LIDAR-Assisted Exact Output Regulation for Multi-Megawatt Wind Turbines

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Abstract

Wind energy is free and accessible almost everywhere on earth. Nevertheless, the utilization of wind energy is associated with the costs of the material, manufacturing, installation, maintenance, and operation. These factors define the Levelized Cost Of Energy and its competency against other energy sources. In order to improve the competitiveness of wind energy in the energy market, wind turbines operational performance and efficiency should be further optimized. The wind turbines performance is improved by maximizing the energy harvest whilst minimizing the mechanical extreme and fatigue loads on the tower structure, blades and the rotor.

Over the past few years, various technologies and methods have been implemented to improve the performance of the wind turbine. Among these technologies, the Light Detection And Ranging devices (LIDARs) have been a point of interest for researchers. The LIDAR’s ability to provide information about the upcoming wind has originated a new generation of wind turbine control techniques. However, effective augmentation of the wind preview information into the wind turbine control systems has proven to be a challenging problem to-date.

This thesis explores the application of a classical control method, namely Exact Output Regulation, to improve the control performance of utility-scale wind turbines by utilizing the LIDAR measured wind information in the control loop. Here, the Exact Output Regulator is designed to reject the known input disturbances, i.e., wind, whilst ensuring that the system output tracks a desired reference signal. The proposed Exact Output Regulator-based wind turbine controller is comprised of a state feedback controller together with a feed-forward gain matrix. The LIDAR wind preview information can be used to obtain a low-order exosystem that models the wind dynamics. This exosystem wind model is used to obtain the feed-forward gain matrix that enables the Exact Output Regulator to effectively reject the impact of the input wind disturbance on the rotor speed and achieve the desired reference tracking.
To perform realistic simulations and analysis and obtain reliable results, different software, such as high fidelity aero-elastic simulators (e.g., FAST), 3-D turbulent wind field generators (e.g., TurbSim), and performance and fatigue evaluation code are required. To this end, a toolbox is developed alongside this thesis which can synthesize the Exact Output Regulator in real-time and apply it to the FAST model of the wind turbine. This toolbox is called Turbine Output Regulator, used for simulations throughout this thesis.

Various simulations are performed on the Exact Output Regulated wind turbine in both partial and full load operating regions using different wind fields of different mean wind speeds. The full nonlinear aero-elastic model of the National Renewable Energy Laboratory’s 5-MW reference wind turbine is used as the wind turbine model. A Continuous Wave LIDAR simulator is used in order to replicate the LIDAR measurements of the wind fields constructed by TurbSim. For performance comparisons, we implemented a feedback Baseline controller and a feed-forward Disturbance Accommodating Controller. It is also shown that the Disturbance Accommodating Controller may be represented as a special case of Exact Output Regulator, if some important parts of the Exact Output Regulator architecture are omitted.

The simulation and analysis results on the turbulent wind scenarios show that, in comparison with a Baseline and Disturbance Accommodating Controller, the Exact Output Regulator can provide a substantial reduction of extreme and fatigue loads. The Exact Output Regulator is shown to be much more reliable in preserving the wind turbine states within the permissible range.
Declaration

This is to certify that

1. the thesis comprises only my original work towards the PhD,

2. due acknowledgement has been made in the text to all other material used,

3. the thesis is less than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices.

______________________________________________
Amin Mahdizadeh, February 2019
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I appreciate the financial support provided by the University of Melbourne and its great research atmosphere. Many thanks to the great engineers and ingenious scientists who worked relentlessly over the history of mankind so that today we can stand upon their shoulders and see further.

I would also like to thank my family for believing in me and supporting me in all the adventures of my life. I would like to thank my dear wife, Elham, who has been a great companion throughout these years and an endless source of support and love during all the challenging moments.
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Preface

This thesis is mainly done by the student who carried out the literature review, research gap identification, solution approach design, computer simulations, results analysis, and technical writing towards his Ph.D. thesis. The principal supervisor has also contributed to the thesis through supervision, technical advice and comments provision, and manuscripts proofreading over regular meeting sessions.

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To my beloved wife, and dearest parents.
This page intentionally left blank.
<table>
<thead>
<tr>
<th>Contents</th>
</tr>
</thead>
</table>

1 Introduction

1.1 Motivation ..................................................... 1
1.2 Literature Review ............................................ 4
1.3 Research Questions ........................................... 12
1.4 Thesis Overview ............................................... 12
1.4.1 Research Objectives and Contributions ............. 13
1.4.2 Structure of the Thesis ............................... 14

2 Technical Background

2.1 History ....................................................... 17
2.2 Nature of the Wind Energy .................................. 19
2.2.1 Spatial Variations ........................................ 20
2.2.2 Temporal Variations ...................................... 20
2.2.3 Turbulence .................................................... 20
2.2.4 IEC Standards for Wind Simulation ............... 21
2.2.5 Extreme Winds and Gust .................................. 23
2.3 Fundamentals of Wind Energy Conversion ............ 23
2.3.1 Wind power extraction limits ...................... 25
2.4 Operating Regions ............................................. 26
2.5 Wind Turbine Components ................................... 28
2.5.1 Rotor and Blades .......................................... 28
2.5.2 Drive Train ................................................. 29
2.5.3 Tower ......................................................... 29
2.6 Analysis of Structural Loads ............................... 30
2.6.1 Design Load Cases ......................................... 30
2.6.2 Fatigue Load Analysis .................................... 31
2.6.3 Extreme Load Analysis ................................... 32
2.7 Definition of Matrix Norms in the Thesis ............ 32
2.8 State Space Representation of Dynamic Systems .... 33
2.8.1 State Estimation of Dynamic Systems ........... 35
2.9 Exact Output Regulation ..................................... 36
2.9.1 The Output Regulation Problem ................. 37
3 Wind Turbine Modeling

3.1 Properties of NREL 5MW Reference Wind Turbine
   3.1.1 Blade Properties .................................................. 42
   3.1.2 Hub and Nacelle Properties ..................................... 43
   3.1.3 Drive-train Properties .......................................... 43
   3.1.4 Tower Properties .................................................. 44

3.2 Full aero-elastic model of the NREL-5MW in FAST
   3.2.1 Aerodynamics in FAST ............................................ 46
   3.2.2 Structural Dynamics in FAST ................................... 47
   3.2.3 Actuators in FAST ................................................ 47
   3.2.4 FAST Measurement Outputs ...................................... 48

3.3 Simplified Model for Estimation and Control
   3.3.1 Simplified Aerodynamics Subsystem Model ..................... 48
   3.3.2 Simplified Mechanical Subsystem Model ....................... 50
   3.3.3 Simplified Electrical Subsystem Model ....................... 53
   3.3.4 Simplified Actuator Subsystem Model ......................... 53

3.4 Linearized Model of the Wind Turbine
   3.4.1 Equilibrium Point Linearisation ................................ 54
   3.4.2 Region 2 Linearized Model ...................................... 56
   3.4.3 Region 3 Linearized Model ...................................... 58
   3.4.4 Model Validation of the Lower Order Model .................. 59

4 Wind Turbine Control Objectives and Methods

4.1 Wind turbine Control Objectives ................................... 61
   4.1.1 Power Generation measures ...................................... 62
   4.1.2 Fatigue Load Measurement ....................................... 63
   4.1.3 Actuator Saturation and Measures ................................ 64
   4.1.4 Spectral Performance Measures: Power Spectral Density .... 66

4.2 Widely used Control Methodologies ............................... 66
   4.2.1 Baseline Control .................................................. 67
   4.2.2 Disturbance Accommodation Control ............................ 69
   4.2.3 LIDAR Variant of the DAC ....................................... 71

