unbalanced aerodynamic load across the rotor disk. The unbalanced load due to deterministic wind property can be minimized by periodic disturbance accommodating controller. However, this control scheme is complex to design and has no performance advantage over DAC after carrying out multi-blade coordinate transformation. Multi-blade coordinate transformation converts a periodic model into an approximated linear time invariant model, and the resulting constant gain controller has similar performance as a period disturbance accommodating controller. If the turbine is assumed to be under influence of both the waveform and stochastic disturbances, stochastic disturbance accommodating controller can be used to reconstruct both the system and disturbance states using measurement signals with noise.

As noted, IPC leads to increased pitch duty cycle which may in turn cause early failure of pitching mechanism. To tackle this problem, MPC has been considered in many studies since it can explicitly take into account constraints during the design stage to avoid violation of pitching actuator limits. To further improve the performance of MPC, LIDAR measurements can also be used to improve its reaction time.

Since most linear controllers are designed for a specific operation point, any significant deviation from this point may lead to performance deterioration. Hence, it is important to consider variable gain controllers such as gain scheduling and linear parameter varying controller in wind turbine application.

To realize the goal of improving the quality of generated power and guaranteeing the reliability in Mega-scale wind turbines, it is inevitable to employ multi-variable control schemes together with emerging technologies such as LIDAR sensors, hybrid drives, and active aerodynamic control devices such as trailing edge flaps and micro tabs. It would be important to combine more than one control strategy to mitigate structural loads in different subsystems rather than considering each subsystem independently as it is the case with most of the proposed controllers. In case of repair- or maintenance-induced replacement of WT components based on different material control strategies may be adapted to take into account the new properties.

2.5 Summary and conclusions

In this chapter, different control strategies used in large wind turbines, both in low and high wind speed regions, are outlined and compared with respect to different operational aspects. Special focus is given to structural load reduction and related control design. Taking the advantage of economies of scale, the cost of producing a unit of power by wind turbine can be reduced if the size and power rating are scaled up. Manufacturing turbines with massive sizes can lead into problems related to structural loads and poor quality of generated power. To fulfill such control demands with contradicting requirements, innovative control methods that can handle multi-objective problems are inevitable.

Although aerodynamic loads are not high during low wind speed region, tracking of maximum power can cause high variation torques in the drive-train, causing failure before reaching desired end of lifetime. To balance between optimum power production and load reduction in drive-train, a multi-variable control method that can manipulate both pitch and generator torque needs to be further explored since most of the reported controllers are single-input single-output. Similarly, in high wind speed region, power/speed and structural load reduction are realized by multi-variable control strategies. It is important to note that majority of documented control approaches for high wind speed region are based on linear models, and are only effective around the design point. Any significant deviations from this operation/design point results into control performance degradation. This can be circumvented by using variable gain controller that adapts the gain depending on the wind speed variation. Effective wind speed can be either estimated using turbine model or using LIDAR technology to measure upstream wind.

It has been pointed out that reaction time of wind turbine can be improved if a controller is designed using information on incoming effective wind speed before it interacts with turbine. This idea can be used during low and high wind speed, but a lot of publications have focused on high wind region. Additionally active aerodynamic control devices can also be used to complement the main control schemes to further improve their performance.

3 Wind Turbine Modeling

In this chapter, details of simulation tools/codes used in this thesis are discussed. First, the inherent challenges that exist in wind turbine modeling are pointed out. Second, the already available modeling codes are discussed against their advantages and computation capabilities. Lastly, a detailed procedure of deriving the linear model used for controller design is delineated.

Since unmodeled dynamics and other inherent uncertainties always exists in modeling, model-based controllers might suffer from poor performance or even instability in a closed-loop system if not properly designed. The stability of a closed-loop system would strongly depend on the the model used to design the controller or observer for observer-based controller. Modeling error might significantly degrade the performance of the controller/observer and sometimes lead to instabilities in the closed-loop system.

The effectiveness of the model-based controller depends largely on the accuracy of the wind model used in the design process; the model should capture all the important dynamics such that all desired performance objectives are realized when the controller is applied. Wind energy conversion system (WECS) consists of the following main subsystems: aerodynamic, mechanical, electrical, and actuation module. Each of these subsystems can be modeled separately and coupled to form a comprehensive model, but such model is normally of higher order, highly nonlinear and contains tightly coupled modes. In the literature, flexible structural parts are normally modeled using finite element method, while rigid components are modeled using multi-body system. Notwithstanding the fact that wind turbine systems are highly nonlinear, the incoming wind field that varies spatially across the rotor disc, further complicating dynamic response of wind turbine.

As noted in [Wri04], getting an accurate model of a wind turbine is a complex and challenging exercise since large number of degrees of freedom are required to capture all important dynamics. Likewise, these dynamics must be accounted for during control design process. Generally, wind turbines are inherently nonlinear and interact with wind profile which spatially varies in both speed and magnitude [PJ09]. Due to nonlinearities in wind turbine, it is difficult to develop a perfect mathematical model that can effectively capture all its dynamics. This challenge is further compounded by the fact that the dynamic behaviors of incoming wind are usually faster than that of turbine itself, unknown, and difficult to predict. Contrastingly, unmodeled dynamics in wind turbine can be compensated for by using appropriate control methods.

For the purpose of controller design in wind turbine applications, appropriate plant model is required. A complex model presents challenges of coming up with a proper controller since the difficulties of control design increases with the complexity of the model used in the design. On the other hand, a simple model does not account for some of important dynamics. For instance, some simple model proposed in the literature considers rotor as a rigid body, neglecting important dynamics related to pitching. Other important dynamics that are neglected in a simplified model includes gyroscopic and gravitational forces effects. Hence, it is important to balance between model simplification as well as capturing all important dynamics when coming up with the appropriate wind turbine model for the purpose of controller design.

Over the last few decades, several simulators such as GH Bladed [Bla], Fatigue, Aerodynamics, Structures, and Turbulence (FAST) [FAS], Flex5 [Øye S.], Automatic Dynamic Analysis of Mechanical Systems (ADAMS) [ADA] etc., have been developed for the purpose of designing and simulating wind turbine structural dynamics. Among these simulators, FAST and GH-Bladed, which are based on "Assumed Mode" method, are the most preferred in control design approaches because it is possible to extract control-oriented models (linear model about a given operation point). Compared to finite element-based models, "Assumed Mode"-based models are less computationally expensive, making them more attractive in control design applications. Again, it is important to mention that some of the aspects outlined in this chapter have already been discussed in [NLS15, NS15, NBS16a].

3.1 Simulation and analysis tools

In this thesis, FAST code which is developed at National Renewable Energy Laboratory (NREL)-USA and verified by Germanischer Lloyd Wind Energie-Germany, is used as the primary aeroelastic computer aided engineering (CAE) simulation tool to evaluate dynamic response of a horizontal-axis wind turbine under different operation conditions. The FAST can be described as a high fidelity aeroelastic model that can simulate dynamics responses of both two- and three-bladed horizontal-axis wind turbines, both in onshore and offshore applications. To capture most of the important dynamics in wind turbines, FAST code uses a combination of modal and multibody dynamic formulation where flexible components like tower and blades are characterized using linear modal representation that assumes small deflections, while rigid components are modeled as multi-body dynamic (MBD) system [JB05]. As noted in [Wri04], the FAST aeroelastic simulation code uses Kanes method [KL85] to set up dynamic equations of motion, which are solved through numerical integration. This method makes use of the generalized coordinate system; hence, eliminating the need to use additional constraints to the equations of motion. To generate aerodynamic forces that mimic a real wind turbine, FAST uses the AeroDyn subroutine package developed by Windward Engineering.

To mimic the dynamic response of a real wind turbine, a three dimensional turbulent full-field wind is used as one of the input to FAST during the simulation. To generate turbulent wind profile, TurbSim code [Tur] from NREL which uses a stochastic model to numerically simulate a time series three-dimensional wind field in a two dimensional vertical grid fixed in space is used. The TurbSim generates wind profiles of different turbulence intensities subject to initial boundary conditions that are used with the main aeroelastic model.

To express the dynamics of wind turbine with respect to a common unifying reference coordinate reference system, a multi-blade coordinate transformation (MBC) [Bir10] is used during the design process of an individual blade pitch controller used in this thesis. As noted in [Bir08], MBC allows the fixed reference coordinate to experience structural loads that contain only particular harmonics of the rotating rotor. In wind energy harvesting MBC is used in variable speed, variable pitch three-bladed horizontal-axis wind turbine which may even have blades with different physical properties.

In this thesis, MLife code [Hay12] from NREL is used to do fatigue load analysis in wind turbines. It is used as a post processing code to calculate damage levels, predict the lifetime, and Goodman calculations of the fatigue analysis. This code is based on a standard rainflow counting algorithm and load range versus cycles to failure (S-N) curve; hence, it require time history for the entire structural load spectrum. Apart from doing damage related analysis, Mlife gives statistical information regarding the time series structural load data generated during simulation.

3.2 Model description

In this thesis, a fictitious WindPACT 1.5 MW wind turbine model developed by National Renewable Energy Laboratory (NREL) is used to design multi-variant controllers. This model is described as a three-bladed, upwind, variable speed horizontal-axis wind turbine with the features outlined in Table 3.1. Other details concerning this model can be found in [MH00]. To determine dynamic response under different loading scenarios, the model is simulated using FAST code. The flexibility of the model depends on the number of enabled Degree of Freedom (DOFs) during simulation. Though the model has 24 DOFs, only those related to the given objectives are enabled when designing the controller. In this thesis, 5 DOFs which are illustrated in Fig. 3.1 are enabled so as to design an individual blade pitch controller for structural load reduction in rotor blades. This can be written in a compact form as $\underline{q} = [\tau, \Psi, \zeta_1, \zeta_2, \zeta_3]^T$, where τ denotes the tower fore-aft deflection mode DOF, Ψ is the generator variable speed DOF, while ζ_1, ζ_2, and ζ_3 represent the first flapwise bending modes DOFs for blades 1, 2, and 3, respectively. It is important to note that other set of DOFs are enabled for structural load consideration on other parts of wind turbine such as drivetrain and tower.

Generally, the dynamics of wind turbine can be represented by the following nonlinear model

$$M(\underline{q}, \underline{u}, t)\ddot{\underline{q}} + f(\underline{q}, \dot{\underline{q}}, \underline{u}, \underline{u}_d, t) = 0, \tag{3.1}$$

Table 3.1: Specifications for WindPACT 1.5 MW wind turbine model

Rated rotor speed	20 rpm
Hub height	84.288 m
Configuration	3-blades, upwind
Cut_in, Rated, Cut_out wind speed	4 m/s, 12 m/s, 25 m/s
Gearbox ratio	87.965
Blade diameter	70 m
Rated power	1.5 MW
Blade pitch range	0∼90°
Pitch rate	10 degrees/second
Control	Variable speed, variable pitch
Nacelle mass	51.170 T
Hub mass	15.148 T
Optimum tip-speed-ratio (λ_{opt})	7.0
Maximum power coefficient ($C_{P_{max}}$)	0.5
Optimal pitch angle (β_{opt})	2.6°

where M represents the mass matrix containing inertia and mass components and f denotes nonlinear function relating DOFs and input variables. The vectors $\underline{q}$, $\underline{\dot{q}}$, and

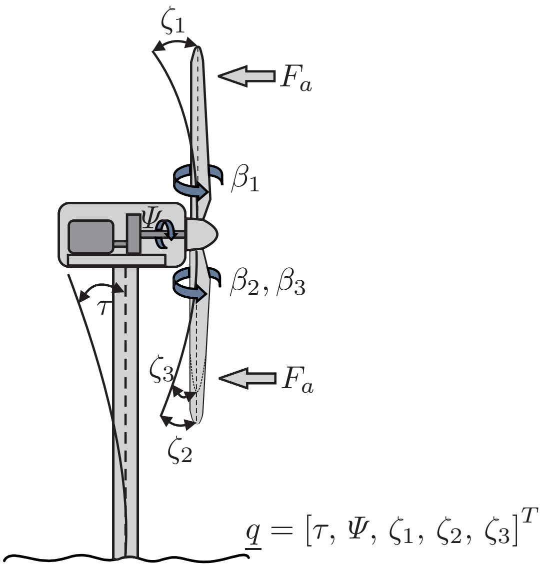


Figure 3.1: Applied model showing some of degrees of freedom used for linearization [NLS14]

$\ddot{\underline{q}}$ are the enabled DOFs displacements, velocities, and accelerations, respectively. The variable $\underline{u}$ is the control input vector which represents either individual blade pitch angles or generator input torque, while $\underline{u}_d$ represents variation of unknown wind input. It is important to emphasize that all variables related to nonlinear model are underlined to distinguish them from other related variables in the linear model that is discussed in the next section.

Linearization

To take the advantages of a well developed linear control theory, a linear model is extracted from nonlinear model by linearization about a preselected operating point either in high wind speed region or in partial load region. As noted in [JB05], linearization is realized in two steps. First, a steady state solution of operating point of enabled DOFs is calculated. Second, numerical linearization about the resulting steady state is performed to form periodic matrices of a linear model. The arising periodicity is due to deterministic loads that interact with wind turbine during operation. In this thesis, a periodic model at 24 equally spaced rotor azimuth steps is generated. A linearized periodic state space model of wind turbine is given by

$$\dot{x}_m = A_m(\psi)x_m + B_m(\psi)u_m + B_{d_m}(\psi)u_{d_m}, \tag{3.2a}$$

$$y_m = C_m(\psi)x_m + D_m(\psi)u_m + D_{d_m}(\psi)u_{d_m}, \tag{3.2b}$$

where $A_m(\psi)$, $B_m(\psi)$, $C_m(\psi)$, $D_m(\psi)$, $B_{d_m}(\psi)$, and $D_{d_m}(\psi)$ refer to rotor azimuth position dependent matrices representing the linear wind turbine model. The state vector is given by $x_m = [\Delta\underline{q}\ \Delta\dot{\underline{q}}]^T$, $u_m = [\Delta\beta_1, \Delta\beta_2, \Delta\beta_3]$ represents the perturbed input vector of independent pitch angles, u_{d_m} is the perturbed hub-height wind speed, and $y_m = [\Delta\zeta_1, \Delta\zeta_2, \Delta\zeta_3]$ denotes the measured output vector containing flapwise root bending moment for each blade. Here, the subscript $_m$ denotes that the model is expressed in mixed reference coordinates, i.e., rotating and fixed reference coordinates. For instance, all dynamics of wind turbine rotor blades are expressed with respect to rotating reference coordinate while dynamics in nacelle and tower are expressed with respect to a fixed reference coordinate. As such the state, control input, and output vectors of Eqn. (3.12) contain entities that are either defined with respect to a fixed or rotating reference coordinate, hence the word mixed reference coordinate system. It is worth noting that the state vector and control input signal are also perturbed variables about their respective operating points and that the resulting linear model is only valid in the vicinity of a steady state operation point about which linearization is carried out. To obtain the periodic linear model (3.2), rotor speed, pitch angle, and constant wind speed are used to define the operation point about which the nonlinear model is obtained.

Multi-blade coordinate transformation (MBC)

During wind power generation, wind turbines are subjected to a complex inflow conditions which have time varying characteristics leading to imbalance loading across the rotor disc. As pointed out earlier, the loading conditions may be stochastic or deterministic in nature. In the context of large wind turbines, the interplay of structural loads is more complex compared to small-sized wind turbines due to the fact that large wind turbines are inherently flexible leading to the possibility of induced vibrations and resonance. As noted in [SB03], the periodicity in wind turbines is caused by unbalanced loads across the turbine rotor due to variation in wind speed, vertical wind shear, tower shadow/reflection, and yaw misalignment among other factors but vertical wind shear and yaw misalignment are the most prominent causes. As shown in Fig. 3.2, it is clear that both wind shear and yaw misalignment errors have great influence on structural loads in wind turbines. To demonstrate the effects of wind vertical shear on rotor blade flapwise bending moments, a constant wind speed is used with vertical wind shear power exponent being change to 0.2 at 30 seconds and then to 0.4 at 80 seconds. As a consequence, the bending moments increases by approximately 35%. On the other hand, when 5% yaw error at 50 seconds is introduced, an increased nacelle yaw bending moment is observed. It is important to note that the unbalanced forces across rotor disc become more pronounced as both wind speed and turbine size increases. Wind shear can either be vertical (increase of wind velocity and/or direction with height) or horizontal (change of horizontal wind velocity and/or direction with horizontal distance).

Figure 3.3 shows the variation of wind field in an upwind horizontal-axis wind turbine due to the effects of vertical wind shear and tower shadow. Since each blade is directly in front of the tower just once per one complete rotor revolution, tower shadow induces 3p, 6p, etc harmonic loads on the fixed structure of wind turbine. On the other hand, a 3-bladed horizontal-axis turbine experiences a 1p harmonic loads on each blade and 3p, 6p, etc harmonic loads on the fixed structure as a result

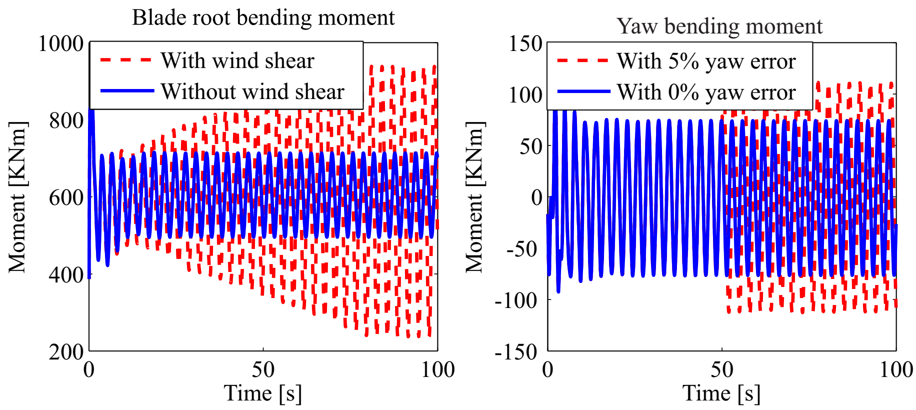
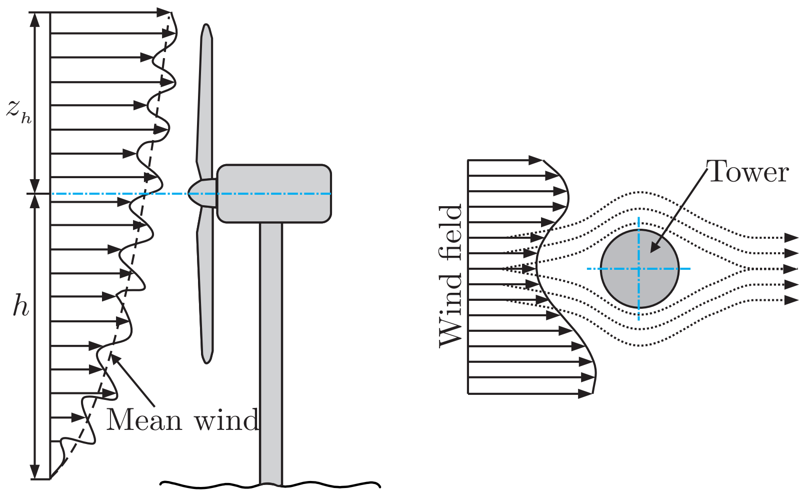


Figure 3.2: Effects of wind shear and yaw error on the structural loads



(a) Vertical wind shear (b) Tower shadow

Figure 3.3: Effects of vertical wind shear and tower shadow on wind speed variation [NS15]

of vertical wind shear. The vertical variation of wind speed $v(z)$ with altitude can be modeled as

$$v(z) = v_h(1 + \frac{z_h}{h})^m, \tag{3.3}$$

where v_h is hub height speed, h denotes hub height, z_h is vertical distance from hub center, and m represents vertical wind shear exponent power law. Apart from individual turbine tower shadow effect, buildings and other wind turbines in the upstream can cause comparable shadowing effect leading to low power production of the turbines located in downstream. From the foregoing discussion, it is evident that a linear wind turbine model evaluated about a given operation point is inherently periodic. If a periodic model is azimuth averaged about the operating point the resulting linear time invariant (LTI) model looses dynamics related to periodicity and such a model is not suitable for a multi-objective control design. To account for the periodicity during controller design, a multi-blade coordinate (MBC) transformation [Bir10] is used to covert the dynamics related to the rotating reference coordinate (individual blade dynamics) to a non-rotating reference coordinate and vice versa. In essence, the transformation provides a unifying stand point for controller design where all the DOFs are expressed with respect to the same reference coordinate. According to MBC transformation, a three-bladed wind turbine with q_i enabled DOFs is defined by

$$\left.\begin{array}{c} q_i = q_o + q_c \cos\left(\psi + \frac{2\pi}{3}(i-1)\right) + q_s \sin\left(\psi + \frac{2\pi}{3}(i-1)\right) \\ i = 1,2,3 \end{array}\right\}, \tag{3.4}$$

where q_o is related to the conic mode, while q_c and q_s refer to the cosine-cyclic and sine-cyclic modes, respectively. Utilizing (3.4), the dynamic model (3.2) can be transformed to a periodic model expressed with reference to the fixed reference coordinate system as

$$\dot{x}_{NR} = A_{NR}(\psi)x_{NR} + B_{NR}(\psi)u_{NR} + B_{dNR}(\psi)u_{d_m}, \tag{3.5a}$$
$$y_{NR} = C_{NR}(\psi)x_{NR} + D_{NR}(\psi)u_{NR} + D_{dNR}(\psi)u_{d_m}. \tag{3.5b}$$

Here, the subscript $_{NR}$ signifies that the model is referenced with respect to non-rotating (fixed) coordinate. The state x_m, control out u_m, and output measurement vectors y_m in Eqn. (3.12) are transformed to the fixed reference coordinate system using $x_m = T_s(\psi)x_{NR}(t)$, $u_m = T_c(\psi)u_{NR}$, and $y_m = T_o(\psi)y_{NR}$, respectively. The controller output signal is converted back to mixed reference coordinate system using the transformation

$$T_c(\psi) = \begin{bmatrix} 1 & \cos(\psi) & \sin(\psi) \\ 1 & \cos\left(\psi + \frac{2\pi}{3}\right) & \sin\left(\psi + \frac{2\pi}{3}\right) \\ 1 & \cos\left(\psi + \frac{4\pi}{3}\right) & \sin\left(\psi + \frac{4\pi}{3}\right) \end{bmatrix}. \tag{3.6}$$

Other transformations related to model matrices, state variables, and output measurement variables can be found in [Bir08]. It is important to emphasize that the perturbed disturbance input u_{d_m} is not transformed because it is already expressed with respect to the fixed reference coordinate. As noted in [SMBN09], the periodic model (3.5) is weakly periodic and can be averaged over the rotor rotational period without losing important dynamics related to periodicity. The resulting approximation of LTI model expressed as

$$\dot{x}_n = A_n x_n + B_n u_n + B_{d_n} u_{d_n}, \tag{3.7a}$$
$$y_n = C_n x_n + D_n u_n + D_{d_n} u_{d_n}, \tag{3.7b}$$

where the subscript n denotes the nominal LTI wind turbine model.

3.3 Turbine pitch actuator dynamics

Since each blade in wind turbine experiences different aerodynamic loads at different azimuth positions and different rotational speeds, modern turbines are equipped with actuators to manipulate each blade independently. The blade pitch actuators can be hydraulic, electromechanical, or a hybrid of the both hydraulic and electromechanical. The hydraulic actuators have high power density and are durable, although they suffer fluid leakage problem. On the other hand, electromechanical actuators are compact, reliable, and consume less power since they don't require

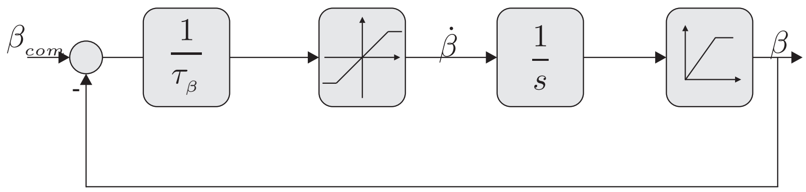


Figure 3.4: Pitch actuator model

pump. In some utility-scale wind turbines, a hybrid actuators are used to take advantages of both the hydraulic and electromechanical actuators.

As pointed out in [JB05], FAST model does not have integrated pitch actuator dynamics; hence, it is possible to get dynamic responses that do not reflect those of a real wind turbine. Since the dynamics of pitch actuators are fast compared to those of other mechanical subsystems of wind turbine, they can be conveniently represented by a first order linear model relating commanded pitch angle to the actual manipulated pitch input angle. To account for pitch actuation dynamics, actuator is modeled as a first order system as

$$\frac{\beta}{\beta_{com}} = \frac{1}{s\tau_\beta + 1}, \tag{3.8}$$

as suggested in [WF08], where β_{com} represents the commanded pitch angle, β denotes the actual pitch angle that manipulates the rotor blade, and τ_β represents the time constant. As depicted in Fig. 3.4, the actual pitch angle is maintained within a desired limits by constraining both the magnitude and the rate.

In individual blade control scheme, each blade pitch actuator is represented by first order model (3.8) which can be represented in state space model as

$$\begin{bmatrix} \dot{\beta}_1 \\ \dot{\beta}_2 \\ \dot{\beta}_3 \end{bmatrix} = \begin{bmatrix} -\frac{1}{\tau_{\beta 1}} & 0 & 0 \\ 0 & -\frac{1}{\tau_{\beta 2}} & 0 \\ 0 & 0 & -\frac{1}{\tau_{\beta 3}} \end{bmatrix} \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix} + \begin{bmatrix} \frac{1}{\tau_{\beta 1}} & 0 & 0 \\ 0 & \frac{1}{\tau_{\beta 2}} & 0 \\ 0 & 0 & \frac{1}{\tau_{\beta 3}} \end{bmatrix} \begin{bmatrix} \beta_{com1} \\ \beta_{com2} \\ \beta_{com3} \end{bmatrix} \tag{3.9}$$

Equation (3.9) can be represented in a generalized state space form as

$$\begin{aligned} \dot{x}_a &= A_a x_a + B_a u_a, && (3.10a) \\ \dot{y}_a &= C_a x_a, && (3.10b) \end{aligned}$$

where $x_a = [\Delta\beta_1 \, \Delta\beta_2 \, \Delta\beta_3]^T$, $u_a = [\Delta\beta_{com1} \, \Delta\beta_{com2} \, \Delta\beta_{com3}]^T$, and $y_a = x_a$. As outlined in [WFS05], the nominal wind turbine model (3.7) can be augmented with pitch actuator to account for pitching actuator dynamics in the FAST model. Here, it is assumed that the control input signal does not directly influence the measured output; hence, the elements of D and D_d matrices are taken as zeros. Therefore, the extended model which includes the pitch actuator dynamic is given by

$$\begin{bmatrix} \dot{x}_n \\ \dot{x}_a \end{bmatrix} = \begin{bmatrix} A_n & B_n C_a \\ 0 & A_a \end{bmatrix} \begin{bmatrix} x_n \\ x_a \end{bmatrix} + \begin{bmatrix} 0 \\ B_a \end{bmatrix} u + \begin{bmatrix} B_{dn} \\ 0 \end{bmatrix} u_d \tag{3.11a}$$

$$\begin{bmatrix} y_n \\ y_a \end{bmatrix} = \begin{bmatrix} C_n & 0 \\ 0 & C_a \end{bmatrix} \begin{bmatrix} x_n \\ x_a \end{bmatrix}. \tag{3.11b}$$

In this thesis, an LTI model represented by Eqn. (3.11) is used to design an individual blade pitch control scheme. For convenient, this model can further be presented in a compact form as

$$\dot{x} = Ax + Bu + B_d u_d \tag{3.12a}$$

$$y = Cx. \tag{3.12b}$$

Though this model is LTI, it weakly captures periodic dynamics of wind turbine due to the application of MBC transformation. To actuate individual rotor blade, control input signal u is transformed back to the mixed reference coordinate system by MBC transformation. It is important to emphasize that although a linear model is used to design controllers, the simulations are carried out using a nonlinear model which contain more degrees of freedom than those used to design the controller.

