Gain-Scheduling Control of Floating Offshore Wind Turbines on Barge Platforms

by

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Abstract

This thesis studies the application of gain-scheduling (GS) control techniques to floating offshore wind turbines on barge platforms. Modelling, control objectives, controller design and performance evaluations are presented for both low wind speed and high wind speed cases. Special emphasis is placed on the dynamics variation of the wind turbine system caused by plant nonlinearity with respect to wind speed.

The dynamics variation is represented by a linear parameter-varying (LPV) model. The LPV model for wind turbines is derived by linearizing the nonlinear dynamics at various operating wind speeds and by interpolating the linearized models.

In low wind speed, to achieve control objectives of maximizing power capture and minimizing platform movements, for the LPV model, the LPV GS design technique is explored. In this region, the advantage of making use of blade pitch angle as a control input is also investigated. In high wind speed, to achieve control objectives of regulating power capture and minimizing platform movements, both LQR and LPV GS design techniques are explored.

To evaluate the designed controllers, simulation studies are conducted with a realistic 5 MW wind turbine model developed at National Renewable Energy Laboratory, and realistic wind and wave profiles. The average and root mean square values of power capture and platform pitch movement are adopted as performance measures, and compared among designed GS controllers and conventional controllers. The comparisons demonstrate the performance improvement achieved by GS control techniques.
Preface

This dissertation is original intellectual property of the author, Omid Bagherieh, under supervision of Dr. Ryozo Nagamune. This work has been completed in the Control Engineering Laboratory at the University of British Columbia. The results presented in Chapters 5 and 6 are going to be submitted for publications.
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</tr>
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<td>$\lambda_{max}$</td>
<td>Tip speed ratio for maximum efficiency</td>
</tr>
<tr>
<td>$\omega_g$</td>
<td>Generator speed (rpm)</td>
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<td>$\omega_{g,\text{ref}}$</td>
<td>Reference for generator speed (rpm)</td>
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<td>$\omega_r$</td>
<td>Rotor speed (rpm)</td>
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\( K_e \) Gain for the error in the state-feedback controller
\( K_v \) Ratio of reference generator speed signal to wind speed in low wind speed
\( K_x \) Gain for the states in the state-feedback controller
\( N \) Gear-box ratio
\( P \) Power capture (W)
\( P(v) \) Plant state-space model
\( P_{avg} \) Average of power capture (W)
\( P_{lyp} \) Lyapunov function
\( P_{rated} \) Rated power capture (W)
\( P_{rms} \) Root mean square of power capture (W)
\( phv \) Platform heave displacement (m)
\( phv_{rms} \) Root mean square of platform heave displacement (m)
\( ppt \) Platform pitch angle (degree)
\( ppt_{rms} \) Root mean square of platform pitch angle (degree)
\( prl \) Platform roll angle (degree)
\( prl_{rms} \) Root mean square of platform roll angle (degree)
\( psg \) Platform surge displacement (m)
\( psg_{rms} \) Root mean square of platform surge displacement (m)
\( psw \) Platform sway displacement (m)
\( psw_{rms} \) Root mean square of platform sway displacement (m)
\( pyw \) Platform yaw angle (degree)
\( pyw_{rms} \) Root mean square of platform yaw angle (degree)
\( Q \) Weighting matrix on states for the linear quadratic regulator
\( R \) Weighting matrix on states for the linear quadratic regulator
\( r \) Blade radius (m)
\( T_g \) Generator torque (N.m)
\( t \) Time (s)
Control inputs to the plant $u$

Disturbance inputs to the plant $u_d$

Wind speed (m/s) $v$

The low wind speed operating range ($Region\ II$) $v_{Region\ II}$

The high wind speed operating range ($Region\ III$) $v_{Region\ III}$

Weighting function for error in LPV gain-scheduling controller $W_e$

Weighting function for platform pitch angle in LPV gain-scheduling controller $W_{ppt}$

Weighting function for control inputs in LPV gain-scheduling controller $W_u$

Weighting function for control inputs’ rate-of-change in LPV gain-scheduling controller $W_{\dot{u}}$

States of the linearized plant $x$

Plant outputs $y$

Generator speed output from the plant (rpm) $y_\omega_g$

Generator speed at an equilibrium condition (rpm) $y_{\omega_g,0}$

Reference for generator speed (rpm) $y_{\omega_g,\text{ref}}$

Platform pitch angle output from the plant (degree) $y_{ppt}$

Reference for the feedback signal $y_{\text{ref}}$
# Acronym

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<td>BaseR3</td>
<td>Baseline controller in high wind speed</td>
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<td>GS</td>
<td>Gain-scheduling</td>
</tr>
<tr>
<td>ICICS</td>
<td>Institute for Computing, Information and Cognitive Systems</td>
</tr>
<tr>
<td>LMI</td>
<td>Linear matrix inequality</td>
</tr>
<tr>
<td>LPV</td>
<td>Linear parameter-varying</td>
</tr>
<tr>
<td>LPV GS</td>
<td>Linear parameter-varying gain-scheduling controller</td>
</tr>
<tr>
<td>LPV GS OF</td>
<td>Linear parameter-varying gain-scheduling controller with output-feedback</td>
</tr>
<tr>
<td>LPV GS SF</td>
<td>Linear parameter-varying gain-scheduling controller with state-feedback</td>
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<tr>
<td>LQR</td>
<td>Linear quadratic regulator</td>
</tr>
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<td>LQR F</td>
<td>Linear quadratic regulator controller with constant gains</td>
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<td>LQR GS</td>
<td>Gain-scheduling linear quadratic regulator controller</td>
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<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
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<tr>
<td>NSERC</td>
<td>National Sciences and Engineering Research Council</td>
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<tr>
<td>RMS</td>
<td>Root mean square</td>
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Acknowledgements

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Omid Bagherieh

The University of British Columbia
August 2013
This thesis is dedicated to my parents.

For their endless love, support and encouragement.
Chapter 1

Introduction

1.1 Wind Energy

The earth is unevenly heated; the poles get less heat from the sun than the equator does, and dry land heats up and cools down more quickly than the sea. These conditions make a global convection system on the earth; the movement of air because of this convection system is called \textit{wind}.

The energy that is available in the wind is significantly higher than the total energy which is used by human beings. At the present time, only a small portion of the energy used by human beings is produced by wind. Nowadays, because of concerns about the limited amount of fossil fuels and their adverse impact on environment, as well as clean and renewable nature of wind energy, there is a trend worldwide that aims at increasing the wind energy production. For example, during the period 2005–2009, the installed wind energy capacity has increased approximately 27 percent per year. In 2009, Denmark wind energy production accounted for approximately 20 percent of total energy usage [41]. Now, European Union is aiming at producing 20 percent of its electrical energy from wind by 2020 [17].

Although the price of wind energy is approaching to that of electricity generated by fossil fuels, it is still a key to reduce further the wind energy cost for the
1.2 Wind Turbines

The energy available in the wind is captured by a device called a wind turbine. A wind turbine converts the kinetic energy in the wind into the mechanical energy by rotating the turbine blades. Then, this rotational energy is transformed into electrical energy through a generator.

1.2.1 Onshore and offshore wind turbines

Wind turbines can be installed on land or at sea which are respectively called onshore and offshore wind turbines. Although most of the currently installed wind turbines are onshore, offshore wind turbines have several advantages over onshore ones. First of all, the wind is usually steadier and less turbulent above the sea due to the even surface of the sea in comparison with the land. In addition, the noise made by turbines due to the rotation of blades is not an issue for the wind turbines that are installed away from the land. Furthermore, the scenery disturbed by wind turbines on the sea is not an issue, because no one is living there.

In this thesis, offshore wind turbines are studied.

1.2.2 Platforms for floating offshore wind turbines

Offshore wind turbines are categorized into two major groups based on the depth of water; shallow or deep. In shallow water, they are connected by piles to the seabed, i.e., non-floating. In this case, they are similar to the onshore wind turbines, but the tower vibrations excited by the waves need to be accounted for in turbines’ performance analysis. On the other hand, in deep water which is more than about 60m depth [37], it is not economical to use the long pile and fix the turbine to the seabed. Rather, a turbine with a platform floating on the water is an economically
viable solution in deep water sea. Three different types of platforms were presented in [23] to be used in deep water, as shown in Figure 1.1. The turbines installed on top of these platforms are called *Floating Offshore Turbines*.

Figure 1.1: Floating platform concepts for offshore wind turbines. (Taken from [23] with the author’s permission.)

In the *Ballast Stabilized Platform* which is also called *Spar-buoy*, sand is added at the bottom of the platform to pull down the center of gravity of the turbine. This added mass stabilizes the system against the disturbances induced by the sea waves and wind. Moreover, this platform is restricted by cables in order to prevent collision between turbines in the wind farm.

In the *Mooring Line Stabilized Platform* which is also called *Tension Leg Platform (TLP)*, the platform is fixed by cables. These cables are under tension and fixed to the anchors which are installed on the seabed. It is relatively expensive
to make the anchors that can tolerate the tension of these cables on the seabed.

In the *Buoyancy Stabilized Platform* which is also called *Barge Platform*, the platform is floated on the sea and restricted by cables to prevent it from colliding with other turbines. This platform is cheaper compared to other platforms, because it is floating on the water. Since part of this platform is above sea level, waves can induce large loads on the platform. These loads will cause fatigue in the structure and components of the turbine, as well as the reduction in the captured energy.

In this thesis, the **Barge Platform** is studied.

### 1.2.3 Mechanisms of wind turbines

The overall structure of a wind turbine and its platform degrees of freedom are shown in Figure 1.2. The wind passes through the rotational plane of the blades. The interaction between the blades and wind produces drag and lift forces, which rotates the blades. This rotation is transmitted to the generator via a gear-box. The reasons for using a gear-box are that the blades which are large mechanical parts cannot rotate with high rotational speed, and that generator speed should be relatively high in order to have lower torque on the generator side due to its torque limitation. Therefore, the gear-box increases the speed and reduces the forces transmitted to the generator.

Each wind turbine has three kinds of actuators, in order to change generator torque, blade pitch angles and nacelle yaw angle. Both generator torque and blade pitch angles are used to control the rotational speed of the shaft and the power capture. The three blades used in a wind turbine can be controlled individually or together which are called *individual blade pitch* and *collective blade pitch* control, respectively. To design a less complex controller, we will use the collective blade pitch method. For offshore wind turbines, blade pitch angles can also affect the platform movements. On the other hand, the actuator for the nacelle yaw angle is used in order to face the turbine in the direction of wind. Here, it is assumed
that the wind direction is not changing and the turbine is always facing the wind direction. Therefore, nacelle yaw angle actuator is not used for this work.

In this thesis, \textbf{generator torque} and \textbf{collective blade pitch angle} are used as control inputs.

Figure 1.2: An illustration of a floating offshore wind turbine system and its platform degrees of freedom.

1.2.4 Operating regions of wind turbines

Figure 1.3 illustrates an example of the operating region for the specific wind turbine considered in [23] and in this thesis. The available energy in wind and also the energy which should be captured by the turbine is shown in this figure. If the wind speed is lower or higher than a limit, the turbine is not in operation. These two limits are called \textit{cut-in} and \textit{cut-out} wind speeds. The operating region of wind turbines
is between these two speeds. If the wind speed is lower than the cut-in wind speed \((\text{Region I})\), the energy in the wind is not enough to rotate the blades. Also, if the wind speed is higher than the cut-out wind speed, the turbine will be shut down to avoid excessive mechanical and electrical loads.

Figure 1.3: The power curve.

The rated wind speed is the lowest wind speed at which the rated power of a turbine is produced. This wind speed divides the operating region of a wind turbine into low wind speed region \((\text{Region II})\) and high wind speed region \((\text{Region III})\). For simplicity, the transition regions between \(\text{Regions I}\) and \(\text{Regions II}\), as well as \(\text{Regions II}\) and \(\text{Regions III}\), are not studied in this thesis.

The low wind speed operating range \((\text{Region II})\) and high wind speed operating range \((\text{Region III})\) for the specific turbine considered in [23] and here are respectively given by

\[
v_{\text{Region II}} := \{ v : 7.8 \leq v \leq 10.5 \}, \quad (1.1)
\]

\[
v_{\text{Region III}} := \{ v : 11.4 \leq v \leq 25 \}, \quad (1.2)
\]

where \(v\) (m/s) denotes wind speed.
In this thesis, Region II and Region III operating regions are studied for the controller design.

1.3 Wind Turbine Control

Wind turbines need to be controlled in order to achieve its objectives. There are multiple levels of control for a wind turbine; supervisory, operational and subsystem. These control levels are explained as follows [41]:

- Supervisory control level: This control level, based on the wind speed, determines whether the turbine should be in operation or not. In addition, the turbine needs to be shut down whenever faults are detected in the system.

- Operational control level: This control level is used in the operating region of wind turbines, and determines the proper values for each control input in order to satisfy the control objectives.

- Subsystem control level: This control level is used inside each actuator and follows the commands given to the actuator at the operational control level.

In this thesis, only the operational control level is considered. This control level will be realized using the actuators for generator torque and blade pitch angle.

1.4 Motivation

To make wind energy competitive with fossil fuel energy, the price of electricity produced by wind turbines should be reduced. Some of the means to reduce the wind energy price are to increase energy efficiency, to increase lifetime of the wind turbine, and to reduce maintenance costs. The last two means can be grouped under the structural loads reduction objective.
One of the most economical ways for achieving these objectives, without involving any additional hardware or modifications to the structure, is to use an effective feedback control algorithm which controls the actuators in the turbines. Therefore, we seek to design a controller which can achieve the mentioned objectives.