5 Utilization of Exact Output Regulation for Wind Turbines

5.1 Synthesis of Exo-systems for EOR ................................. 76
   5.1.1 Parameter Estimation in Discrete Time ......................... 76
   5.1.2 Computation of the disturbance and reference signals ........ 79
   5.1.3 EOR Controller Design .......................................... 81

5.2 Mathematical Relationships Between DAC and EOR ............... 82
   5.2.1 Generality: DAC as special case of EOR ...................... 82
   5.2.2 Solvability of DAC Equations .................................... 83
This page intentionally left blank.
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>IEC-61400 Turbulence intensity (right) and turbulence standard deviation (left) graphs for the normal turbulence model</td>
<td>22</td>
</tr>
<tr>
<td>2.3</td>
<td>Wind Turbine Blade represented as an airfoil</td>
<td>24</td>
</tr>
<tr>
<td>2.4</td>
<td>Expansion of the slow moving air cross-section of a Wind Turbine</td>
<td>25</td>
</tr>
<tr>
<td>2.5</td>
<td>Power of the wind (Blue) vs Betz-Joukowsky power limit (Red) and the 5 MW NREL Wind Turbine maximum power capacity (Orange) for a 63 meters radius rotor</td>
<td>26</td>
</tr>
<tr>
<td>2.6</td>
<td>Wind Turbine Operating Regions [101]</td>
<td>27</td>
</tr>
<tr>
<td>2.7</td>
<td>Block diagram of EOR</td>
<td>37</td>
</tr>
<tr>
<td>3.1</td>
<td>Schematic diagram of a Horizontal axis Wind Turbine with LIDAR</td>
<td>42</td>
</tr>
<tr>
<td>3.2</td>
<td>Schematic diagram of internal components of the nacelle</td>
<td>43</td>
</tr>
<tr>
<td>3.3</td>
<td>Power co-efficient surface of NREL-5MW wind turbine.</td>
<td>50</td>
</tr>
<tr>
<td>3.4</td>
<td>Thrust co-efficient surface of NREL-5MW wind turbine.</td>
<td>51</td>
</tr>
<tr>
<td>3.5</td>
<td>Two-mass-system drive-train model of the wind turbine.</td>
<td>51</td>
</tr>
<tr>
<td>3.6</td>
<td>Tower Dynamics modeled as mass spring damper system with the aero dynamic force as input</td>
<td>52</td>
</tr>
<tr>
<td>3.7</td>
<td>Torque and Blade Pitch Angle Actuators of the Wind Turbine</td>
<td>54</td>
</tr>
<tr>
<td>3.8</td>
<td>Averaging the wind speed results compared by the 1 hour wind data produced by TurbSim for an average wind speed parameter of 18 m/sec.</td>
<td>56</td>
</tr>
<tr>
<td>3.9</td>
<td>Frobenius Distance between two $A_F$ and $A_E$ matrices in Region 2</td>
<td>59</td>
</tr>
<tr>
<td>3.10</td>
<td>Frobenius Distance between $A_F$ and $A_E$ matrices in Region 3</td>
<td>60</td>
</tr>
<tr>
<td>4.1</td>
<td>Weibull distribution of wind speed variation from measured data at the height of 102 m in Bremerhaven [82].</td>
<td>64</td>
</tr>
<tr>
<td>4.2</td>
<td>Block Diagram of the typical industry Baseline Controller [108]</td>
<td>68</td>
</tr>
<tr>
<td>4.3</td>
<td>Block Diagram of the DAC</td>
<td>70</td>
</tr>
<tr>
<td>4.4</td>
<td>Block Diagram of the LIDAR augmented DAC</td>
<td>72</td>
</tr>
<tr>
<td>5.1</td>
<td>Block diagram of EOR for wind turbine control</td>
<td>76</td>
</tr>
<tr>
<td>5.2</td>
<td>Recursive least square estimation of parameters</td>
<td>78</td>
</tr>
<tr>
<td>5.3</td>
<td>Equilibrium locus of the controlled outputs of $\theta^*$ Region 3 wind speed (Blue line). Tangent line slope is the output gain of $L_e$ (Red)</td>
<td>80</td>
</tr>
<tr>
<td>5.4</td>
<td>Actual wind speed vs discrete exosystem output. The measured wind speed is shown by red line while the fitted exo-systems are shown in black</td>
<td>81</td>
</tr>
</tbody>
</table>
6.1 Block Diagram of TOR. Thick gray lines represent matrices and thin black lines represent signals. The blocks shown by blue color are public domain open source softwares and white blocks are developed in this work.  

6.2 Three-Dimensional wind fields generated by TurbSim for aero-elastic simulations  

6.3 Coordinate system of wind turbine and nacelle mounted LIDAR shown by $x$, $y$, and $z$. The distance of the focal point of CW-LIDAR is $f$ and $R$ is the scan radius.  

6.4 Finite Length LPF impulse response with the total length of 50 sample  

6.5 Blue: A 200 second sample of a Region 2 Class-A wind with mean speed of 8 m/sec, measured at the hub height. Red: Output of the CW-LIDAR model.  

7.1 Comparison of the results from the standard Baseline controller (Blue), Disturbance Accommodation Control (Green) and Exact Output Regulator (Red) for low turbulence wind with mean wind speed of 9 m/sec.  

7.2 Comparison of the results from the standard Baseline controller (Green), Disturbance Accommodation Control (Blue) and Exact Output Regulator (Red) for a sample Class A turbulent wind with mean wind speed of 18 m/sec.  

7.3 Standard deviation of electric power production for Class-A turbulent winds with mean wind speeds from 8 m/sec to 24 m/sec.  

7.4 Standard deviation of rotor speed for Class-A turbulent winds with mean wind speeds from 8 m/sec to 24 m/sec.  

7.5 Tower root fore-aft bending moment DEL for Class-A turbulent winds with mean wind speeds from 8 m/sec to 24 m/sec.  

7.6 Tower root side to side bending moment DEL for Class-A turbulent winds with mean wind speeds from 8 m/sec to 24 m/sec.  

7.7 Low speed shaft DEL for Class-A turbulent winds with mean wind speeds from 8 m/sec to 24 m/sec.  

7.8 Blade root flap-wise bending moment DEL for Class-A turbulent winds with mean wind speeds from 8 m/sec to 24 m/sec.  

7.9 Blade root edge-wise bending moment DEL for Class-A turbulent winds with mean wind speeds from 8 m/sec to 24 m/sec.  

7.10 Power Spectral Density Graphs of Tower root fore-aft bending moment $M_{yT}$ with mean wind speed of 20 m/sec.  

7.11 Power Spectral Density Graphs of Tower root side to side bending moment $M_{xT}$ with mean wind speed of 20 m/sec.  

7.12 Power Spectral Density Graphs of $LSS$ torque with mean wind speed of 20 m/sec.  

7.13 Power Spectral Density Graphs of Blade root flap-wise bending moment $M_{yB}$ with mean wind speed of 20 m/sec.  

7.14 Power Spectral Density graphs of Pitch Rate $\dot{\theta}$ with mean wind speed of 20 m/sec.  

7.15 Power Spectral Density graphs of generated Power $P$ with mean wind speed of 20 m/sec.  

7.16 Command Torque Rate for Class-A turbulent winds with mean wind speeds from 8 m/sec to 24 m/sec.  

7.17 Pitch Travel in Region 3 for Class-A turbulent winds with mean wind speeds from 12 m/sec to 24 m/sec.
7.18 Simulation results for the extreme operation conditions with EOG 13.5 m/sec. Preemptive actuation of EOR is distinguishable before the EOG starts at time $t = 100$.  
7.19 Simulation results for the extreme operation conditions with EOG 25 m/sec 