3.4 Summary

To effectively control a wind turbine, a reliable model that captures all relevant dynamics is a prerequisite. To come up with a comprehensive model that effectively captures all the dynamics of wind turbine is normally a challenge task. Like many other application fields, modeling wind turbine is normally challenging due to inherent nonlinearities and highly coupled dynamics among different subsystems. As such the resulting model is prone to modeling errors and uncertainties due to assumptions made during modeling stage. Notwithstanding the fact that considerable efforts have been made to come up with robust control method to compensate for modeling errors and uncertainties, several high fidelity wind turbine models have been developed. The existing wind turbine models are based on assumed mode, finite element analysis, or multi-body dynamics analysis. The assumed mode-based models are normally preferred in control design since they are computationally inexpensive and possibility to extract control oriented models.

In this thesis, FAST code is used to extract linear model for control design. The nonlinear model is linearized about given operation point to come up with linear models that are rotor azimuth position dependent (periodic model). To account for periodicity in control design process, MBC transformation is used to come up with an approximated LTI model that is weakly periodic; hence, integrating dynamics of rotating rotor into the resulting controller.

To carry out dynamic simulation in FAST, a full field stochastic wind profile generated by TurbSim code is used. This code generates wind profiles with different turbulence intensities and different wind shear effects. Generated wind fields have similar characteristic as real wind field since the site meteorological boundary conditions are considered during simulation process. In wind turbine applications, it is important to have knowledge of how the turbines' components degrade with time during power generation. This kind of information can be obtained by doing fatigue load evaluation to determine lifetime and rate of degradation for a given loading conditions. In this study, Mlife is used as a post process algorithm to extract fatigue related information from the loading output from FAST. Additionally, fatigue damage evaluation algorithm based on online rainflow counting is developed to implement a control strategy based on the health condition of wind component is discussed in chapter 6

4 Multi-Objective Control for High Wind Speed Region

A multi-objective control strategy for structural load reduction and power/speed regulation in Mega-scale wind turbines is discussed in this chapter. Since the structural loads are more prevalent during strong winds, the proposed control strategy is designed for region III (above the rated speed) region. The control approach aims at optimizing the trade-off between structural load reduction and power/speed regulation because they are two competing objectives. In essence, the lifetime of wind turbine is extended, albeit at a cost of slightly compromising the objective of power/speed regulation. The concept and the results discussed in this chapter have already been published as scientific papers [NLS14, NS15, NLS15].

4.1 Introduction

As the size of wind turbine increases, the structural loads become more conspicuous due to the influence of gravitational force and increased weight. Likewise, the flexibility of wind turbine increases with size leading to challenges caused by induced vibrations and resonance. As a matter of fact, all large wind turbines are inherently flexible and always experience unbalance aerodynamic load across the rotor disc. Therefore, it is important to develop advanced control strategies that minimize the structural loads while at the same time realize the mainstream objectives of regulating power/speed and maximizing power extraction in wind turbines. The objectives of regulating speed/power and rotor blade structural load reduction conflict each other; therefore, a compromise has to be made to realize the two objectives.

To realize the two competing objectives of controlling speed/power and structural load minimization, two control loops are employed in this thesis. The first loop, collective pitch controller (CPC), is designed to regulate rotor rotation speed by reducing aerodynamic power coefficient in high speed regime to maintain the rotor rotational speed around its rated value. Then, an observer-based multi-input multi-output (MIMO) controller is used in the second control loop to fulfill the objective of load reduction in rotor blades by perturbing individual angles around the nominal CPC control signal. The performance of the proposed control algorithm is evaluated against a standard baseline Proportional-Integral controller (PI-Controller) for speed regulation. The results demonstrate that the proposed control strategy is able to realize the objective of reducing structural load without much sacrifice on the speed regulation objective.

Recently, a number of control algorithms have been proposed to realize the above mentioned objectives of minimizing the structural load and power regulation. A control algorithm for reducing loads caused by rotor asymmetries is proposed in [PJB15].

Here, a set of parallel individual pitch controllers (IPC) are used to mitigate both the lower and higher harmonics loads. This control scheme is based on d-q transformation whereby respective cosine- and sine-cyclic modes are tuned using independent PI-control loops. In [NLS15], similar objectives were realized using Kalman filter-based individual blade pitch controller. Unlike the strategy proposed in this chapter, damping of tower fore-aft deflections and compensation of wind speed variation were not considered. Other related contributions [XXZ+08, XX11, Bos03] in which once per revolution (1p) loads on rotor blades are mitigated have been reported in the literature. Similarly, contributions regarding speed regulation have been documented in [RJ14, AF13]. In most cases researchers only concentrate on a particular objective without considering its converse effects on other important objectives that determine the overall operational goals of the wind turbine.

In this chapter a multi-objective control algorithm that can regulate power/speed and minimize the structural loads at the same time during high wind speed is proposed. More specifically, an individual blade pitch controller (IPC) is designed to reduce flapwise rotor blade bending moments. A collective pitch controller which is mandated to regulate speed and minimize tower fore-aft deflection is fused with IPC to achieve the multi-objective task of power regulation and load mitigation. Mlife simulation code [HBJ12] developed by National Renewable Energy Laboratory (NREL) is used to calculate fatigue damage equivalent loads (DEL) for rotor blades, drivetrain, and tower.

In this chapter, an observer-based MIMO controller is discussed. The design steps of a stochastic PI-Observer [Sor89] for states and unknown disturbance inputs to wind turbine is discussed in details as an example to other system state estimation methods used in [NLS15, NS15]. The stochastic PI-Observer has similar structure as classical PI-Observer described in [SYM95]. In fact, according to [BSL99], the two observers are equivalent if it is assumed that the plant is affected by exogenous stochastic process and measurement noises with known statistical properties.

4.2 Standard control proportional integral (PI) for benchmarking

In this chapter, a gain scheduling PI-controller with anti-windup scheme as discussed in [WF08] is used for benchmarking the performance of the proposed multivariable control strategy for structural load reduction and power/speed regulation. In region 3, wind speed is higher than rated wind speed and wind turbine control task is to limit generator power around its rated value in this region. Variable blade pitch control applies rotor speed as feedback to adjust the blade pitch for power regulation. When wind speed is higher, blade pitch angle is used to mitigate the excessive aerodynamic load by minimizing power coefficient C_p, consequently keeping the output power around the rated value.

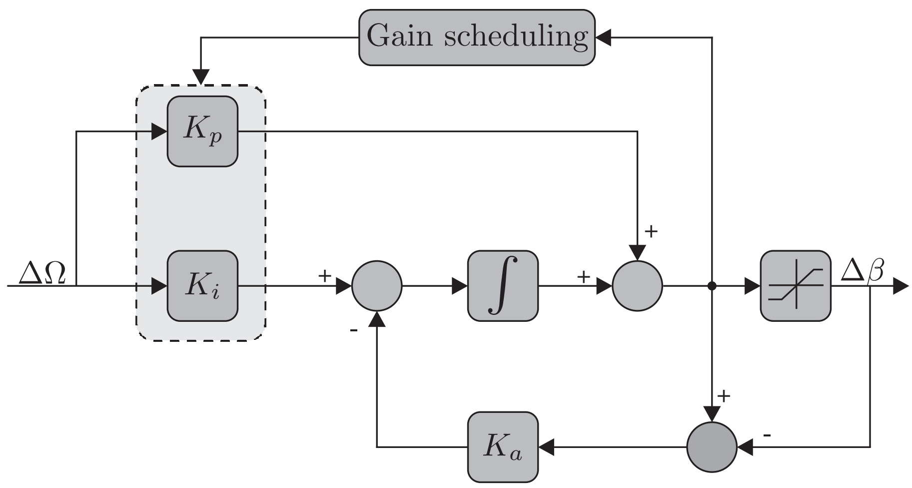


Figure 4.1: PI controller with gain scheduling and anti-windup

The Proportional-Integral-Derivative (PID) control is the most widely used control method in wind turbine industry where rotor rotational speed is used as the feedback signal to minimize the error between measured rotational speed and desired rotational speed. The operation principle and design steps of a PID control is simple and easy to understand, making it a preferred choice for many industrial applications. There are a set of methods to design and tune the parameter to achieve desired control performance of the closed-loop system. When the robustness against unknown disturbances and measurement noises is of utmost important and fast response of the system is not required, a PI controller is an appropriate method to realize control objectives.

During wind power production, a gust wind might cause a sudden negative speed error which leads to building up of a negative pitch angle contribution due to integration of negative speed error. If building up of negative speed error is not prevented, it might lead to system instability or even damage of wind turbine. To avoid such occurrence, anti-windup scheme is employed. In Fig. 4.1, a block diagram of a PI controller with anti-windup and gain scheduling scheme is illustrated. Provided that the actuator output is equal to the controller output signal, the anti-windup scheme is not activated and the PI controller acts normally. In the event of actuator saturation, the anti windup scheme is activated to prevent against windup by driving the integrator output to a value that make the controller output closer to the saturation value via anti-windup gain K_a. To synthesize a PI controller, a nonlinear dynamic model of the plant to be controlled is linearized about a given steady state operating point to extract linear model. The controllers designed from such linear models are only effective within the vicinity of the operating point. Due to modeling uncertainties and the effects of exogenous disturbances acting on the system, the operating point is likely to change leading to performance deterioration. To accommodate nonlinearities and model uncertainties in control loop, gain scheduling

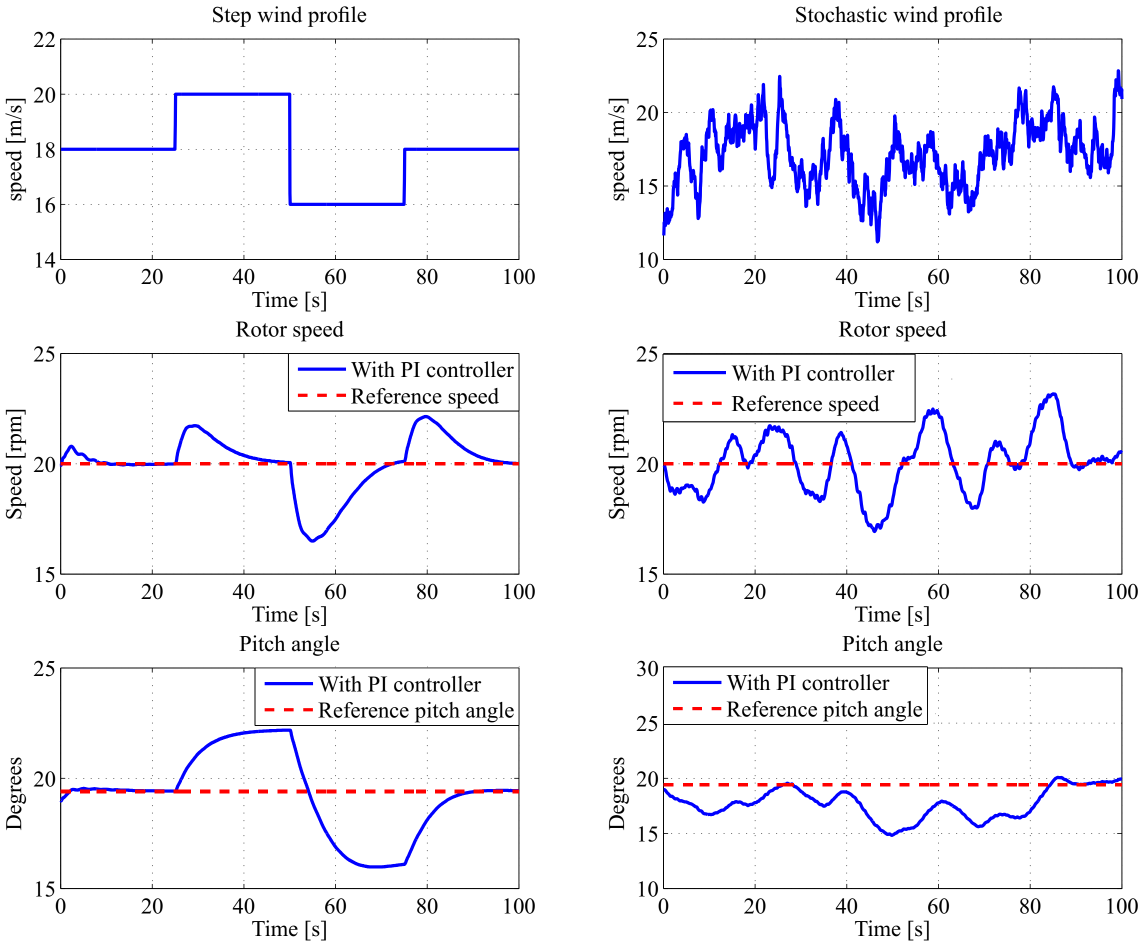


Figure 4.2: Response for a PI-controller to a step and stochastic wind profiles

method is used to compensate for the changes in operation point. Gain scheduling PI controller is expressed as

$$\beta_c(\theta) = K_p(\beta)\Omega_e + K_i(\beta)\int_0^t \Omega_e(\tau)d\tau, \tag{4.1}$$

where $\Omega_e = \Omega_d - \Omega$ denotes the rotor rotational speed error. The PI controller gains K_p and K_i are function of gain scheduling variable which in this case is nominal blade pitch angle β of the wind turbine. This controller is designed such that the desired performance characteristics are realized as well as stabilizing the wind turbine by assigning suitable gains. The PI controller is based on a SISO control structure where a single measurement (rotor speed) is used while a common pitch angle is utilized to actuate the rotor blade. One of the major drawbacks of this method is assumption that rotor blades have similar physical properties and they experience equal amount of aerodynamic loads during operation.

A linear dynamic model used to design a PI controller is extracted by linearizing a nonlinear FAST model at operating point defined by a rotor speed of 20 rpm, steady wind speed of 18 m/s, and pitch angle of 19.4°. For the purpose of regulating rotor rotational speed, only one DOF related to speed generator mode is enabled during linearization. In this chapter, a PI controller is designed to achieve a damping ratio of 0.6 and undamped natural frequency of 0.7 rad/s. A more detailed design procedure for a similar PI controller can be found in [WF08].

To illustrate the performance of the benchmark PI-controller used in this thesis, a step and a stochastic wind profiles are used to excite dynamics of wind turbine. As depicted in Fig. 4.2, a step wind profile with varying steps is used to demonstrate how fast the rotor speed tracks the rated value at which the linearization is carried out. At 25 second , wind speed is stepped up to 20 m/s, then at 50 second it is stepped down to 16 m/s, and finally it is stepped back to 18 m/s at 75 seconds. It is observed that the wind turbine rotates at the rated speed of 20 rpm when excited with a steady wind speed of 18 m/s. However, when the step wind disturbances are introduced transient effects, which decay with time, are observed at 25s, 50s, and 75s. The amount and direction of deviation of the rotor speed from the rated value depend on the profile of the exciting wind profile. The pitch angle is varied to compensate the effects of varying wind speed. A stochastic wind wind with a mean speed of 18 m/s is also used to excite wind turbine dynamics. Like in the case of step wind profile, the rotor rotation speed is maintained around the rated value of 20 rpm, with the deviations corresponding to the variation of incoming wind speed.

4.3 Multi-variable control strategy

As wind turbines are inherently multi-input multi-output (MIMO) systems, single-input single-output controllers like standard proportional-integral-derivative (PID) controller cannot fulfill all control requirements, especially in large wind turbines. To realize the multi-objective of regulating speed/power and structural load reduction, this thesis proposes an observer-based MIMO controller that is able to simultaneously accomplish these two contradicting objectives.

An example of a multiple objective control framework is illustrated in Fig. 4.3. Here, the antagonizing control requirements of regulating generator speed/power as well as structural load reduction can be realized. The two control loops are employed: The first loop is utilized for generator speed regulation by generating nominal demanded pitch angle, while the second loop is used for structural load mitigation. This approach is based on a linear wind turbine model in high wind speed regime. Different control design approaches can be used to realize these contradicting objectives. In this case, the control strategy should be such that the two control loops do not interfere with each other by limiting the size of perturbed output MIMO controller signals Δu_{IPC} in addition to tuning a MIMO controller such that it does not attempt to actively regulate generator speed. In this example, blade

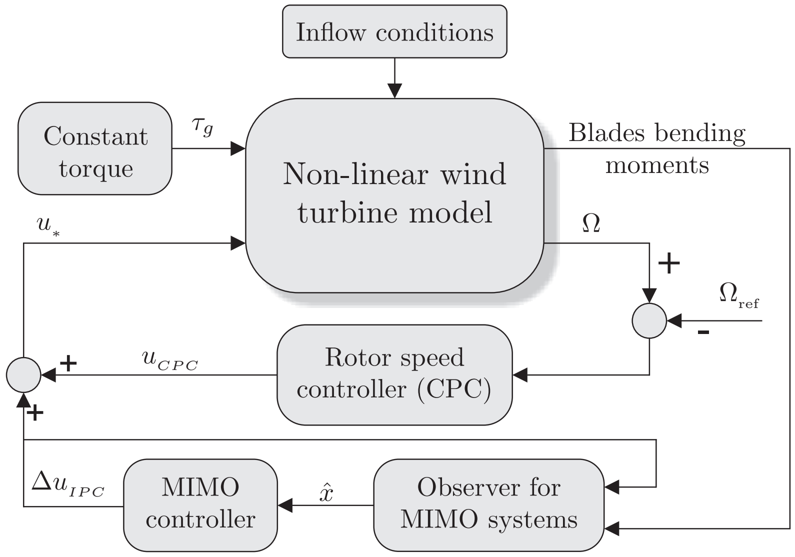


Figure 4.3: A generalized structure of observer-based individual blade pitch controller for structural load reduction [NS16]

flapwise bending moments measurement are used to reconstruct system states used to design an observer-based MIMO controller, although other measurements can also be used depending on which structural member is under investigation. The overall manipulated variable u_* is computed by adding perturbed individual control signals Δu_{IPC} to the nominal control signal u_{CPC}.

Apart from regulating rotor rotational speed, a collective pitch control loop can be utilized for actively reducing tower fore-aft deflections by using small perturbations around the nominal collective pitch angle, while the individual pitch control (IPC) loop is utilized for minimizing flapwise blade root bending moments. In this thesis, the electrical generator torque τ_g is held constant at rated value while blade pitch angles are actuated independently to regulate speed and reduce asymmetric load across the rotor disc. Since the system states are internally defined in aeroelastic FAST code and are not externally accessible, an appropriate observer can be used to reconstruct system states for a realizable full state feedback control design. To realize a multi-objective control strategy based on an individual blade pitch controller, rotor speed Ω and individual root bending moments $[\zeta_{d1}\ \zeta_{d2}\ \zeta_{d3}]^T$ are used as measurements to reconstruct system states and unknown disturbances in this chapter. With the estimated system states $\hat{x}$, a realizable full state multivariable feedback controller is designed to realize the objective of mitigating structural on rotor blades using perturbed individual blade pitch angle Δu_{IPC}. As mentioned, the multi-objective strategy is realized by perturbing nominal collective blade pitch control signal u_{CPC} using individual blade pitch control signal Δu_{IPC}. To generate appropriate control signals Δu_{IPC} and u_{CPC}, a number of control approaches have been proposed to realized a given closed loop performance in the sense of stability and robustness against changes of operating point due to variation of wind speed.

4.3.1 Control design approaches

In the literature, there are several control approaches that have been proposed, both for linear and nonlinear dynamic systems. In wind turbine applications, a control approach that guarantee stability and robustness against parameter variation due to model nonlinearities, uncertainties, and variation of wind speed is always desired. In this subsection, two most common control approaches based on linear model are highlighted. It is important to note that there are other control approaches that have been proposed in the literature to design observers and multivariable controllers. First, a $\mathcal{H}_\infty$ control approach that guarantees robustness against unknown wind speed variations is considered. Second, an optimal control approach that generate manipulated variable by minimizing a given performance index is briefly described. Here, states and control weighting matrices are used to balance state regulation and control energy usage. In this thesis, optimal linear quadratic method is used to design both the controller and observer.

$\mathcal{H}_\infty$ control

It is practically impossible to come up with a plant model that captures all dynamics of a real system; hence, dynamic model will always have uncertainties. It is therefore important to design controllers that guarantees robustness to the plant model uncertainties and external exogenous disturbances. A generalized feedback control system can be described by Fig. 4.4, where w denotes all exogenous input to the system which includes unknown disturbances, measurement noise, and reference signals, u represents control inputs, z is outputs or error signals, and y is the measured outputs.

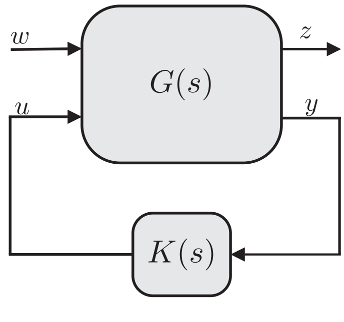


Figure 4.4: A generalized block for a feedback control system

The inputs and outputs of generalized feedback control system can also be related using the following expression

$$\begin{aligned} \begin{bmatrix} z \\ y \end{bmatrix} &= \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \begin{bmatrix} w \\ y \end{bmatrix}, \\ u &= Ky. \end{aligned} \tag{4.2}$$

The $\mathcal{H}_\infty$ control synthesis entails finding a suitable stabilizing controller $K(s)$ for the closed loop system such that $\mathcal{H}_\infty$ norm of the closed loop transfer function between the exogenous inputs w and the controller output z, normally referred to as linear fractional transformation (LFT), is minimized. It can easily be shown that LFT is given by

$$T_{zw} = F_l(G, K) = G_{11} + G_{12}K(I - G_{22}K)^{-1}G_{21}. \tag{4.3}$$

The $\mathcal{H}_\infty$ norm can be defined as the maximum of the largest singular value of the transfer function between exogenous inputs and the controlled outputs z. i.e.,

$$||F_l(G, K)||_\infty = \max_{0 \leq \omega < \infty} \overline{\sigma}(F_l(G, K)(jw)). \tag{4.4}$$

In terms of performance evaluation, minimization of $||.||_\infty$ norm on $F_l(G, K)$ can be interpreted as a reduction of the worst case gain on the controlled output as a result of unknown disturbance inputs. To find an optimal controller which minimize $||F_l(G, K)||_\infty$ might be computationally expensive and tedious. Normally, a suboptimal controller that is closer to the optimal one is used such that for a $\gamma > 0$ a suitable controller is designed so that $||F_l(G, K)||_\infty < \gamma$. As noted in [DG89], γ can be iteratively reduced to realize a solution that is very close to the optimal one.

Linear quadratic regulator (LQR) control

This control method is applied to linear systems, either linear time invariant or time varying system, to design an optimal control input that minimizes a quadratic performance index. For a given linear system, a stabilizing full state controller $u = -Kx$ that minimizes the following quadratic cost function

$$J_{LQR} = \int_0^\infty (x^T Q x + u^T R u) dt, \tag{4.5}$$

subject to the dynamic constraint expressed by

$$\dot{x} = Ax + Bu, \quad x(0) = x_0, \tag{4.6}$$

is evaluated. Here, $Q = Q^T \geqslant 0$ and $R = R^T > 0$ are the states and control input weighing matrices used to penalize the states and control efforts, respectively. The

R matrix is required to be strictly positive definite since its inverse is required to compute the optimal control gain. Normally, a Algebraic Riccati Equation (ARE) is used to evaluate the optimal feedback gain. The optimal solution converges if and only if (A, B) is stabilizable. Therefore the closed loop cost function is expressed as

$$J_{_{LQR}} = \int_0^\infty x^T(Q + K^T RK)xdt. \tag{4.7}$$

The resulting closed loop dynamic system $\dot{x} = (A - BK)x,\ \ x(0) = x_0$ is always asymptotically stable for a given stabilizing optimal gain K. In this thesis, linear quadratic method is utilized to design optimal multi-objective controller and observer.

4.3.2 States and disturbance observer design

To design a full state feedback, all the state variables must be available for the feedback. Often, not all state variable are measurable in the real life application; hence, it desirable to use a few measurements to estimate all states to design a realizable feedback controller. It is also cost effective to use just a few measurements to estimate the states especially for a complex systems that have many state variables. In wind turbine applications, variation of wind speed from its mean reference speed and variation of wind speed with increase in altitude are regarded as disturbances. If these disturbances are not considered during control design, it may lead to performance degradation of the closed loop system. Therefore, it is important to design observers that can effectively estimate both the system states and unknown disturbances into the system. In the literature, a number of observers that can reconstruct both the states and disturbances have been proposed. In this thesis, the state estimation methods discussed in [NLS14,NLS15,NS15] are briefly re-examined. A classical PI-Observer is used to reconstruct system states and variation of hub-height wind speed as unknown disturbance to regulate the rotor rotational speed [NLS14]. The PI-Observer is an extension of the Luenberger observer, with proportional and integral feedback loops for reconstruction of unknown disturbances, system states, unmodeled dynamics, and uncertainties. As noted in [SYM95], the use of high gain in PI-Observer can improve its performance. However, the presence of measurement noise can lead to performance degradation since measurement noise are amplified by the proportional gain. When the sensor and actuator noises are present, the classical PI-Observer does not effectively estimate the system state and decouple unknown disturbances. To avoid poor performance due to change of operating point, an advance PI-Observer with adaptive gain is proposed in [LS12]. Additionally, PI-Observer are used to detect and isolate faults in both sensors and actuators such that the system is robust in the sense of fault tolerance [EOP15]. A Kalman state estimator is discussed in [NLS15], where the system states are reconstructed using measurement signals containing noise. Here, the system is assumed to be influenced by noises that are Gaussian such that the Kalman filter minimizes the square error of the system states. However, when Kalman estimator and feedback state regulator are used in a closed loop system result to poor stability margin. To improve stability margin, loop transfer recovery (LTR) is used. On the contrary, the use of PI-Observer can lead to improved stability margin. In [NS15], a stochastic PI-observer which is combines the concept of classical PI-Observer and Kalman filter is discussed to reconstruct system states and disturbances using measurements that have Gaussian noise. In this thesis, the design procedure of a stochastic PI-Observer is discussed in details since it has advantages of both Kalman estimator and PI-Observer.