The current state of the art in controlling the wind turbine can get the power efficiency of less than 50 percent [41]. However, the Betz law [41] states that maximum achievable efficiency is 59.3 percent. This gap exists because of mechanical limitations such as friction in the system, and also because of underdeveloped control techniques. By implementing a proper controller, this gap can be reduced. Even one percent increase in energy efficiency of a wind farm of 100 MW can increase the income more than $120,000 annually [41]. On the other hand, better regulation of power capture in high wind speed can reduce the power fluctuation of the produced electricity fed into the electrical grid.

Since the wind turbine is an expensive device, the equipment and maintenance cost play a substantial role in the end-price of the produced electricity. This cost will be influenced by large structural loads in the system, because these loads will produce fatigue, leading to the decreased lifetime of the turbine and the increased maintenance costs. Therefore, reduction in the structural loads is one of the most important objectives in designing the controller for the turbines.

In the floating wind turbines, the base of the structure is not fixed to the seabed, and can move in water. These movements are rotations and displacements in any direction which will cause structural loads on the system in addition to reduction in the amount of energy capture. These structural loads can produce fatigue, decrease the lifetime of the turbine, and also increase maintenance costs. Therefore, considering the floating platform movements reduction in the controller design is important.
1.5 Wind Turbine Control Goals

Considering the objectives mentioned in the previous section, the problem is investigated in two wind speed regions: Region II and Region III. In Region II, the goals are to maximize power capture and simultaneously reduce structural loads on the system. In Region III, the power capture goal is changed to regulating the power of turbines to the rated power, and at the same time trying to reduce structural loads on the system.

These problems are for both onshore and offshore wind turbines. However, in the case of offshore wind turbine, the platform movements can affect energy capture as well as structural loads on the system. Therefore, platform movements reduction needs to be considered in the problem.

Also, waves introduce another disturbance which exists at sea. This disturbance mainly affects platform movements which in turn affects the energy capture. The effects of waves need to be reduced using proper control algorithms.

The control problem is stated mathematically for each region in the subsequent chapters.

1.6 Literature Review

The European Union targets 20 percent of total electrical energy production to come from wind by 2020 [20, 17]. This decision shows the importance and growth of wind energy. The main problem for development of wind energy is its cost in comparison with other sources of energy. The National Renewable Energy Laboratorys (NREL) National Wind Technology Center estimated the cost for onshore and offshore wind turbines in [18]. This estimation can help to investigate the feasibility of developing wind farms for each specific location. The installation cost for offshore wind turbines is much higher than onshore ones, but there is more potential for power capture in offshore sites.
Offshore wind turbines are still in the development process. The basic concepts used in offshore wind turbines and the different platforms used for shallow and deep water were investigated in [33, 37, 42]. Also, the engineering challenges in offshore wind turbines were presented in [14]. In June 2009, the world’s first floating offshore wind turbine was installed in the North Sea [10]. This turbine uses a spar-buoy platform.

In this section, the current state of the art in modelling and control of onshore and offshore wind turbines are explained. Then, the control theories needed to design the controllers are explained. Also, software used for running simulations are introduced.

1.6.1 Wind turbine modelling

A model which describes system behaviours is necessary to design a controller. The wind turbine models for both onshore and offshore wind turbines have been developed. In [7], the model was presented for an onshore wind turbine as an interconnection between mechanical subsystems such as rotor, blades and generator. Since this model is non-linear, it should be linearized for controller design based on linear control theories [46].

The model of floating offshore wind turbines is also non-linear. This non-linear model of floating offshore wind turbines was thoroughly explained by Jonkman in [26]. He implemented this non-linear model in software FAST. This software is capable of not only running simulations using the non-linear model, but also obtaining the linearized model of the turbine at each operating point. On the other hand, an overview of offshore wind turbine modelling was presented by [36]. This overview mainly focuses on modelling for the controller design purposes. Also, a control oriented model of offshore wind turbines were explained in [6].

The linearized models obtained in these papers are only accurate around the linearization point and the linearized models will vary by the change in operating
points. Therefore, a linear model which can take into account this variation should be found. The linear parameter-varying (LPV) model of the system is one solution to this problem, because it will take into account the plant variation and at the same time offers a linear model for the system. The LPV model of onshore wind turbines is developed in [49]. Also, the LPV model for offshore wind turbines is obtained in [4]. This LPV model only takes into account the blade rotation angle as the varying parameter. Therefore, a more general LPV model which considers the change in operating conditions of the wind turbine as the varying parameter should be developed.

1.6.2 Wind turbine controllers

The wind turbine control is necessary for the operation of a wind turbine from start-up to shut-down. The controllers for starting up and shutting down the turbine are developed in [23] and [32]. The operation of a turbine between start-up and shut-down moments are called the operating region of a turbine. As mentioned, this operating region is divided into Region II and Region III. In [9] and [40], one controller is designed for the entire operating region. However, the controllers are usually designed separately for these two regions [5, 1, 21, 23, 24, 38, 39] and a controller for the transition between these regions is employed [8, 23]. In this thesis, we only consider the design of separate controllers for Region II and Region III; the transition controller is beyond the scope of this thesis.

Several different control methods have been applied to onshore wind turbines for both Region II and Region III. In Region II, an output feedback controller was presented by [23]. To improve the system performance, LPV gain-scheduling controllers were designed in [9, 40]. In Region III, model predictive control and receding-horizon control were designed for onshore wind turbines in [46] and [47], respectively. These controllers were designed based on the model of a turbine at one operating point. On the other hand, the PI gain-scheduling controller which
considers the model variation is presented in [19]. This controller has a PI structure and its gains are scheduled by the change in operating conditions. Other advanced controllers which consider the LPV model of the system in the controller design were developed in [7, 8, 9, 1, 34, 35, 40, 43, 44, 45].

Control of floating offshore wind turbines has been an active research topic recently; An overview for the controller design in offshore wind turbines was given in [48]. As far as wind turbine control in Region II is concerned, it is conventional that generator torque is manipulated to regulate generator speed by fixing the blade pitch at its optimal angle, in order to achieve the optimal power efficiency [23]. This strategy is optimal when platform movements do not exist. However, for floating wind turbines, since the tower and platform oscillation induced by wind and waves will increase fatigue loadings to the structure, it is questionable whether the control strategy with fixed blade pitch is still optimal. Perhaps a more complete concept of optimality would incorporate power efficiency, maintenance, and lifespan. One of the chapters in this thesis investigates a potential advantage of employing blade pitch control using LPV gain-scheduling technique for Region II. This chapter uses LPV gain-scheduling technique in order to consider plant dynamics variation in the controller design.

In order to control offshore wind turbines in Region III, different control methods such as state-feedback, loop shaping and model predictive control [27, 28, 38, 39] are considered. These controllers, however, do not address the variation in plant dynamics. In [4, 5], constant controllers were designed based on the LPV model of floating offshore wind turbines. Also, similar to onshore wind turbines, a PI gain-scheduling controller which deals with the plant dynamics variation was proposed in [23]. The constant and PI controllers may encounter some performance limitations, because they have only one or two tuning parameters. If more complex control structures are adapted, there will be potentials for performance improvement. On the other hand, it is shown in [38, 39] that the state-feedback structure
can improve the turbine performance compared to the output-feedback structure. Therefore, in this thesis, gain-scheduling controllers considering plant dynamics variation are investigated by using both output and state-feedback structures.

The performance of these controllers should be investigated under the standard meteorological conditions such as wind and waves. *International Electrotechnical Commission (IEC)* has developed the standards [13] for wind and waves profiles used in performance evaluation as well as standards for designing onshore and offshore wind turbines.

### 1.6.3 Control design theory

There are two control theories used in this paper; the linear quadratic regulator (*LQR*) and LPV gain-scheduling control. These control theories are explained sequentially.

The application of LQR control to wind turbines was proposed in [38]. The LQR control uses state-feedback structure; the plant’s states are fed back and multiplied by the designed gains for the state-feedback controller. These gains can be obtained using pole placement or LQR methods, see, e.g., [11, 50]. The pole placement methods determine gains based on the given poles of the closed loop system, while the LQR method with an integrator finds these gains in order to minimize the objective function given by

\[
J = \int_{0}^{\infty} [(y_{ref} - y(t))^T Q (y_{ref} - y(t)) + \dot{u}(t)^T R \dot{u}(t)] dt,
\]

where \(Q\) and \(R\) are the design parameters which are positive definite matrices. Also, \(y_{ref}\), \(y\) and \(u\) are the reference, output and input signals to the plant.

In this thesis, the LQR method is used and the control objectives can be considered in controller design using (1.3). Minimization of this objective function attempts to reduce control efforts as well as the error on the output signal. Parameters \(Q\) and \(R\) will determine the relative importance of the control effort reduction and the error.
The LQR controller, designed based on the system model in one operating point, cannot guarantee performance for the entire operating region. Therefore, in this thesis, an LQR gain-scheduling (LQR GS) method, which designs different LQR controllers for different operating points, is proposed. The LQR GS controller is obtained using linear interpolation between the designed controllers. The stability of this controller is not guaranteed in the design stage, but the quadratic stability is analyzed after the design.

The gain scheduling LPV technique is developed in [3]. In this method, an LPV controller is designed based on the LPV model of the system. Therefore, the designed controller depends on the parameter which characterizes the dynamics variation of the system. This parameter is measured in real time and used for controller update. Closed-loop stability and performance are guaranteed over the entire parameter region. Another advantage of this technique is the capability of solving multi-objectives control problems systematically.

1.6.4 Simulation software

The main computer software which is widely used for wind turbine modelling and simulation is FAST [23, 34, 35, 38, 39]. This software was developed specifically for wind turbines by the NREL’s National Wind Technology Center [25], and validated in [12, 23, 31]. This software can be linked with other software such as MATLAB or ADAMS in order to take advantages of these numerical and graphical environments.

1.7 Research Objectives and Methodology

We will investigate the usefulness of gain-scheduling control techniques for control problems in offshore floating wind turbines with barge platforms. Moreover, utilizing blade pitch angle actuator in low wind speed and using state-feedback structure in high wind speed are investigated. To apply these kind of controllers, we would like to:
• obtain LPV models of the system,
• define the control objectives and performance measures based on these control objectives,
• propose proper feedback structures,
• apply existing advanced GS techniques,
• do the closed-loop simulations using FAST,
• compute performance measures and compare the designed controllers with the existing ones.

1.8  Organization of Thesis

The organization of this thesis is illustrated in Figure 1.4. In Chapter 2, modelling of floating offshore wind turbines for both Region II and Region III is explained. In Chapter 3, first control objectives and feedback structures are given. Then, the general settings needed for running the simulations and performance indices evaluated after running the simulations are introduced. Chapter 4 addresses the baseline controllers used to compare our controllers’ results. The designed controllers for Region II and Region III are given in Chapter 5 and Chapter 6, respectively. Lastly, a chapter summary is given at the end of each chapter, and the thesis’ conclusion is given in Chapter 7.
Figure 1.4: Thesis organization.
Chapter 2

Wind Turbine Modelling

To design a feedback controller, it is important to acquire a mathematical model accurately for the plant to be controlled. If the derived model represents the dynamics of the plant accurately, it is expected that the controller designed based on the model performs well. An accurate mathematical model for a floating offshore wind turbine is described in [23]. This non-linear model was implemented in software FAST [25] by Jonkman.

The non-linear floating offshore wind turbine model in FAST is an aero-hydro-servo-elastic model. The aero-hydro-elastic model of the turbine represents the open-loop non-linear model of the turbine. The term *aero* refers to the interface between the turbine and wind, while the term *hydro* refers to the turbine’s interface with waves, sea currents and mooring lines. The dynamics of different parts such as the rotor, drive train and blades are contained in this model which corresponds to the term *elastic*. On the other hand, the term *servo* represents a feedback structure built inside FAST for running simulations in FAST. In this thesis, instead of using the *servo* model in FAST, the feedback structure is realized with MATLAB by importing the aero-hydro-elastic model of the turbine and embedding the designed control law into Simulink.

In this chapter, a method to derive an LPV model numerically for offshore
Floating wind turbines is presented, by using the software \textit{FAST}. The model is used in subsequent chapters for controller design. This chapter first reviews a non-linear model realized in \textit{FAST} briefly, and then presents a method for the LPV modelling from linearized models at various operating points of the non-linear model. The LPV modelling method is applied to a specific wind turbine, \textit{Offshore NREL 5.0 MW Baseline Wind Turbine}, which is a combination of the \textit{Onshore NREL 5.0 MW Baseline Wind Turbine} and the \textit{ITI Energy Barge Platform} [23]. This turbine is called \textit{NREL 5 MW} throughout this thesis.

\section{2.1 Non-linear Model}

The non-linear model of an offshore wind turbine realized in \textit{FAST} is represented in a state-space form as

\begin{equation}
\begin{aligned}
\dot{x}(t) &= f(x(t), u(t), u_d(t)), \\
y(t) &= Cx(t).
\end{aligned}
\end{equation}

Here, the control input vector \(u\) consists of generator torque, blade pitch angle and nacelle yaw angle, and the disturbance input vector \(u_d\) is comprised of wind and waves disturbance inputs. The vectors \(x\) and \(y\) are state and output vectors, respectively, and their components depend on the system complexity that can be specified by \textit{FAST} users. The block diagram representation of (2.1) is shown in Figure 2.1.