8.1 Variation of $S$ matrix comparing its condition number against its initial value during operation with Class-A 20 m/sec mean wind speed. 
8.2 The Ratio of Frobenius norm of the $\Delta G$ and the instantaneous Frobenius norm of feed-forward gain vector $G$. 
8.3 Cumulative density of $R[n]$ vs variations $\%$. 

xix
This page intentionally left blank.
## List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Expected value of the turbulence intensity at 15 m/sec for different classes of turbulence.</td>
<td>22</td>
</tr>
<tr>
<td>2.2</td>
<td>List of IEC 61400-1 design load cases</td>
<td>31</td>
</tr>
<tr>
<td>3.1</td>
<td>The NREL 5-MW Wind Turbine Specifications</td>
<td>44</td>
</tr>
<tr>
<td>3.2</td>
<td>Undistributed Blade Structural Properties</td>
<td>44</td>
</tr>
<tr>
<td>3.3</td>
<td>Nacelle and Hub Properties</td>
<td>45</td>
</tr>
<tr>
<td>3.4</td>
<td>Drive-train Properties</td>
<td>45</td>
</tr>
<tr>
<td>3.5</td>
<td>Tower Properties</td>
<td>45</td>
</tr>
<tr>
<td>3.6</td>
<td>Available and Enabled DOFs in FAST code</td>
<td>47</td>
</tr>
<tr>
<td>4.1</td>
<td>Actuators saturation limits</td>
<td>65</td>
</tr>
<tr>
<td>6.1</td>
<td>Enabled DOFs in FAST code</td>
<td>92</td>
</tr>
<tr>
<td>7.1</td>
<td>Available FAST Output Signals for Controller Design</td>
<td>97</td>
</tr>
<tr>
<td>7.2</td>
<td>List of FAST Output Signals for Load and Performance Analysis</td>
<td>97</td>
</tr>
<tr>
<td>7.3</td>
<td>Power Generation Performance</td>
<td>103</td>
</tr>
<tr>
<td>7.4</td>
<td>Weighted average of DEL and Power results for class A turbulent wind in both regions</td>
<td>108</td>
</tr>
<tr>
<td>7.5</td>
<td>Performance comparison: Peak values derived from the simulations for extreme operation conditions shown in Figure 7.18</td>
<td>115</td>
</tr>
<tr>
<td>7.6</td>
<td>Performance comparison: Peak values derived from the simulations for extreme operation conditions shown in Figure 7.19</td>
<td>116</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>BEM</td>
<td>Blade Element Momentum</td>
<td></td>
</tr>
<tr>
<td>CART</td>
<td>Controls Advanced Research Turbine</td>
<td></td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
<td></td>
</tr>
<tr>
<td>DAC</td>
<td>Disturbance Accommodation Control</td>
<td></td>
</tr>
<tr>
<td>DEL</td>
<td>Damage Equivalent Load</td>
<td></td>
</tr>
<tr>
<td>DLC</td>
<td>Design Load Cases</td>
<td></td>
</tr>
<tr>
<td>DOF</td>
<td>Degree of Freedom</td>
<td></td>
</tr>
<tr>
<td>EOG</td>
<td>Extreme Operational Gust</td>
<td></td>
</tr>
<tr>
<td>EOR</td>
<td>Exact Output Regulation</td>
<td></td>
</tr>
<tr>
<td>FAST</td>
<td>Fatigue, Aerodynamics, Structures, and Turbulence</td>
<td></td>
</tr>
<tr>
<td>GL</td>
<td>Germanischer Lloyd</td>
<td></td>
</tr>
<tr>
<td>HAWT</td>
<td>Horizontal Axis Wind Turbine</td>
<td></td>
</tr>
<tr>
<td>HMI</td>
<td>Human Machine Interface</td>
<td></td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
<td></td>
</tr>
<tr>
<td>IEC</td>
<td>International Electrotechnical Commission</td>
<td></td>
</tr>
<tr>
<td>IMP</td>
<td>Internal Model Principle</td>
<td></td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
<td></td>
</tr>
<tr>
<td>IPC</td>
<td>Individual Pitch Control</td>
<td></td>
</tr>
<tr>
<td>LCOE</td>
<td>Levelized Cost Of Energy</td>
<td></td>
</tr>
<tr>
<td>LIDAR</td>
<td>Light Detection And Ranging</td>
<td></td>
</tr>
<tr>
<td>LTI</td>
<td>Linear Time Invariant</td>
<td></td>
</tr>
<tr>
<td>MIMO</td>
<td>Multi-Input-Multi-Output</td>
<td></td>
</tr>
<tr>
<td>MW</td>
<td>Megawatt</td>
<td></td>
</tr>
<tr>
<td>MPC</td>
<td>Model Predictive Control</td>
<td></td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
<td></td>
</tr>
<tr>
<td>NMPC</td>
<td>Nonlinear Model Predictive Control</td>
<td></td>
</tr>
<tr>
<td>PDF</td>
<td>Probability Density Function</td>
<td></td>
</tr>
<tr>
<td>PID</td>
<td>Proportional Integral Derivative</td>
<td></td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory Control And Data Acquisition</td>
<td></td>
</tr>
<tr>
<td>SDAC</td>
<td>Stochastic Disturbance Accommodation Control</td>
<td></td>
</tr>
<tr>
<td>SISO</td>
<td>Single-Input Single-Output</td>
<td></td>
</tr>
<tr>
<td>SLOW</td>
<td>Simplified Low Order Wind turbine</td>
<td></td>
</tr>
<tr>
<td>TOR</td>
<td>Turbine Output Regulator</td>
<td></td>
</tr>
<tr>
<td>TSR</td>
<td>Tip Speed Ratio</td>
<td></td>
</tr>
</tbody>
</table>
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Chapter 1

Introduction

1.1 Motivation

A sustainable civilization requires sustainable energy sources and so far our civilization has not been very successful in achieving this requirement. However, in this regard, renewable energy resources and technologies such as wind and solar have shown a lot of promises over recent decades. The renewable energy sources have been experiencing a sharp trend in the utilization growth and a constant decline in the costs due to economies of scales and technological improvements. However, it seems that the competition between the renewables and hydrocarbon-based energy resources is ambitious and challenging in which only the economic viability will have the final say and not the concerns over the global warming or climate crisis.

The wind energy is one of the major sources of clean energy today and provides a large portion of the total stream of renewable energy throughout the electrical power distribution networks. According to the International Energy Agency (IEA), total world electricity generation from renewable energy will increase from 5% in 2012 to 14% in 2040 and the wind energy capacity is expected to have a 25% share in this mix [16]. Wind energy facilities have low maintenance costs compared to thermal energy conversion stations and moreover, their energy source (wind) is free. However, the construction cost is a substantial part of the enterprise, for example, foundation and tower material costs in off-shore large wind turbines are responsible for roughly 40% of the total costs of a wind power plant [65]. Therefore, as one can expect, any contribution in reducing the material cost or increasing the life-span of the wind turbines would result in a lower Levelized Cost Of Energy (LCOE), i.e., the per-kilowatt hour cost (in real dollars) of manufacturing, maintaining, and operating the wind turbines.
The LCOE is not straightforward to calculate and depends on many factors such as the type of the wind turbine, the installation location, logistics, and the energy prices at the point of the grid connection. However, it makes sense to see it as a ratio between the total energy value that is produced and the total maintenance costs over the wind turbines lifetime. To reduce the LCOE, different approaches can be taken. One approach is to increase the total energy production by building larger wind turbines. However, larger wind turbines are more costly to build and maintain as they become more flexible by upscaling the size which induces more fatigue loads on the turbine structure. This may even increase maintenance expenses to a level that defeats the purpose of larger wind turbines. The tower is subject to aerodynamic load variations which induces fatigue on its structure which is the major determinant of the turbine life-span. Therefore, if the tower fatigue loads can be reduced, the period of time during which the wind turbine remains profitable can be extended.