Stochastic PI-Observer

A stochastic PI-Observer is used to estimate unknown variation of incoming wind and the plant states. As illustrated in Fig. 4.5, its structure is almost similar to that of classical PI-Observer [SYM95] only that the plant is influenced by stochastic process noise in additional to measurement noise. The stochastic PI-Observer gains are computed so as to minimize the state estimation covariance error in spite of the presence of both process and measurement noises. Commonly, PI-Observer can estimate nonlinearity, unmodeled dynamics, and unknown inputs. As demonstrated in [BSL99], stochastic PI-Observer is equivalent to augmented Kalman filter (AKF) when unknown disturbances have known statistical properties. The idea of eliminating unknown disturbances is based on the well known Disturbance Accommodating Control (DAC) theory [Joh76] which was proposed by Johnson in 1974.

In this thesis, a PI-Observer for a plant with stochastic noise [Sor89] is used to estimate the system states of the wind turbine and the variation of wind speed as disturbance. Unlike classical PI-Observer, it has additional disturbance which has stochastic characteristics. The wind turbine model used for controller design is given by

$$\dot{x} = Ax + Bu + B_d u_d + B_{dn} u_n, \tag{4.8a}$$

$$y = Cx + v_n. \tag{4.8b}$$

It is assumed to be influenced by the unknown stochastic system and measurement noise. Here, the plant is excited by two unknown disturbance components: waveform disturbance u_d and stochastic component u_n.

Dynamic model of unknown disturbance is also assumed to be influenced by stochastic noise and is expressed as

$$\dot{z}_d = F z_d + \vartheta \epsilon_d, \tag{4.9a}$$

$$u_d = H z_d, \tag{4.9b}$$

where ε_d, u_n, and v_n are assumed to be stochastic with given properties. They are usually presumed to be uncorrelated, zero mean Gaussian noises, i.e., $E[u_n(t)] = E[\epsilon_d(t)] = E[v_n(t)] = 0$, $E[u_n(t)u_n^T(\tau)] = Q_{dn}\delta(t-\tau)$, $E[\epsilon_d(t)\epsilon_d^T(\tau)] = \xi\delta(t-\tau)$, and $E[v_n(t)v_n^T(\tau)] = \eta_d\delta(t-\tau)$. The variable z_d is used to express disturbance states, while F, ϑ, and H are matrices of appropriate dimensions expressing the dynamics of disturbance.
Augmenting the nominal plant (4.8) with disturbance dynamic model (4.9), the following extended model is obtained

$$\begin{bmatrix} \dot{x} \\ \dot{z}_d \end{bmatrix} = \underbrace{\begin{bmatrix} A & B_d H \\ 0 & F \end{bmatrix}}_{A_e} \begin{bmatrix} x \\ z_d \end{bmatrix} + \underbrace{\begin{bmatrix} B \\ 0 \end{bmatrix}}_{B_e} u + \underbrace{\begin{bmatrix} B_{dn} & 0 \\ 0 & \vartheta \end{bmatrix}}_{B_{en}} \begin{bmatrix} u_n \\ \epsilon_d \end{bmatrix}, \tag{4.10a}$$

$$y = \underbrace{\begin{bmatrix} C & 0 \end{bmatrix}}_{C_e} \begin{bmatrix} x \\ z_d \end{bmatrix} + \underbrace{\begin{bmatrix} v_n \\ 0 \end{bmatrix}}_{v_e}. \tag{4.10b}$$

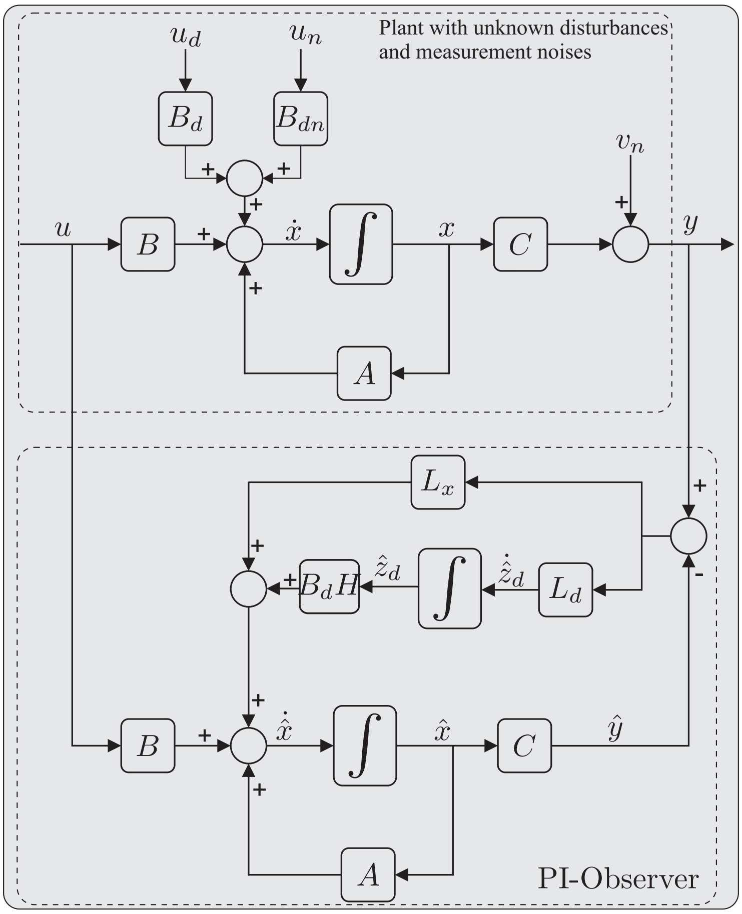


Figure 4.5: Structure of PI-Observer for a linear system with stochastic noises [NS15]

The resulting extended dynamic model has the same structure as an ordinary Kalman filter which optimally estimates the plant state in spite of the presence of process and measurement noises. Similarly, stochastic PI-Observer estimates both the system and disturbance states in optimal sense by minimizing the following states and disturbance covariances

$$E(\{x-\hat{x}\}\{x-\hat{x}\}^T),\ E(\{z_d-\hat{z}_d\}\{z_d-\hat{z}_d\}^T). \tag{4.11}$$

The observer dynamic equation of the resulting augmented plant model is given by

$$\begin{bmatrix} \dot{\hat{x}} \\ \dot{\hat{z}}_d \end{bmatrix} = \underbrace{\begin{bmatrix} A & B_dH \\ 0 & F \end{bmatrix}}_{A_e} \begin{bmatrix} \hat{x} \\ \hat{z}_d \end{bmatrix} + \underbrace{\begin{bmatrix} B \\ 0 \end{bmatrix}}_{B_e} u + \underbrace{\begin{bmatrix} L_x \\ L_d \end{bmatrix}}_{L_e} (y-\hat{y}), \tag{4.12a}$$

$$\hat{y} = \underbrace{\begin{bmatrix} C & 0 \end{bmatrix}}_{C_e} \begin{bmatrix} \hat{x} \\ \hat{z}_d \end{bmatrix}, \tag{4.12b}$$

where $L_e = P_e C_e^T R_e^{-1}$ can be calculated using the Algebraic Riccati Equation (ARE)

$$P_e A_e + A_e^T P_e - P_e C_e^T R_e^{-1} C_e P_e + Q_e = 0, \tag{4.13}$$

where $P_e = P_e^T > 0$ is a positive definite matrix. Here, Q_e and R_e are symmetric positive definite matrices defined as

$$Q_e = Q_e^T = \begin{bmatrix} Q_{dn} & 0 \\ 0 & \xi \end{bmatrix} \text{ and } R_e = R_e^T = \begin{bmatrix} \eta_d & 0 \\ 0 & \gamma_d \end{bmatrix}. \tag{4.14}$$

It is worth noting that the solution of (4.13) is possible if the plant model is fully observable. ie.,

$$\text{rank}\left\{\begin{bmatrix} I\lambda_i - A_e \\ C_e \end{bmatrix}\right\} = \dim(x) + \dim(z_d), \tag{4.15}$$

where λ_i denotes the eigenvalues of the augmented system matrix A_e. After the states variable and unknown disturbance estimation, the next task is to design an appropriate state feedback controller in combination with disturbance compensation approach.

4.3.3 Individual pitch control design and disturbance compensation

To realize a multi-objective goal of rotor blade load mitigation a speed/power regulation, a MIMO full state feedback controller

$$u = -\begin{bmatrix} K_x & K_d \end{bmatrix} \begin{bmatrix} x \\ z_d \end{bmatrix}, \tag{4.16}$$

is designed. Here, x and z_d are system and disturbance states, respectively. The control approach is designed regulate the system states as well as compensating for unknown disturbances and nonlinearities. More specifically, $-K_x x$ is used to improve state response with respect to given inputs, while $-K_d z_d$ is utilized in mitigation of asymmetric structural load imbalance across the rotor disc due to variation of wind speed among other factors. As stated earlier, not all states are available for measurement; besides, the information about the variation of incoming wind is completely unknown. Hence, it is important to design an observer that can estimate both the system states and unknown disturbances. Consequently, a realizable full state controller is used, where the real system and disturbance states are replaced by estimated states as

$$u = -\begin{bmatrix} K_x & K_d \end{bmatrix} \begin{bmatrix} \hat{x} \\ \hat{z}_d \end{bmatrix}. \tag{4.17}$$

The task is to design appropriate controller gains $\begin{bmatrix} K_x & K_d \end{bmatrix}$ that could stabilize the closed loop system as well as attaining the the desired performance requirements.

4.3.4 Disturbance rejection methods

As noted before, wind turbine is highly nonlinear, exhibiting tightly coupled dynamic behaviors. To control wind turbines using linear control methods, a nonlinear model is normally linearized about a given operating point to extract linear model. Then the linear controllers designed from such models are only effective within the environs of this operating point. For wind turbine application a constant wind speed is used as one of the variables to define the operating point about which the linearization is carried out. On the other hand during the operation, wind turbines are subjected to spatially varying wind profile which might lead to degradation of control system. To circumvent this challenge, a number of disturbance rejection have been proposed to guarantee the stability and robust dynamic performance for a given system [Joh76, SYM95, Dav72]. In this subsection various disturbance rejection approaches (both static and dynamic) are briefly discussed with respect to wind turbine control. In the literature static disturbance accommodation approach is widely reported in wind turbine applications [Joh76, SRB00, NS09, SB03]. Neglecting the stochastic disturbance type, the control input (4.16) can be applied to the nominal wind turbine model resulting to

$$\dot{x} = (A + BK_x)x + (BK_d + B_d H). \tag{4.18}$$

For static disturbance compensation approach, the effects of persistence disturbance can only be cancel if and only if

$$BK_d + B_d H = 0. \tag{4.19}$$

With this approach, it is practically impossible effectively cancel disturbance effects, unless the disturbances enter the system through the same channel as the the input control signal [BLK98]. As such, the effects of persistent disturbance can only be minimized by designing appropriate K_d so as to minimize the following norm

$$||BK_d + B_dH||. \tag{4.20}$$

In the literature, static disturbance gain is approximated as $K_d = -B^+ B_d H$, where B^+ is evaluated using Moore-Penrose pseudoinverse, $B^+ = (B^T B)^{-1} B^T$.

To address the shortcomings of static disturbance compensation approach, dynamic disturbance compensation approaches have been proposed: Davison approach [Dav72] and extended dynamic disturbance rejection method proposed by Söffker [SYM95]. In Davison approach exogenous disturbances are modeled as

$$\begin{aligned} \dot{z}_d &= S z_d + B_\varrho \varrho_p, && (4.21a)\\ \varrho_p &= y_p - w_p, && (4.21b) \end{aligned}$$

where, S denotes the disturbance model system matrix, while y_p and w_p represents vectors of appropriate dimensions. Substituting Eqn. 4.21 into nominal wind turbine model, the resulting extended system is given by

$$\begin{bmatrix} \dot{x} \\ \dot{z}_d \end{bmatrix} = \begin{bmatrix} A & 0 \\ B_\varrho C_p & S \end{bmatrix} \begin{bmatrix} x \\ z_d \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u + \begin{bmatrix} B_d \\ 0 \end{bmatrix} u_d + \begin{bmatrix} 0 \\ -B_\varrho \end{bmatrix} w_p. \tag{4.22}$$

For this approach to adequately accommodate for the unknown disturbances while stabilizing the given system, the pairs (A, B) and (S, B_ϱ) must be controllable. Additionally, the dynamic model of the disturbance S is assumed to be available and does not contain transmission zeros of the nominal plant. To evaluate feedback control gain, LQR or pole placement design method is used using the extended system model (4.22). Again, assuming that the controller gain is given as $K = -[\ K_x \quad K_d\ ]$, the closed loop system is expressed as

$$\begin{bmatrix} \dot{x} \\ \dot{z}_d \end{bmatrix} = \begin{bmatrix} A - BK_x & -Bk_d \\ B_\varrho C & S \end{bmatrix} \begin{bmatrix} x \\ z_d \end{bmatrix} + \begin{bmatrix} B_d \\ 0 \end{bmatrix} u_d + \begin{bmatrix} B_{dn} \\ 0 \end{bmatrix} u_n. \tag{4.23}$$

The extended dynamic disturbance compensation approach that was proposed by Söffker [SYM95] is an extension of [Dav72] method, where the disturbances to be compensated are modeled as

$$\dot{z}_d = F z_d + \delta_\epsilon x, \tag{4.24}$$

where δ_ϵ couples system states to unknown disturbances and is usually a matrix containing elements with very small values. Unlike the Davison approach, the extended approach uses all state to dynamically compensate for disturbances instead of using the output channel $\varrho_p = y_p - w_p$. By using the disturbance model (4.24), the augmented plant model can be expressed as

$$\begin{bmatrix} \dot{x}(t) \\ \dot{z}_d(t) \end{bmatrix} = \underbrace{\begin{bmatrix} A & B_d H \\ \delta_\epsilon & F \end{bmatrix}}_{A_{ec}} \begin{bmatrix} x(t) \\ z_d(t) \end{bmatrix} + \underbrace{\begin{bmatrix} B \\ 0 \end{bmatrix}}_{B_{ec}} u(t). \tag{4.25}$$

Here, it is assumed that A, B and F, δ_ϵ are controllable. From (4.25), the gain can be calculated using linear quadratic regulator LQR or pole placement method to get the desired dynamic response. In this thesis, LQR design approach is used to calculate control gain $K = [\ K_x \quad K_d\ ]^T = R_{ec}^{-1} B_{ec}^T P_{ec}$, where P_{ec} is evaluated by solving the following Algebraic Riccati Equation (ARE)

$$A_{ec}^T P_{ec} + P_{ec} A_{ec} + Q_{ec} - P_{ec} B_{ec} R_{ec}^{-1} B_{ec}^T P_{ec} = 0. \tag{4.26}$$

The state weighting matrix Q_{ec} and control action usage matrix R_{ec} has to be symmetric positive definite. The matrices Q_{ce} and R_{ec} are designed such that IPC controller does not counteract the generator speed regulation to avoid performance degradation. Substituting Eqn. 4.16 into nominal plat model, the controlled system can be expressed as

$$\begin{bmatrix} \dot{x} \\ \dot{z}_d \end{bmatrix} = \begin{bmatrix} A - BK_k & -K_d z_d \\ \delta_\epsilon & F \end{bmatrix} \begin{bmatrix} x \\ z_d \end{bmatrix} + \begin{bmatrix} B_d \\ 0 \end{bmatrix} u_d. \tag{4.27}$$

Assuming that both the system states and disturbance can be effectively estimated, the complete closed loop control system including the estimated states and disturbance is given by

$$\begin{aligned} \begin{bmatrix} \dot{x} \\ \dot{\hat{x}} \\ \dot{\hat{z}}_d \end{bmatrix} = \begin{bmatrix} A & -BK_x & -BK_d \\ L_x C & (A - BK_x - L_x C) & (B_d H - BK_d) \\ L_d C & 0 & F \end{bmatrix} \begin{bmatrix} x \\ \hat{x} \\ \hat{z}_d \end{bmatrix} + \\ \begin{bmatrix} B_d \\ 0 \\ 0 \end{bmatrix} u_d + \begin{bmatrix} B_{dn} \\ 0 \\ 0 \end{bmatrix} u_n. \end{aligned} \tag{4.28}$$

As noted in [SYM95], the matrix δ_ϵ can be chosen as $\delta_\epsilon = (NH)^T$ provided that all system states and related unknown disturbance dynamics can be effectively reconstructed. It is important to note that the extended disturbance rejection approach is adopted in this thesis to compensate for unknown wind speed variations.

4.3.5 Results and discussion

Before discussing the results presented in this chapter, it is important to examine the dynamic equations utilized to design the proposed multi-objective controller for speed/power regulation and structural load reduction. As noted in [JB05], the matrices of the linear dynamic model of wind turbine represented by Eqn. 4.8 can be expressed in the following general form

$$\begin{aligned} A &= \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ M^{-1}K \end{bmatrix}, \\ B_d &= \begin{bmatrix} 0 \\ -M^{-1}F_d \end{bmatrix}, \quad C = \begin{bmatrix} D_{sp}C & VelC \end{bmatrix}, \end{aligned} \tag{4.29}$$

where M denotes the mass matrix, C is the damping/gyroscopic matrix, K represents the stiffness matrix, F_d is the disturbance input matrix, while $DspC$ and $VelC$ are displacement and velocity output matrices, respectively. As noted before, the linearization of wind turbine model about a given operating point is carried out numerically using FAST aeroelastic simulation tool. After carrying the multi-blade coordinate transformation as discussed in chapter 3, the matrices representing the dynamic model given by (4.8) are expressed as follow

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ -6.83 & 0.00032 & 1.25 & 0.27 & -0.04 & -0.09 & 0.24 & 0.045 & 0.006 & -0.001 \\ -0.09 & 0.00031 & 0.42 & 0.01 & -0.005 & -0.002 & 0.03 & 0.02 & -0.002 & 0.0008 \\ 17.67 & -0.012 & -79.73 & -0.48 & 0.96 & -10.86 & -58.24 & -7.61 & 0.43 & -0.16 \\ 8.10 & 7.64 & -1.74 & -62.52 & -15.22 & -6.56 & 10.39 & 0.70 & -7.29 & -4.08 \\ -2.10 & -12.59 & 0.12 & 14.25 & -61.79 & 5.05 & -4.33 & -0.27 & 4.29 & -6.78 \end{bmatrix} \tag{4.30}$$

$$B = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1.27 & -0.093 & -0.34 \\ 1.057 & -0.23 & -0.056 \\ -708.59 & 32.89 & -8.22 \\ 52.29 & -698.28 & 7.37 \\ -20.58 & 6.95 & -659.55 \end{bmatrix}, \quad B_d = B_{d_n} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0.032 \\ 0.00009 \\ 11.23 \\ 0.126 \\ 0.195 \end{bmatrix} \tag{4.31}$$

$$C = \begin{bmatrix} 0 & 0 & 0.91 & -4.8 \times 10^{-18} & -1.12 \times 10^{-17} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 8.67 \times 10^{-18} & 0.91 & 3.39 \times 10^{-18} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 8.56 \times 10^{-18} & -2.02 \times 10^{-17} & 0.91 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{4.32}$$

In this chapter, the DOFs related to tower fore-aft deflection mode, variable generator speed mode, and individual blade flapwise bending modes are enabled to realized the linear model used to design the controller. To realize the required closed-loop performance of the wind turbine with respect to power/speed regulation and structural load reduction, the extended plant model (4.25). Here, LQR control design approach is used to compute the extended plant gain where the following state and control weighting matrices are used.

$$Q_{ec} = \begin{bmatrix} 1\times10^{-6} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 10 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 10 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 10 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1\times10^{-1} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1\times10^{-6} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 10 \end{bmatrix} \tag{4.33}$$

$$R_{ec} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4.34}$$

As previously noted, the perturbed signals from individual blade pitch controller should not actively regulate the speed to avoid performance degradation.Therefore, the state matrix elements related to variable generator speed mode are less weighted. On the other hand, the elements related to blade flapwise bending mode are more weighted.

Figure 4.6 illustrates a comparison of estimated hub height speed and actual hub wind speed used for simulation. The proposed stochastic PI-Observer is used to

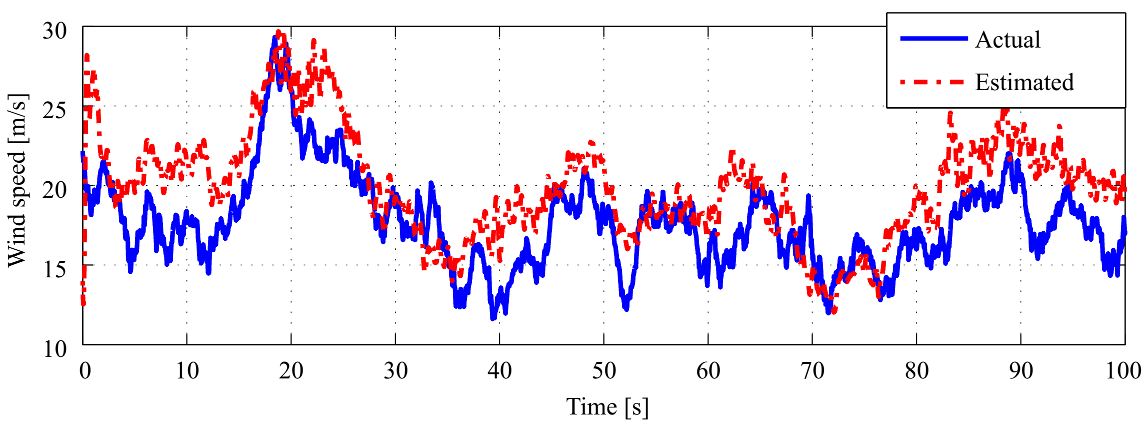


Figure 4.6: Estimation of hub wind speed as disturbance

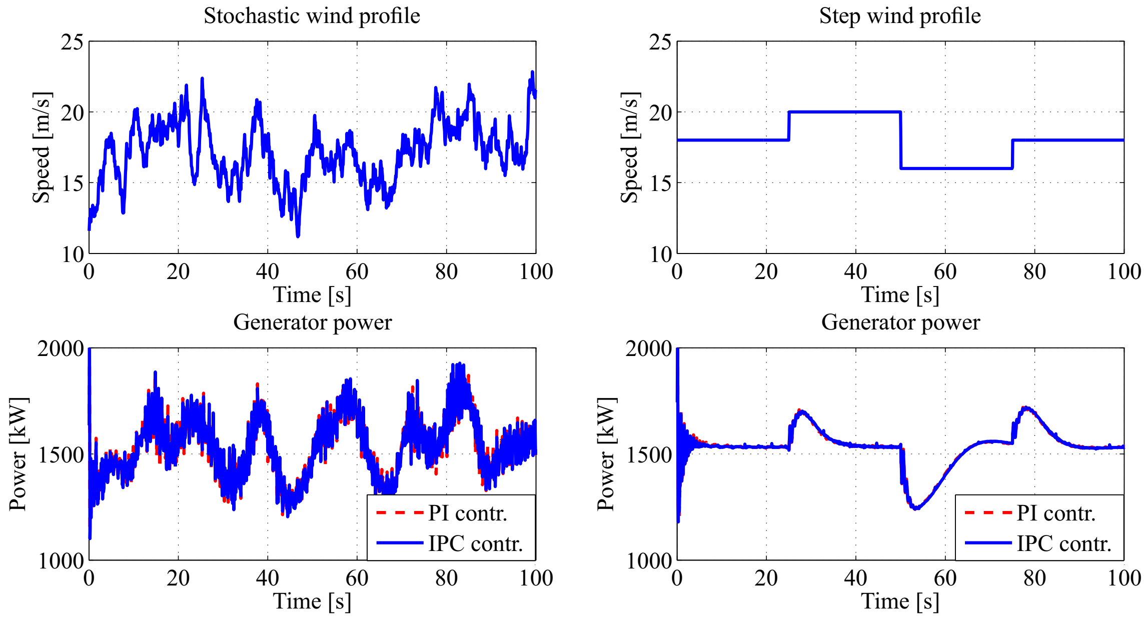


Figure 4.7: Comparison of generator power for PI-controller and IPC controller

indirectly estimate wind speed. The unknown perturbed hub wind speed is estimated as a disturbance using PI-Observer, then to compute the instantaneous wind speed, the estimated wind perturbations are added to the nominal speed value of 18 m/s. Although there is general agreement on the trend of estimated and actual wind profiles, estimation errors are observed as wind speed deviate from its nominal linearized value due to rapid variation of wind speed and and large inertial loads of wind turbines.

Although linear control methods are applied to design a multi-objective control strategy proposed in this thesis, a nonlinear wind turbine model is used for simulation to evaluate dynamic response due to different wind profiles. Additionally, it is important to mention that additional DOFs not utilized in control design are enabled during simulation to investigate the performance of the proposed controller on unmodeled modes. A stochastic wind profile with a vertical wind shear exponent of 0.2 and average speed of 18 m/s and a step wind profile with vertical exponent of 0.2 as illustrated in Fig. 4.7 are used to simulate dynamic response of wind turbine in this study. The turbulence of the generated stochastic wind is based on von Karman with spectrum intensity of 19.5% [Jon12]. The stochastic wind profile is generated using TurbSim full-field turbulent wind simulator [Tur] where spatial wind field is defined using 3-components time series wind speed vectors.

For performance evaluation of the proposed control scheme, results are compared with that of PI-controller discussed in section 4.2, which has single-input single-output (SISO) structure. The focus is in this chapter is to develop a multi-objective controller which regulates the generated power while reducing the structural loads.

These two objectives cannot be effectively achieved by PI-controller since they are competing with each other; hence, a MIMO control strategy is employed to reconcile these two conflicting objectives.

The collective pitch control (CPC) loop generates the nominal demanded pitch angle to realize the objective of regulating generator power, Individual pitch controller is used to mitigate asymmetrical unbalanced load across the rotor disc. Here, the generator power is maintained about the rated value as indicated in Fig. 4.7. As depicted in the figure, the variation of out power is strongly related to the profile of wind profile used to excite the wind turbine. It is observed that when a step wind profile is used, power output response is in the same direction as wind speed deviation from its nominal value. After a step wind is introduced, a step in output power is observed, but transient effects diminishes and settle to the reference value. The deviation of output power is a directly related to the variation of wind speed as depicted at 25 s and 55 s of the step wind profile. On the other hand, if stochastic wind profile is used, the output power tries to track the profile of incoming wind. However, it is difficult for output power response to be perfectly similar to that of wind profile because of inertia load and the fact that wind speed changes more rapidly compared to the turbine dynamics. It is evidence that when the PI-controller and IPC are compared, no significant difference with respect to output power regulation; structural load reduction does not influence power regulation objective. Examining the standard deviation of the output power when stochastic wind profile is applied, the subtle difference between the two controllers can be distinguished, with the relative standard deviations being 9.12% and 9.25% for PI controller and IPC, respectively.