The non-linear model (2.1) can be a complex model with a number of degrees of freedom and outputs. Depending on the purpose of modelling, we can simplify the model by enabling only relevant degrees of freedom. Also, inputs and outputs can be selected based on the specific problem to be dealt with. In this thesis, the following simplified model is considered;

\footnote{The basic properties of this wind turbine are as follows; the total mass is about 6000 tons, the tower height about 87 m, the blade length about 63 m and the platform diameter about 45 m. See [23].}
Figure 2.1: The block diagram representation of the non-linear model (2.1) in FAST.

- States ($x$): Platform pitch angle ($ppt$ [rad]), platform pitch rate ($\dot{ppt}$ [rad/s]) and rotor speed ($\omega_r$ [rad/s]). The states of the system are divided into platform states and wind turbine states. For the platform states, platform pitch angle and its derivative are considered, because platform pitch movement is the most significant among all the platform movements, under the assumption that wind is normal to the rotational plane of the blades. On the other hand, only rotor speed is considered as a wind turbine state. Flexibility of the drive train, blades and tower are ignored for the purposes of the simplified model.

- Control inputs ($u$): Generator torque and blade pitch angles. The yaw angle is fixed with the assumption of a fixed wind direction.
  - In Region II, blade pitch angles ($\beta$ [rad]) and generator torque ($T_g$ [N.m]) are used as control inputs. However, blade pitch angles are fixed for some of the designed controllers in this region.
  - In Region III, generator torque ($T_g$ [N.m]) is fixed and blade pitch angles ($\beta$ [rad]) are used as control inputs.

- Disturbance inputs ($u_d$): Wind speed ($v$ [m/s]) and wave elevation ($w$ [m]).

- Outputs ($y$): Platform pitch angle ($ppt$ [rad]) and generator speed ($\omega_g$ [rpm]).
These signals are summarized as follows\(^2\):
\[
\begin{cases}
  x &= [ppt, \dot{ppt}, \omega_r]^T, \\
  u &= \begin{cases}
    [eta, T_g]^T, & \text{for Region II}, \\
    \beta, & \text{for Region III}
  \end{cases}
  \\
  u_d &= [v, w]^T, \\
  y_{ppt} &= ppt, \\
  y_{\omega_g} &= \omega_g.
\end{cases}
\tag{2.2}
\]

Platform pitch angle and generator speed, which are considered output signals, can be calculated using the states and inputs of the system by substituting the following equation into (2.1).
\[
\begin{align*}
  C_{ppt} &= \begin{bmatrix}
    1 & 0 & 0
  \end{bmatrix}, \\
  C_{\omega_g} &= \begin{bmatrix}
    0 & 0 & \frac{60N}{2\pi}
  \end{bmatrix}.
\end{align*}
\tag{2.3}
\tag{2.4}
\]

In this equation, \(N\) denotes the gear-box ratio. This number represents the rotational speed ratio between the two sides of the gear-box.

### 2.2 Model Linearization

Using the non-linear model (2.1), we will derive the linearized model of the floating offshore wind turbine. The FAST linearization process does not have the capability of handling waves as disturbance inputs. Instead, the model is linearized in still water. Study of the wave effects on the model is future work, which may help to further reduce wave effects on the system.

Figure 2.2 shows the inputs and the outputs of the linearized model. Since the linearized wind turbine model varies by the change in operating points, the LPV model is obtained for this system. This linearized model is represented by
\[
\delta \dot{x}(t) = A(x_0, u_0, u_{d,0}) \delta x(t) + B(x_0, u_0, u_{d,0}) \delta u(t) + B_d(x_0, u_0, u_{d,0}) \delta v(t), \tag{2.5}
\]

\(^2\)Waves are only used as disturbance inputs for running simulations and they are not considered in model linearization for controller design purposes.
where signals $x_0$, $u_0$ and $u_{d,0}$ determine the equilibrium points. We will show that the equilibrium points are functions of the disturbance input which is wind speed $v$ here. By having the equilibrium points and using (2.3) and (2.4), signals $y_{ppt,0}$ and $y_{\omega_g,0}$ can be calculated. The signals $\delta x$, $\delta u$, $\delta u_d$, $\delta y_{ppt}$ and $\delta y_{\omega_g}$ represent deviation from these equilibrium points;

$$
\delta x := x - x_0(v),
$$
(2.6)

$$
\delta u := u - u_0(v),
$$
(2.7)

$$
\delta u_d := u_d - u_{d,0}(v),
$$
(2.8)

$$
\delta y_{ppt} := y_{ppt} - y_{ppt0}(v),
$$
(2.9)

$$
\delta y_{\omega_g} := y_{\omega_g} - y_{\omega_{g,0}}(v),
$$
(2.10)

and the system matrices are calculated analytically as:

$$
A(x_0, u_0, u_{d,0}) := \frac{\partial f}{\partial x} \bigg|_{x=x_0,u=u_0,u_d=u_{d,0}},
$$
(2.11)

$$
B(x_0, u_0, u_{d,0}) := \frac{\partial f}{\partial u} \bigg|_{x=x_0,u=u_0,u_d=u_{d,0}},
$$
(2.12)

$$
B_d(x_0, u_0, u_{d,0}) := \frac{\partial f}{\partial u_d} \bigg|_{x=x_0,u=u_0,u_d=u_{d,0}}.
$$
(2.13)

To obtain the LPV model (2.5) of the system, first equilibrium points and state space matrices in (2.11)-(2.13) are calculated for each operating point. Then, interpolation is used to find the LPV model between the points.
In order to determine the equilibrium points, signals $x_0$, $u_0$ and $u_{d,0}$ should be obtained. Based on the definition of equilibrium points, the rate of change for the states should be zero. In other words, according to (2.1), we have to solve the non-linear equation

$$f(x_0, u_0, u_{d,0}) = 0.$$  \hspace{1cm} (2.14)

FAST has an ability to solve the equation (2.14) when a part of parameter values in $x_0$, $u_0$ and $u_{d,0}$ are specified. The specified and unspecified parts of these parameter values at a given disturbance input $u_{d,0}$ (wind speed) are presented in Table 2.1 by using check-marks and question-marks, respectively. The unspecified parameter values will be determined by solving (2.14) using FAST.

The platform pitch rate is one of the specified parameter values and according to (2.14), its value is zero. Also, other specified parameter values for Region II and Region III are explained here:

- In Region II, generator speed $\omega_g$ is a function of wind speed $v$ (see (3.1)), and blade pitch angle $\beta$ is set to zero.

- In Region III, generator speed and torque are set to their rated values.

Table 2.1: Specified parameter values of equilibrium points at a given disturbance input $u_{d,0}$.

<table>
<thead>
<tr>
<th>Wind speed operating region</th>
<th>$x$</th>
<th>$u$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ppt</td>
<td>ppt</td>
</tr>
<tr>
<td>Region II</td>
<td>?</td>
<td>✓</td>
</tr>
<tr>
<td>Region III</td>
<td>?</td>
<td>✓</td>
</tr>
</tbody>
</table>

As one can see in Table 2.1, the unspecified parameters for determining equilibrium points include one of the control inputs and the platform pitch angle.
These parameters are obtained in each operating point by substituting specified 
parameters for a given wind speed into (2.14) and using FAST to slove this equation. 
Therefore, equilibrium points for each operating point can be completely determined 
using wind speed at that point. In other words, the states of the system and control 
inputs are functions of wind speed ($v$). Accordingly, system matrices can be shown 
as:

$$
A(x_0, u_0, u_{d,0}) =: A(v), 
$$
(2.15)

$$
B(x_0, u_0, u_{d,0}) =: B(v), 
$$
(2.16)

$$
B_d(x_0, u_0, u_{d,0}) =: B_d(v). 
$$
(2.17)

For each equilibrium point corresponding to wind speed $v$, to obtain the 
matrices in (2.15)-(2.17) numerically, $A(v)$, $B(v)$ and $B_d(v)$ are parametrized in 
terms of $v$, using the following procedure.

1. Take samples $v^{(k)}$, $k = 1, 2, 3, \ldots$, from the operating wind speed range.

2. For each sample $v^{(k)}$, calculate system matrices using FAST as

$$
A^{(k)} = A(v^{(k)}), 
$$

$$
B^{(k)} = B(v^{(k)}), 
$$

$$
B_d^{(k)} = B_d(v^{(k)}). 
$$
(2.18)

3. Parameterize $A(v)$ and $B(v)$, e.g.,

$$
A(v) =: A_0 + A_1 v, 
$$

$$
B(v) =: B_0 + B_1 v, 
$$

$$
B_d(v) =: B_{d0} + B_{d1} v. 
$$
(2.19)

4. Using curve-fitting techniques, obtain the coefficient matrices in (A.2) such 
that the equalities in (2.18) are satisfied within a certain accuracy.
The coefficient matrices of $A(v)$, $B(v)$ and $B_d(v)$ are calculated for the NREL 5 MW in Region II and Region III considering the difference in control inputs for these regions. These matrices are shown in Appendix A.

### 2.3 Summary

The non-linear model realized in the software FAST was explained first. Then, for controller design based on linear control theory, we provided a procedure to derive LPV models in terms of wind speed from the non-linear model.
Chapter 3

General Control Strategy and Performance Measures

The model of the floating offshore wind turbine system was obtained in the previous chapter. Using this model, various controllers are designed in the subsequent chapters, and their performances are compared by simulations.

This chapter first presents control objectives for floating offshore wind turbines. To achieve these objectives, typical structures of the feedback control systems for both Region II and Region III are reviewed. Then, the settings needed to run simulations, using these feedback structures, are explained. At the end, performance measures to be evaluated are introduced.

3.1 Control Objectives

The ultimate goal in the wind energy industry is to reduce the cost of produced electricity. From a control engineering viewpoint, this goal is tackled by defining proper objectives on power capture and fatigue loads. These control objectives are defined separately in Region II and Region III.
3.1.1 Control objectives for Region II

In the low wind speed operating range (Region II), the power which can be captured by the turbine is less than the rated power of generator. Therefore, we try to maximize energy capture. Also, platform movements, which cause large structural loads and degradation of energy capture, need to be minimized. Therefore, the control objectives in Region II can be summarized as:

(OL1) maximization of power capture,

(OL2) minimization of platform movements.

Energy capture is maximized by regulating the generator speed $\omega_g$ so that it tracks the desired speed. This desired speed is determined by wind speed $v$ as

$$\omega_{g,ref}(v) := K_v \times v,$$

where the gain $K_v$ is defined by

$$K_v := \frac{\lambda_{max}}{r} \times \frac{60N}{2\pi}.$$  \hspace{1cm} (3.2)

Equation (3.1) shows dependence of reference generator speed on wind speed for Region II. In this equation, $\lambda_{max}$ is the tip speed ratio associated with the maximum efficiency path for the generator speed. The tip speed ratio is defined as the ratio of the blade tip speed over the wind speed. $N$ and $r$ denote the gear-box ratio and radius of turbine blades, respectively. For the NREL 5 MW \cite{23}, the following values are used: $\lambda_{max} = 7.55$, $r = 63$ (m) and $N = 97$.

For the case of onshore wind turbines and offshore wind turbines with fixed foundations, we do not have the control objective (OL2), whereas in the case of floating offshore turbines, platform movements need to be minimized in controller design. As described in Section 2.1, since this thesis considers only platform pitch movement among all the platform movements in the controller design phase, its minimization needs to be achieved.

In summary, the control objectives for Region II are:
\[(OL1) \, \text{min} \, |\omega_g - \omega_{g,\text{ref}}|,\]
\[(OL2) \, \text{min} \, |y_{pp}|.\]

### 3.1.2 Control objectives for Region III

In the high wind speed operating range (Region III), the power which can be captured by the turbine is more than the rated power of the generator. Therefore, we need to regulate power capture at the rated power. As with Region II, reduction of platform movement is again one of the control objectives. These movements induce structural loads on the system and hinder power regulation. Thus, the control objectives in Region III can be presented as:

\[(OH1) \, \text{regulation of power capture},\]
\[(OH2) \, \text{minimization of platform movements}.\]

Note that the main difference between control objectives for Region II and Region III is seen by the difference between \((OL1)\) and \((OH1)\). In \(OL1\), power capture is maximized, while in \(OH1\), power capture is regulated to the rated power.

The captured power, denoted by \(P\), is obtained using the following equation:

\[P = T_g \times \omega_g.\]  \hspace{1cm} (3.3)

There are two standard methods to regulate the power capture to the rated power \(P_{\text{rated}}\) using (3.3):

- Fixing generator torque \(T_g\) to the rated torque \(T_{\text{rated}}\), and regulating generator speed \(\omega_g\) to the rated generator speed \(\omega_{g,\text{rated}}\) using blade pitch angle \(\beta\).
- Directly regulating power capture \(P\) to the rated power \(P_{\text{rated}}\) using generator torque \(T_g\) and blade pitch angle \(\beta\) simultaneously.
The first method simplifies the controller and reduces loads on the turbine, but increases power fluctuations. The second method regulates power more effectively, but adds complexity to the controller and increases loads on the turbine [38].

In this thesis, to make the controller less complex and to reduce turbine loads, the first method is studied. However, the second method is used for the design of the baseline controller, because there was an instability issue in the baseline controller simulation using the first method. The reason for this instability was most likely the fact that the simulation contained more degrees of freedom than were incorporated in the design of the controller [51].