The aerodynamic load variations create oscillations which induce fatigue loads on the wind turbine components and drive the wind turbine states out of their optimal trajectories which also cause losses of the harvested wind energy. With the aid of more advanced controllers and sensor equipment, these oscillations can be reduced while maintaining or even improving the energy harvesting efficiency. The load mitigation permits the structure of the wind turbines to be lighter and consequently more cost effective while reducing the maintenance and operational costs.

Similar to many control problems, wind turbine control aims to achieve multiple goals, some of which can be conflicting. For example, in high wind speeds, it is essential to maintain the rotor speed at the rated level as there is a small margin for the wind turbine to over speed safely. Therefore, regardless of the turbulence, the controller must be able to keep the rotor speed within the permissible range. This requires high speed pitching of the blades to regulate the aerodynamic torque at the rated value. A high-gain pitch controller that takes feedback from the slightest rotor speed changes is very likely to fulfill this task. However, such a control approach not only puts excessive stress on the actuation system, but also causes high frequency changes on the aerodynamic thrust. The tower and blades which are subject to this aerodynamic thrust, experience rapid changes in the exerted force. This can cause severe oscillations and consequently fatigue damages on both the tower and the blades that in the long run will reduce the life-span of the components.

To date, various control approaches have been implemented for more effective wind turbine
control. Also, emerging wind measurement technologies such as LIDAR provide short and long term wind speed and direction forecasting that allow for better planning, control, and operation of wind turbines. LIDAR can provide valuable information about the dynamics of the wind up to several hundred meters in front of the rotor. Such information can open the gates to a whole new class of controllers which have not previously been implemented.

For almost a decade various attempts have been carried out to augment the LIDAR provided wind information into the existing and conventional control methodologies as well as implementing new control architectures. This work contributes to this line of research by proposing a novel approach based on the Exact Output Regulation in a form that can readily exploit look-ahead wind measurements provided by LIDAR. This approach can perform preemptive control actions in order to compensate for the slow response time of the turbine when it is exposed to the wind disturbances. As a consequence, the wind turbine is controlled along its optimal states with smoother actuation. This will contribute to the load reduction, and therefore positively impact the wind turbine life-span and ultimately the energy cost.

Additionally, the utility scale wind turbines are usually part of a power network with intrinsic limitations, standards, and regulations. Inconsistent injection of large amounts of active and reactive power into the grid may cause instabilities in the voltage and frequency. Therefore, a power network can also benefit from a control scheme that is able to improve regulation of the rotor speed and power deviations during turbulent wind conditions.

It is worth mentioning that in this thesis, a practical approach is taken in design of the wind turbine controller considering that the industrial controllers have limitations in computational power due to reliability concerns. Therefore, for practical reasons it is absolutely necessary for any controller to be implementable in real-time on the relatively weak industry grade control hardware such as PLCs. Hence, another motive aspect of this work has been implementing the controller with the minimum possible calculations per time-step.
1.2 Literature Review

Reliable power production from the wind is a difficult problem due to the intermittent nature of the wind. It has been the subject of research from the early days of electrical wind turbine. Although the kinetic energy of the wind is transformed into mechanical and subsequently electrical energy by the wind turbines, it comes with the cost of the wind power plant structure, installation, and maintenance. Two different but parallel approaches that can be taken to reduce the LCOE are maximizing the energy harvesting efficiency and reducing the cost of maintenance by reducing the wind turbine fatigue and extreme loads [13].

The wind energy harvested can be increased by scaling up the size of the rotor swept area to interact with more wind. To use a larger rotor, a taller tower is required to provide the necessary ground clearance and to carry more weight due to larger nacelle and blades. A taller tower and longer blades comprise a more flexible mechanical system with more oscillations when it is subject to the wind disturbances. Hence, up-scaling the wind turbines may well contradict the second goal of reducing the maintenance costs and even lead to higher energy production costs.

Energy harvesting efficiency can also be improved by more precisely steering the wind turbine states on their optimal trajectories. From the control engineering point of view, both of these problem may be solved through a combination of greater sensor information and the use of superior control methodologies.

There are three different levels of control for utility scale wind turbines: "supervisory control", "operational control" and "subsystem control" [78] with different sampling times used for the controller. The supervisory control level decides the activation of the wind turbine with respect to the wind speed. Health monitoring and long term data logging for future references also happen within this layer of control. Conventionally, this layer is called Supervisory Control And Data Acquisition or "SCADA". Sampling times (time steps) in SCADA systems can be from seconds to minutes. Human Machine Interfaces (HMI) are usually interfaced into SCADA systems. The second level, the operational control deals with the control objectives such as maximum power harvesting, rotor speed control and etc. Usually sampling frequencies in operational levels are from a few Hertz up to few hundred Hertz depending on the time constants of the devices. In the lowest level of control, the subsystem level, the generator torque, yaw, pitch and other actuators are regulated to perform as desired and according their given set-points. Sampling frequencies
are highest in the subsystem level. For example, for the generator torque control, magnetizing and torque generating currents (in case of induction generators) should be switched at rates up to several kilo-Hertz as the time constants are very low. The subsystem and operational level are interconnected with nested loops. For example, generator torque control loop is nested inside the rotor speed control loop in which the former is at the subsystem level as mentioned and the latter is at the operational level. However, it is possible sometimes to merge these two levels by some advanced control architectures such as modern model-based feedback controllers. In such cases, operational control objectives can be achieved with improved performance by using superior architectures and more sensor data.

Mechanical load and structural stress reduction, can be also categorized as operational control objectives. Therefore, it can be expected to improve upon these objectives by using advanced controllers. For example, mechanical loads on the wind turbine structure induced by sudden variations of the wind can be mitigated by the suitable manipulation of the blade pitch angle and generator torque [73].

The use of feedback control is a typical approach for stabilizing and regulating dynamical systems. Similarly, feedback control algorithms have been traditionally used in wind turbines for the torque and pitch control, both of which use rotor speed as the feedback. For example, during high wind speeds, when there is more wind energy available than turbine’s capacity, conventional wind turbine controllers often use a Proportional Integral Derivative (PID) feedback scheme to pitch the blades. In this scheme the rotor speed is compared to the rated value to calculate an error signal. Next, this error signal is used to compute the suitable pitch angle of the blades in order to balance the aerodynamic torque around the rated value [9], [61]. Like most industrial applications, sensitivity to measurement noise requires the derivative term to be combined with a low-pass filter or else completely omitted. This leaves just a PI controller for pitch actuation which is also gain scheduled because of the nonlinear relation of the aerodynamic torque and pitch angle. At low wind speeds on the other hand, where the available wind energy is less than turbine’s rated capacity, maximizing energy harvesting is essential. In these conditions, rotor speed is also used as the feedback signal and forced to track an optimum trajectory depending the wind speed variations [11].

Controlling the blade pitch angles maybe carried out in a collective or independent form. In
the collective pitch control, all the blade pitch angles are equal at all times. Therefore, a single-
input, single-output (SISO) controller is enough to govern the pitching system. Alternatively,
blade pitch angles may also be measured and controlled independently from each other which is
usually refereed as the individual pitch control method. Since the modern pitch servo systems
provide full measurements on the actuators such as actuation torque, rate and angle, multi-input,
multi-output (MIMO) control on the pitch system is possible for an increased performance of the
wind turbine [32, 66] and [64]. Asymmetrical loads on the blades (for example non-uniform mass
distribution) induce extra oscillations by the dominant frequency of once per revolution (1p) [112].
With a MIMO controller using Individual Pitch Control, asymmetrical loads on the blades can be
reduced which yields lower structural damage on the blades. Several works on the individual pitch
control concentrated on the 1p harmonic rotor blade load can be found at [7, 28] and [112].