As mentioned, rotor blades of wind turbines are normally subjected to unbalanced structural loads during power production, especially in Mega-scale wind turbines. This is contributed by linear horizontal and vertical variation of wind mean wind speed with altitude in addition to the fact that it is practically impossible to have three blades in wind turbine with perfectly matching aerodynamic properties/characteristics, necessitating the need to control each blade individually. To minimize flapwise blade load, IPC control loop is integrated into speed control loop as described in section 4.3. Again, the results for PI-controller and IPC with regard to minimization of blades root bending moments apply the step wind profile and the stochastic wind profile are presented. As illustrated in Fig. 4.8, there is a significant reduction in flapwise blade root bending moment when PI-controller and IPC are compared, in both cases where step and stochastic wind profiles are used to excite the dynamics of wind turbine. The relative standard deviations for when PI-controller and IPC are 30.3% and 20.6%, respectively. As shown in the Fig. 4.8, the amount of structural load increase as wind speed increases. For step wind profile, the flapwise bending moments are higher between 25 s and 50 s where wind speed is 20 m/s, while is relatively lower between 50 s and 75 s when the wind speed is 16 m/s. Like output power profile, the profile of flapwise bending moments

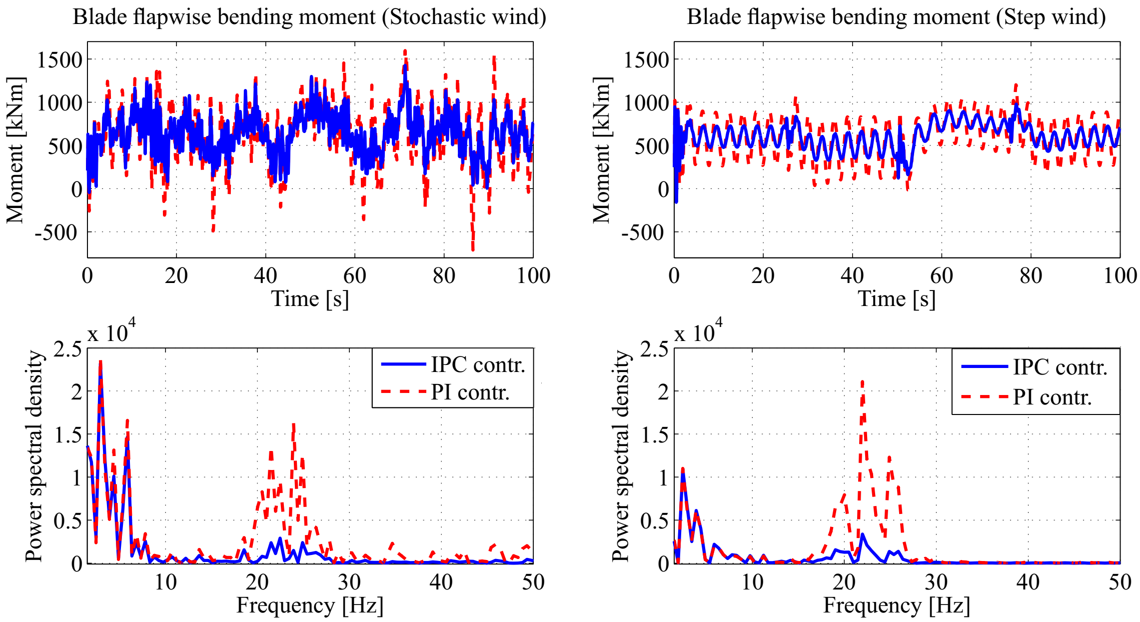


Figure 4.8: Blade flapwise bending moment

are strongly influenced by the wind profile exciting the wind turbine. A comparison of power spectral density of flapwise rotor blade bending moments between the two control schemes is shown in the same figure. Comparing PI-controller and IPC, there is a significant reduction in flapwise blade bending at around 20 and 25 Hz

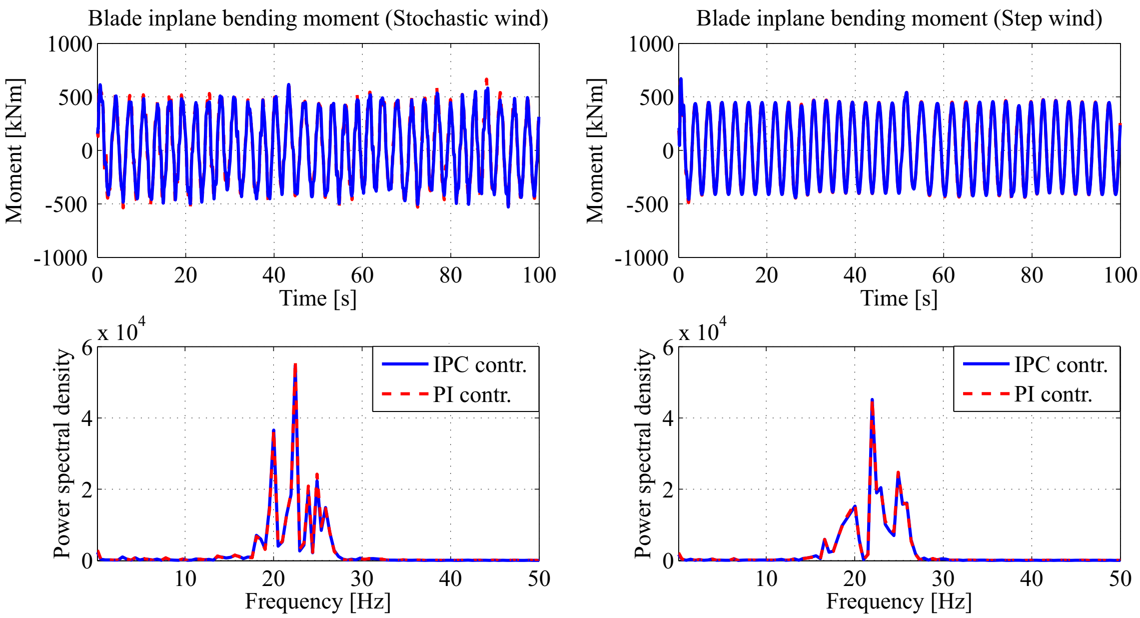


Figure 4.9: Blade inplane bending moments

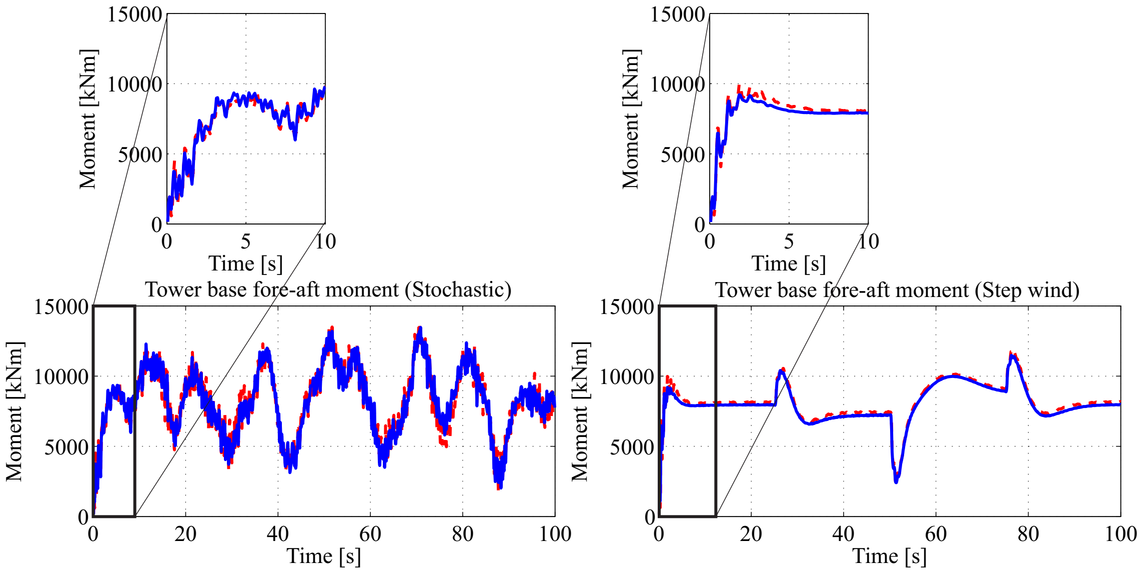


Figure 4.10: Tower base fore-aft bending moments

when a stochastic wind profile and step wind profiles are applied.

The effect of the designed multi-objective control scheme is also investigated on inplane blade bending moments. As shown in Fig. 4.9, there is no performance improvement when PI-controller and IPC controller are compared, both for step and stochastic wind profiles. Although, inplane bending moments are not as high as flapwise bending moment in response to stochastic aerodynamic forces, it important to mitigate them especially in large wind turbine because they are directly influenced by gravitational and centrifugal forces as well as effects of horizontal wind shear. When the main objective is to mitigate rotor blades inplane structural load, IPC can be modified with a focus of reducing in-plane structural load. For instance, in [DPLC13], an individual pitch control strategy based on edgewise moment using single neuron PID controller for minimization of in-plane bending moments is proposed.

It is also important to investigate the effect of proposed individual pitch controller on the tower fore-aft deflection mode since there is a very strongly coupling between rotor blade flapwise deflection mode and tower fore-aft deflection mode. Therefore, it is important to consider the two modes simultaneously when designing a controller since they influence each other. As shown in Fig 4.10, there is subtle difference between PI-controller and IPC on tower base fore-aft bending moments. The response to step wind profile is similar to that of output power, such that when step wind is introduced, there is some transient deflections which dies out with time. As discussed in 4.4, tower fore-aft deflection mode can be reduced by introducing an extra control loop on the collective blade pitch control signal, albeit at a slight compromise on power production objective.

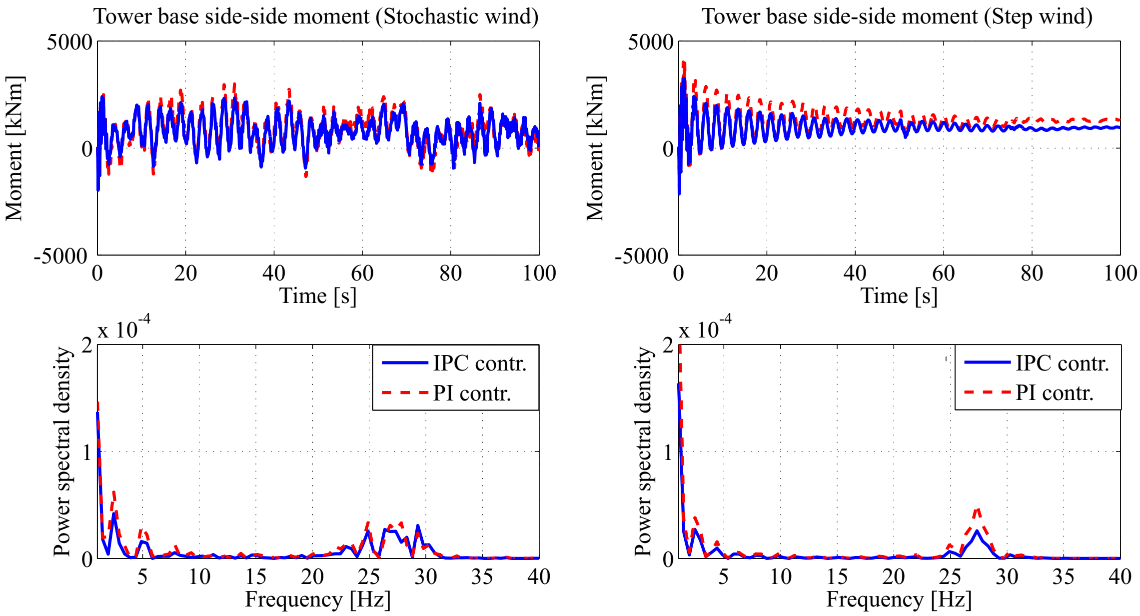


Figure 4.11: Tower base side-side bending moments

In Fig. 4.11, the performance of PI-controller and IPC controller with regards to reduction of tower side-side deflection is compared. Again there is no significant reduction on tower base tower side-side bending moment, both for stochastic and step wind profiles. As depicted by response to step wind profile, change in wind speed does not strongly influence side-side tower deflection mode. It can be observed from power spectral density plot that there is just a slight reduction on tower side-side vibration mode at around 27 Hz. As noted in [WS07], tower side-side deflection/vibration can actively be realized by using generator torque control method. Additionally, there is a very strong coupling between tower side-side deflection mode and drivetrain vibration mode and can be minimized by using modified torque controller. Another method employed in the literature to mitigate tower side-side and drivetrain vibration is use of notch filters. In this thesis, the load reduction is limited to rotor blade, as such generator torque is held constant which individual blade pitch is utilized to mitigate unbalanced load on rotor disc. The aim is to investigate the effect of the proposed multi-objective control scheme on tower side-side deflection without designing an additional generator torque controller since small torque excursion during high wind speed may lead to degradation of output power quality.

Due to deterministic effects like vertical wind shear and tower shadow, the rotor blade of a 3-bladed upwind horizontal axis wind turbine will experience $1p$ harmonic load on each blade and as a result $3p$, $6p$, etc. loads are transmitted to the fixed structure. To account for the dynamics of rotating rotor during individual pitch control design, the DOFs related to rotating parts are transformed to a fixed referencing coordinate system using MBC transformation [Bir10]. All wind turbine dynamics are transformed to two mutually perpendicular axis: tilt and yaw. As shown in Fig.4.12 and Fig. 4.13, the individual pitch controller has a very strong influence bending moment about tilt and yaw axis on the fixed coordinate system. Similar to flapwise bending moment, both the tilt and yaw bending moments increase as the wind speed increases. From power spectral density, it is observed that there is strong reduction of structural loads at around 20 and 25 Hz. In Fig. 4.14, a comparison of a PI-controller and IPC with regard to mitigation of drivetrain vibration is illustrated. There is insignificant difference between the two control method. As mentioned, there is a very strong coupling between drivetrain mode, blade edgewise mode. As noted in [BWF10], the vibrations in drivetrain can actively been damped using filter-based methods or perturbed torque control using linear state space methods. Like, output power and tower fore-aft dynamic response to the input wind profile, the response of drivetrain vibration is greatly influenced by excitation direction of input wind.

Another method of evaluating structural load reduction is by computing fatigue Damage Equivalent Load (DEL) for various structural parts in wind turbine. Damage equivalent load is usually defined as a constant magnitude load that would lead to the same damage as that caused by time varying load over the same period of time [FM00]. In this chapter, DELs are calculated using Mlife [Hay12] simulation code which is based on rainflow counting algorithm and Palmgren Miner's linear damage model is used. Here, structural loads related to rotor blades, tower, and drivetrain are compared to evaluate the performance of the proposed control strategy

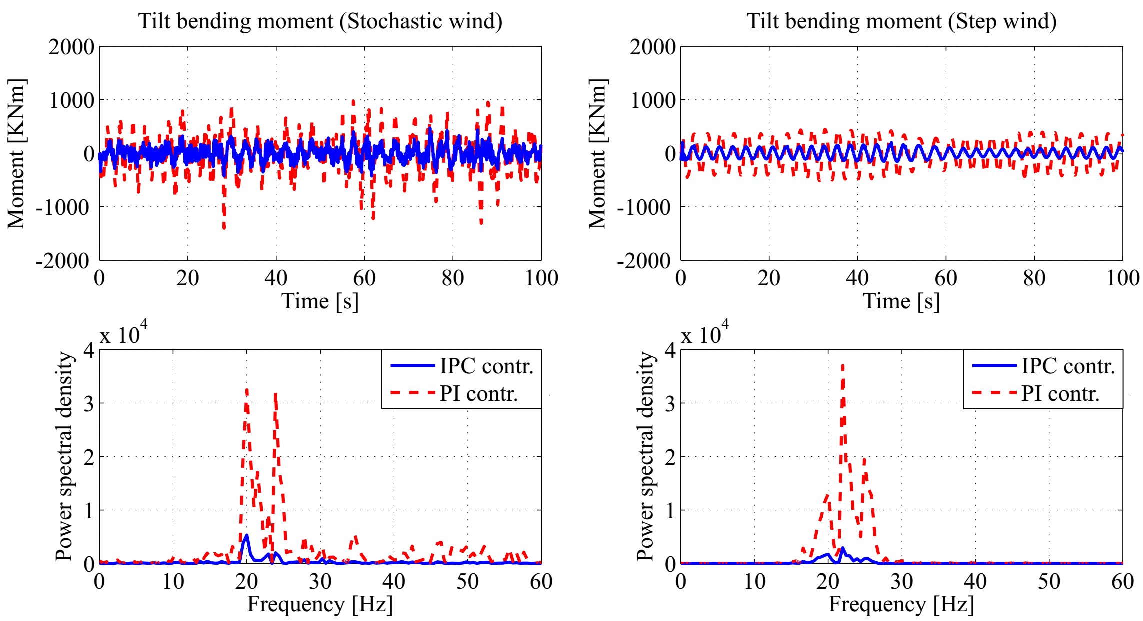


Figure 4.12: Tilt bending moments at the nacelle

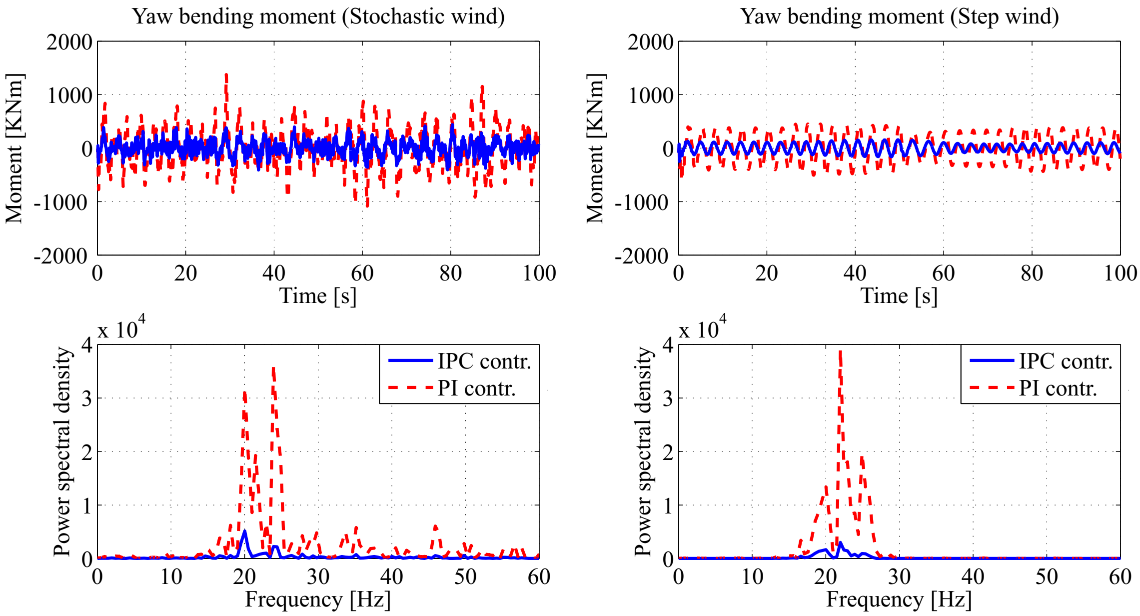


Figure 4.13: Yaw bending moment at the nacelle

with respect to structural load mitigation and power/speed regulation. As depicted in Fig. 4.15, the proposed control scheme has strong influence on both the flapwise blade bending moment and nacelle tilt and yaw bending moments. On the other hand it does not have significant influence on tower side-side bending moments.

As indicated in Fig. 4.16, individual pitch angle demands varies in a cyclic manner

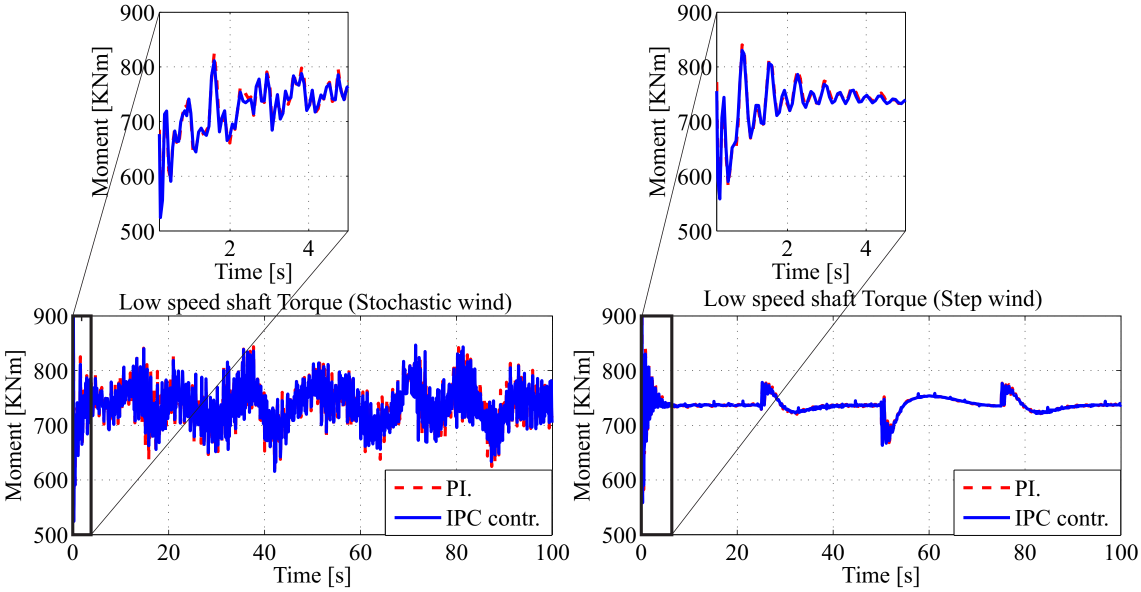


Figure 4.14: Low speed shaft torsional torque

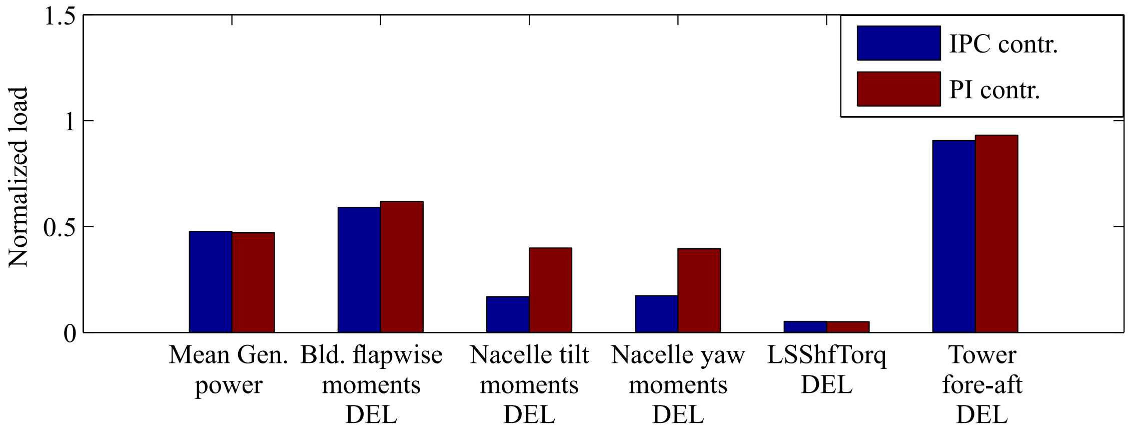


Figure 4.15: Comparison of damage equivalent loads

as they follow the nominal collective pitch angle demand. As mentioned, perturbed individual blade pitch signals should be limited not to interfere with the objective of power/speed regulation. The perturbed individual control signals have an effect of reducing unbalanced load across the rotor disk resulting from deterministic effects without significant sacrifice on generator power regulation. As a price to reduced structural loads reduction, individual blade pitch control leads to increased pitch actuation duty cycle (ADC); thus, a compromise on load mitigation and actuator used must be made for the proposed controller to be practically feasible. In this thesis, the pitching rate is limited to 10 degree/second which is the pitching rate

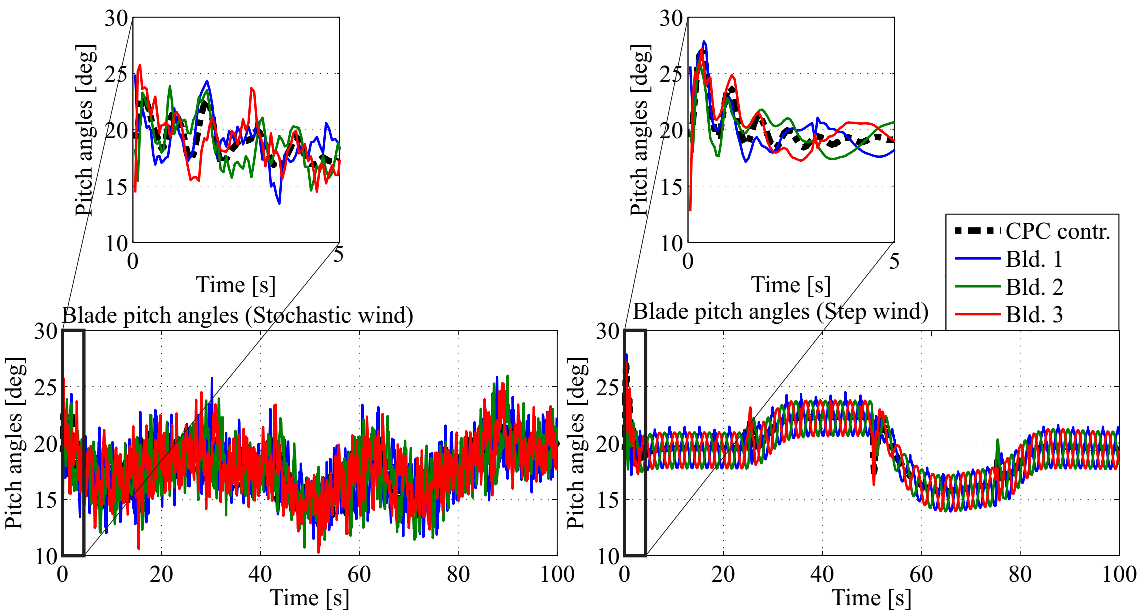


Figure 4.16: Variation of individual blade pitch angles

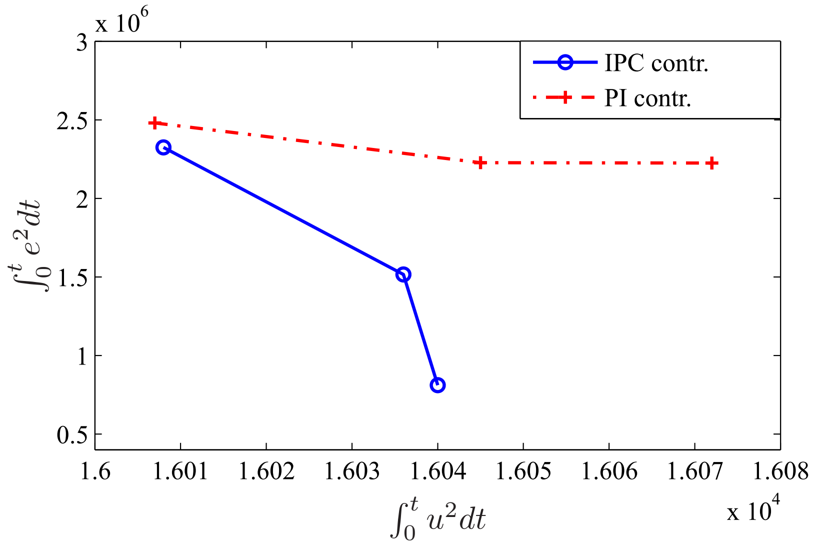


Figure 4.17: Energy versus error performance analysis

limit for the model used to design a multivariable controller.