To regulate generator speed in the first method, the torque applied by the wind must be manipulated, because generator torque is fixed. The torque applied by the wind is a function of wind speed and blade pitch angle. This torque can be controlled by modifying blade pitch angle in order to compensate for the variation in wind speed. In other words, the objective \( OH1 \) is to regulate generator speed to the rated generator speed \( |\omega_g - \omega_{g,rated}| \) by controlling the blade pitch angle. This objective is exactly similar to regulation of power \( |P - P_{rated}| \), because generator torque is assumed to be constant.

Objective \( OH2 \) is the minimization of platform movements. As it was mentioned in the previous section, the only platform movement that will be considered for design of the controller is pitch movement \( |y_{ppt}| \)). However, other platform movements are compared after running simulations.

In summary, the control objectives for Region III are:

\[
(OH1) \min |P - P_{rated}|,
\]

\[
(OH2) \min |y_{ppt}|.
\]
3.2 Feedback Structure for Controller Design

In order to design controllers, the linearized model depicted in Figure 2.2 is used. The states and output are fed back to the controller for making the general feedback structure illustrated in Figure 3.1. Using this feedback structure, different controllers are designed for Region II and Region III. The inner structure of each controller is explained in detail in later chapters. In the general feedback structure in Figure 3.1, the term $\delta$ is used to show the deviation of signals from equilibrium conditions. These equilibrium conditions are obtained in Chapter 2.

Figure 3.1: A general feedback structure for controller design.

In Figure 3.1, $u_d$ represents disturbances to the system. These disturbances are wind and waves for floating offshore wind turbines. However, only wind speed is considered in the controller design. Blade pitch angle ($\beta$) and generator torque ($T_g$) are the control inputs. Depending on the operating region of the wind turbine and the type of the controller, blade pitch angle or generator torque may be considered constant and the non-constant term is used as a control input. The feedback signals are output and state signals. The output signal is generator speed ($y_{\omega_g}$) and the state signals are rotor speed ($\omega_r$), platform pitch angle ($ppt$) and platform pitch rate ($\dot{ppt}$). In this thesis, whenever state-feedback is used, we assume that all the states are directly measurable. Also, the reference signal is the reference for generator
speed.

Using this feedback structure, different controllers are designed for Region II and Region III. The inner structure of each controller is explained in detail in later chapters.

### 3.3 Simulation Settings

To evaluate the designed controllers, simulations are conducted for the closed-loop system depicted in Figure 3.1. The simulation block diagram used in MATLAB is shown in Figure 3.2. Since the controllers are designed for the linearized plant, the input and output of the designed controllers are the deviation from the equilibrium points. This deviation is calculated in the simulation by adding or subtracting the equilibrium values to the related signals wherever needed. These equilibrium values for reference signal and output signal are not illustrated in this figure, because they will cancel out each other. The elements of this figure are explained in this section.

![Figure 3.2: A general feedback structure for simulations.](image-url)
Non-linear Model in FAST

The non-linear model (2.1) has been realized with an interconnection between Simulink and FAST [25] as a Simulink block. Since the block contains a complete model with a number of inputs and outputs which are irrelevant to this thesis, unnecessary signals are eliminated from the block.

Sensor measurements $y_{\omega}, g$ and $x$

Although noise exists in any measurement in real implementation, for simplicity, measurements are assumed to be noise-free in this thesis. If the noise is significant in this application, the noise effect can be reduced by inserting a low-pass filter in the feedback path.

Saturation block

There are constraints on system inputs and their rates of changes due to the physical limitations of actuators. These constraints for the NREL 5 MW are given as:

$$\beta \leq 90 \text{ (degree)},$$

$$\dot{\beta} \in [-8, 8] \text{ (degree/s)},$$

$$T_g \leq 47402.91 \text{ (Nm)},$$

$$\dot{T}_g \in [-15000, 15000] \text{ (Nm/s)}.$$  (3.4)  (3.5)  (3.6)  (3.7)

These constraints are realized in the saturation blocks.

Controller

The designed controllers are plugged into the ‘Controller’ block in order to compare closed-loop performances.
Disturbance inputs

Wind and wave are disturbance inputs to the system. The properties of these wind and wave profiles for Region II and Region III are shown in Table 3.1. The wave properties are selected for each wind speed profile using IEC Standards [13]. Figures 3.3 show the wind profiles for these different meteorological conditions. These wind profiles are generated by software TurbSim [22]. Also, wave profiles which are generated by FAST are shown in Figures 3.4.

Table 3.1: Meteorological conditions in Region III.

<table>
<thead>
<tr>
<th>Meteorological conditions</th>
<th>Average wind speed $(m/s)$</th>
<th>Significant wave height $(m)$</th>
<th>Peak spectral period $(s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region II</td>
<td>9.3</td>
<td>1.08</td>
<td>5.8</td>
</tr>
<tr>
<td>Region III/Cond. I</td>
<td>18</td>
<td>3.25</td>
<td>9.7</td>
</tr>
<tr>
<td>Region III/Cond. II</td>
<td>20</td>
<td>3.67</td>
<td>13.4</td>
</tr>
</tbody>
</table>

Reference profile

The reference $\omega_{g,\text{ref}}$ for generator speed is different in Region II and Region III. In Region II, this reference signal is generated using (3.1) and wind profile in Figure 3.3(a). In Region III, the reference $\omega_{g,\text{ref}}$ for generator speed is set to the rated generated speed. This reference speed will regulate the power capture to the rated power. These reference signals are given by

$$\omega_{g,\text{ref}} = \begin{cases} 
K_v \times v & \text{for Region II}, \\
\omega_{g,\text{rated}} & \text{for Region III},
\end{cases} \tag{3.8}$$

where $K_v$ is obtained in (3.2).
Figure 3.3: Wind speed profiles for simulations.
Figure 3.4: Wave elevation profiles for simulations.
Initial operating conditions

The controllers in this thesis are not designed for starting the turbine and therefore, the initial condition of the system should be defined. Here, the initial condition is considered to be the equilibrium condition for the given initial wind speed disturbance input\(^1\). The procedure for obtaining the equilibrium point at a given wind speed disturbance input is presented in Section 2.2.

First, the parameters specified with check-mark in Table 2.1 should be specified. These parameters are as follows:

- **Region II**: \( \omega_r, \dot{\text{ppt}}, \beta \),
- **Region III**: \( \omega_r, \dot{\text{ppt}}, T_g \).

In **Region II**, initial rotor speed is calculated based on the reference signal for generator speed (3.1) using initial wind speed \( v_{int} \). In **Region III**, initial generator speed is set to the rated generator speed. Accordingly, the initial rotor speed in **Region II** and **Region III** are given by

\[
\omega_{r,int} = \begin{cases} 
K_v \times v_{int}/N, & \text{for Region II,} \\
\omega_{g,\text{rated}}/N, & \text{for Region III.}
\end{cases}
\]  

(3.9)

Also, platform pitch rate, which is the derivative of one of the states, is zero, because initial condition is assumed to be an equilibrium condition. On the other hand, one of the control inputs in each region is already specified. In **Region II**, initial blade pitch angle is set to zero for getting maximum efficiency. In **Region III**, generator torque is also set to the rated generator torque.

By considering these specified parameters and running the open-loop simulation, the equilibrium point is found. In this way, the initial platform pitch angle, generator torque for **Region II** and blade pitch angle for **Region III**, which are the unspecified parameters in Table 2.1, are determined.

---

\(^1\)For simplicity, water is assumed to be still in determining the equilibrium condition.
3.4 Performance Measures for Comparisons

Based on the control objectives presented in Section 3.1.1 and 3.1.2, several performance measures are defined in order to evaluate performance of designed controllers. These measures are summarized in Table 3.2.

Table 3.2: Wind turbine performance measures

<table>
<thead>
<tr>
<th>Wind speed region</th>
<th>Control objectives</th>
<th>Evaluated parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region II</td>
<td>(OL1) maximization of power capture</td>
<td>$P_{avg}$</td>
</tr>
<tr>
<td></td>
<td>(OL2) minimization of platform movements</td>
<td>$ppt_{rms}, ppt'_{rms}$</td>
</tr>
<tr>
<td>Region III</td>
<td>(OH1) regulation of power capture</td>
<td>$P_{rms}$</td>
</tr>
<tr>
<td></td>
<td>(OH2) minimization of platform movements</td>
<td>$ppt_{rms}, ppt'_{rms}$</td>
</tr>
</tbody>
</table>

In Region II, the achievement of objective (OL1) is evaluated by comparing the average power capture, denoted $P_{avg}$, among designed controllers. In this region, the second objective (OL2) is minimization of platform pitch movement. Therefore, the root mean square (RMS) of platform pitch angle ($ppt_{rms}$) and its derivative $ppt'_{rms}$, which is directly affected by platform pitch movement, are calculated as performance measures.

In Region III, the objective (OH1) is regulation of power capture. This is evaluated by taking the RMS value of the difference between the power capture and rated power. This parameter is denoted by $P_{rms}$. Similar to Region II, the objective (OH2) is evaluated by the RMS value of platform pitch angle $ppt_{rms}$ and its derivative $ppt'_{rms}$.

Furthermore, the RMS value of other platform movements and their derivative are calculated as performance measures. These performance measures are displayed in Table 3.3. Since the reduction of these movements are not considered in the controller design, we cannot predict their behaviour. However, their performance
can be compared based on the simulation results.

Table 3.3: Platform performance measures not considered in the controller design

<table>
<thead>
<tr>
<th>Platform movements</th>
<th>Evaluated parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll angle</td>
<td>$p_{rl_{rms}}$</td>
</tr>
<tr>
<td>Roll rate</td>
<td>$\dot{p}<em>{rl</em>{rms}}$</td>
</tr>
<tr>
<td>Yaw angle</td>
<td>$p_{yw_{rms}}$</td>
</tr>
<tr>
<td>Yaw rate</td>
<td>$\dot{p}<em>{yw</em>{rms}}$</td>
</tr>
<tr>
<td>Sway displacement</td>
<td>$p_{sw_{rms}}$</td>
</tr>
<tr>
<td>Sway rate</td>
<td>$\dot{p}<em>{sw</em>{rms}}$</td>
</tr>
<tr>
<td>Surge displacement</td>
<td>$p_{sg_{rms}}$</td>
</tr>
<tr>
<td>Surge rate</td>
<td>$\dot{p}<em>{sg</em>{rms}}$</td>
</tr>
<tr>
<td>Heave displacement</td>
<td>$p_{hv_{rms}}$</td>
</tr>
<tr>
<td>Heave rate</td>
<td>$\dot{p}<em>{hv</em>{rms}}$</td>
</tr>
</tbody>
</table>

3.5 Summary

The general control strategy has been explained in this chapter by first presenting control objectives for Region II and Region III. Then, the general feedback structure for designing controllers which can achieve these objectives has been introduced. This feedback structure will be used for running the simulations and the required settings for running these simulations have been explained. In order to compare different controllers, performance measures have been defined and will be used to evaluate the behaviour of the controllers in simulations.
Chapter 4

Baseline Controllers in

*Region II* and *Region III*

The basic controllers for *Region II* and *Region III* developed in [23] are reviewed in this chapter. These controllers are popular among wind turbine researchers for comparison purposes [4, 5, 15, 16, 27, 38, 39]. In subsequent chapters, performance measures for designed controllers will be compared with those of the baseline controllers.

Since this baseline controller was designed for the onshore wind turbine and it was applied to the offshore wind turbine by [23], the platform movements reduction objective was not considered in the controller design. Using this controller may not be optimal and therefore in this thesis, we seek to design a controller which can also consider platform movements reduction in the controller design.

### 4.1 Low Wind Speed (*Region II*)

The baseline controller for *Region II* called *BaseR2* is explained in this section. First, its controller structure is introduced. Then, simulation results are presented.
4.1.1 Controller structure

The general feedback structure was given in Figure 3.2. The baseline controller for Region II which was presented by [23] is substituted in the controller block, as shown in Figure 4.1\(^1\).

\[ T_g = K \omega_g^2, \quad K = 2.55764 \times 10^{-2} N.m/rpm^2. \] \hspace{1cm} (4.1)

This generator torque regulate the generator speed in order to follow the maximum efficiency path given in (3.1). Also, the blade pitch angle is fixed with \( \beta_{eq} = 0 \), because the maximum power is captured at this angle.

4.1.2 Simulation results

Simulation results for NREL 5 MW are calculated based on the inputs given in Figures 3.3 and 3.4. The control input (generator torque) and system responses

\(^1\)The output for generator torque of the baseline controller is an absolute value and we do not need to add an equilibrium value.
(platform pitch angle and generator speed) are given in Figures 4.2 and 4.3. Also, the performance measures for the parameters listed in Table 3.2 are calculated in Table 4.1. The performance measures for other platform movements are given in Table B.1 and B.2.

![Figure 4.2: Control inputs for the baseline controller in Region II.](image)

(a) Generator torque (N.m)  
(b) Blade pitch angle (degree)

Figure 4.2: Control inputs for the baseline controller in Region II.