As wind turbines deal with external disturbances, feed-forward control has also been used
(or merely proposed by the simulations [74]) to minimize or cancel the effects of wind speed
variations. Disturbance Accommodation Control (DAC) has been one of the most widely used
feed-forward methods for wind turbine control during the last decade [3, 51, 107], due to its sim-
licity and capacity to estimate the effective wind speed on the rotor. It was first applied to wind
turbines in [3], to counteract the effects of wind disturbances. Later, DAC methods have been
used in [107] and [36] on a two-bladed, 600 kW wind turbine to reduce blade fatigue loads in-
duced by the wind disturbances. Two type of dynamics (fast and slow) were assumed for the
actuator. Comparing results against a standard PI controller under these two assumption showed
that both controllers perform similarly using the slow actuator dynamics. However, when the wind
turbine operated further from the linearisation point due to the mean wind speed variations, the
PI controller was shown to be more robust. On the other hand, with fast actuators DAC showed a
superior performance compared to the PI controller. Despite being a promising result, assuming
fast actuators is less realistic in larger wind turbines and reveals the inherent shortcomings of the
DAC architecture. This case will be thoroughly explained in the future chapters and the limitations
of the DAC will be elaborated. In [98] it was applied for canceling asymmetric blade mass effects
of a two-bladed wind turbine causing periodic loads. A field test on the Controls Advanced Re-
search Turbine (CART) [109] showed that, compared to a baseline PI controller, DAC can reduce
structural dynamic loads.
DAC relies on the estimation of wind speed using an exogenous state observer. However, such estimation is affected by measurement noise which also contributes to the estimation errors. Therefore, stochastic disturbance accommodating controller (SDAC) tries to deal with the un-modeled dynamics and exogenous disturbance. In [33] an augmented Kalman estimator is used in the feedback loop to estimate the disturbance and system states in the presence of the output measurement noise to reduce speed regulation errors and improve drivetrain vibration mitigation.

SDAC is also used for structural load reduction and power regulation in [14]. Since the aero-dynamic loads on the wind turbines have statistical properties, it was assumed that wind turbine is influenced by both the stochastic process noises and measurement noise. The results shows that 1p harmonic loads were mitigated by the controller while maintaining the rotor speed around the nominal value.

While the conventional DAC treats the external disturbances as wave forms, the SDAC regards disturbances comprised of the wave form along with stochastic components. These components which can be attributed to the model uncertainties and unknown exogenous disturbances- which are ignored in the conventional DAC- can have adverse affects of the controller performance. In [30] and [31] linear (SDAC) controller, also using an Augmented Kalman Filter, were proposed to estimate the system states as well as the unknown inputs (disturbances). Then the appropriate controller was synthesized for stabilizing the system and compensating for the disturbances. Additionally, the analysis showed that in order to guarantee closed-loop stability, weighting gains must be lower-bounded for the Kalman filter.

None the less, feedback and feed-forward control systems for turbines which rely on measurement for feedback or wind estimation for their feed-forward component, may not yield satisfactory system behavior under the highly turbulent winds conditions, as it assumes the turbine only reacts to the variations of the wind which may have already influenced the system states and driven them away from their desired values.

To address this problem, it has been proposed to use LIDAR in wind turbine control systems. LIDAR can provide estimates of upcoming wind speeds prior to the wind interacting with the turbine blades [38]. Although LIDAR technology has been available since the 1970s, until recently its cost has been too great for widespread industrial use [92]. Recent LIDAR cost reductions have enabled the use of nacelle or hub-based LIDAR systems to obtain real-time wind speed and
direction information up to several hundred meters ahead of the wind turbine. This has opened a new research area on the use of feed-forward control for large scale wind turbines [103].

An early work involving LIDAR for feedforward control of the wind turbines [86] showed that an augmented LIDAR feedforward control may improve energy harvesting and load reduction. Further investigations using a non-causal series expansion mode-inverse method appeared in [22], where it was shown that a lower damage equivalent load (DEL) on tower fore-aft oscillations could be obtained relative to a baseline controller, without any loss in the produced power. In [63], a preview-based feedforward method assuming highly idealized wind measurements concluded that wind evolutions in more realistic conditions can eliminate advantages gained by using preview-based feedforward techniques. Another LIDAR-assisted design in [21] used three different model inversion methods: the nonminimum-phase zeros-ignore, the zero-phase-error tracking controller and the zero-magnitude-error tracking controller in order to augment with the feedback loop. By assuming no wind evolution between the measurement point and the blades, they showed reduction in some of the loads. More realistic wind measurements were considered in [88] where a robust feedforward controller using a LIDAR simulator was presented. Two early field testing surveys of LIDAR-based feed-forward control using model inversion methods were carried out in [91] and [83]. The results showed evidence of tower load reduction by 10% due to the utilization of LIDAR, confirming the previous results from simulations. In [35] load reductions were improved by using Continuous-Wave LIDAR (CW-LIDAR). Although model inversion methods are feasible in the presence of look-ahead LIDAR information, they require the use of approximate models of the plant inverse to avoid the effects of non-minimum phase zero inversion.

LIDAR-assisted control has also been tested for improving energy harvesting at below rated wind speeds. Results from [85] also showed that LIDAR-aided rotor speed and yaw angle control yielded increased energy production. Field tests of the methods proposed in [85] were extended in [84] with real data collected from LIDAR where 0.3% improvement in energy gain was achieved at the cost of doubling the loads on the shaft. In [103] three different methods of wind turbine control are augmented by LIDAR and compared at below rated wind speeds: The optimally tracking rotor (OTR) control scheme [52], Preview Control [99] and DAC, sometimes also known as Disturbance Tracking Control [97]. However, these methods were only able to increase energy harvesting by very small amounts, and these improvements came at the cost of substantial increases in some
fatigue loads.

Efforts have been made to enhance DAC by augmenting the controller with LIDAR information, replacing the estimated wind speed with LIDAR measured speed. However, to date only modest performance improvements have been achieved. [103] showed that the LIDAR augmented DAC (DAC+LIDAR) achieved less than 0.5% improvement in power production, and this improvement came at the cost of a 5.7% increase in rotor shaft DEL. Another attempt to improve DAC with LIDAR wind information was carried out in [104] where the structural loads were decreased by 2%.

Model Predictive Control (MPC) methods have also been a point of interest since they can accommodate LIDAR information with little modification. In [87] loads on the structure were reduced and the energy harvesting enhanced by using nonlinear MPC. Extreme loads have also been mitigated by NMPC in [101] at the critical range of transition region. Despite NMPC being a multi-variable controller, a key limitation is the substantial number of numerical operations which are required at each time step, making it infeasible for real-time applications on conventional industry grade controllers.

In this thesis we present a novel method for turbine control that can make effective use of LIDAR information, without requiring the excessive computational costs of MPC. Our approach will employ the Exact Output Regulation (EOR) control methodology, and our results will show that it can deliver substantial reductions in fatigue loads, without compromising energy harvesting. Additionally, its rapid computation time makes it feasible for real-time implementation.