Another performance criteria which considers error and control energy as proposed in [LS14] is also used to compare the two control schemes. Here, the amount of energy exploited for each control scheme is compared with achieved load reduction within a given time window T

$$P_k = \left[\int_0^t u^2 dt, \int_0^t e^2 dt \right], \tag{4.35}$$

where P_k is a trajectory relating control energy and control error as a function of control gain for a given time window T. Here, K denotes the controller gain. Using the error and control energy performance evaluation criteria, the trajectory P_k for both the IPC and baseline PI-controller are shown in Fig. 4.17. Here, the time window T is taken as 100 s. It is evident that the proposed IPC has better performance compared to baseline PI-controller since it realizes less control error without much control energy.

4.4 Active tower vibration control

To mitigate tower fore-aft vibrations, the dynamics of flexible tower are approximated using a linear model as follows

$$\begin{bmatrix} \dot{x}_t \\ \ddot{x}_t \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\dfrac{k_t}{M_t} & -\dfrac{D_t}{M_t} \end{bmatrix} \begin{bmatrix} x_t \\ \dot{x}_t \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{F_t}{M_t} \end{bmatrix} u_t, \tag{4.36}$$

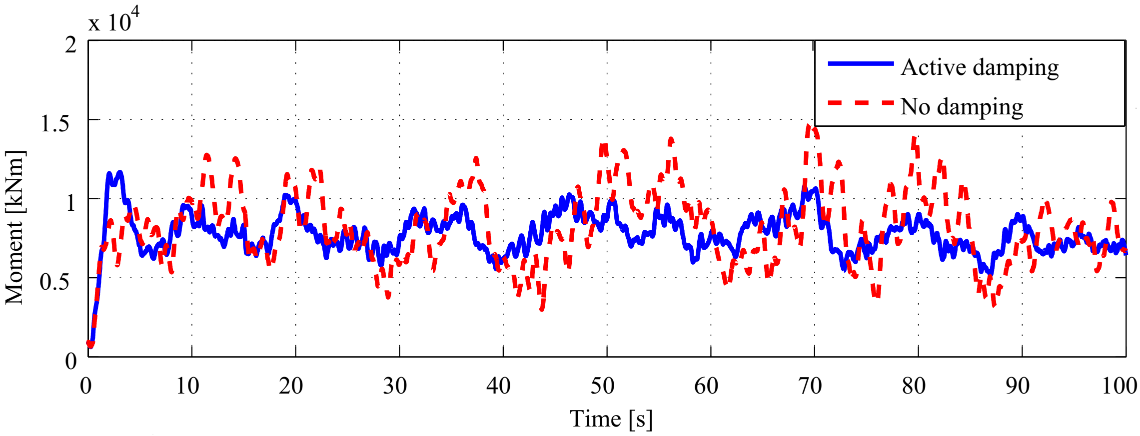


Figure 4.18: Active damping of tower fore-aft vibration

where x_t, $\dot{x}_t$, and $\ddot{x}_t$ denote the perturbed tower top position, velocity, and acceleration, respectively. The variables M_t, C_t, and K_t represent the tower mass, damping, and stiffness coefficients, respectively. The control input is given by u_t, while the input variable gain is expressed as F_t. To realize the objective of active tower fore-aft vibrations damping, control input can be assumed to be proportional to tower velocity as noted in [WF08]. i.e

$$u_t = \Theta \dot{x}_t. \tag{4.37}$$

Hence, by adjusting Θ the desired performance characteristics can be achieved. In this thesis, the linear model described by Eqn. 4.36 is obtained by linearizing the nonlinear wind turbine model about a given operation point that is defined in terms wind speed, pitch angle, and rotor rotational speed. The linearization is realized in the FAST by switch the first tower fore-aft deflection mode DOF and top tower as fore-aft acceleration the only measurement. Then the perturbed control signal u_t is added to the collective pitch control loop to actively damp the tower fore-aft vibrations. Additionally, the tower fore-aft state variables are tuned to minimize tower fore-aft loads. As shown in Fig. 4.18, tower base fore-aft bending moment is significantly reduce as compared to PI-controller.

4.5 Summary

A multi-variant control method that can simultaneously regulate generator power/ speed and minimize the structural load during high wind speed region is proposed in this chapter. This control scheme shows better performance compared to PI-controller since it offers a good trade off between two contradicting objectives. The unknown disturbances, in this case the variation of wind speed from it nominal value, are estimated and compensated dynamically. Stochastic PI-Observer is used to optimally estimate both unknown disturbances and plant states. Then dynamic controller is used for state regulation and disturbance compensation. In this study, the plant was assumed to be influenced by process and measurement noise with known statistical properties. It is worth mentioning that like other control methods based on statistical assumptions, stochastic PI-Observer may not be effective in estimating disturbances that do not have statistical properties. Finally, the control method proposed in this chapter can reduce the cost of wind energy production by extending service lifetime by mitigating fatigue load without sacrificing power production.

5 Multi-Objective Control for Partial Load Region

In this chapter, a control strategy that balance between power production maximization and structural load reduction in low wind speed region is proposed. Normally, during low wind speed the main objective is to capture as much wind energy as possible by operating the turbine at optimum operating point. To capture maximum power during low wind speed, an optimal operating point defined by optimal tip speed ratio, optimal rotor speed, and wind speed must be properly tracked. However, due to large inertial loads of utility-scale wind turbines as well as strong variations of incoming wind speed, the optimal operating point cannot be perfectly tracked, leading to sub-optimal operation. On the other hand, strict tracking of optimal power curve in wind turbines results to undesirable loads on its structural members; hence, it is important to balance between these two contradicting control requirements. The ideas and results discussed in this chapter have already been examined in [NBS16b].

5.1 Overview

To simultaneously realize the objective of maximizing power production and structural load mitigation, two control loops are used. Here, optimally tracking rotor (OTR) control is used to maximize power production, while perturbed individual blade pitch signals are utilized for structural load minimization. The performance of the proposed control approach is evaluated against the standard baseline torque control in low wind speed region. The results indicate that the proposed multi-objective control strategy can make a reasonable compromise between power optimization and structural load reduction; consequently, guaranteeing extended operational lifetime without much compromise on power maximization objective.

Due to to increasing demand of wind power production, the focus in the last decades is to make it more affordable and reliable compared to other alternative power sources. Wind turbines are operated in three regions, each with distinct operation objectives: below rated wind speed region, high wind speed region, and a transition region between low and high wind speed region. However, as noted in [JFBP04] more than half of the annual energy capture of a modern wind turbine are said to occur within the operation below rated wind speed region (region II).

Variable speed wind turbines have gained popularity in Mega-scale turbines because they can be operated optimally over a wide range of wind speeds as well as supporting active minimization of fatigue load on drivetrain system, albeit at an additional cost of power converters that ensures that power is fed to the grid at the right frequency and power factor. Power optimization is made possible by regulation of rotor speed such that the speed of incoming wind is tracked leading to operation of wind turbine at the maximum aerodynamic efficiency.

In large wind turbines applications, squirrel cage induction generator (SCIG), doubly fed-induction generator (DFIG), and permanent magnet synchronous generator (PMSG) are the commonly used generator types. The choice for a given generator type is influenced by cost, efficiency, and reliability aspects. Regardless of the type of generator used, the amount of power captured by wind turbine during low wind speed regime largely depend on the accuracy at which the maximum power curve is tracked by the maximum power point (MPP) algorithm employed [JSH15]. As a matter of fact, the amount of extractable wind power is strongly related to the operating point in wind turbine defined by wind speed, rotor rotational speed, and blade pitch angle.

As noted in [AYTS12], maximum power point tracking (MPPT) control methods can be categorized as: methods that rely on wind speed, methods relying on measurement of output power, and those depending on the optimum characteristic curve of the wind turbine. Essentially, three traditional MPPT control algorithms are applied to wind turbines including: tip speed ratio (TSR) control, power signal feedback (PSF), and hill-climb searching (HCS). Both the TSR and PSF control methods require prior knowledge of wind turbine parameters, while HCS control method is based on iterative search of optimum power point using power and rotational speed measurements or converter duty cycles [EAF13]. The tip speed control method requires knowledge of optimum tip speed ratio λ_{opt} and the measurement of effective wind speed to give accurate results. On the contrary, its is not possible to accurately measure effective wind speed using anemometer, so effective wind speed has to be estimated to make such control method applicable in practice. Additionally, it is not practical to come up with an optimal tip-speed-ratio for entire service life of wind turbine because its aerodynamic properties changes with time due to aging and variation of air density.

In HCS method, generated power measurement and either generator speed or duty cycle is used as perturbed signal untill the maximum power point is attained. To balance between the trade-off between the rate of convergence to the MPP and the amount of the steady state oscillations, varying perturbing step size can be employed [AYTS12]. The varying perturbation steps are determined depending on the power variation of the previous applied step such that large step sizes are used when far from MPP and small steps when closer to MPP. However, this MPPT method is bound not to converge to the MPP if the distinction between the step change due to the previous recorded value and due to variation of wind speed cannot be made. In large wind turbines, the convergence problem is exacerbated since there is sluggish response to control input due to large inertia of the rotor blades and the fact that the wind dynamics are faster than those of wind turbine.

In the literature, several control methods for maximization of power production in wind turbines during low wind speed have been proposed, especially model-based and model-free-based approaches. For model-based approaches, the performance is strongly related to the system operation point which is on the other hand influenced by variations of inflow conditions. Although the performance of model-free approaches are not dependent on a particular wind turbine operation point, the convergence rate to the optimum power point that correspond to the maximum power is limited by dynamics of turbine and the variation rate of incoming wind speed. One of the model-free approach used for maximum power point tracking during low wind speed is extremum seeking control (ESC). The extremum seeking approach is based on hill climbing search method which does not require explicit measurement of wind speed and output power. In [LLW$^+$14], an improved extremum seeking-based MPPT control strategy consisting of tracking controller, HCS extremum seeking module, and a look-up table is proposed. This MPPT control method balances between the tracking precision of maximum power curve and efficiency of settling to the MPP. The results indicated that the proposed MPPT control method has improved performance compared to the standard MPPT methods in terms of tracking precision and efficiency. A sliding mode-based extremum seeking control for variable-speed constant-frequency wind energy conversion system is proposed in [PJJ08], where generator active power is used as the only input. Unlike other ESC methods that require sensing of gradient function to set the direction of optimum point, the proposed sliding mode extremum seeking control does not require gradient measurement, so amplification of noise and instability at high frequencies is avoided. The proposed MPPT control method was tested on a DFIG-based wind turbine. The performance was evaluated under step and stochastic wind profiles to demonstrate the effectiveness of the proposed control scheme under different operating conditions.

Another model-free-based approach is multi-resolution simultaneous approximation (MR-SPSA) technique proposed in [AAS14] for maximization of power production in wind farm. This control approach aims at using information of wind farm configuration such as wind direction and turbine locations are to realize fast controller tuning in order to maximize power production. The results demonstrated that the MR-SPSA-based approach has better performance with respect to maximum power production and convergence rate for different wind speeds. However, the study did not consider induction of structural load on wind turbine due to tracking of the maximum power.

In [TL10], a fuzzy logic-based MPPT (MPPT-FLC) control method for a PMSG-based wind turbine is proposed. The proposed method aims to maximize power production by searching and tracking the MPPT using the conventional hill climb searching (HCS) method. This control scheme uses DC output power and DC/DC converter duty cycle step change as input to FLC, while the output from FLC is DC/DC converter duty cycles. Unlike most MPPT control methods, this control scheme does not depend on the characteristic of wind turbine and does not require measurement of wind speed and generator power. Compared to conventional HCS, the FLC-based scheme demonstrated good performance with respect to power maximization. However, the improve performance on power maximization was not investigated whether it had influence on structural load. In a different study, a data-driven method that generate a Takagi-Sugeno-Kang (TSK) fuzzy model for optimizing power extraction in a variable-speed wind turbine during low wind speed is proposed in [GPS08]. The performance of the TSK-based MPPT method was tested on a doubly-fed induction generator wind turbine, where improved performance with respect to computational speed, fault tolerance, and learning capability was observed. However this control method assumes prior knowledge of the maximum extractable power for given rotor speed.

A neural network-based MPPT control method for tracking the optimum rotational speed corresponding to the maximum power for a squirrel-cage induction generator wind turbine is proposed in [MM12]. The proposed method uses rotor rotational speed and generator power output as input signals, while the effective wind speed as output signal for training neural network. Then, the optimal reference speed is computed from the optimal tip-speed-ratio calculated using output signal from neural network. This control method is able to drive the wind turbine at optimum rotation speed due to fast tracking of incoming wind dynamics. Since wind speed measurement is required during training stage, this control approach can result to poor estimation of wind speed because it is challenging to measure the effective wind speed. As indicated in [Bar10], wind speed estimation is realized by feed-forward artificial neural network. The neural network is trained to estimate wind speed with measured generator power, rotor speed, and blade pitch angle. Sliding mode control is used to maximize wind power and limit generator power around rated value in related operating regions. The simulation results showed that generator power is regulated, but how to use this feed-forward artificial neural network and sliding mode control for load reduction is not demonstrated.

Another artificial intelligence-based MPPT control method applied to variable-speed wind turbines to maximize power production is Adaptive Neuro-Fuzzy Inference System (ANFIS). The ANFIS combines the strong features of both neural network and fuzzy logic. In [SPADV15], ANFIS-based MPPT is proposed to maximize power production for a doubly-fed induction generator wind turbine. This method aims to regulate rotor speed in accordance with the variation of incoming wind speed in order to track the maximum power point. For training, wind speed is used as input signal and the rotor speed is given as an output. Other control methods used to optimize power capture in wind turbines during low wind speed include adaptive and adaptive disturbance tracking controllers. In [BLMF11], a linear adaptive disturbance tracking control for large wind turbines is design to track and accommodate the variation of wind speed in order to maximize power capture during low wind speed region. The adaptive disturbance tracking controller aims at tracking the wind speed variation; hence, keeping the tip-speed-ratio at a constant optimum value corresponding to the maximum power. This control scheme is based on a linear model, implying that it is only effective on the vicinity of the operating point about which the model was linearized. A nonlinear generator torque adaptive controller is considered in [JPBF05]. Here, unlike the standard torque controller which has a fixed gain, an adaptive gain is used to adapt parameter variation during operation due to aging or change in inflow conditions.

It should be noted that most of the proposed methods for power capture optimization in partial load region of wind turbines do not consider mitigation of structural loads, leading to extended lifetime and reduced failure rate especially in large wind turbines. In [SZW06], an individual blade pitch controller for the Control Advanced Research Turbine (CART) is designed to mitigate structural load in both the partial load region and in high wind speed region. The performance was evaluated against standard baseline controller where it was observed that the individual blade pitch controller significantly reduced tower side-side fatigue damage in high wind speed region, but no noticeable reduction in partial load region was realized. A negligible drop in energy capture was observed when individual blade pitch controller was applied in both operation regions. As noted in [WF08], precise tracking of the incoming wind speed during low wind speed can lead to induction of undesired mechanical stress on turbine structural parts; hence, the need to consider mitigation of structural loads in this region is stated. Active reduction of mechanical stress on drivetrain system of wind turbine have been reported in the literature, but mostly focusing on the high wind speed region. As shown in [LULEJ15], band pass filter-based and model-based methods are two commonly used approach to suppress drivetrain vibration, although band pass filter method is suffers from performance deterioration due to model uncertainties.

In this chapter, a multi-objective control strategy is proposed to balance between power production optimization and structural load reduction on rotor blade, tower, and drivetrain system. To realize this objective, an optimally tracking rotor (OTR) controller together with linear state-space-based controllers are used. The aim is to enhance the maximum power point tracking by maintaining optimum power coefficient, while at the same time mitigating undesirable structural loads. To reduce flapwise rotor blade deflection, individual pitch angle signals are perturbed about the optimum angle that corresponds to the maximum lift during low wind speed. To evaluate the performance of the proposed multi-objective method, a standard baseline torque controller is used as benchmark. It is important to mention that the idea for structural load reduction for high wind speed region discussed in [NLS15, NS15] is extended in this contribution to the low wind speed region.

5.2 Wind turbine characteristics

Wind turbines can be operated in three distinct regions: low wind speed region, high wind speed region, and transition region. For each region, specific performance objectives during wind power production have to be considered. Irrespective of the region at which wind turbine is operated, the amount of power captured is strongly influenced by turbine characteristics. Wind turbine rotor blades are designed to attain the maximum possible aerodynamic efficiency especially in the low wind speed region. The aerodynamic efficiency is mostly influenced by the shape and size of the blade, aerofoil shape, and the angle of twist; therefore, it is important to use optimal blade parameters that leads to the maximum aerodynamic efficiency. Notwithstanding this, according to Betz [Bet66] the amount of maximum extractable wind energy by a wind turbine is limited to a theoretical value of 59.3% of the available wind energy, with majority of utility-scale turbine realizing only 40%.

Independent from rotor blades design parameters, wind turbine power characteristics is described by power coefficient C_p as a nonlinear function of tip-speed-ratio λ and blade pitch angle β. It is important to note that C_p is a turbine specific and its optimum value is bound to change due to aging and variation of operating point as a result of changing inflow conditions. The power coefficient for a given operating point can determined either through experimental or theoretical methods such as blade element momentum (BEM) theory. In the literature, some empirical approximations of the power coefficients have been proposed, but in this contribution the approximation described by

$$C_p(\lambda, \beta) = k_1 \left(\frac{k_2}{\lambda_i} - k_3\beta - k_4 \right) e^{-\frac{k_5}{\lambda_i}} + k_6\lambda, \tag{5.1}$$

with

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}, \tag{5.2}$$

is used to plot power curves for various wind speeds [PC11]. The constants k_1 to k_6 are approximated using theoretical method or determined empirically using experimental data. Here the parameters are chosen as, $k_1 = 0.5176$, $k_2 = 116$, $k_3 = 0.4$, $k_4 = 5$, and $k_6 = 0.068$. As depicted in Fig. 5.1, maximum power occurs only at a given optimum blade pitch angle β_{opt} and tip speed ratio λ_{opt} for a particular wind speed. In most of MPPT control methods, blade pitch angle is held at a constant optimum value that yields the maximum aerodynamic lift such that the power coefficient is a function of tip-speed-ratio only.

To capture maximum power for different wind speeds, appropriate maximum power point control method are employed to track optimum power curve for different wind speeds. The amount of power extracted in partial load regime is determined by the efficacy of tracking the optimum power curve as the wind speed vary. It follows that the maximum extractable power for a given optimum power coefficient is given by

$$P_{a_{max}} = \frac{1}{2}\rho\pi R^5 \left(\frac{C_p(\lambda_{opt}, \beta_{opt})}{\lambda_{opt}} \right) \Omega_{opt}^3, \tag{5.3}$$

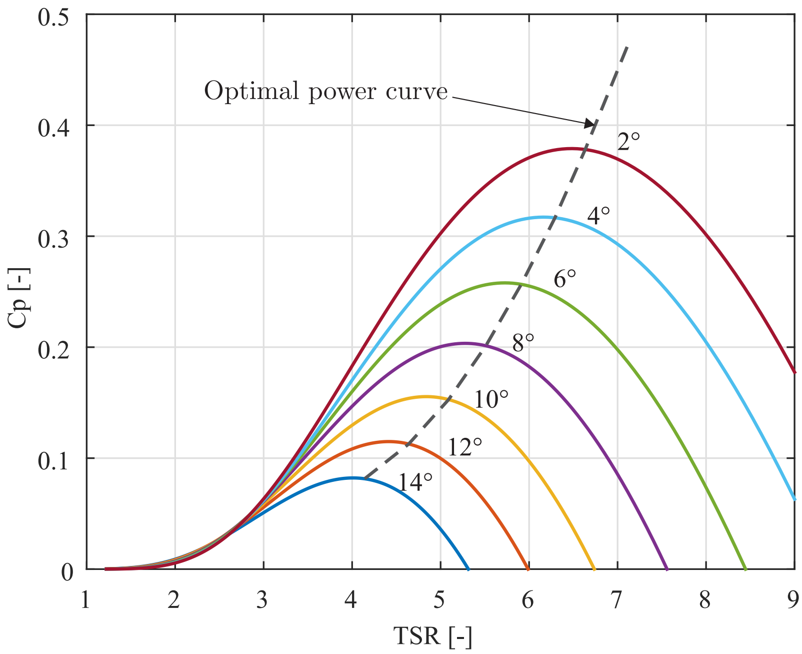


Figure 5.1: A plot of optimal power curve for maximum power capture

where the optimum rotor rotational speed is given by

$$\Omega_{opt} = \frac{\lambda_{opt} v}{R}. \tag{5.4}$$

The main challenge of control system during low wind regime is to establish the operation conditions corresponding to the maximum power irrespective of rapidly changing dynamics of incoming wind. The standard control method for low wind speed region is given by

$$\tau_g = \begin{cases} k\omega^2, & \text{For } v_w < \text{rated speed} \\ \tau_{rated}, & \text{For } v_w \geq \text{rated speed}, \end{cases} \tag{5.5}$$

where it is assumed that the braking generator toque is a function of a rotor speed squared and the constant k is determined such that the turbine is operated at maximum power point most of the time. However, the challenge is to effectively determine the value of k yielding maximum power for varying operating points due to rapid change of inflow conditions. Hence, it is important to establish appropriate control strategies to ensure maximum power capture irrespective of wind speed variations, especially in large wind turbines where large inertial loads leads to slow response to control inputs.

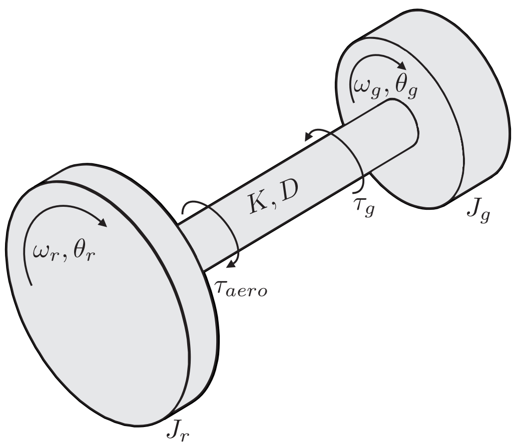


Figure 5.2: Wind turbine two mass drivetrain model

5.3 Wind turbine system modeling

Again, a fictitious 1.5 MW WindPACT wind turbine model is used to design a multi-objective control strategy for low wind speed region. The model represents a variable-speed, 3-bladed, upwind horizontal axis wind turbine. To evaluate the performance of the proposed control strategy, a nonlinear aeroelastic wind turbine simulation code [FAS] is used. In this model, the drivetrain is modeled using mass-spring-damper system.

To model dynamics of drivetrain system in wind turbine, a two mass model depicted in Fig. 5.2 is commonly employed due to its simplicity, although in the literature a 3 mass model also has been proposed to account for coupling between drivetrain and rotor blade in-plane symmetrical modes [LULEJ15]. To model the dynamics of a two mass model with high speed shaft dynamics referred to the lower speed shaft, the following differential equations are used

$$\begin{aligned}
J_r\dot{\omega}_r &= \tau_{aero} - K\left(\theta_r - \frac{\theta_g}{N}\right) - D\left(\dot{\theta}_r - \frac{\dot{\theta}_g}{N}\right), \\
J_g\frac{\dot{\omega}_g}{N} &= -N\tau_g - K\left(\frac{\theta_g}{N} - \theta_r\right) - D\left(\frac{\dot{\theta}_g}{N} - \dot{\theta}_r\right), \\
\dot{\theta}_r - \frac{\dot{\theta}_g}{N} &= \omega_r - \frac{\omega_g}{N},
\end{aligned} \tag{5.6}$$

where J_r [kgm^2] represents the rotor (hub and blades) moment of inertia, J_g [kgm^2] denotes the generator inertia, ω_r and ω_g are rotor and generator rotational speed in rad/s. The low speed shaft (LSS) and high speed shaft (HSS) angular positions are given by θ_r and θ_g, respectively. The constants K and D denote equivalent LSS and

HSS stiffness and damping coefficients referred to the LSS and are expressed as

$$\frac{1}{K} = \frac{1}{K_{LSS}} + \frac{1}{K_{HSS}N^2}, \quad \frac{1}{D} = \frac{1}{D_{LSS}} + \frac{1}{D_{HSS}N^2}. \tag{5.7}$$

The natural frequency of a two mass drivetrain model is given by

$$f_n = \frac{1}{2\pi}\sqrt{K\left(\frac{1}{J_r} + \frac{1}{J_g}\right)}. \tag{5.8}$$

The drivetrain model (5.6) can be written in state-space model as

$$\begin{aligned} \begin{bmatrix} \dot{\omega}_r \\ \dot{\theta}_r - \frac{\dot{\theta}_g}{N} \\ \dot{\omega}_g \end{bmatrix} &= \begin{bmatrix} -\frac{D}{J_r} & -\dfrac{K}{J_r} & \frac{D}{NJ_r} \\ 1 & 0 & 1 \\ \frac{ND}{J_g} & \frac{NK}{J_g} & -\frac{D}{J_g} \end{bmatrix} \begin{bmatrix} \omega_r \\ \theta_r - \frac{\theta_g}{N} \\ \omega_g \end{bmatrix} + \begin{bmatrix} -\frac{1}{J_r} & 0 \\ 0 & 0 \\ 0 & \frac{N^2}{J_g} \end{bmatrix} \begin{bmatrix} \tau_{aero} \\ \tau_g \end{bmatrix} \\ y &= \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \omega_r \\ \theta_r - \frac{\theta_g}{N} \\ \omega_g \end{bmatrix}. \end{aligned} \tag{5.9}$$

To capture flexibility of blades in a 3-mass model, the drivetrain system (which contains rotor blade, gearbox, and generator) is modeled as two separate parts: the rigid and the flexible part [LULEJ15]. The rigid part represents the hub and other rigid parts of the rotor, while the flexible part represents blades flexibility. Modeling of rotor blade dynamics is complex due to non-uniform distribution of mass, stiffness, and angle of twist along the blade span. In the aeroelastic FAST code, the rotor blades and tower are modeled as flexible parts, while the nacelle is modeled as rigid body. It is important to note the existence of couplings between different modes in wind turbine and that the flexibility is defined by the number of enabled DOFs. In this chapter, both nonlinear model and linear model are used to design the proposed multi-objective control strategy for maximizing power production and structural load reduction. The linear model is described by the dynamics at the operating point defined by pitch angle, rotor rotational speed, and stead state wind speed in partial load region. According to [MH00], the turbine presented in this chapter is designed for a maximum power coefficient of 0.5, an optimal blade pitch angle for maximum aerodynamic lift of 2.6°, and an optimal tip speed ratio of 7.0. Notwithstanding the variation in wind speed, the controller for partial load region should be designed to realize maximum power extraction without inducing extra structural loads on wind turbine; hence, a trade-off to balance these two conflicting objectives is required.