![Figure 4.3: System responses for the baseline controller in Region II.](image)

(a) Platform pitch angle (degree)  
(b) Generator speed (rpm)

Figure 4.3: System responses for the baseline controller in Region II.
Table 4.1: Evaluated performance measures for the baseline controller in Region II

<table>
<thead>
<tr>
<th>$P_{avg}$ (MW)</th>
<th>ppt$_{rms}$ (degree)</th>
<th>ppt$_{rms}$ (degree/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.937</td>
<td>1.403</td>
<td>0.126</td>
</tr>
</tbody>
</table>

4.2 High Wind Speed (Region III)

The baseline controller for Region III called BaseR3 is presented by first introducing the control structure. Then simulation results are given for this controller.

4.2.1 Controller structure

The baseline controller for Region III presented by [23] is substituted in the controller block in Figure 3.2. The detailed structure of this baseline controller is illustrated in Figure 4.4.

Figure 4.4: The baseline controller structure in Region III.
The control inputs for \textit{NREL 5 MW} are given in [23]:

\[
T_g = \frac{P_{\text{rated}}}{\omega_g}, \quad P_{\text{rated}} = 5.2966 \text{ MW}, \quad (4.2)
\]

\[
\beta = K_p(\beta)\delta\omega_g + K_I(\beta)\int \delta\omega_g, \quad (4.3)
\]

where

\[
K_p(\beta) = \frac{0.01882681}{(1 + \beta/6.302336)}, \quad (4.4)
\]

\[
K_I(\beta) = \frac{0.008068634}{(1 + \beta/6.302336)}. \quad (4.5)
\]

As one can see, the controller gains for the blade pitch input are not fixed. These controller gains vary over time and this controller is called a PI-gain scheduling controller. This gain-scheduling controller is considered to take into account dynamics variation according to the change of operating conditions\textsuperscript{2}.

\subsection*{4.2.2 Simulation results}

Simulations for \textit{NREL 5 MW} with the baseline controller are conducted, with the disturbance inputs given in Figures 3.3 and 3.4. The control inputs (blade pitch angle and generator torque) and system responses (platform pitch angle and generator speed deviation) for meteorological conditions \textit{Cond. I} and \textit{Cond. II} are shown in Figures 4.5–4.8. Also, the performance measures for the parameters listed in Table 3.2 are calculated from simulation results and given in Table 4.2. The performance measures for other platform movements are presented in Tables D.1 and D.2.

\subsection*{4.3 Summary}

The baseline controllers which are used to compare the performance of our designed controllers in \textit{Region II} and \textit{Region III} were reviewed in this chapter. These baseline

\textsuperscript{2}The right hand side of (4.3) will determine $\beta$ for the next time step.
controllers were designed for onshore wind turbines and have been applied to offshore wind turbines in [23]. In the design of these controllers, power maximization for Region II and power regulation for Region III are considered. However, platform movements reduction was not considered. The controller for Region II fixes blade pitch angle and controls generator torque, while the controller for Region III controls both blade pitch angle and generator torque.
Figure 4.7: System responses for the baseline controller in Region III under Cond. I.

Figure 4.8: System responses for the baseline controller in Region III under Cond. II.

Table 4.2: Evaluated performance measures for the baseline controller in Region III

<table>
<thead>
<tr>
<th>Meteorological Conditions</th>
<th>$P_{rms}$ (MW)</th>
<th>$ppt_{rms}$ (degree)</th>
<th>$ppt_{rms}$ (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cond. I</td>
<td>1.752</td>
<td>2.605</td>
<td>1.336</td>
</tr>
<tr>
<td>Cond. II</td>
<td>2.518</td>
<td>4.110</td>
<td>2.103</td>
</tr>
</tbody>
</table>
Chapter 5

Gain-scheduling Control in

Region II

The LPV gain-scheduling controller for Region II is developed in this chapter. In Region II, it is conventional that only generator torque is used as the control input, by fixing the blade pitch angle to zero. However, the possibility of utilizing blade pitch angle as a control input in addition to generator torque for the reduction of platform movements is also studied. Then, closed-loop simulations will be carried out, and the performance measures are obtained and compared with those of the baseline controller.

5.1 Control Objectives

As mentioned in Chapter 3, the general control objectives for Region II are summarized as:

\( OL1 \) \( \min |\omega_g - \omega_{g,ref}|, \)

\( OL2 \) \( \min |y_{ppt}|, \)
where $\omega_{g,\text{ref}}$ is the speed that offers maximum power capture, and is calculated by (3.1).

## 5.2 LPV Gain-scheduling Controller

Wind turbine dynamics change with the variation in operating conditions. Therefore, the corresponding linearized model is different at each operating point. To account for this model variation in controller design, a well-known LPV gain-scheduling control method [3] is utilized. This method takes into account the plant variation by designing a varying controller.

To achieve the control objectives $(OL1)$ and $(OL2)$, the following two controllers are designed and their performances are compared.

**$\text{(GS I)}$** The LPV gain-scheduling controller with fixed blade pitch angle,

**$\text{(GS II)}$** The LPV gain-scheduling controller with varying blade pitch angle.

In the controller $(GS I)$, generator torque is the only control input, while in the controller $(GS II)$, blade pitch angle is added to reduce the platform pitch movement.

In this section, first the controller structure used for the controller design is explained. Then, by having the complete closed-loop structure, the control design problem is defined and controllers are tuned. Following this, simulation results are discussed for the designed controllers. Finally, the chapter is summarized.

### 5.2.1 LPV gain-scheduling controller structure

Two different structures for the LPV gain-scheduling controller in Region II are substituted into the general feedback structure shown in Figure 3.2. Figures 5.1 (a) and (b) show the feedback structures for controllers $(GS I)$ and $(GS II)$, respectively.
To mathematically formulate a controller design problem reflecting the control objectives \((OL1)\) and \((OL2)\), we will consider the more detailed feedback structure depicted in Figure 5.2, where reference and error signals are introduced as follows:
\begin{align}
  y_{\omega_g,\text{ref}}(v) &:= \omega_{\text{g,ref}}(v), \quad (5.1) \\
  e &:= y_{\omega_g,\text{ref}}(v) - y_{\omega_g}, \quad (5.2)
\end{align}

and the LPV gain-scheduling controller \( K(v) \) is represented by

\[
K(v) : \begin{cases}
  \dot{x}_K = A_K(v)x_K + B_K(v)e, \\
  \delta u = C_K(v)x_K + D_K(v)e.
\end{cases} \quad (5.3)
\]

Figure 5.2: A feedback control structure

According to Figure 5.1, the control inputs \( u \) for controllers (\( GS I \)) and (\( GS II \)) are generator torque and the combination of generator torque and blade pitch angle, respectively.

The closed-loop system in Figure 5.2 can be reconfigured into a form with a generalized plant \( G(v) \) and a controller \( K(v) \) as drawn in Figure 5.3. In this figure, the signals \( \text{ppt}_W := W_{\text{ppt}}\delta y_{\text{ppt}} \), \( e_W := W_e e \), \( \delta u_W := W_u \delta u \) and \( \delta \dot{u}_W := W_{\dot{u}} \delta \dot{u} \) are respectively the weighted platform pitch angle, the weighted error, the weighted input deviation from the operating point \( u_0 \), and the weighted input rate deviation. The purpose of weighting functions \( W_{\text{ppt}}, W_e, W_u \) and \( W_{\dot{u}} \) is to take the trade-off among the regulation of generator speed, the minimization of platform...
pitch movement, and the fulfilment of the control inputs and control inputs rate constraints.

The constraints on control inputs and their rates are due to the physical limitation of actuators. For the NREL 5 MW [23], these constraints are given in (3.4).

5.2.2 LPV gain-scheduling controller design problem

Using the feedback system in Figure 5.3, the controller design problem can be formulated as follows: Given $G(v)$ and specified weighting functions $W_{ppt}$, $W_e$, $W_u$ and $W_{\dot{u}}$, design a gain-scheduling controller $K(v)$ such that, for any trajectory of $v(\cdot)$ in the operating range with constraints on rate-of-changes$^1$

$$|\dot{v}| \leq 1 \ (m/s^2), \quad (5.4)$$

$^1$The constraints on rate-of-changes are imposed to design less conservative gain-scheduling controllers.
the closed-loop system is asymptotically stable, and the worst-case $L_2$-gain$^2$ from the exogenous inputs $[\delta v, y^T_{\omega_{g,ref}}(v), y^T_{\omega_{g,0}}(v)]^T$ to the performance outputs $[e^T_W, \delta u^T_W, \delta u^T_W, ppt^T_W]^T$ is minimized.

To design gain-scheduling controllers that solve the formulated problem, the well-known method in [3] is used. This method is based on convex optimization with linear matrix inequality constraints.

### 5.2.3 LPV gain-scheduling controller tuning

The controller parameters are tuned by selecting proper weighting functions. There are four weighting functions in this control problem; $W_{ppt}$, $W_e$, $W_u$ and $W_{\dot{u}}$. The role of $W_u$ and $W_{\dot{u}}$ is to prevent the violation of constraints on control inputs given in (3.4). Weighting functions $W_{ppt}$ and $W_e$ relatively emphasize the regulation of generator speed and the reduction of platform pitch angle.

The appropriate weighting functions are searched for by trial and error. The selected weighting functions are given for both controllers ($GS I$) and ($GS II$) in Table 5.1.

**Table 5.1: Weighting functions for LPV gain-scheduling controllers in Region II**

<table>
<thead>
<tr>
<th>Controller</th>
<th>$W_{ppt}$</th>
<th>$W_e$</th>
<th>$W_u$</th>
<th>$W_{\dot{u}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$GS I$</td>
<td>$1$</td>
<td>$\frac{0.001s + 0.5656}{s + 5.527}$</td>
<td>$0.03981$</td>
<td>$0.003162$</td>
</tr>
<tr>
<td>$GS II$</td>
<td>$0.1$</td>
<td>$\frac{0.0003162s + 1.491}{s + 46.06}$</td>
<td>$\begin{bmatrix} 0.003162 &amp; 0 \ 0 &amp; 0.3162 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 0 \ 5012 \end{bmatrix}$</td>
</tr>
</tbody>
</table>

$^2$L$_2$-gain of a system with the input $u$ and the output $y$ is defined by $\sqrt{\int_0^\infty y^T(t)u(t)\,dt / \int_0^\infty u^T(t)u(t)\,dt}$.
5.3 Simulation Results

To compare the performance of the GS I and GS II with the baseline controller, performance measures introduced in Section 3.4 are calculated from time domain simulations\(^3\). As explained in Chapter 3, average absorbed power \((P_{avg})\) is compared among different controllers to compare energy efficiency. Moreover, for comparing the fatigue load, the RMS value of platform pitch angle and its rate \((ppt_{rms} \text{ and } \dot{ppt}_{rms})\) are computed. According to the defined objectives in Section 5.1, the increase in the value of \(P_{avg}\) and decrease in the values of \(ppt_{rms}\) and \(\dot{ppt}_{rms}\) are desired. The values of computed measures for the controllers are shown in Table 5.2. The performance variation in percentage compared to the controller \((BaseR2)\) is also given in this table.

Table 5.2: Evaluated performance measures and their percent variation compared to BaseR2 in Region II

<table>
<thead>
<tr>
<th>Controller</th>
<th>(P_{avg}) (MW)</th>
<th>(ppt_{rms}) (degree)</th>
<th>(\dot{ppt}_{rms}) (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaseR2</td>
<td>2.937</td>
<td>1.403</td>
<td>0.126</td>
</tr>
<tr>
<td>GS I</td>
<td>2.911 (-0.89%)</td>
<td>1.366 (-2.64%)</td>
<td>0.119 (-5.56%)</td>
</tr>
<tr>
<td>GS II</td>
<td>2.886 (-1.74%)</td>
<td>1.303 (-7.13%)</td>
<td>0.118 (-6.35%)</td>
</tr>
</tbody>
</table>

Using only generator torque as a control input in \((GS I)\) has reduced platform pitch angle and its rate by about 2.64 and 5.56 percent, respectively. However, power capture has decreased by about 0.89 percent. The main reason for this power reduction is that a fraction of control effort for the generator torque has been used

\(^3\)The performance measures for other platform movements are given in Table B.1 and B.2.
for the reduction of platform pitch movement in addition to maximization of power.

In controller (\( GS\ II \)), utilization of both generator torque and blade pitch angle as control inputs have decreased the average platform pitch angle and its rate respectively by 7.13 and 6.35 percent, with 1.74 percent loss of energy capture compared to the (\( BaseR2 \)). In this way, the platform pitch movement is decreased by sacrificing a small amount of energy capture. This loss of power capture is expected because of deviating blade pitch from its maximum efficiency angle.

Therefore, compared to the \( BaseR2 \) controller, the platform pitch movement can be reduced by using multi-objective gain-scheduling controller (\( GS\ I \)) at the cost of losing small portion of power capture. If the user wants to reduce platform pitch movement further, one can use the controller (\( GS\ II \)) to utilize slight changes in blade pitch angle. This will improve platform pitch movement at the cost of a small drop in power capture.

Control inputs (blade pitch angle and generator torque) for these controllers are shown in Figure 5.4, while the platform pitch angle and generator speed error from reference signal \( \omega_{g,ref} \) are drawn in Figure 5.5. Figure 5.4(a) indicates that blade pitch angle for the controller \( GS\ II \) is relatively small. Therefore, the selection of \( \omega_{g,ref} \) of zero blade pitch angle for non-zero blade pitch application can be justified. Blade pitch angle is fixed to zero for \( BaseR2 \) and \( GS\ I \) controllers. On the other hand, generator torque is used as a control input for all the controllers and shown in Figure 5.4(b). Figure 5.5(a) demonstrates that (\( GS\ II \)) has the smallest platform pitch movement, while (\( BaseR2 \)) has the largest platform movement. Also, generator speed error is the smallest for \( BaseR2 \), which can be seen in Figure 5.5(b).