The Exact Output Regulation methodology has played a central role in modern control systems design for several decades [102]-[81]. For linear systems, the regulation problem has been rigorously studied in the 1970s in [18] and seminal works by Francis in [25], and [26]. The most notable outcome of these researches is the Internal Model Principle (IMP) which converts the output regulation problem into a pole placement problem for an augmented linear system [43]. There are also nonlinear variations of the output regulation problem. Some early works in [19, 26], and [46] considered special cases of constant exogenous signals. In [50] the output regulation problem was studied for time varying exogenous signals and full information on nonlinear plant models without parameter uncertainty. Later on, robust versions of the same problem considering different levels of uncertainties were also studied [12, 41, 44, 45, 80] and [46].
Since we will deal with linearized plant models of the wind turbine, the scope of the output regulation control methodology is confined to linear versions. The linear output regulation problem considers a multivariable linear time invariant (LTI) plant that is assumed to be subject to known input time-varying disturbances, and whose output is desired to track a known time-varying reference signal. The reference signals and external disturbances are modeled as the outputs of a linear exo-system. The solution of the problem requires the design a combined state feedback and feed-forward controller that will internally stabilize the plant, while rejecting the disturbances and ensuring the output converges asymptotically to the desired reference signal.

For wind turbine control, effective disturbance rejection involves the minimization of wind disturbances on the control actuation. These are the rotor torque and also the blade pitch angle. Effective reference tracking below the rated power involves operation of the turbine rotor and blades so as to generate the optimal energy from the wind. The problem is difficult as the wind frequency variation (turbulence) is much faster than the turbine response. The availability of LIDAR wind preview information enables the wind signal to be modeled as a low-order linear dynamical system. This linear system may then be incorporated into the EOR control methodology as an exo-system whose outputs provide the input disturbance and the output reference signal [69], [70]. The feedback and feed-forward gain matrices required for the design of the EOR controller are readily computable [81], making the EOR method suitable for real-time control implementation when the LIDAR sensor can provide wind preview information several seconds prior to the wind reaching the turbine blades.

A simulation environment known as TOR has been developed by the author to apply EOR to the control of a 5-MW reference Horizontal Axis Wind Turbine (HAWT) wind turbine [54]. To simulate the turbine response, the Fatigue, Aerodynamics, Structures, and Turbulence (FAST) code using a high-order aero-elastic nonlinear turbine model developed by NREL [55] will be used. The NREL Turbsim package [53] is used to simulate realistic wind fields, and Damage Equivalent Loads are computed by the Rain-Flow-Counting-Algorithm open source MATLAB code [75]. For performance comparison purposes, TOR obtains a feedforward controller using the DAC method, and also a baseline torque controller. Energy harvesting and DELs are computed within the TOR simulation environment to allow performance comparisons of these three controllers, for a broad range of wind speeds and intensities.
Our simulations studies on the high-order aero-elastic nonlinear turbine model show that, in comparison with DAC and the baseline method, the EOR controller can substantially reduce the fatigue loads on the tower, blades and low speed shaft. Additionally EOR is able to reduce the standard deviation of rotor speed and output power, without any loss in energy harvesting. The author believes that EOR is able to obtain these improvements through its superior modeling of the wind dynamics. Where DAC treats the wind signal as a constant disturbance, and does not consider any output tracking objective, EOR is able to accommodate derivatives of the wind signal, leading to improved tracking performance and disturbance rejection.
1.3 Research Questions

LIDAR technology has been the point of interest in the wind industry during the last decade. There have been various attempts to explore the possible benefits of the LIDAR in wind turbine control performance and power production. For this regard, we have developed a framework to answer the following questions:

**Research Question 1:** Can effective use of LIDAR be achieved by adapting the Exact Output Regulation scheme in order to utilize LIDAR information? The Exact Output Regulation is able to track output of a known exosystem as well as rejecting disturbances to the system. We will address this in Chapter 5.

**Research Question 2:** Can such an adaptation of EOR contribute to the fatigue load reduction in wind turbines? If so, what will be the difference to the existing main stream control methods? We can expect that with more information about the disturbance, the performance of the system maybe improved. LIDAR provides such information as raw numerical data. We will address this in Chapters 6 and 7.

**Research Question 3:** Can LIDAR be used for increasing the energy production? Once more, being informed about future disturbances may enable the system to better track the optimum points on the power curve of the wind turbine and harvest more energy from the passing wind. Therefore, one can expect that use of LIDAR may increase the energy yield of the wind turbines below rated wind speed. We will see the results of utilization of LIDAR on the energy production in Chapter 7.

1.4 Thesis Overview

This thesis investigates the application of EOR in LIDAR assisted control of the wind turbines, with the objectives of structural load reduction, improved energy harvesting and reduced power fluctuations. EOR can be potentially have an impact on the wind turbine control community due to its ability to systematically incorporate LIDAR data into the controller architecture.
1.4 Thesis Overview

1.4.1 Research Objectives and Contributions

Effective use of LIDAR in the field of wind turbine control is still an open problem due to the limitations of the LIDAR technology [15, 94]. The main research objective of the thesis is to design and construct a framework for wind turbine controllers which can incorporate information from LIDAR on the upcoming wind. This framework named *Turbine Output Regulator* or (TOR), must be compared against conventional feedback controllers or available LIDAR-enabled control methods. The first contribution of the thesis is presentation of the idea that the LIDAR-assisted wind turbine control is compatible with the Exact Output Regulation architecture. Although assuming the wind disturbance as an exogenous signal is not new in the wind turbine control literature such as DAC, utilization of reference tracking based on the exogenous signal (which is one of the EOR schemes) has not been attempt in this field. Moreover, the wind disturbance has been treated just as a signal in these methods (such as DAC) and not as the output from a dynamic system. TOR views the wind as an output of a dynamic system and takes advantage of the information known about its state variables such as higher derivatives of the wind speed and rate of its change. In order to achieve a closed form model of the wind which can describe the dynamics of the wind speed in very short times (up to few seconds), TOR uses LIDAR measurements as time series and builds a describing difference equation. Another contribution of the thesis is a method to synthesize disturbance and reference exo-systems which are fundamental parts of the output regulation scheme. TOR does also allow tuning in order to have smoother or more rigid disturbance rejection properties. This can give the designer the choice to shift the design freely between the disturbance rejection or load reduction according the requirements as they are usually conflicting control objectives. Finally the thesis shows that the conventional DAC control method can be derived as a very special case of the TOR in which the reference exo-system is omitted and disturbance exo-system is assumed to have no dynamics. Chapter 4 and 5 discuss these methods and answer the research questions.
1.4.2 Structure of the Thesis

Chapter 2: Technical Background

In chapter 2, a background of wind energy and fundamentals of wind energy conversion will be provided. Later, components of conventional horizontal axis wind turbines and their role will be discussed.

Chapter 3: Wind Turbine Modeling

In this part, the modeling of wind turbines will be explained. Also the properties of a reference 5-MW wind turbine will be articulated. The NREL 5 MW wind turbine model is a reference provided by National Renewable Energy Laboratory as an open access platform for the research and development objectives. Each component of this wind turbine will be explained and the parameters are given in their associated tables.

In order to perform high fidelity simulations, information on the FAST is provided which is also developed by NREL as an open access code for research and commercial works. To have an internal model for sake of controller design, a simplified nonlinear model of the 5 MW reference wind turbine is also described and parameterized. This nonlinear model will be linearized and compared with the linearized models generated by FAST to validate its use for the controller design.