5.4 Multi-objective control strategy

To realize two competing objectives of optimizing power capture and structural load reduction during low wind speed, a multi-objective control strategy comprising of

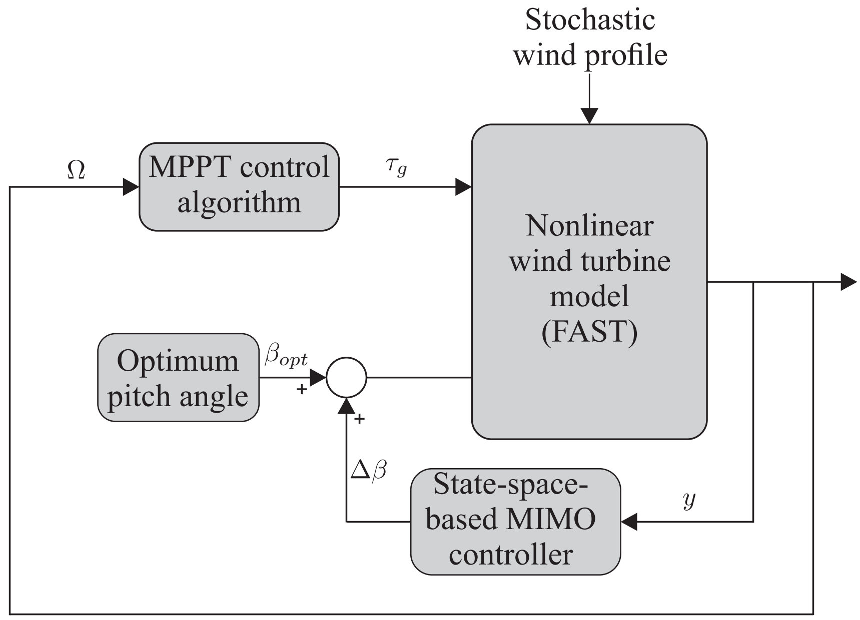


Figure 5.3: Block diagram for multi-objective control scheme

torque controller and a linear MIMO controller is proposed in this section. The control strategy offers an optimal compromise between extension of wind turbine lifetime through structural load reduction and maximization of power production. In this chapter, load reduction in rotor blades and tower is considered. One of the main challenges in synthesizing controllers for wind turbines is strong coupling between different subsystems, variation of wind speed, and nonlinearity due to aerodynamic forces. Notably is a very strong coupling between blades deflection modes and tower deflection mode. As noted in [GC10], active damping of fore-aft tower deflection might lead to instability if the coupling between speed control and blade deflection is not suitably considered during control design.

The proposed multi-objective control strategy is depicted in Fig. 5.3. Here, two control loops are used to realize two contradicting objectives. First, torque control loop is used to maximize power extraction by tracking the variation of wind speed. Second, perturbed individual blade pitch control signals about the optimum blade pitch angle ($\beta_{opt} = 2.6°$) are utilized for structural load reduction. It is important to note that the perturbed individual blade pitch angle are limited around the optimal pitch angle to avoid large excursion of generator torque possibly leading to power production reduction as well as instabilities. Most of the control methods that are proposed in the literature including the standard torque controller use a constant optimal blade pitch angle λ_{opt}, while generator torque is utilized to maximize power production in partial load region.

5.4.1 Optimally tracking rotor (OTR) control

As mentioned earlier, one of the main challenges in MPPT control methods is to realize design parameters that ensures fast convergence to the maximum power point despite the variation in wind speed. In some cases, optimal tracking of maximum power point is not realized especially in large wind turbines if the dynamics of incoming wind are rapidly changing compared to that of the turbine itself. In this chapter, optimally tracking rotor (OTR) control method proposed in [JFBP04] is used to maximize power production during low wind speed. This control method is an improvement of the standard torque controller, where the generator torque is utilized to enhance tracking of incoming wind speed variations. The operation principle behind this controller is motivated by the need to avoid loss of power due to inability of wind turbines to accelerate or decelerate fast enough to track the variations of incoming wind speed. In order to achieve optimum tip speed ratio that corresponds to the maximum power coefficient $C_{p_{max}}$, generator torque is utilized to enhance the rate of acceleration and deceleration of the rotor such that the turbine spend much of the time near the optimal C_p. The standard torque generator controller expressed as

$$\tau_g = K\Omega^2 = \left\{ \frac{1}{2}\rho\pi R^5 \frac{C_{p_{opt}}(\beta_{opt}, \lambda_{opt})}{\lambda_{opt}} \right\} \Omega^2, \tag{5.10}$$

is modified to

$$\tau_g = K\Omega^2 - G(\tau_{aero} - K\Omega^2). \tag{5.11}$$

Here, the gain G is used to realize the trade-off between acceleration/deceleration rate of wind turbine and other design consideration such as avoidance of motoring, especially in the case of sudden change in wind speed (wind gust).

5.4.2 Individual pitch control design for low speed region

To reduce structural load while maximizing power production in partial load scheme, an additional control loop to the MPPT control loop is used. An individual pitch controller similar to the one proposed in [NLS15] is used to reduce the rotor blade flapwise vibration and tower fore-aft vibration. To design a linear MIMO controller, a nonlinear wind turbine model is linearized about a given operating point in low wind speed region. In this chapter, the operating point about which the linear model is extracted is defined by constant wind speed of 8 m/s, rotor speed of 14.2 rpm, and optimal blade pitch angle of 2.6°. After linearization and carrying out multi-blade coordinate transformation, the resulting linear time invariant (LTI) model is given as

$$\dot{x} = Ax + Bu + B_d u_d, \tag{5.12a}$$

$$y = Cx, \tag{5.12b}$$

where $x = [\Delta q \ \ \Delta\dot{q}]^T$ is the state space vector, $u = [\Delta\beta_1 \ \ \Delta\beta_2 \ \ \Delta\beta_3]^T$ represents control variable vector, u_d denotes unknown disturbance vector which in this case is a variation of wind speed around the mean value; A, B, and C are matrices of appropriate dimensions that describes the dynamics of wind turbine, and y is the measured output. The variable q represents the degrees of freedoms (DOFs) that are used to describe the flexibility of the linear model used to design the controller. In this chapter, DOFs related to blade flapwise deflection mode, generator speed mode, and tower f-a deflection mode are enabled to realize a linear dynamic model. It is important to mention that multi-blade coordinate transformation is used to integrate the inherent wind turbine periodic dynamics into the resulting linear model; hence, accounting for asymmetric load variation in the rotor blade during control design process. A linear quadratic regulator is designed such that the following objective function J_{QR} is minimized

$$J_{QR} = \int_0^t \left(x^T Q x + u^T R u\right) dt, \tag{5.13}$$

where Q and R are states and control input weighting matrices, respectively. The weighting matrices, provide a trade-off between state regulation and control efforts. To realize the objective of reducing structural load on blades and tower vibration, the elements of the weighting matrix related to blades and tower are tuned to offer a trade-off since these two modes are tightly coupled to each other. Because not all states are available for measurement, they are estimated to design a full state feedback controller. In this study, a Kalman filter is used to estimate the system state using measurements containing noise such that the steady state error covariance described as

$$\lim_{t\to\infty} E\left(\{x - \hat{x}\}\{x - \hat{x}\}^T\right), \tag{5.14}$$

is minimized. To actuate blade angle individually in the rotating coordinate system, an inverse multi-blade transformation is carried out using the transformation matrices described in [Bir10].

5.5 Simulation results and discussion

To evaluate the performance of the proposed multi-objective control strategy, the standard baseline generator torque controller is used as benchmark. In the standard torque controller, blade pitch angle is held constant at an optimum value of 2.6° and generator torque controller is used to track the maximum power point. In this chapter both blade pitch and generator torque are manipulated to realize the conflicting objectives of maximizing power production and load reduction. A stochastic wind profile with a mean value of 8 m/s (Fig. 5.4) is used to excite wind turbine

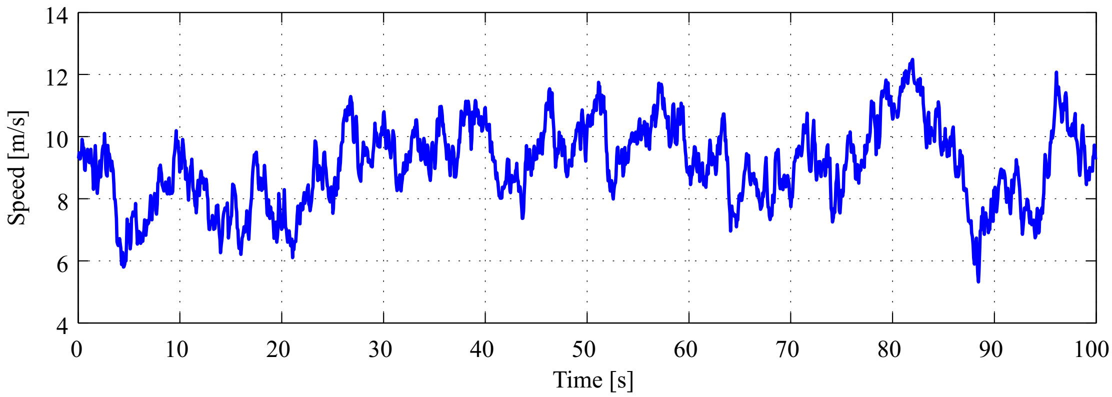


Figure 5.4: A representative stochastic wind profile for partial load region

dynamics in low wind speed region. The stochastic wind profile that mimic a real wind field with a vertical wind shear exponent of 0.2 is generated using TurbSim code developed by National Renewable Energy Laboratory (NREL).

The main objective during low wind speed is to capture as much wind energy as possible by maintaining optimum tip-speed-ratio that corresponds to the maximum power. Since the wind turbine model used to design the controller represent a turbine with optimum tip-speed-ratio of 7, the controller targets to use generator torque to regulate rotor speed in order to maintain this optimal value in spite wind speed variation.

As depicted in Fig. 5.5, no noticeable compromise on power optimization is observed when the individual pitch controller is used together with optimally tracking rotor controller to realize the multi-objective of power maximization and structural load

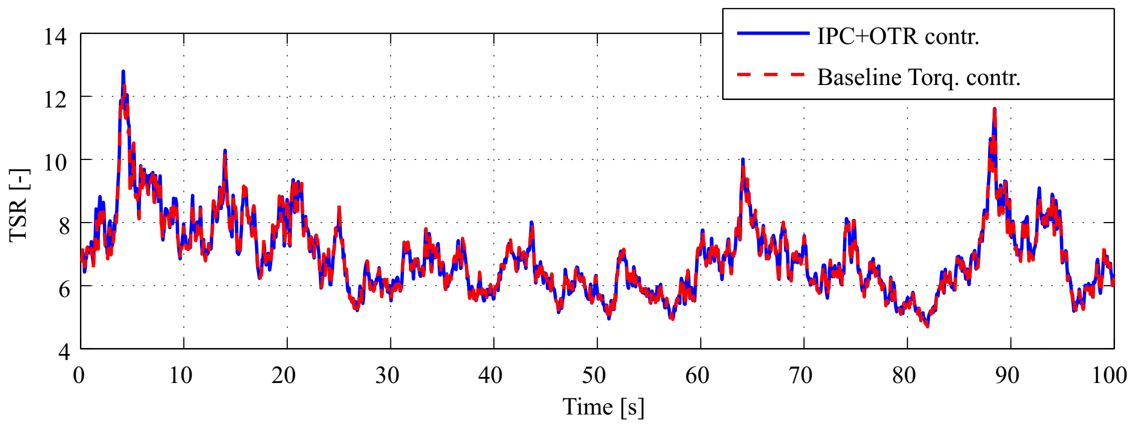


Figure 5.5: Comparison of tip speed ratio using baseline controller and load reduction strategy

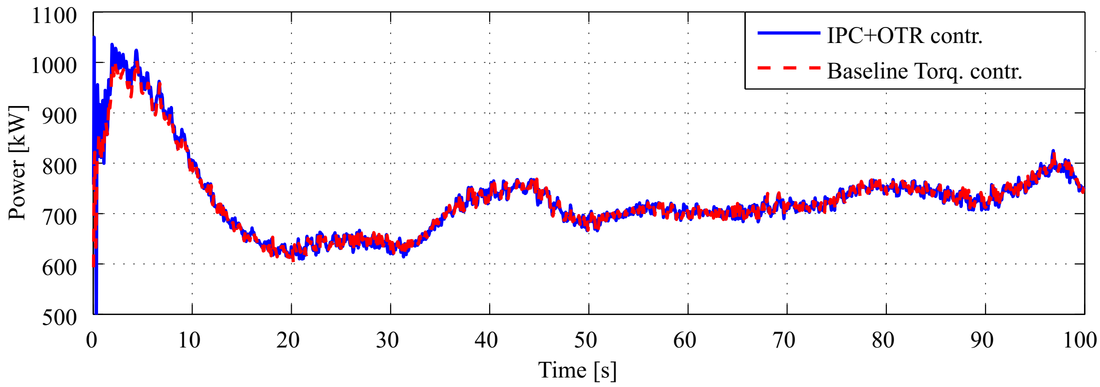


Figure 5.6: Variation of generator output power

reduction. In large wind turbines, optimally tracking of the maximum power curve is challenging because of large inertia loads. As noted in [JFBP04], power capture in large wind turbines can be slightly increased during low wind speed region if the standard torque control gain is slightly reduced because large inertial load cause the turbine to take longer time to regain the lost optimum tip-speed-ratio λ_{opt} due to sudden change in wind speed.

As shown in Fig. 5.6, generated power is below the rated value of 1.5 MW; therefore, it is important to operate wind turbine in a manner that maximizes power production for a given wind speed. Comparing the baseline controller with the proposed control strategy, no much difference in terms of output power production as depicted in Fig. 5.5 and Fig. 5.6 can be detected.

Although the main objective during low wind speed is to optimize power production, it is important to mitigate structural loads induced during power production to guarantee prolonged service lifetime and reduce failure rates. A lot of reported work

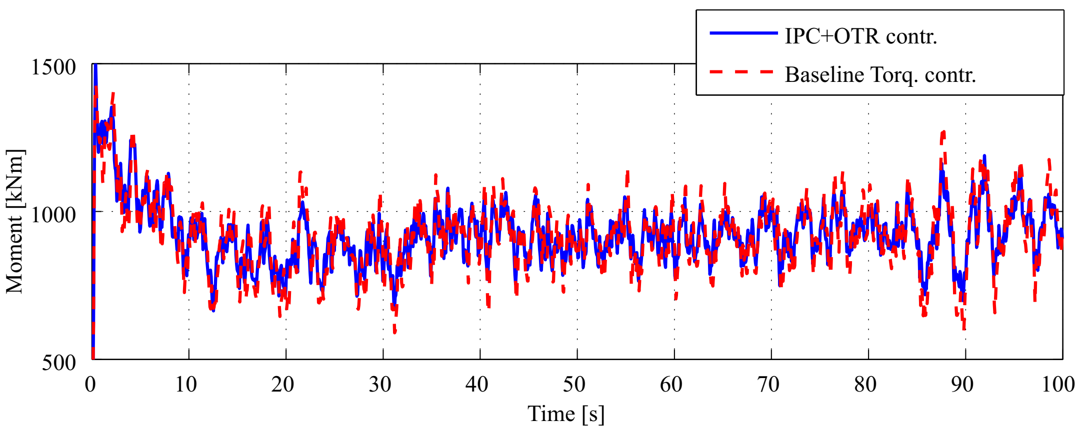


Figure 5.7: Rotor blade flapwise bending moment

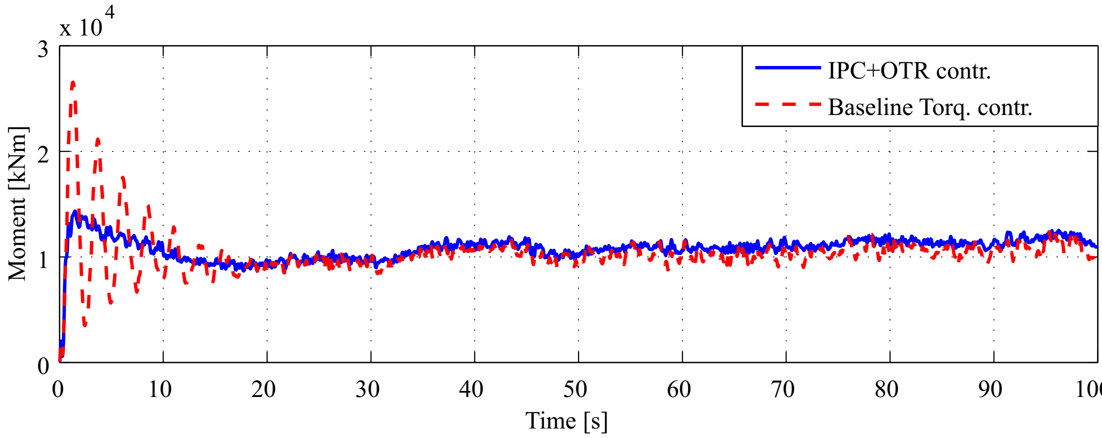


Figure 5.8: Tower base fore-aft bending moment

on structural load reduction has focused on high wind speed region. On the contrary, not much has been reported for low wind speed region. Therefore, it is important to consider structural load reduction against power optimization for lifetime extension. In this chapter, structural loads on the rotor blades and the tower are considered. A comparison between the proposed control strategy and the baseline controller with respect to rotor flapwise load reduction is illustrated in Fig. 5.7. It is apparent that the proposed control strategy has better performance compared with baseline torque controller in terms of reduction of rotor blade flapwise bending moments. The standard deviations for flapwise rotor blade moment are 14.61% and 11.47% for the baseline torque controller and load mitigation control strategy, respectively.

During wind turbine operation, aerodynamic force leads to deflection of the tower in the fore-aft direction due to thrust force affecting the apparent wind speed being experienced by rotor blades. Likewise, tower fore-aft deflection influences blade flap-

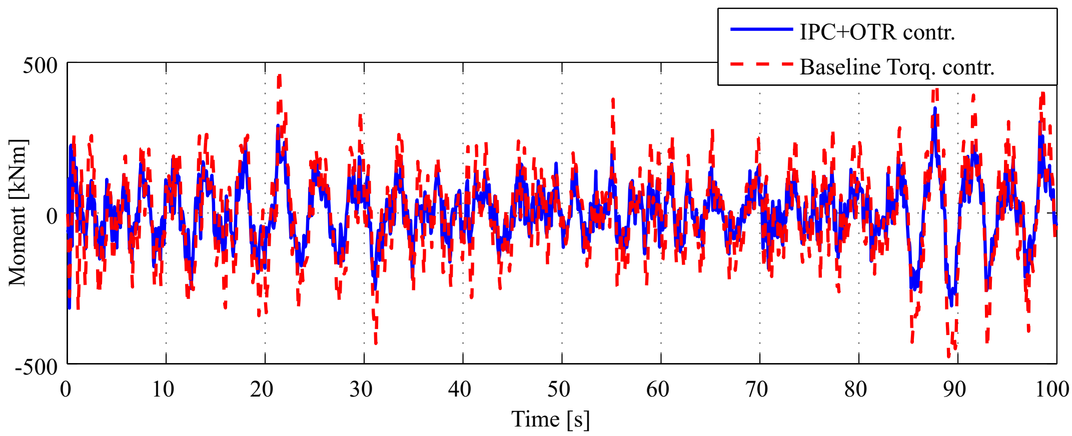


Figure 5.9: Reduction of tilt bending moment

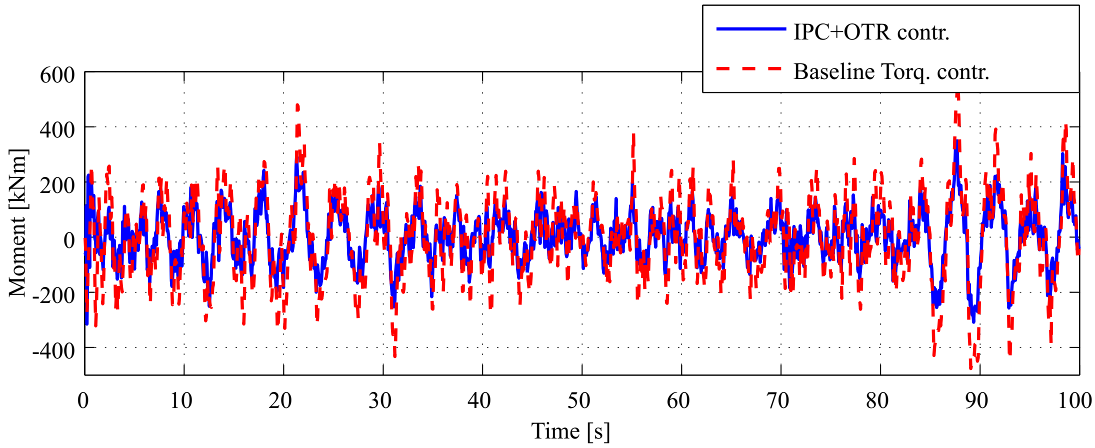


Figure 5.10: Reduction yaw bending moment

wise deflection mode; therefore, it is important to consider these two mode together when designing a controller to avoid possible instability because of the existing coupling between this two modes. The weighing matrix elements related to tower fore-aft state variables are tuned to minimize tower fore-aft loads are tuned in order to realize load reduction both in rotor blades and tower. As shown in Fig. 5.8, tower base fore-aft bending moment is significantly reduced compared to baseline torque controller. A standard deviation of 20.1% for baseline controller and 10.4% for IPC+OTR controller can be calculated.

It is important to investigate the effects of reducing blade flapwise moments on the fixed structure of the wind turbine. To evaluate the effects of rotor blade loads on the fixed structural parts of wind turbine, blade root bending moments are transformed into fictitious tilt and yaw bending moments on the fixed structure. For a three-bladed, horizontal axis wind turbine $3p$, $6p$ etc. harmonic loads are transmitted from blade to the fixed structure. As shown in Figures 5.9 and 5.10, mitigation of

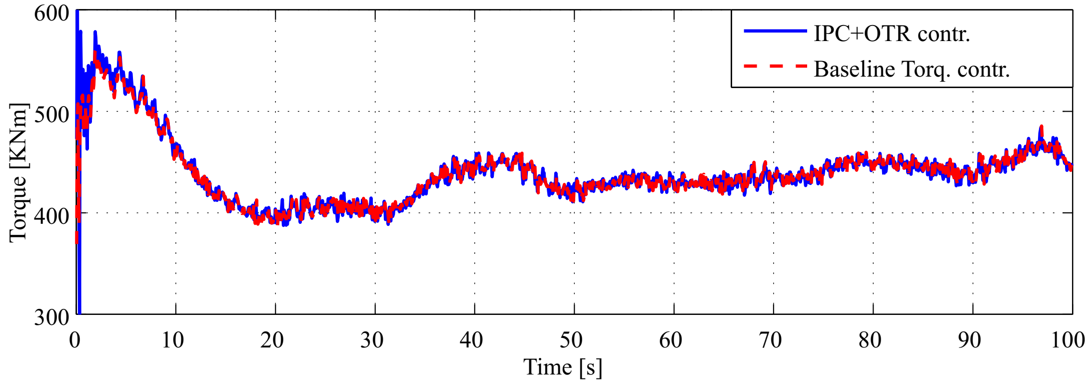


Figure 5.11: Variation of high speed shaft torque

flapwise bending moments leads to a significant reduction of nacelle tilt and yaw bending moments.

In Fig. 5.11 the variation of low speed shaft torque is shown. Again, the proposed control strategy does not show performance improvement compared to the baseline controller. It is evident that no noticeable variation about its mean value can be obtained.

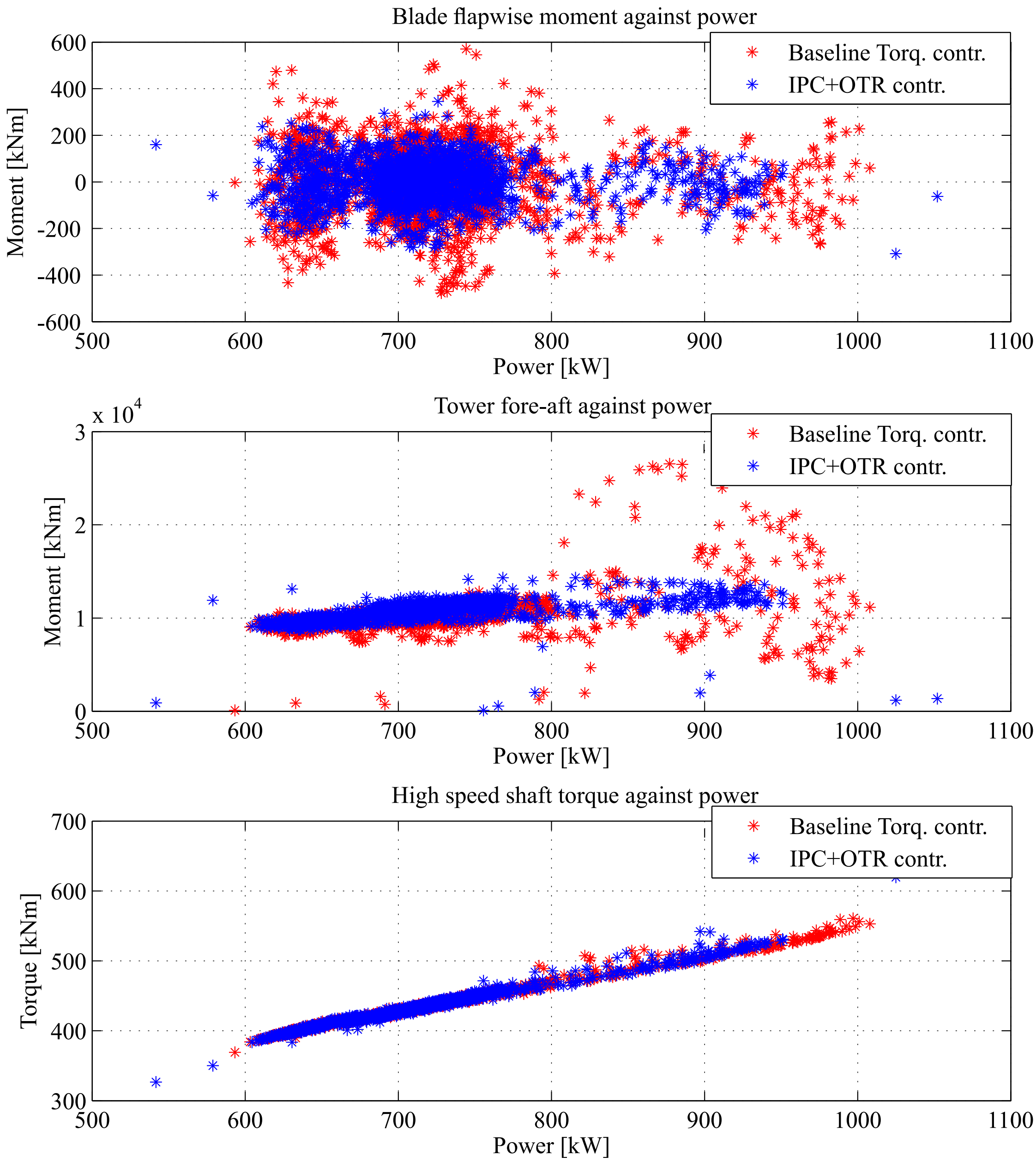


Figure 5.12: Comparison of structural load against power production

The proposed control scheme targets to reduce the structural loads without sacrificing power maximization objective. As depicted in Fig. 5.12, loads on the blades, tower, and drivetrain can be plotted against generator power to evaluate the performance of the proposed control scheme. It is observed that the IPC+OTR control scheme has strong influence on the blade flapwise and tower fore-aft compared to the baseline torque controller. On the other hand, no significant difference with respect to high speed shaft torque reduction is observed when the two control schemes are employed.