5.4 Summary

In this chapter, we investigated application of the \( LPV\ GS \) control and also the utilization of blade pitch angle for reducing the platform oscillation caused by wind and waves in \( Region\ II \). Two LPV controllers were designed by considering maximization
of power capture and minimization of platform pitch movement as a multi-objective problem. Generator torque is a control input for both of the controllers, while blade pitch angle is only utilized in one of these controllers. Their simulation results are compared with the baseline controller presented in Chapter 4. Generated power
Figure 5.5: System responses.

and platform oscillation are the parameters which are considered for comparison purposes.

The important results for this chapter is summarized as follows:
• Multi-objective controllers are designed which can reduce platform pitch movement at the cost of losing a small amount of power capture.

• Utilization of blade pitch angle as a control input will reduce the platform pitch movement.

• In the sense of platform pitch movement reduction, the LPV gain-scheduling controller with varying blade pitch was the best, and the BaseR2 was the worst.

• In the sense of power capture increase, the BaseR2 was the best, and the LPV gain-scheduling controller with varying blade pitch was the worst.

• The percentage of improvement in the platform pitch movement reduction is greater than the percentage of reduction in power capture.
Chapter 6

Gain-scheduling Control in

Region III

The basic method used to control the floating offshore wind turbines in Region III is explained in Chapter 4. In order to improve the performance, the LQR control method using state-feedback structure was proposed by [38]. This method designs an LQR controller based on one wind speed and applies this controller to the whole Region III.

Since turbine dynamics is changing over different operating points, designing a controller based on one operating point cannot guarantee performance over the whole operating region. Therefore, gain-scheduling LQR control, which considers variation in plant dynamics, is selected in this thesis. The gains in the gain-scheduling LQR controller vary with changes in operating conditions.

For both fixed and gain-scheduling LQR controllers, stability is a concern, because the fixed LQR controller is not effective far away from its design point, and also transitioning from one controller to the next using the gain-scheduling LQR method can make the system unstable. Therefore, these LQR controllers cannot guarantee stability over the whole operating region, and the stability analysis is necessary. The stability is analysed using the quadratic stability method [2].
In order to consider both stability and dynamics variation in the controller design, the LPV gain-scheduling controller is designed. The process for designing an LPV gain-scheduling controller is well established in [3]. The dynamics variation of the plant is considered in the controller design and a varying controller is designed. This gain-scheduling LPV controller is designed for both output-feedback and state-feedback structures. The advantage of state-feedback structure over the output-feedback structure is that more information is fed back which can improve the controller performance.

In this thesis, the LQR fixed controller designed for one wind speed and LQR gain-scheduling controller designed for the entire Region III are called $LQR_F$ and $LQR\ GS$, respectively. Also, the LPV gain-scheduling ($LPV\ GS$) controllers with output-feedback and state-feedback are called $LPV\ GS\ OF$ and $LPV\ GS\ SF$, respectively. Table 6.1 summarizes some of the properties of these controllers as well as the baseline controller ($BaseR3$) [23]. As one can see in this table, stability only can be guaranteed in the controller design using the $LPV\ GS$ method. In other words, for the case of $PI\ GS$ and $LQR$, the stability will be analyzed after controller design and we cannot guarantee the stability in the design stage.

<table>
<thead>
<tr>
<th>Controllers</th>
<th>Feedback Structure</th>
<th>Design Method</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BaseR3$</td>
<td>Output feedback</td>
<td>$PI\ GS$</td>
<td>Analyzed</td>
</tr>
<tr>
<td>$LQR\ F$</td>
<td>State feedback</td>
<td>LQR</td>
<td>Analyzed</td>
</tr>
<tr>
<td>$LQR\ GS$</td>
<td>State feedback</td>
<td>$LQR\ GS$</td>
<td>Analyzed</td>
</tr>
<tr>
<td>$LPV\ GS\ OF$</td>
<td>Output feedback</td>
<td>$LPV\ GS$</td>
<td>Guaranteed</td>
</tr>
<tr>
<td>$LPV\ GS\ SF$</td>
<td>State feedback</td>
<td>$LPV\ GS$</td>
<td>Guaranteed</td>
</tr>
</tbody>
</table>

In this chapter, control objectives are presented first. Then, controllers are
designed based on LQR and LPV GS methods. At the end, simulation results of these controllers are compared.

### 6.1 Control Objectives

As mentioned in Chapter 3, the general control objectives for Region III are summarized as:

\[
(OH1) \min |P - P_{\text{rated}}|, \\
(OH2) \min |y_{\text{ppt}}|.
\]

where \(P_{\text{rated}}\) is the rated power of the turbine. As mentioned in Section 3.1.2, the objective \((OH1)\) is simplified to the regulation of generator speed \((\min|\omega_g - \omega_{g,\text{rated}}|)\), because generator torque is assumed to be constant for the design of controllers in Region III.

The control objective \((OH1)\) which is the regulation of power is only considered in the design of LQR controllers. However, the LPV gain-scheduling controllers are designed considering both objectives simultaneously.

### 6.2 LQR Controllers

In this section, fixed and gain-scheduling controllers using the LQR method are designed. The structure for these controllers is a full state-feedback structure with an integrator. The states, as mentioned in Chapter 2, are rotor speed, platform pitch angle and platform pitch rate; all of which can be measured by the available sensors in the plant. Therefore, similar to [38, 39], the full state-feedback structure is considered. On the other hand, an integrator is used inside the structure in order to reduce the steady state error for generator speed regulation. This integrator also helps to compensate for the constant disturbance in the system such as wind and waves.
While the LQR F controller is designed by considering the turbine model at one operating point, the LQR GS controller is designed by considering the variation of plant dynamics over the entire operating region. Moreover, quadratic stability for these LQR controllers is analyzed.

6.2.1 LQR controller structure

The LQR control structure is substituted into Figure 3.2. This new feedback structure is presented in Figure 6.1, where $K_x$ and $K_e$ are control gains for state and error signals, respectively.

Using this feedback structure, LQR F and LQR GS controllers are designed. The controller gains for the LQR F controller are constant, while these gains are functions of wind speed for the LQR GS controller.

**LQR F controller**

The LQR F controller is designed based on the plant model at the middle point of the operating range ($v = (11.4 + 25)/2 = 18.2 \text{ m/s}$). The obtained controller gains are
constant, and are applied to the entire operating region. The LQR method places the closed-loop poles at proper positions in order to minimize the defined cost function. This cost function ($J$) for an infinite horizon LQR problem with an integrator is defined in (1.3), where $R$ is set to $10^4$ and $Q = 10^{-6}, 10^{-5.5}, 10^{-5.0}, \ldots, 10^{-2}$.

**LQR GS controller**

To design an LQR GS controller, the operating region of wind turbines (wind speed) is gridded, and an LQR F controller is designed at each gridded point using the same design parameters as for the LQR F case. Then, a varying controller at each operating point (wind speed) is obtained by linear interpolation of the controller gains at the two adjacent gridded points.

**6.2.2 Stability analysis**

The LQR F controllers are designed based on the model of the plant at one operating point, while they have been applied to the entire operating region. For this reason, stability is not guaranteed for all operating points. On the other hand, stability of LQR GS control is not guaranteed because transition between the controllers was not considered in the controller design. Therefore, stability should be analyzed for both fixed and gain-scheduling LQR controllers.

To analyze the stability of the controllers, quadratic stability using the Lyapunov stability criteria is considered. In the Lyapunov method, if a positive definite matrix $P_{lyp}$ satisfies

$$A_{cl}^T P_{lyp} + P_{lyp} A_{cl} < 0,$$

the system is quadratic stable at that point. Therefore, the operating region is gridded into several points and a common positive definite $P_{lyp}$ should be found by solving (6.1) for all of the gridded points using linear matrix inequality (LMI). If such a $P_{lyp}$ exists, quadratic stability is approved; otherwise, the designed controller may or may not be stable. In this case, another controller is designed by increasing
the number of points at which $LQR \ F$ are designed. Then, the stability is analyzed again.

### 6.3 LPV Gain-scheduling Controllers

The procedure for designing LPV gain-scheduling controllers in Region II and Region III is similar. However, the differences in control objectives and control inputs should be taken into account. This procedure is presented in Chapter 5 for wind speed in Region II. As it was explained, a well-known LPV gain-scheduling control method [3] is used to take into account the plant variation by designing a varying controller.

#### 6.3.1 LPV controller structures

A general feedback structure is given in Figure 3.2. Two feedback structures for LPV gain-scheduling controllers are substituted into said figure and are given in Figure 6.2. Figure 6.2 (a) is an output feedback structure used for designing $LPV \ GS \ OF$, and Figure 6.2 (b) is a state feedback structure used for designing $LPV \ GS \ SF$. In these structures, generator torque is constant and blade pitch angle is considered a control input.

**LPV GS OF controller**

This controller uses an output feedback structure with generator speed as its output feedback signal. To mathematically formulate a control design problem reflecting the control objectives ($OH1$) and ($OH2$), we will consider the feedback structure depicted in Figure 6.3 (a), where the control input $u$ is collective blade pitch angle and controller $K(v)$ is given in (5.3).

In order to use the well-known gain-scheduling technique presented in [3], the closed-loop system in Figure 6.3 (a) can be reconfigured with a generalized plant $G(v)$ as drawn in Figure 6.3 (b). In the figure, the weighting functions $W_{ppt}$, $W_e$
Figure 6.2: LPV GS feedback structures for Region III.
and $W_u$ are used to compromise between the regulation of generator speed, the minimization of platform pitch movement, and the fulfilment of the control input constraints.

The definition of the gain-scheduling control design problem is similar to Chapter 5. However, the control objectives for Region III, $(OH1)$ and $(OH2)$, are considered in the design process. Also, the control input $u$ is collective blade pitch angle.
**LPV GS SF controller**

The procedure for designing an LPV GS SF controller is similar to that of the LPV GS OF. However, instead of feeding back generator speed, all the states are fed back. The feedback structure used for controller design and also the generalized plant are given in Figure 6.4 (a) and (b), respectively. Matrix $C_{\omega g}$ is given in (2.3).

![Diagram of feedback control structure](image1)

(a) A Feedback control structure

![Diagram of feedback structure with a generalized plant](image2)

(b) A feedback structure with a generalized plant

Figure 6.4: *LPV GS SF controller for Region III.*

### 6.3.2 LPV gain-scheduling controller tuning

The controller parameters are tuned by selecting proper weighting functions. The weighting functions used in this control problem are: $W_{ppt}$, $W_e$ and $W_u$. By increas-
ing degree of weighting functions, the controller structure becomes more complex. This means that the controller will have more freedom and theoretically it can improve the performance.

The weighting functions are selected by comparing several simulation results. The weighting functions for \( LPV\ GS\ OF \) and \( LPV\ GS\ SF \) are given in Appendix C.

### 6.4 Simulation Results

Five controllers have been designed for Region III: \( BaseR3, LQR\ F, LQR\ GS, LPV\ GS\ OF \) and \( LPV\ GS\ SF \) controllers. Time-domain simulations are carried out for these controllers, with simulation settings as explained in Section 3.3, under two meteorological conditions given in Table 3.1. Figures 3.3 and 3.4 show their wind and wave profiles over time. These meteorological conditions have also been used in [38].

In order to compare the performance of the designed controllers, the performance measures introduced in Table 3.2 are evaluated. These performance measures are the RMS value of power regulation error, platform pitch angle and its derivative. According to the defined objectives in Section 6.1, the decrease in the values of all the parameters \( P_{rms}, ppt_{rms} \) and \( ppt_{rms} \) is desired.

For each controller, simulations are run for various design parameter values under the mentioned meteorological conditions. The evaluated performance measures for meteorological conditions (Cond. I and Cond. II) are shown in Figures 6.5 and 6.6, respectively. These figures depict the relations between the RMS value of power regulation error and the RMS values of platform pitch angle and its rate of change. Also, the performance measures evaluated for the \( BaseR3 \) controller are given in Table 4.2. Using these performance measures, different controller structures are compared. Then, one controller from each structure is selected in order to compare the performance parameters over time. The performance measures for the \( BaseR3 \) are given in Table 4.2. By comparing these results with the evaluated
performance measures for other designed controllers given in Figures 6.5 and 6.6, one can see that all the presented controller types can improve the performance measures compared to the BaseR3 by reducing both power regulation error and platform pitch movement at the same time. Specifically, power regulation has been improved substantially compared to the BaseR3.

Figures 6.5 and 6.6 imply that there is a trade-off between reduction of power regulation error and platform pitch movement for the LQR controllers. However as one can see in these figures, reduction of the platform pitch movement is restricted. By decreasing $Q$ less than approximately $Q = 10^{-4.0}$ in these simulations, power regulation will increase without improvement in the platform pitch movement. Also, improvement in power regulation is limited due to the stability guarantee issue. By increasing $Q$ more than approximately $Q = 10^{-2.5}$ in these simulations, which lead to high improvement in power regulation, the stability cannot be guaranteed using quadratic stability, even though the closed-loop system turned out to be stable in simulations. The LQR F and LQR GS controllers which can guarantee the stability are denoted by $LQR F Stable$ and $LQR GS Stable$. Another important result inferred from these figures is that the $LQR GS$ improves both power regulation and platform pitch compared to the $LQR F$. The main reason for this improvement is that the controller $LQR GS$ is designed as a time-varying controller, with the consideration of plant dynamics variations.