Chapter 4: Control Objectives and Methods

Chapter 4 addresses some of the widely used the wind turbine control methodologies and objectives. These control methodologists are mainstream methods which can be used as benchmarks in this thesis due to the broad utilization of the feedback PI regulator. Also the Disturbance Accommodation Control method, is chosen as the second benchmark since it has been adapted into a LIDAR-assisted variant and also has similarities with the proposed novel control method in this thesis. Moreover, utility-scale wind turbine control objectives are discussed in this chapter and will be reviewed with regarding the power generation, loads and fatigue damages.
Chapter 5: Utilization of Exact Output Regulation for Wind Turbines

A new, wind turbine control approach based on Exact Output Regulation is proposed in this chapter. Furthermore, continuous and discrete methods of augmentation of LIDAR information within the EOR architecture as homogeneous linear exo-systems is explored. Synthesis methods for the parameters of the exo-systems are also described in detail. Consequently, the EOR for the wind turbines will be articulated. Also the mathematical relationships between the DAC and EOR controllers are elaborated regarding their solvability and generality. In this chapter it is shown that by some simplifications and omitting some of the parameters of the EOR formulation, the DAC controller is obtained. Therefore, EOR is theoretically able to outperform or at least match the DAC performance in any level. Furthermore, such generality allows EOR to be applicable to much greater classes of plant systems while DAC is generally unsolvable if some of the system dynamics are not ignored.

Chapter 6: Simulation Environment

In Chapter 6 a toolbox for the application of EOR on the wind turbine is developed, known as TOR. This consists of all required elements of simulating wind turbines in realistic conditions and forms the simulation environment for this thesis. This environment is built partially from the open access codes provided by NREL such as FAST and TurbSim. The reminder is the toolbox is developed in Simulink® to rapidly synthesize an EOR controller for a given wind turbine model.

With some preliminary experiments, this chapter shows that the dynamics of the exo-systems constructed to describe the wind speed variations in the next few seconds of the operation do not vary considerably by the advance of time despite the high turbulence of the wind. Furthermore, the generated feed-forward gain calculated obtained from solving the regulator equations also does not show considerable variations during the simulations. Therefore, this chapter suggests that it can be safely assumed that the proposed EOR controller parameters remain time invariant during the operation of wind turbine. Wind fields are generated based on the IEC-61400-1 standard by Turbsim and provided to the LIDAR model. A CW-LIDAR model is also part of TOR and will be articulated in this chapter.
Chapter 7: Simulation Results and Analysis

In Chapter 7, a set of extensive simulations will be carried out for various reference wind speeds. The raw results and data from the simulation outputs will be analyzed with different performance measures. The performance of the wind turbine will be assessed in different regions of operation and compared against the baseline methods. Finally a spectral analysis of the fatigue loads and power production will be presented.

Chapter 8: Conclusion and Outlook

In this chapter, some potential future works in the direction of the thesis will be suggested. Also, some more potential fields of control systems will be proposed to be investigated as suitable for EOR with the same architecture used through in this thesis.
Chapter 2
Technical Background

In this chapter a brief history of wind energy along with the required technical background will be presented. The fundamentals of wind energy conversion and its limitations are presented. Then conventional wind turbine components are elaborated, and the operating regions for wind turbines are described. Moreover, load analysis based on the relevant part of design load cases standards is given.

The mathematical background presented in this chapter consists of the definition of the norms which are used in this thesis, as well as state-space representation of dynamical systems (which will be used for modeling and controller design), state estimation methods and finally a detailed background on the Exact Output Regulation which is the axis of the proposed method in thesis.

2.1 History

For thousands of years, mankind has used wind energy in different forms for various applications. Sailing ships and boats are the iconic applications of wind energy for transportation and military purposes. In various parts of the world throughout history, wind has also been used for powering milling apparatus and water pumps making it an important part of irrigation and agricultural systems since ancient times.

Historically, the oldest known windmills were made in ancient Persia which were vertical axis panemone mechanisms [110]. In this regard, also the earliest chronological reference to windmills available today belongs to the seventh century which is an anecdotal story of a conversation between a captured Persian technician and Caliph Omar [93]. Before becoming a slave during the early Islamic wars, Piruz Nahavandi built windmills. In 644 AD., he brought a complaint about
the high taxes to Caliph Omar which was then refused after the Caliph corresponded with Piruz’s master. It is also recorded that the Caliph asked later the craftsman if he was truly able to build a mill driven by the wind, to which Piruz replied, ”By God, I will build this mill of which the world will talk” [110].

Although generating electricity from wind might seem a very modern technology, its first practices go back to the late 19th century when Charles F. Brush built the first automatically operated wind turbine with a 12 KW DC generator in the United States. It was used to power around 350 incandescent light bulbs in daily use. The machine had a 17 m diameter rotor with 144 blades and ran for 20 years until 1908 [96]. It was a landmark in the history of wind energy because of its ambitious design and combining the latest technology of the time on DC generators and aerodynamics. During the years from 1888 to 1900 more experimental windmills were constructed to generate electricity both in Denmark and the United States. In the last decade of 19th century, Professor Poul LaCour in Denmark conducted wind turbine research in Askov and took important steps in the transition towards modern wind turbines. He was one of the first researchers to use a wind tunnel for aerodynamic experiments [93]. LaCour was able to derive some set of rules to achieve the optimal rotor performance and developed practical wind turbines for electric power generation. His designed wind turbines ranged from 5 to 25 KW, and were mostly for agricultural use in Denmark.

However, the emergence of the diesel engine created a difficult time for Danish wind power plants due to its versatility and convenience over wind turbines [56]. Although the First and Second World Wars and consequent oil supply deprivation caused temporary resurrections of wind turbines, their come back was not sustained until the international oil crises of 1972. Moreover, growing public concerns on the environmental issues in recent decades has put wind turbines in the front line of renewable energy technologies. In the next sections we discuss the fundamentals of wind energy conversion systems.

1 The aftermath, was the assassination of the Caliph a day after by Piruz.
2.2 Nature of the Wind Energy

This section presents some brief description about the nature of the wind and some standards used for realistic wind field simulations which are used in this thesis. Wind is the motion of the air due to the air pressure gradients in the atmosphere which are caused naturally by the difference in the solar radiation absorption ratio on the non-uniform surface of the Earth.

The seasonal, synoptic and daily variations of the wind are usually slow (See Figure 2.1). Therefore, mean wind speed during this periods are assumed to be constant with only the turbulent content of wind to be dynamic. In a cross section of a wind turbine rotor, the perpendicular component of the wind can be assumed to be comprised of finite temporal and spatial divisions. This small divided spaces together can be assumed as a Turbulence box which marches towards the wind turbine assuming the mean value of the speed will not change. This assumption is known as Taylor’s Frozen Turbulence Hypothesis which is fundamental to many modeling schemes of the wind [11].
2.2.1 Spatial Variations

The sun is the source of wind energy as with most other renewable energies. The sun’s radiation on geographical features heats up the earth surface and consequently the low altitude atmosphere. Then warm air rises into the upper stages of atmosphere and plunges into areas with cooler surface. Then the earth’s rotation affects this motion by Coriolis forces which contributes to a global wind circulation pattern. The surface of earth is vastly non-uniform, especially on land areas. Therefore, in small scales it perturbs the global wind circulation patterns in a highly nonlinear and complex way which makes the wind variations chaotic and in some sense unpredictable.

2.2.2 Temporal Variations

At a given geographical location, temporal variability persists in different frequencies. On a large scale, the wind speed may vary based on extremely low frequencies such as annual variations or even longer time-scales. In order to make accurate predictions in such scales which are crucial for the assessment of economic viability of wind farms, precise long-term weather models are yet to be developed. This leaves us to rely on short-term wind and weather models that can predict the wind availability from few hours up to few days. These might not be enough for assessing the economic feasibility of a planned wind farm during it’s 20 years or so life span, but they can be well used for planning purposes in the energy grid and integration of wind energy in the power network.