5.6 Summary

This chapter mainly focuses on maximization of power production as well as mitigation of structural loads. A variable speed wind turbine is considered using a multi-objective control strategy during low wind speed. To operate wind turbine at the maximum efficiency it is always desirable so as to extract as much power as possible. However, the induced structural loads lead to reduced reliability and possible total failure before the end of lifetime. Considering aspects of power optimization and load reduction together can result to reduced production cost of wind power through lifetime extension and reduced failure rate. In this chapter, a multi-objective control scheme comprising of an OTR controller and an individual pitch controller is proposed to realize these two conflicting objectives of structural load reduction and power production optimization. The results demonstrate that the propose control strategy can effectively meet the requirement of power optimization as well as structural loads reduction. The proposed control strategy aims at optimizing a trade-off between the power production maximization and structural load reduction in order to guarantee extended service lifetime.

6 Prognostic-Based Lifetime Extension of Wind Turbine

Since wind turbines are likely to fail due to fatigue loads emanating from variation of wind speed and other induced loads such as gyroscopic loads, it is important to employ structural health monitoring and prognostic (SHMP) techniques to monitor the health status as well as extending their lifetime. Most of the utility-scale wind turbines are designed to operate for 20 years before they loss their functionality. Like many systems, wind turbines lifecycle can be assumed to follow a typical bathtub curve [STvK09] as shown in Fig. 6.1. The reduced failure rate being observed at the infant stage and high failure rate at the wear out period (normally near the end of lifetime). At the middle stage, the turbine experiences lower constant failure rate. To reduce downtime and extend the service lifetime in wind turbines, it is important to integrate monitoring and prognostic tools in their operation for the entire lifespan. In this chapter, a prognostic-based control strategy aimed at extending lifetime of wind turbine is considered. The results discussed in this chapter have already been considered in scientific papers [BNRS15, NBS16a].

6.1 Introduction

In this chapter, a novel scheme for extending lifetime of a wind energy conversion system by integrating an online damage evaluation model into structural load reduction control strategy is proposed. Wind turbines are oft subjected to continuously changing mechanical stress due to intermittent variability of wind speed and effects of induced loads during their operation, leading to premature failure before the desired lifetime is reached. A structural load reduction strategy with varying

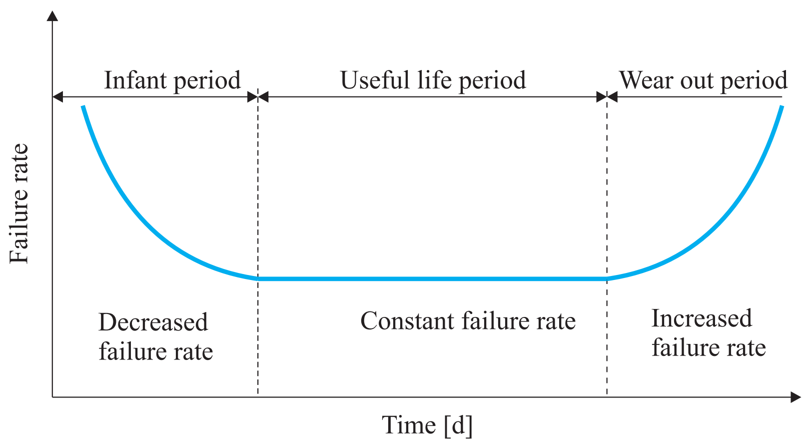


Figure 6.1: Typical failure rate bathtub curve

controller gains defining a compromise between power production and extension of wind turbine lifetime is designed. An online damage calculation model is used to determine damage levels in rotor blades then an appropriate controller corresponding to a given damage level is assigned to reduce structural loads. Depending on damage accumulation level, power production is slightly sacrificed to extend the service lifetime of wind turbine or to reach given goals with respect to the desired useful lifetime. The results indicate that the proposed method can effectively extend the lifetime of wind turbine without significant reduction in power production. The approach introduced serves as an example for a new type of service-oriented control algorithms taking into account diagnostic results from monitoring and supervision algorithms.

Although the cost of wind power has steadily declined, related production costs are still higher compared to other alternative technologies [KMA09] due to high initial investment cost as well as high operation and maintenance (O&M) costs among other factors. To make wind energy more competitive compared to other alternative sources, its overall production costs need to be reduced. This can partly be achieved by optimizing power production and embracing technologies that enhance reliability and sustainability. Operation and maintenance costs contribute to a sizeable share of the overall cost of wind power; hence, reducing it increases cost-competitiveness of wind power compared to other technologies. Reduction of O&M costs is realized by adopting suitable operational and maintenance strategies. Operational schemes that can be adopted including the employment of appropriate SHMP techniques.

After installation of wind turbines, annual operating expenses (AOE), which include O&M costs and replacement/overhaul costs, are the only adjustable charges to be minimized to reduce the cost of energy (COE). As stated in [KP13], the COE of a single wind turbine is given by

$$\mathrm{COE} = \frac{(\mathrm{FCR}\times\ \mathrm{ICC})}{\mathrm{AEP}_{\mathrm{net}}} + \mathrm{AOE}, \tag{6.1}$$

where FCR is the fixed cost rate required to recoup the capital cost, ICC denotes initial capital cost, AOE represents annual operation expenses, $\mathrm{AEP}_{\mathrm{net}}$ is the net annual energy production. In this contribution, the COE is lowered by operating the wind turbine based on its health status to extend the remaining useful life (RUL).

The assessment of the wind turbine health status and prediction of the RUL can lead to the adoption of condition-based maintenance (CBM) or predictive maintenance such that planning and scheduling of maintenance tasks are based on the health condition of the components rather than time. Condition-based operation (CBO), which is the main contribution of this chapter, can be successively used to extend the service lifetime of wind turbine by using load mitigation control strategies in conjunction with lifetime prediction models or by downscaling the operation capacity.

According to [She13, PMTP13], the main causes of downtime in wind energy conversion systems (WECS) are power, drivetrain, and rotor modules, accounting for around 67% per failure. Drivetrain and rotor modules are more expensive to repair since they are not easily accessible during maintenance compared to power modules. It is further stated in [STvK09] that maintenance of drivetrain system and rotor blades accounts for the highest downtime in wind turbine applications. As depicted in Fig. 6.2, the control system has the highest failure rate compared to other subsystems, while the drivetrain has the lowest failure rate. In contrast, failure in drivetrain leads to longer downtime. To demonstrate the application of CBO in wind turbines, structural load reduction of rotor blades is considered in this chapter as an example.

Recently, the interest to develop robust and reliable SHMP systems has sharply increased, especially in offshore applications due to harsh environmental conditions and related high maintenance cost. Accordingly, researchers have developed algorithms for determining health status of machine components as well as prognostic models, which are either based on experimental data or models. The focus of this contribution is on prognostic-based lifetime extension but further information on condition monitoring and fault detection can be found in [TWO+14,HHC+09,CF15]. It is worth mentioning that a suitable condition monitoring system should be capable of detecting the presence of a fault, determine its location, establish the extent of damage, and monitor the propagation behavior of the defect [HHC+09].

In [ETJ12], condition monitoring and prognostic challenges are discussed with a view of presenting requirements that adequately cope with multiple, complex faults,

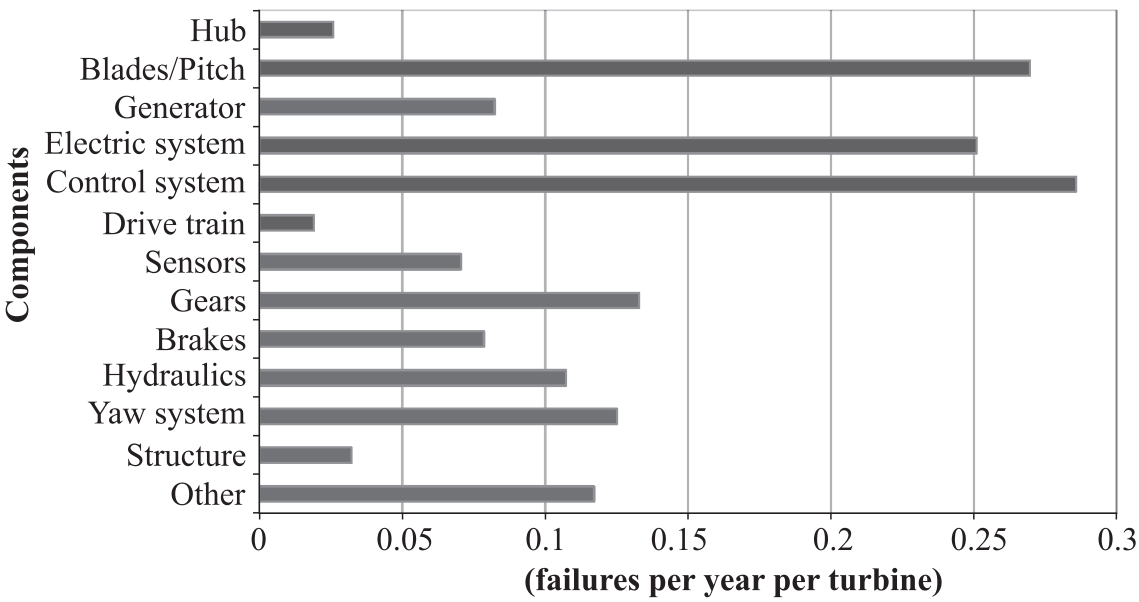


Figure 6.2: Average rate of failure of wind turbine components [PMTP13]

and different failure mode types. In offshore applications O&M costs are about 2-5 times those of land-based wind turbines [GYR+14]. Here, SHMP schemes play a very crucial role in operation and management of wind turbine systems. The concept of integrating SPHM into O&M process of offshore wind turbines is discussed in [GYR+14], with rotor blades used as an application example. The key issues considered deal with the development of multi-scale modeling and simulation tools to evaluate the effects of damage on the component's health status, and to identify and evaluate turbine structural load through appropriate control strategies in order to mitigate exacerbation of damage growth.

Before a prognostic and health management (PHM) system is implemented in wind turbines, a cost-benefit analysis is normally carried out to establish related feasibility. However, decisions or actions after prognostic indication from such systems are not explicitly quantified [HSP14]; hence, it is important to do an evaluation to determine the action to take after prognostic indication. Depending on prognostic indicator, a number of actions can be taken which include: reduction of structural loads, tactical control, and the accommodation of faults [Kad13].

An optimal prognostic-based maintenance opportunity for multiple wind turbines in an offshore wind farm that is managed via output-based contracts such as power purchase agreement (PPA) is presented in [LSGB15]. In this scheme, a stochastic discounted cash flow (DCF) approach which assumes that prediction maintenance is always implemented on a particular selected opportunity, and a simulation-based real options analysis (ROA) approach are compared. It was demonstrated that the results from the two approaches were similar when the predictive maintenance value is higher than the predictive maintenance cost for all maintenance opportunities.

A scheme to integrate SHMP management with a contingency controller is proposed in [FGO13] to extend lifetime of a wind turbine with a minor defect on the blade. The scheme aims at achieving a trade-off between optimizing power capture and extending lifetime by mitigating further damage, albeit at reduced power production. The results indicated that by applying the contingent controller and the structural health monitoring system, reduces structural load of damaged rotor blades. Similar work is reported in [SEPO15] where model predictive control (MPC) used to minimize the damage of wind turbine components is discussed.

In [WIHD15], a strategy to monitor the consumption of fatigue life of offshore wind turbines monopile foundations is considered. In this approach, only a few instrumented wind turbines are used to collect the data, the results are extrapolated for the whole offshore wind farm. To apply such an extrapolation, the relationship between operational conditions, environmental conditions, and fatigue life consumption was first sought. The results indicate that for a reliable assessment of RUL, different fatigue behaviors under different operational cases of wind turbines need to be considered.

An automated online fault prognosis scheme is presented in [CMT15, GMW13, GM13], where real-time operation data from a supervisory control and data acquisition (SCADA) system is analyzed to determine the health status as well as to extract prognostic indicators used to realize predictive maintenance. The robust approach provided to classify SCADA data allows to establish and therefore to detect the fault development. This can be used to support predictive maintenance strategies.

Although a number of control strategies to mitigate fatigue loads have been proposed [NLS15, SKW+09a, ZCC13], the scientific question on how aging models can be used to extend fatigue life of wind turbine system without much sacrifice on other important objectives such as maximization of power production and speed regulation is not extensively discussed in literature.

In this chapter, the idea presented in [BNRS15] is detailed and realized with the goal of mitigating the structural load depending on the level of damage accumulation; thus, extending the useful lifetime. Based on the health status of the rotor blade, a tactical control strategy is employed to mitigate structural loads, although at the expense of compromising speed/power regulation objectives.

In this chapter, a description of the traditional rainflow counting method and Palmgren Miner rule commonly used to evaluate fatigue loads is first described. Then, a condition-based operation strategy used to extend lifetime of wind turbine is outlined. Later, a control strategy used to optimize the trade-off of power/speed regulation and extension of lifetime is presented. Finally, a method of extending lifetime by operating turbine generator slightly below its rated capacity is introduced.

The main challenges in wind turbine fault detection are: inherent nonlinearities, variability of incoming wind speed, and the presence of noise in measurement signals. One way to surmount these challenges is to use a robust data-driven fault detection schemes like one proposed in [YWK14]. The proposed method involves generation of an optimal residual/parity vector subject to a given performance index and optimization criteria, then followed by an evaluation to make the final decision regarding faults. The results indicated that the scheme is effective and robust in fault detection, especially in scenarios where system is influenced by unknown disturbances and contain signals contaminated with noise.

In [NOGM14], a model-based prognostic model is presented for detecting faults in wind turbine drivetrain system. The fault is modeled by changing the stiffness and clearance parameters for meshing gears. In this scheme angular speed measurements of low speed and high speed shafts in combination with two more measurements of intermediate shaft located inside the gearbox are used in fault detection. The change in energy levels in frequency spectrum of an error function of input and output angular speed is treated as an anomaly. This method is relatively simple and does not require additional condition monitoring system; it is possible to effectively detect the fault before failure occurs.

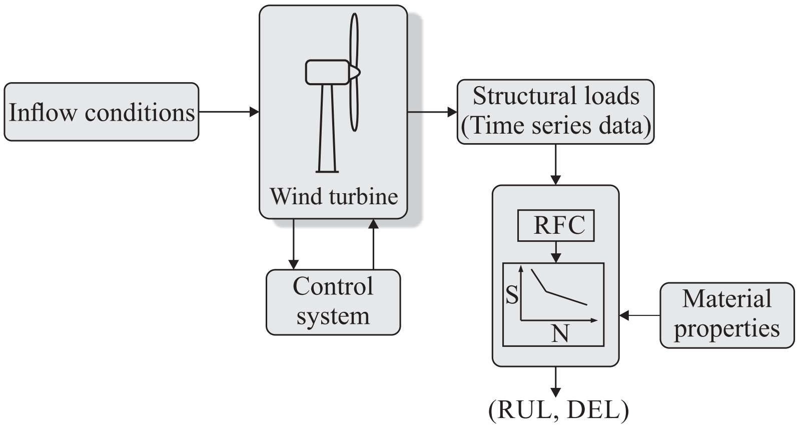


Figure 6.3: General procedure for determining the remaining useful lifetime [NBS16a]

6.2 Fatigue load evaluation based on the offline rainflow counting (RFC) algorithm

Useful lifetime extension requires knowledge about the actual status of used lifetime (or accumulated damages). To establish related measures, suitable methods are utilized to infer damage levels from applied structural loads. In a second step, information from structural load evaluation scheme is used for effecting the control system, thereby operating wind turbines depending on its health status.

In the literature, a number of models have been proposed to evaluate fatigue life of machine components [RM07,BCLP15]. For general applications, load cycle counting-based (rainflow counting and Palmgren miner) algorithm is popular due to its simplicity. The Palmgren miner damage rule assumes a linear damage accumulation. Other complex nonlinear fatigue damage models exist [HB13, YLH^{+}14]. In this thesis a linear load cycle counting model is assumed.

During the operation of wind turbine, most of its components are subjected to varying mechanical stresses due to variability of wind speed. This in turn leads to gradual degradation of individual components until a total failure occurs. This process starts in micro-scale due to irreversible changes in microstructure and propagates with time until its manifests itself as a defect leading to loss of functionality of a given component [CMT15]. The knowledge on how a component degrades with time is very important since it can give an estimate of remaining useful life (RUL) before it looses its functionality.

As depicted in Fig. 6.3, load counting algorithm uses time series input data and calculates the remaining useful life of the turbine through extrapolation. Additionally, a constant magnitude equivalent fatigue load (EFL) that gives rise to the same fatigue damage as a varying amplitude load over the same number of cycles can be determined using this model.

Damage degradation in machine components can be described by a Wöhler equation given by

$$s^m N = K, \tag{6.2}$$

where N is the number of cycles to failure for a given stress range s. The constants m and K are material specific parameters. In wind turbine applications, m referred to as Wöhler coefficient, is taken to be equal to 3 for components made of steel and 10 for rotor blades made of fiber composite material [RM07]. Using rainflow counting and Palmgren-Miner rule, damage accumulation is calculated as

$$D_k = \sum_{i=1}^{k} d_i = \sum_{i=1}^{k} \frac{n_i}{N_i} = \sum_{i=1}^{k} \frac{n_i s_i^m}{K}, \tag{6.3}$$

where s_i denotes stress range corresponding to the i_{th} stress cycle, N_i is the number of cycles the material endures until it fails, and k is the total number of cycles. The component under investigation is considered to have reached the end of life if D_k is equal to one. The end of lifetime is evaluated as

$$T_f = T_k D_k^{-1}, \tag{6.4}$$

where T_f is the time to failure and T_k denotes principal load units required to accumulate damage D_k. Accordingly, the remaining useful lifetime (RUL) can be calculated if the turbine service lifetime is known from the manufacturer.

To calculate EFL, Eqn. (6.3), is modified as

$$EFL = \left(\sum_{i=1}^{k} \frac{s_i^m}{N_i} \right)^{\frac{1}{m}}. \tag{6.5}$$

In Fig. 6.4, an offline method for calculating damage accumulation using time series data set of blade bending moments is illustrated. The rainflow counting toolbox as proposed in [Nie09] is used to establish the peak data points, followed by damage levels calculation which are used in damage accumulation computation. The load data of 600 s is used, but for the sake of clarity only 100 s are displayed for the extremum data point plot. It is important to note that run-to-failure data is not used to determine the service life of wind turbine, rather a representative time series data is used to extrapolate the time it would take to fail when subjected to similar loading conditions. This methods assumes that the operation conditions do not change during the entire lifetime which is rarely the case in real life operation. Moreover, this method does not account for downtime due to maintenance; it assumes 100%

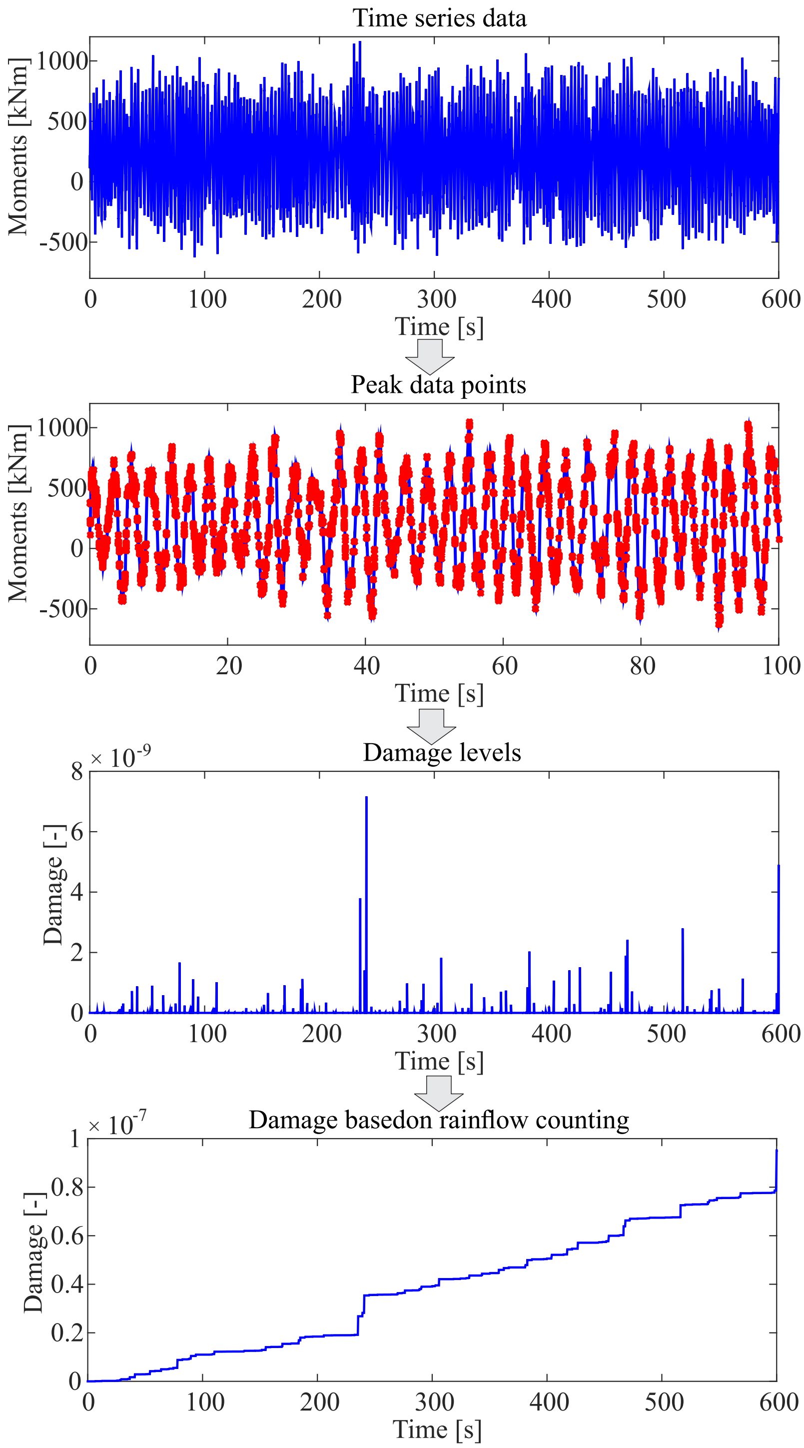


Figure 6.4: Steps for rainflow counting methods-based damage evaluation [NBS16a]

availability of the wind turbine for the entire lifetime. Furthermore, this algorithm cannot predict component life at stress ratios different from those used to develop its stress-cycle curve (S-N curve) [VMK10]. To address some of these shortcomings, the National Renewable Energy Laboratory (NREL) modified this algorithm to include load cycles over a wider spectrum of stress ratios as well as adding other enhanced features to come up with a fatigue analysis tool called MLife [HBJ12]. The MLife is used as a post processing program and cannot be used for online realization. Of course this kind of calculation can be used for real-time damage evaluation as required in this context.

6.3 Control loop for load reduction

In this chapter, a multiple-input multiple-output (MIMO) control scheme similar to one described in [NLS15] is used together with an aging model to extend operational lifetime of wind turbine. A frame that integrates load reduction strategy and prognosis model is illustrated in Fig. 6.5. Here, a number of individual blade pitch controllers at different operation points are designed to mitigate flapwise bending moments. Accordingly, an online damage evaluation model is used to determine fatigue damage accumulation during the operation of wind turbine. Depending on the predefined thresholds, the control strategy is adjusted to reduce the structural loads; thus, extension of lifetime. The scheme aims at optimizing the trade-off between speed/power regulation and reliability in the sense of extending the lifetime. The RUL is computed as $T_k(1 - D_k^{-1})$. In this thesis, the RUL is controlled indirectly by deploying different load reduction controllers depending on the accumulated damage level to reach the desired end of lifetime which assumed to be known in this case.

Assuming that the presence of a fault can be accurately detected by fault detection algorithms, the prognostic-based control scheme proposed in this chapter can be used to extend the lifetime of a faulty turbine to reach its desired lifetime without causing collateral damage to other critical components. As illustrated in Fig. 6.6, a fault appears at t_i. Then, a prognostic-based control scheme is employed to ensure that turbine reaches its end of lifetime at $t_{_{end}}$ by reducing damage levels per sampling time, although at a reduced power production and poor speed regulation. If the fault is induced, it will lead to increased damage development and therefore leading to a reduction of useful lifetime. In this illustration, a faulty wind turbine is considered to have reach end of lifetime at $t_{_f}$ if nominal controller is still used after fault has occurred. On the other hand if structural load mitigation control scheme is employed, the lifetime can be extended by $\Delta t_{_f}$ to reach the initial desired end of lifetime. Such damage can result from extreme operation conditions such as gust wind. It is important to note that the proposed scheme is based on online damage accumulation and it is independent from the wind profile acting on wind turbine.