To guarantee the stability at the design stage, the $LPV GS$ controllers are designed. In Figures 6.5 and 6.6, the trade-off between the reduction of power regulation error and platform pitch movement can also be seen for the $LPV GS$ controllers. In these figures, performance of the $LPV GS OF$ controller is better than that of the $LQR F$ for the small platform pitch movement. However, by increasing platform movements, the performance of $LQR F$ controller outperforms $LPV GS OF$ controller. The main reason for the less favorable performance of $LPV GS OF$ controller compared to the $LQR$ controller is that the $LPV GS OF$
Figure 6.5: Error in power versus platform pitch response for different controllers (Cond. I)

Figure 6.6: Error in power versus platform pitch response for different controllers (Cond. II)
controller uses only the output as the feedback signals, while LQR controllers feed
back more information and use all the states as the feedback signal. On the other
hand, performance of the LPV GS SF controller which uses all the states as the
feedback signal is better than all other controllers in the sense of reducing power
regulation error and platform pitch movement. The performance of the LPV GS
SF controller is close to that of the LQR GS controller for the range of platform
movements achieved by the latter. The great advantage of the LQR GS SF controller
is that it can reduce platform pitch movement substantially at the cost of increasing
error in power regulation compared to other controllers.

Platform pitch movement is only considered in the design of LPV GS con-
trollers. Also, other platform movements were not considered in the controller de-
sign. Therefore, performance of only platform pitch movement for LPV GS con-
trollers can be predicted. Performance of platform pitch movement for LQR con-
trollers and all other platform movements are compared based on the simulation
results. These simulation results are given in Appendix D. In these simulations, the
LPV GS SF controller can generally improve platform roll, pitch and sway move-
ments by sacrificing power regulation and at the same time increasing the yaw and
surge movements. Also, heave movement is almost constant.

In order to compare the response of different controller structures over time,
one controller from each structure is selected. The selected controller is the one
which have achieved high reduction in platform pitch movement in that structure.
The parameters for the selected controllers are given in Table E.1. Also, the control
inputs are presented in Figures E.1 and E.2. Finally, the performance measures are
compared in Tables 6.2 and 6.3

As one can see from Tables 6.2 and 6.3, and also time domain simulations
in Figures 6.7 and 6.8, power regulation for all of the designed controllers has been
improved substantially compared to the baseline controller. In the sense of platform
movements reduction, LPV GS SF is the best, while in the sense of power regulation,
Table 6.2: Evaluated performance measures for selected controllers in Region III (Cond. I)

<table>
<thead>
<tr>
<th>Controller</th>
<th>$P_{rms}$ (MW)</th>
<th>$\theta_{rms}$ (degree)</th>
<th>$\hat{\theta}_{rms}$ (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaseR3</td>
<td>1.752</td>
<td>2.605</td>
<td>1.336</td>
</tr>
<tr>
<td>LQR $F$</td>
<td>0.376 (-78.54%)</td>
<td>2.101 (-19.35%)</td>
<td>1.071 (-19.84%)</td>
</tr>
<tr>
<td>LQR $GS$</td>
<td>0.247 (-85.90%)</td>
<td>1.981 (-23.95%)</td>
<td>0.982 (-26.50%)</td>
</tr>
<tr>
<td>LPV GS OF</td>
<td>0.298 (-82.99%)</td>
<td>2.072 (-20.46%)</td>
<td>1.031 (-22.83%)</td>
</tr>
<tr>
<td>LPV GS SF</td>
<td>0.423 (-75.86%)</td>
<td>1.222 (-53.09%)</td>
<td>0.472 (-64.67%)</td>
</tr>
</tbody>
</table>
Table 6.3: Evaluated performance measures for selected controllers in Region III (Cond. II)

<table>
<thead>
<tr>
<th>Controller</th>
<th>$P_{\text{rms}}$ (MW)</th>
<th>$\theta_{\text{rms}}$ (degree)</th>
<th>$\theta_{\text{rms}}$ (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaseR3</td>
<td>2.518</td>
<td>4.110</td>
<td>2.103</td>
</tr>
<tr>
<td>LQR F</td>
<td>0.483 (-80.82%)</td>
<td>3.223 (-21.58%)</td>
<td>1.636 (-22.21%)</td>
</tr>
<tr>
<td>LQR GS</td>
<td>0.410 (-83.72%)</td>
<td>3.141 (-23.58%)</td>
<td>1.579 (-24.92%)</td>
</tr>
<tr>
<td>LPV GS OF</td>
<td>0.433 (-82.80%)</td>
<td>3.438 (-16.35%)</td>
<td>1.730 (-17.74%)</td>
</tr>
<tr>
<td>LPV GS SF</td>
<td>0.622 (-75.30%)</td>
<td>1.275 (-68.98%)</td>
<td>0.492 (-76.60%)</td>
</tr>
</tbody>
</table>
LQR GS is the best. However, the LPV GS SF structure can achieve almost the same power regulation and platform pitch movement as the LQR GS by changing its weighting functions, see Figures 6.7 (a) and 6.8 (a). In LPV GS SF, weighting functions are selected to improve platform pitch angle substantially compared to other controllers at the cost of increasing power regulation error.

6.5 Summary

In Region III, regulation of power capture and reduction of platform movements are the original objectives that have been simplified to regulation of generator speed and reduction of platform pitch movement.

In this chapter, we have utilized the advantages of state-feedback structure and gain-scheduling controller technique. The state-feedback structure provides more information than the output-feedback structure. Also, the gain-scheduling technique considers the plant dynamics variation and designs a varying controller. The important simulation results for this chapter are summarized as follows;

- Improvement of power regulation and platform pitch movement in all of the designed controllers compared to the baseline controller (Substantial improvement of power regulation),

- Improvement of power regulation and platform pitch movement in LQR GS compared to LQR F because of considering plant dynamics in the controller design,

- Improvement of power regulation and platform pitch movement in LQR GS compared to LPV GS OF because of using a state-feedback structure,

- Improvement of power regulation and platform pitch movement in LPV GS SF compared to all other controller because of considering plant dynamics in
Figure 6.7: System responses for time-domain simulations for selected controllers in Region III (Cond. I)
Figure 6.8: System responses for time-domain simulations for selected controllers in Region III (Cond. II)
the controller design, using a state-feedback structure and also utilizing the 
LPV GS technique,

- Guaranteeing stability in the design stage for LPV GS controllers rather than 
analyzing the stability in LQR controllers after controller design,

- Capability of LPV GS SF controller for substantial improvement of platform 
pitch movement compared to all other controllers.
Chapter 7

Conclusion

The important achievements accomplished in this thesis are first summarized. Then, the contributions of this thesis and potential future work follow.

7.1 Summary of Achievements

The operating region of wind turbines is divided into Region II and Region III. Separate controllers were designed for these two regions and compared with the conventional controllers presented in [23, 38].

In Region II, LPV gain-scheduling controllers were designed for both fixed and varying blade pitch angle. The advantages of using an LPV gain-scheduling controller are consideration for plant dynamics and consideration for the multi-objectives problem in the controller design. The simulation results show that reduction of platform pitch movement is possible with a slight loss in energy capture, and that the varying blade pitch strategy is more effective in platform movements reduction than the fixed blade pitch strategy.

In Region III, LQR gain-scheduling and LPV gain-scheduling controllers with both state feedback and output feedback structures were designed. These controllers were compared with the conventional controllers such as baseline and fixed LQR.
controllers presented in [23, 38]. The simulation results show that all the designed controllers have better performance compared to the conventional controllers in the sense of better power regulation and platform pitch movement reduction. Among the three designed controllers, the LPV gain-scheduling controller with state-feedback surpassed the other two controllers, especially in the sense of platform pitch reduction.

While stability can be guaranteed in the design stage for the LPV gain-scheduling controllers, this is not the case for the LQR controllers. For LQR controllers, stability can be analyzed after controller design using quadratic stability.

7.2 Contributions

The main contributions addressed in this thesis for the control of floating offshore wind turbines can be categorized as follows;

- LPV model of the system was developed using interpolation.

- Gain-scheduling controllers were demonstrated to be efficient in improving energy capture and platform pitch movement in simulations.

- Blade pitch angle in Region II was utilized in order to reduce platform pitch movement with a slight loss in energy capture.

- The LPV gain-scheduling controller with state feedback was found to perform better than other gain-scheduling controllers in Region III.

7.3 Future Work

Control of floating offshore wind turbines is a field that has a great deal of potential for improvement. Some of the future work which can be done in this area is summarized below;
• **Considering other platform movements in the controller design:** In the designed controllers, only reduction of platform pitch was considered. However, other platform movements also induce structural loads on the system. Therefore, reduction of these movements can be considered in the controller design.

• **Modelling the wave effects on the system:** Wave affects platform movements substantially and can diminish performance of wind turbines. As a future work, the effects of waves on the system should be modelled and incorporated into controller design.

• **Designing a switching gain-scheduling controller for both state-feedback and output feedback structures:** If the LPV gain-scheduling controller is designed for a smaller operating range, there is a possibility for performance improvement. Therefore, switching gain-scheduling controllers [29, 30] can be considered as future work. In this method, different gain-scheduling controllers are designed for different operating regions and they are switched between the regions based on the operating points.
Bibliography


Appendix A

LPV Model of the Wind Turbine

The state-space matrices, $A(v)$, $B(v)$ and $B_{d,\text{wind}}(v)$, are calculated for the NREL 5 MW in both Region II and Region III. These matrices are obtained using samples of wind speed for every 0.5m/s and parameterizing according to Section 2.2.

A.1 LPV Model for Region II

The LPV model of the wind turbine for Region II is parameterized as

$$
A(v) =: A_0 + A_1 v, \\
B(v) =: B_0 + B_1 v, \\
B_d(v) =: B_{d0} + B_{d1} v.
$$ (A.1)
These coefficients are given here for the condition that generator torque is the only control input.

\[
A_0 = \begin{bmatrix}
0 & 1 & 0 \\
-2.909 \times 10^{-1} & -4.353 \times 10^{-3} & 1.811 \times 10^{-4} \\
3.075 \times 10^{-2} & -5.76 \times 10^{-3} & 9.266 \times 10^{-5}
\end{bmatrix},
\]

\[
A_1 = \begin{bmatrix}
0 & 0 & 0 \\
-5.348 \times 10^{-4} & -6.525 \times 10^{-3} & 4.741 \times 10^{-4} \\
-5.531 \times 10^{-3} & -9.395 \times 10^{-2} & -5.735 \times 10^{-3}
\end{bmatrix},
\]

\[
[B_0, B_1] = \begin{bmatrix}
0 & 0 \\
1.348 \times 10^{-12} & -2.17 \times 10^{-13} \\
-2.215 \times 10^{-6} & 0
\end{bmatrix}
\]

\[
[B_{d0}, B_{d1}] = \begin{bmatrix}
0 & 0 \\
2.075 \times 10^{-6} & 1.334 \times 10^{-4} \\
2.644 \times 10^{-4} & 2.062 \times 10^{-3}
\end{bmatrix}
\]

Also, the coefficients of state-space matrices are obtained for the condition that control inputs are generator torque and blade pitch angle.

\[
A_0 = \begin{bmatrix}
0 & 1 & 0 \\
-2.909 \times 10^{-1} & -6.688 \times 10^{-3} & -5.761 \times 10^{-4} \\
3.048 \times 10^{-2} & -1.354 \times 10^{-2} & 8.465 \times 10^{-1}
\end{bmatrix},
\]

\[
A_1 = \begin{bmatrix}
0 & 0 & 0 \\
-5.229 \times 10^{-4} & -6.537 \times 10^{-3} & 5.090 \times 10^{-4} \\
-5.434 \times 10^{-3} & -9.584 \times 10^{-2} & -1.146 \times 10^{-1}
\end{bmatrix},
\]

\[
[B_0, B_1] = \begin{bmatrix}
0 & 0 & 0 \\
-9.008 \times 10^{-13} & 2.842 \times 10^{-2} & 6.692 \times 10^{-14} & -6.578 \times 10^{-3} \\
-2.215 \times 10^{-6} & -1.493 \times 10^{-2} & 0 & -4.928 \times 10^{-3}
\end{bmatrix}
\]
[B_{d0}, B_{d1}] = \begin{bmatrix}
0 & 0 \\
-1.541 \times 10^{-5} & 1.331 \times 10^{-4} \\
-5.413 \times 10^{-4} & 2.091 \times 10^{-3}
\end{bmatrix}

A.2 LPV Model for Region III

The LPV model of the wind turbine for Region III is parameterized as

\begin{align}
A(v) &= A_0 + A_1v + A_2v^2 + A_3v^3 + A_4v^4, \\
B(v) &= B_0 + B_1v + B_2v^2 + B_3v^3 + B_4v^4, \\
B_d(v) &= B_{d0} + B_{d1}v + B_{d2}v^2 + B_{d3}v^3 + B_{d4}v^4.
\end{align}

(A.2)