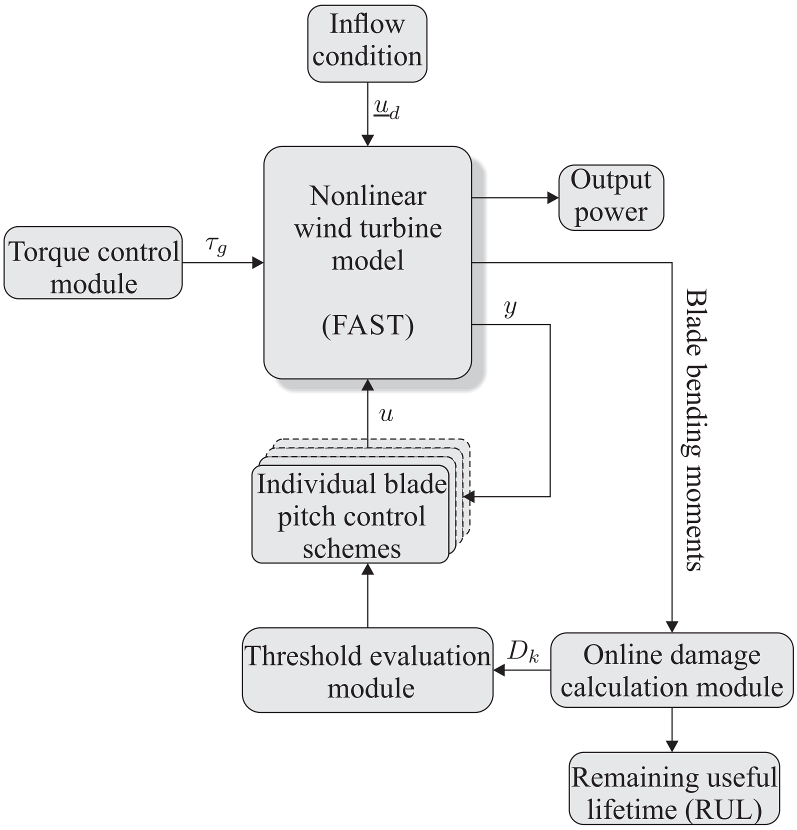


Figure 6.5: Control strategy integrating online damage evaluation model [NBS16a]

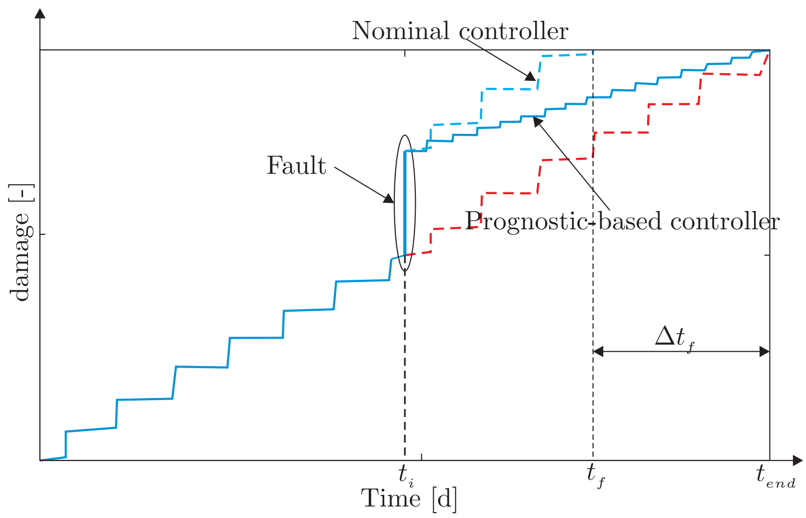


Figure 6.6: Lifetime extension for a faulty turbine [NBS16a]

6.3.1 MIMO control design for load reduction

In this chapter, an approximation LTI model is used to design a structural load reduction scheme. To design the controller, wind turbine is described by following state-space dynamic model

$$\begin{aligned} \dot{x} =& Ax + Bu + B_d u_d, \\ y =& Cx + v, \end{aligned} \tag{6.6}$$

where $x \in \mathbb{R}^n = \left[\Delta \underline{q},\ \Delta \dot{\underline{q}}\right]^T$ is the system state vector, $u \in \mathbb{R}^m = [\Delta\beta_1,\ \Delta\beta_2,\ \Delta\beta_3]^T$ denotes the control input, $y \in \mathbb{R}^p$ is the measurement output, $A \in \mathbb{R}^{n\times m}$ represents system matrix, $B \in \mathbb{R}^{n\times m}$ is the input matrix, and $C \in \mathbb{R}^{p\times n}$ denotes the output measurement matrix. In addition to unknown exogenous disturbances u_d, the measurement y is assumed to be noisy with v as additive noise.
The controllers used are based on linear quadratic (LQ) control design approach where an optimal control input is sought that minimizes the following performance index

$$J = \int_0^t (x^T Q x + u^T R u) dt. \tag{6.7}$$

The state weighting matrix $Q = Q^T \in \mathbb{R}^{n\times n} \geq 0$ and control weighting matrix $R = R^T \in \mathbb{R}^{m\times m} > 0$ are used to optimize a trade-off between state regulation and control input usage. The matrix Q and R are tuned to get a series of control gains that correspond to different structural load levels. Depending on the predefined damage levels, the control gains are changed to reduce the structural, albeit at slight compromise on speed regulation objective.

Since the incoming wind possesses stochastic properties and the fact that the output measurements are noisy, the Kalman estimator can be effectively used to reconstruct the system states using control input and noisy measurement signals. The continuous Kalman estimator is defined by the following dynamic model

$$\begin{aligned} \dot{\hat{x}} =& A\hat{x} + Bu + L(y - C\hat{x}), \\ \hat{y} =& C\hat{x}, \end{aligned} \tag{6.8}$$

where $\hat{x}$ is the estimated state, while $\hat{y}$ is estimated measured output, and L denotes the Kalman gain. Unlike the classical Luenberger observer, the gain L is designed such that state estimation error covariance $E\left[(x - \hat{x})(x - \hat{x})^T\right]$ is minimized in a sense of a given quadratic performance index related to disturbance and measurement noise covariance matrices. A realized feedback controller is designed using estimated states as

$$u = K\hat{x}, \tag{6.9}$$

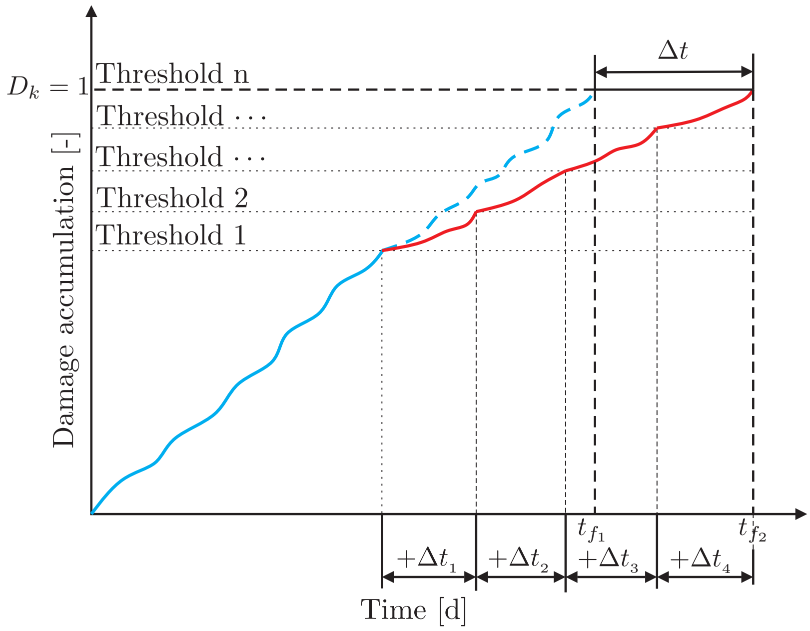


Figure 6.7: Remaining useful lifetime extension scheme [NBS16a]

where K is optimally designed by minimizing the performance index given by Eqn. (6.7). Similarly, similar control strategy can be realized by using a stochastic disturbance accommodating controller as discussed in [NS15] to compensate for unknown system disturbance using measurement signal that is contaminated by noise.

6.4 Extension of wind turbine lifetime: An illustrative example using NREL 1.5 MW turbine

Modern wind turbines have an approximate lifespan of 20 years or 2.7×10^8 fatigue stress cycles [HP14] but in most cases there is a likelihood of failure before reaching this time due to fatigue damage. Consequently, a lot of efforts are being made to develop models that monitor wind turbine deterioration process or predict its lifetime before it fails. This damage evaluation model can also support reliability oriented maintenance techniques such as condition-based maintenance [ETJ12] to accurately forecast the occurrence of faults and plan for the future maintenance schedules. Another approach being employed to extend the operational life of wind turbine is the use control strategies to mitigate structural loads. While this approach is promising, very little has been reported on the integration of control strategies with damage evaluation models to quantify the extent of lifetime extension.

This chapter aims to combine structural load reduction control strategy with lifetime prediction model so as to extend the lifetime of wind turbine. In Fig. 6.7 a generalized scheme of using an damage evaluation description used as aging model together with a load reduction control strategy to delay the degradation of wind turbine is shown.

Without structural load reduction consideration, the turbine looses its functionality at time t_{f_1} which is lower than the expected life time t_{f_2}. Assuming that this loss of lifetime can be quantitatively defined by a suitably designed diagnosis scheme, the remaining life time will be shortened if control scheme is not changed. With the proposed strategy, the objective is to extend the lifetime of wind turbine by Δt to compensate for the lost URL, hence reaching the desired lifespan. Using the introduced Wöhler/Palmgren Miner calculation which assumes a linear damage accumulation, the nominal and the resulting lifetime of the damaged/faulty systems can be assumed as known [Söf01, Söf00]; therefore, the control strategy is used to make sure that the wind turbine does not cease before its desired lifespan is reached. Likewise, similar control strategies can be used to extend the lifetime of a slightly damaged wind turbine to reach it nominal end of lifetime to avoid unwarranted downtime. Similarly, power production is optimum when the load reduction control method is not employed. In other words, the load reduction control strategy seeks to optimize a trade-off between lifetime extension and the quality of the generated power. Instead of using a continuously operating strategy in this chapter, a discrete multi model approach is realized in order to reduce the complexity for practical realization. Without loss of generality, the proposed approach can be extended to a very detailed mesh or even continuously smoothed approach. Predetermined thresholds are used to switch between controllers depending on the accumulated damage levels.

Since an online damage evaluation model is required in this strategy, the damage model based on the rainflow counting method discussed in section 6.2 cannot be used. To do an online rainflow counting and subsequent calculation of damage accumulation, the algorithm presented in [MJ12b] is used in this chapter. At first, the wind turbine is operated at optimum power without considering load reduction strategy, then it degrades until the damage accumulation reaches the first threshold. There after the load reduction strategy is engaged at varying levels to the end of lifetime.

In Fig. 6.8 damage accumulation levels for different wind speeds and different controllers with varying load reduction capabilities is depicted. The wind speeds are varied from 12 m/s to 22 m/s at a step of 2 m/s. In this chapter, controller 1 represents a case where the objective of speed/power regulation is perfectly realized, but at a cost of increased structural loads. On the other hand, controller 5 has strong structural load mitigation ability though at at slightly compromised output power regulation. It is evident from the figure that structural loads reduce as wind speed reduces. It is important to mention that full-field turbulent wind profiles generated by NREL TurbSim simulation code are used in this chapter to determine fatigue related damages.

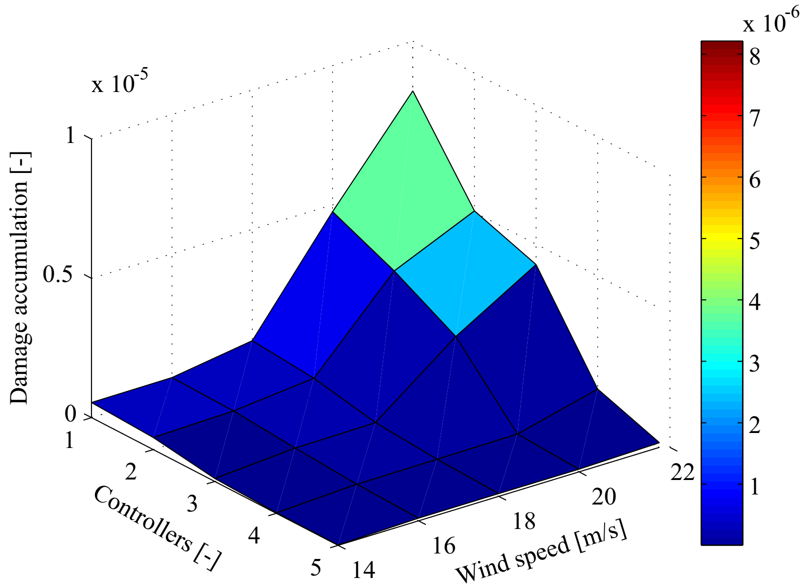


Figure 6.8: Damage accumulation for different controllers and wind speeds [NBS16a]

In Fig. 6.9, a correlation between structural load mitigation and power variation is drawn. In this case, independent blade pitch controllers with varying degrees of mitigating structural load are designed. It is observed that the variation of mean output power increases as the DEL reduces, although at a very small rate: a 21.38% reduction in DEL results in a 1.55% increment in mean output power fluctuation. Though the influence on output power variation might not be that significant, structural load reduction might lead to undesirable spin-off effects such as increased pitch actuation duty cycle (ADC); hence, a careful trade-off between various performance characteristic is paramount in achieving the overall objective of extending lifetime and power production. For a 600 s simulation window, it is evident that the level of accumulated damage reduces as the controllers are switched from 1 to 5. To demonstrate the concept of integrating prognosis model into control loop, five multivariable controllers with different load reduction capacities are designed for a wind speed of 18 m/s. Then, these controllers are operated depending on the level of damage for the machine part under investigation. For the simulation period of 600 s, the accumulated damage reduced by around 40% when the damage evaluation model is integrated in control loop as illustrated in Fig. 6.10. As mentioned, the aim is to strike balance between lifetime extension and power regulation.

6.5 Lifetime extension by de-rating generator

If the occurrence of fault and its mode of propagation can be predicted, tactical operation can be employed to extend the lifetime until of wind turbine the next

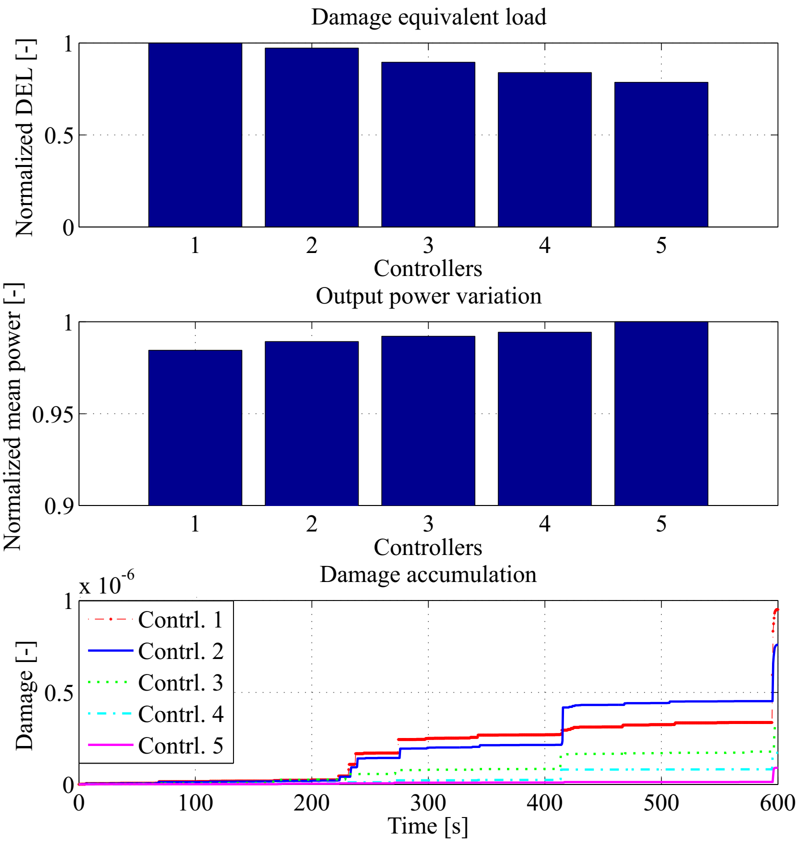


Figure 6.9: Correlation between load reduction and power production [NBS16a]

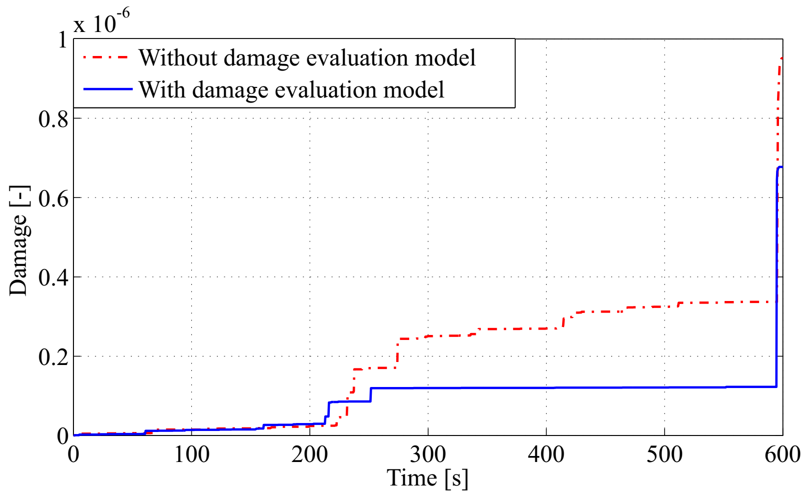


Figure 6.10: Comparison of damage accumulation with and without prognostic model [NBS16a]

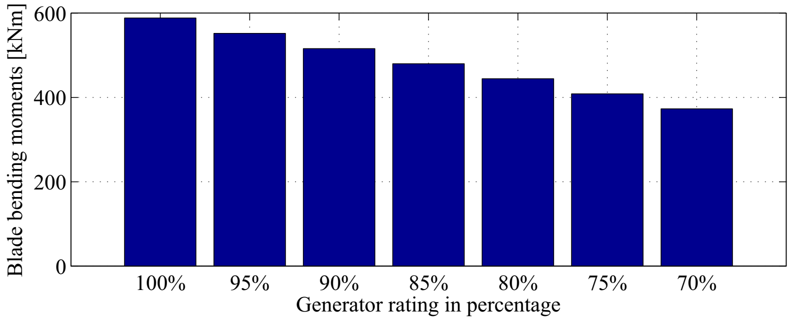


Figure 6.11: Reduction of load by de-rating generator [NBS16a]

planned/scheduled maintenance, although at a reduced power production or at the cost of compromising other important objectives such as regulation of speed/power. One of the tactical operations employed in wind energy harvesting is to run the turbines at a downscaled operation capacity. The aim of this approach is to optimize the trade-off between maximization of power production and extending the lifetime of wind turbine. This condition-based operation strategy is very crucial in applications where wind power is supplied under contractual obligations like PPA or in situations where lead time before replacement/repair of damaged turbine is long due to logistics challenges, especially in offshore applications [FGO13]. The adoption of condition-based operation can significantly reduce the occurrence of unscheduled maintenance which can contribute to a substantial portion of the overall O&M cost. Additionally, the chances of collateral damage to other wind turbine components can be significantly reduced if the defective components are identified and timely appropriate corrective action is taken.

In large composite rotor blades, defects can manifest itself in the form of delamination, and if the severity level of damage are not acute, the RUL of such blade can still be utilized with a view of optimizing the production cost of wind power, albeit at a compromised performance. In model-based approaches of investigating the performance of defective wind turbine blades, faults can be induced by altering the local flap-wise and edge-wise stiffnesses along the blade span length [GYR+12, CDLM13].

In Fig. 6.11, the effect of de-rating wind turbine generator on the flapwise rotor blade bending moments is illustrated. Here, the generator is de-rated from 100% to 70% of the rated value. As a result, the blade flapwise bending moment is reduced by 36.6%. A similar observation is expected in edgewise bending moments, although flapwise loads are more pronounced compared to edgewise blade loads.

6.6 Summary

In this chapter, a framework to integrate an online damage evaluation model into a control loop of wind turbine is presented. The aim of this scheme is to extend the lifetime of wind turbine either by optimizing the trade-off between structural load reduction and speed/power regulation, or by mitigation of structural loads and maximization of power production. The knowledge of how components in wind turbine system degrade during power production is an important aspect in planning and scheduling of maintenance since it can lead to increased availability and reduction of overall production cost of wind power.

An online fatigue damage evaluation model is adopted in this chapter to adjust structural load control strategy so as to compromise the trade-off between reliability and optimization of power production. It is important to note that a damage evaluation model based on linear damage accumulation is used in this chapter for the purpose of demonstrating the concept; otherwise, fault propagation in wind turbine might be highly nonlinear due to variability of wind speed and the inherent nonlinearities in turbine itself. It has also been demonstrated that severity of damage propagation can be abated by operating wind turbines at a scaled down capacity. Again this strategy can be used to optimize the maintenance scheduling. The results demonstrate that the proposed condition-based operation can lead to optimized wind energy production, especially in offshore applications due to logistic challenges related to maintenance.

7 Summary, Conclusion, and Future work

7.1 Summary and conclusion

In this thesis, multi-objective control strategies for wind turbines in low and high wind speed region are developed. During high wind speed individual blade pitch controller is used to mitigate structural load as well as regulating power/speed about the rated values. Since these two objectives do conflict with each other, a trade-off is made so that the desire performance is realized while at the same time extending lifetime of wind turbine by reducing structural loads. In this thesis, perturbed individual blade pitch angles are used about the nominal collective blade pitch control signal to come up with multi-objective control strategy. To avoid performance degradation, individual pitch control signals are only maintained as small perturbations of the nominal control loop. Additionally, the individual pitch controller should not actively regulate rotor rotational speed; the element related to speed regulation should not be weighted in individual blade controller. Since the focus was to mitigate the structural loads on rotor blades, electrical generator torque is maintained constant at the rated value, while rotor blades were controlled individually to achieve the desire performance.

In low wind speed region, a multi-objective control strategy is extended so that the maximum power extraction is realized in additional to mitigating structural loads. When wind speed is lower than the rated value, the main control objective is to maximize power extraction by tracking the maximum power curve. As a result undesired vibrations are induced to other structural part of wind turbine due to variation of wind speed. Hence, it is important to track the maximum power curve while mitigating the structural loads. To achieve a multi-objective control objective both the pitch and and torque control methods are used at the same time. However, the perturbed output from pitch controller is limited to avoid induction of undesired vibrations to other structural members.

Nowadays, the trend in wind power production is to upscale the size of the turbines so as to increase the power production, with offshore applications offering greater potential of upscaling due to higher wind speed in offshore sites. Due to the harsh conditions under which offshore wind turbines are subjected, a comprehensive structural health monitoring and control methods must be adopted to make power production economically viable. In this thesis, a prognostic-based control strategy is discussed. Here, an online damage evaluation model is integrated into the main wind turbine control loop to extended its remaining useful lifetime by reducing blade structural loads. This aims at making a trade-off between extending the lifetime and regulating speed and power production. Likewise a similar strategy can used to de-rate wind turbine generator according to the level of accumulated damage such that the desired end of lifetime is reached. If unpredictable faults occur like cracks in the rotor blade, a prognostic-based control similar to one proposed in this thesis can be applied to extend power production until the next scheduled maintenance. Additionally, for offshore applications, condition-based operation can significantly improve the availability of wind turbine as well as optimally plan for maintenance scheduling given the logistic challenges associated with accessing such sites for maintenance routines.

In large wind turbines applications, direct drivetrain is being adopted as an alternative to geared drivetrain due to reliability issues and low maintenance costs. While direct drivetrain offer more advantages over geared drivetrain, the issues of its future production sustainability remains unresolved. This is due the fact that permanent magnet synchronous generator used in direct drive train is made from rare earth metal whose mining process poses great environmental degradation.

To evaluate the effectiveness of the multi-objective control strategies proposed in this thesis, baseline controllers are used: the standard baseline PI controller for speed regulation is used in high wind speed region, while a standard baseline torque controller is used in low wind speed region. It was demonstrated that a reasonable compromised between structural load mitigation and speed/power regulation can be realized by the multi-objective control strategy proposed for high wind speed region. Additionally, it has been demonstrated that a multi-objective of power extraction maximization and structural load reduction can be achieved at the same time in low wind speed region. Moreover, it was shown that the application of prognostic-based control strategy can be effectively applied to extend lifetime of wind turbine. In this thesis, the end of lifetime was assumed to be known such that in case of unexpected damage occurring, a prognostic-based control is applied to ensure that the end of lifetime is reached or wind turbine lifetime is extended beyond nominal end of lifetime till it completely losses functionality.

7.2 Future work

In this thesis, the partial load and high wind speed region are treated as two distinct regions, and a multi-objective control strategy is designed for each region independently without considering transition control strategy between these two regions. As future work, the consideration for transition between low speed region to high wind speed region can be investigated. The control strategies presented in this thesis is based on onshore wind turbines and it is important to investigate performance of control strategies on offshore wind turbines to take into consideration additional disturbance due to ocean waves.

Wind speed variation and vertical wind shear are considered as unknown disturbances that can be compensated for to improve the performance of the closed loop system. In this study, unknown disturbance are estimated and compensated dynamically using extended disturbance rejection approach. As an extension, measurements LIDAR system can be integrated into control system to compensate for wind speed variation as well as vertical wind shear.

The damage evaluation model used in this thesis to design a prognostic-based control strategy assumes linear damage accumulation so as to compute end of lifetime of wind turbine. It is also assumed that turbine has 100% availability (without considering downtime due to maintenance), which is not practical in real life application. To improve on the proposed prognostic-based control strategy, a more realistic damage evaluation model that give more accurate prediction on the time failure is likely to occur. In this case, a nonlinear damage model could be used to forecast evolution of damage with time.

Other control approaches could be applied to come up with a multi-objective control strategies like model predictive control using LIDAR system to explicitly take into consideration constraints of the actuators in control synthesis process. Since wind turbines are inherently nonlinear, a data-driven or nonlinear control methods could also be applied to accomplish the desired control performance.

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This thesis is based on the results and development steps presented in the following previous publications:

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Conference papers

[NLS15] Njiri, J.G.; Yan, L.; Söffker, D.: Multivariable Control of Large Variable-Speed Wind Turbines for Generator Power Regulation and Load Reduction. *IFACPapersOnLine*, 48(2015), pp. 544-549

[NLS14] Njiri, J.G.; Liu, Y.; Söffker, D.: Disturbance Attenuation using Proportional-Integral-Observer for Wind Turbine Speed Regulation. In: *Proc. ASME 2014 Dynamic Systems and Control (DSC) Conference*, Vol. 3, 2014, pp. V003T53A005.

[BNRS15] Beganovic, N.; Njiri, J.G.; Rothe, S.; Söffker, D.: Application of Diagnosis and Prognosis to Wind Turbine System Based on Fatigue Load. In: *Proc. IEEE Conference on Prognostics and Health Management PHM 2015, Austin, TX, USA*, 2015, pp. 1-6.

[NS15] Njiri, J.G.; Söffker, D.: Multi-objective Optimal Control of Wind Turbines for Speed Regulation and Load Reduction. In: *Proc. ASME 2015 Dynamic Systems and Control (DSC) Conference*, Vol 1, 2015, pp. V001T05A002

In the context of research projects at the Chair of Dynamics and Control, the following student thesis has been supervised by Jackson Gĩthu Njiri and Univ.-Prof. Dr.-Ing. Dirk Söffker. Development steps and results of the research projects and the student theses are integrated with each other and hence are also part of this thesis.

[Jin15] Jin Q., Individual Blade Pitch Control of Large Wind Turbine for Power Regulation and Structural Loads Reduction, Master Thesis, February 2015