These coefficients are given here for the condition that blade pitch angle is the only control input.
\[
A_0 = \begin{bmatrix}
0 & 1 & 0 \\
-3.341 \times 10^{-1} & 8.874 \times 10^{-1} & 1.499 \times 10^{-1} \\
-3.842 \times 10^{-2} & 1.238 \times 10^1 & -7.296 \times 10^{-1}
\end{bmatrix},
\]

\[
A_1 = \begin{bmatrix}
0 & 1 & 0 \\
8.372 \times 10^{-3} & -2.051 \times 10^{-1} & -2.793 \times 10^{-2} \\
8.079 \times 10^{-2} & -2.754 \times 10^0 & 1.761 \times 10^{-1}
\end{bmatrix},
\]

\[
A_2 = \begin{bmatrix}
0 & 1 & 0 \\
-6.714 \times 10^{-4} & 1.574 \times 10^{-2} & 1.975 \times 10^{-3} \\
-6.499 \times 10^{-3} & -7.062 \times 10^{-1} & -1.478 \times 10^{-2}
\end{bmatrix},
\]

\[
A_3 = \begin{bmatrix}
0 & 1 & 0 \\
2.336 \times 10^{-5} & -5.357 \times 10^{-4} & -6.525 \times 10^{-5} \\
2.176 \times 10^{-4} & -7.062 \times 10^{-3} & 4.65 \times 10^{-4}
\end{bmatrix},
\]

\[
A_4 = \begin{bmatrix}
0 & 1 & 0 \\
-3.015 \times 10^{-7} & 6.803 \times 10^{-6} & 8.123 \times 10^{-7} \\
-2.754 \times 10^{-6} & 9.071 \times 10^{-5} & -5.712 \times 10^{-6}
\end{bmatrix},
\]

\[
[B_0, B_1, B_2, B_3, B_4] =
\]

\[
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
3.283 \times 10^{-1} & -7.799 \times 10^{-2} & 5.918 \times 10^{-3} & -2.012 \times 10^{-4} & 2.548 \times 10^{-6} \\
1.112 \times 10^1 & -2.266 \times 10^0 & 1.674 \times 10^{-1} & -5.717 \times 10^{-3} & 7.268 \times 10^{-5}
\end{bmatrix}
\]

\[
[B_{d0}, B_{d1}, B_{d2}, B_{d3}, B_{d4}] =
\]

\[
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
4.633 \times 10^{-3} & -7.126 \times 10^{-4} & 5.553 \times 10^{-5} & -1.898 \times 10^{-6} & 2.397 \times 10^{-8} \\
1.102 \times 10^{-1} & -2.037 \times 10^{-2} & 1.662 \times 10^{-3} & -5.638 \times 10^{-5} & 7.065 \times 10^{-7}
\end{bmatrix}
\]

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Appendix B

Performance Measures for the Designed Controllers in Region II

The performance measures for the $BaseR2$ and the two gain-scheduling controllers ($GS1$ and $GS2$) are presented in Tables B.1 and B.2.

Table B.1: Evaluated performance measures for power capture and platform movements in Region II.

<table>
<thead>
<tr>
<th>Performance Measures</th>
<th>$P_{avg}$ (MW)</th>
<th>$prl_{rms}$ (degree)</th>
<th>$ppt_{rms}$ (degree)</th>
<th>$pyw_{rms}$ (degree)</th>
<th>$ps_{grms}$ (m)</th>
<th>$ps_{wrms}$ (m)</th>
<th>$ph_{v rms}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BaseR2$</td>
<td>2.937</td>
<td>0.127</td>
<td>1.403</td>
<td>0.718</td>
<td>25.867</td>
<td>0.329</td>
<td>0.409</td>
</tr>
<tr>
<td>$GS1$</td>
<td>2.911</td>
<td>0.141</td>
<td>1.366</td>
<td>0.710</td>
<td>25.442</td>
<td>0.332</td>
<td>0.409</td>
</tr>
<tr>
<td>$GS2$</td>
<td>2.886</td>
<td>0.140</td>
<td>1.303</td>
<td>0.607</td>
<td>24.680</td>
<td>0.340</td>
<td>0.409</td>
</tr>
</tbody>
</table>
Table B.2: Evaluated performance measures for derivative of platform movements of the baseline controller in *Region II*.

<table>
<thead>
<tr>
<th>Performance Measures</th>
<th>$prl_{rms}$ (degree)</th>
<th>$ppt_{rms}$ (degree)</th>
<th>$pyw_{rms}$ (degree)</th>
<th>$psq_{rms}$ (m)</th>
<th>$psw_{rms}$ (m)</th>
<th>$phv_{rms}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>BaseR2</em></td>
<td>0.036</td>
<td>0.126</td>
<td>0.107</td>
<td>0.488</td>
<td>0.017</td>
<td>0.314</td>
</tr>
<tr>
<td><em>GS1</em></td>
<td>0.048</td>
<td>0.119</td>
<td>0.105</td>
<td>0.453</td>
<td>0.017</td>
<td>0.314</td>
</tr>
<tr>
<td><em>GS2</em></td>
<td>0.047</td>
<td>0.118</td>
<td>0.089</td>
<td>0.445</td>
<td>0.0164</td>
<td>0.314</td>
</tr>
</tbody>
</table>
Appendix C

Design Parameters for LPV Gain-scheduling Controllers in Region III

The weighting functions for the LPV GS OF and LPV GS SF controllers are presented here. The values of $W_{e1}$, $W_{u1}$ and $W_{ppt1}$ used in Table C.1 are:

\begin{align*}
W_{e1}(s) &= \frac{0.003162s + 0.1491}{s + 0.4606}, \quad (C.1) \\
W_{u1}(s) &= \frac{1 \times 10^5 s^2 + 1.257 \times 10^5 s + 3.952 \times 10^4}{s^2 + 4.513s + 5.091}, \quad (C.2) \\
W_{ppt1}(s) &= \frac{15.85s + 74.33}{s + 0.4583}. \quad (C.3)
\end{align*}

Also, the values of $W_{e2}$, $W_{u2}$ and $W_{ppt2}$ used in Table C.2 are:

\begin{align*}
W_{e2}(s) &= 10^0, \quad (C.4) \\
W_{u2}(s) &= 10^{2.5}, \quad (C.5) \\
W_{ppt2}(s) &= 10^{3.5}. \quad (C.6)
\end{align*}
Table C.1: Weighting functions for LPV GS OF controllers in Region III

<table>
<thead>
<tr>
<th>$W_e$</th>
<th>$W_u$</th>
<th>$W_{ppt}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_{e1}$</td>
<td>$W_{u1}$</td>
<td>$W_{ppt1}$</td>
</tr>
<tr>
<td>$10^{-0.2} \times W_{u1}$</td>
<td>$W_{ppt1}$</td>
<td></td>
</tr>
<tr>
<td>$10^{-0.4} \times W_{u1}$</td>
<td>$W_{ppt1}$</td>
<td></td>
</tr>
<tr>
<td>$10^{-0.6} \times W_{u1}$</td>
<td>$W_{ppt1}$</td>
<td></td>
</tr>
<tr>
<td>$10^{-0.8} \times W_{u1}$</td>
<td>$W_{ppt1}$</td>
<td></td>
</tr>
<tr>
<td>$10^{-1.0} \times W_{u1}$</td>
<td>$W_{ppt1}$</td>
<td></td>
</tr>
<tr>
<td>$10^{-1.2} \times W_{u1}$</td>
<td>$W_{ppt1}$</td>
<td></td>
</tr>
<tr>
<td>$10^{-1.4} \times W_{u1}$</td>
<td>$W_{ppt1}$</td>
<td></td>
</tr>
<tr>
<td>$10^{0.5} \times W_{e1}$</td>
<td>$10^{-1.4} \times W_{u1}$</td>
<td>$W_{ppt1}$</td>
</tr>
<tr>
<td>$10^{1.0} \times W_{e1}$</td>
<td>$10^{-1.4} \times W_{u1}$</td>
<td>$W_{ppt1}$</td>
</tr>
</tbody>
</table>

Table C.2: Weighting functions for LPV GS SF controllers in Region III

<table>
<thead>
<tr>
<th>$W_e$</th>
<th>$W_u$</th>
<th>$W_{ppt}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_{e2}$</td>
<td>$W_{u2}$</td>
<td>$W_{ppt2}$</td>
</tr>
<tr>
<td>$10^{0.25} \times W_{e2}$</td>
<td>$W_{u2}$</td>
<td>$W_{ppt2}$</td>
</tr>
<tr>
<td>$10^{0.50} \times W_{e2}$</td>
<td>$W_{u2}$</td>
<td>$W_{ppt2}$</td>
</tr>
<tr>
<td>$10^{0.75} \times W_{e2}$</td>
<td>$W_{u2}$</td>
<td>$W_{ppt2}$</td>
</tr>
<tr>
<td>$10^{1.0} \times W_{e2}$</td>
<td>$W_{u2}$</td>
<td>$W_{ppt2}$</td>
</tr>
<tr>
<td>$10^{1.25} \times W_{e2}$</td>
<td>$W_{u2}$</td>
<td>$W_{ppt2}$</td>
</tr>
<tr>
<td>$10^{1.50} \times W_{e2}$</td>
<td>$W_{u2}$</td>
<td>$W_{ppt2}$</td>
</tr>
<tr>
<td>$10^{1.75} \times W_{e2}$</td>
<td>$W_{u2}$</td>
<td>$W_{ppt2}$</td>
</tr>
<tr>
<td>$10^{2.00} \times W_{e2}$</td>
<td>$W_{u2}$</td>
<td>$W_{ppt2}$</td>
</tr>
</tbody>
</table>
Appendix D

Performance Measures for the Designed Controllers in Region III

The performance measures are computed for different controllers designed in Region III. These simulations are carried out under two meteorological conditions (Cond. I and Cond. II). Figures D.1-D.8 show the performance measures for the designed controllers, while Tables D.1 and D.2 show these performance measures for the baseline controller.
Figure D.1: Platform angle response for different controllers (Cond. I)

Figure D.2: Platform angular rate response for different controllers (Cond. I)
Figure D.3: Platform displacement response for different controllers (Cond. I)

Figure D.4: Platform translational rate response for different controllers (Cond. I)
Figure D.5: Platform angle response under for different controllers (Cond. II)

Figure D.6: Platform angular rate response for different controllers (Cond. II)
Figure D.7: Platform displacement response for different controllers (Cond. II)

Figure D.8: Platform translational rate response for different controllers (Cond. II)
Table D.1: Evaluated performance measures for power capture and platform movements of the baseline controller in Region III.

<table>
<thead>
<tr>
<th>Performance Measures</th>
<th>( P_{\text{rms}} ) (MW)</th>
<th>( prl_{\text{rms}} ) (degree)</th>
<th>( ppt_{\text{rms}} ) (degree)</th>
<th>( pyw_{\text{rms}} ) (degree)</th>
<th>( ps_{\text{rms}} ) (m)</th>
<th>( ps_{\text{rms}} ) (m)</th>
<th>( phv_{\text{rms}} ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cond. I</td>
<td>1.752</td>
<td>1.081</td>
<td>2.605</td>
<td>1.761</td>
<td>20.344</td>
<td>1.800</td>
<td>2.866</td>
</tr>
<tr>
<td>Cond. II</td>
<td>2.517</td>
<td>1.504</td>
<td>4.110</td>
<td>2.114</td>
<td>19.512</td>
<td>1.977</td>
<td>2.053</td>
</tr>
</tbody>
</table>

Table D.2: Evaluated performance measures for derivative of platform movements of the baseline controller in Region III.

<table>
<thead>
<tr>
<th>Performance Measures</th>
<th>( prl_{\text{rms}} ) (degree)</th>
<th>( ppt_{\text{rms}} ) (degree)</th>
<th>( pyw_{\text{rms}} ) (degree)</th>
<th>( ps_{\text{rms}} ) (m)</th>
<th>( ps_{\text{rms}} ) (m)</th>
<th>( phv_{\text{rms}} ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cond. I</td>
<td>0.592</td>
<td>1.336</td>
<td>0.189</td>
<td>0.523</td>
<td>0.097</td>
<td>2.289</td>
</tr>
<tr>
<td>Cond. II</td>
<td>0.827</td>
<td>2.103</td>
<td>0.236</td>
<td>0.693</td>
<td>0.118</td>
<td>1.581</td>
</tr>
</tbody>
</table>
Appendix E

Time Domain Simulations for the Selected Controllers in Region III

The controller parameters for the controllers which have been selected for comparison of time-domain simulations are given in Table E.1. The values of parameters $W_{e1}$, $W_{u1}$, $W_{ppt1}$, $W_{e2}$, $W_{u2}$ and $W_{ppt2}$ are given in (C.1)-(C.6). Also, Figures E.1 and E.2 show the control inputs of these selected controllers.

Table E.1: Controller parameters for selected controllers in Region III

<table>
<thead>
<tr>
<th>Controller parameters</th>
<th>$Q$</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LQR $F$</td>
<td>$10^{-4}$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>LQR $GS$</td>
<td>$10^{-4}$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>Controller parameters</td>
<td>$W_e$</td>
<td>$W_u$</td>
</tr>
<tr>
<td>LPV $GS$ $OF$</td>
<td>$W_{e1}$</td>
<td>$W_{u1}$</td>
</tr>
<tr>
<td>LPV $GS$ $SF$</td>
<td>$10^{0.25 \times W_{e2}}$</td>
<td>$W_{u2}$</td>
</tr>
</tbody>
</table>
Figure E.1: Control inputs for time-domain simulations for selected controllers in Region III (Cond. I)
Figure E.2: Control inputs for time-domain simulations for selected controllers in Region III (Cond. II)