The higher frequency wind variations spanning from minutes to few seconds are usually called turbulence which have to be seriously considered regarding for their impact on individual wind turbine performance and life span. Moreover, those wind frequencies which are comparable to the grid’s voltage and frequency dynamics, can contribute to significant issues in power systems reliability and stability.

2.2.3 Turbulence

Wind speed fluctuations with relatively high frequencies are often referred to as turbulence [11] and corresponds to the highest peak in its frequency spectrum in about one minute intervals. Up to the time-scale of several hours, wind speed variations can be seen as constant wind speed (corre-
2.2 Nature of the Wind Energy

Corresponding to the average wind speed) superimposed with higher frequency variations (corresponding to turbulence). Therefore, turbulence can be decomposed from the wind when the 10 minute average is subtracted from instantaneous wind speed. Thus, turbulent fluctuations have a zero mean. From the control engineering perspective, turbulence is the main challenge in optimally operating of the wind turbines due to its lower predictability and higher dynamics. However, it is rational to think of wind variations as physical phenomena which obey certain physical rules, such as conservation of mass, momentum and energy. Nonetheless, in order to precisely describe the turbulence by these rules, a very complicated model is required which includes all determining factors of air flow dynamics and therefore, may not be useful for analysis and controller design purposes. For this reason, in order to have a general description of the wind, a statistical representation of the wind can be helpful. Statistical models of turbulence range from a stationary process with a simple intensity value to very detailed three-dimensional models of the wind speed components as non-stationary random processes.

The intensity of turbulence, when modeled as a random process, is a measure of how rapidly the wind speed varies compared to its main component (mean value). Therefore it is defined as:

\[ I = \frac{\sigma}{\bar{v}}, \]

where \( \sigma \) is the standard deviation of wind speed variations and \( \bar{v} \) is the mean wind speed over a 10 minute interval. The distribution of this random process can be approximately assumed to be a normal distribution with standard deviation of \( \sigma \) and mean of \( \bar{v} \).

The turbulence intensity depends on the surface roughness (i.e. trees or buildings), altitude, topographical features (i.e. mountains and valleys) and thermal behavior of the atmosphere. Therefore, the air flow at lower altitudes is affected more strongly by the earth’s surface and is usually called the boundary layer. Since modern wind turbines have tower height of around 100 meters, the properties of the boundary layer play an important role in the behavior of wind turbines.

2.2.4 IEC Standards for Wind Simulation

There are different guidelines for wind turbulence intensity values. However, in this thesis we will only use IEC-61400-1 standard as the reference for generating wind fields in the simulations since
all wind turbines must be certified to the IEC standards. For the normal turbulence model, the representative value of the standard deviation of turbulence, $\sigma$ shall be given by [49]

$$\sigma = I_{ref} (0.75V_{hub} + b), \quad b = 5.6 \text{ m/sec}$$  \hspace{1cm} (2.2)

in which $I_{ref}$ is the expected value for turbulence intensity at the average wind speed of $\bar{v} = 15 \text{ m/sec}$. Table 2.1 represents the values for $I_{ref}$ for different for category A,B and C intensities which are associated wind high, medium and low turbulence characteristics respectively. Figure 2.2 shows the values for the turbulence standard deviation $\sigma$ and the turbulence intensity $I$ for given hub-height wind speed $V_{hub}$.

We note that there are other models for wind fields which are not given by IEC but are still supported in TurbSim. In such non-IEC wind fields the spectral models are different IEC models. They also require additional boundary conditions as well.
2.2.5 Extreme Winds and Gust

Wind turbines are designed to withstand severe conditions such as extreme winds. Such extreme conditions can be very high mean wind speeds and gusts. These conditions are characterized by their frequency or return time [11]. For instance a 50 year gust is expected to occur once on average within a 50 year period. However, due to the long life time of the wind turbines, they must be built to withstand and continue to operate after that event has passed even if it has to shut down for a short time.

According to the IEC standard there are different types of these severe events and gusts which are categorized as follows [49]

- extreme operating gust;
- extreme direction change;
- extreme coherent gust;
- extreme coherent gust with direction change;
- extreme wind shear.

These events are defined as deterministic gusts and assumed to occur independently from the normal turbulence and do not reflect closely what happens exactly during an extreme gust in nature. Therefore, they are only used for the study of wind turbine behavior in similar events.

2.3 Fundamentals of Wind Energy Conversion

In this section some fundamental concepts are presented on the conversion of wind energy to mechanical energy and its limitations regardless of the machine used for the conversion. A wind driven machine can generally be referred to as any device which can capture the kinetic energy of the passing air and convert it into other forms of energy which are conventionally mechanical or electrical. In a narrower sense, we will assume the wind turbine has a horizontal axis rotating rotor with multiple blades.

Modern wind turbine blades are made in a shape of a specific airfoil (See Figure 2.3). When the moving air (wind) passes around this airfoil two areas form above and below the airfoil. By
changing the angle of attack of the blade using the pitch actuator, the lift co-efficient of the blade may be changed [1]. As a natural byproduct of the created lift, the natural interaction of the air flow with the blades creates a drag force (shown by green arrow) which pushes the wind turbine backward and creates bending moments on the blades and tower. Since the blades are attached to the hub from one side, the generated lift creates torque around the hub and consequently turns the rotor shaft.

As the blades pitch angle is adjustable in the utility scale modern wind turbines, the amount of the total lift on the blades can be altered. Therefore, blade pitch controlled wind turbines are able to manipulate aero-dynamical torque by changing the blade pitch angles. This ability is one of the main control inputs which can be used to achieve various control objectives. Aerodynamic torque when the rotor is rotating in a fixed speed determines how much energy is captured from the wind. Therefore, it can be assumed that the wind turbine removes some of the kinetic energy of the wind by slowing it down as it passes the rotor blades. If the rotor area is assumed as a disk which the fast moving air moves into and the slow moving air exits from, the mass of the slower moving air must remain equal to the faster at every given time. Also, since the exiting air is not compressed, the cross-sectional area of the slow moving air must be larger than the faster air to incorporate the same air mass (see the Figure 2.4). This expanded down-wind region of air which has lower atmospheric pressure level and moving speed is called the wake of the turbine. This phenomena can be explained more precisely by Blade Element Momentum theory (BEM) [62].
2.3 Fundamentals of Wind Energy Conversion

2.3.1 Wind power extraction limits

The total power in the wind is calculated as energy per time unit as in [11]:

\[ P_{\text{wind}} = \frac{1}{2} \rho \pi R^2 v_x^3, \quad (2.3) \]

where \( v_x \) is the magnitude of perpendicular component of the wind speed vector to the rotor plane, \( R \) is the rotor radius and \( \rho \) is the air density for given time \( t \) that wind passes through the rotor span area. The instantaneous mechanical power extracted from the wind by a turbine is given by

\[ P_{\text{mech}} = \Omega_r M_r, \quad (2.4) \]

where \( \Omega_r \) and \( M_r \) are the wind turbine’s rotor speed and rotor torque respectively. The turbine’s power coefficient \( C_p \) is defined to be the ratio of the extracted mechanical power to the available wind power:

\[ C_p := \frac{P_{\text{mech}}}{P_{\text{wind}}}, \quad (2.5) \]
This power coefficient is subject to a theoretical upper bound known as the Betz-Joukowsky limit [76], equal to $16/27$ or 59% [29]. This limit is seldom obtained by any turbine in practice. For each turbine, the coefficient’s maximum value is typically in the range 40% to 50%. For a wind turbine with blade swept area of $A_R$, the instantaneous mechanical power is given by

$$P_{mech} = \frac{1}{2} \rho C_p A_R v_x^3.$$  \hspace{1cm} (2.6)

The extracted mechanical power can be optimised by control of the turbine rotor torque. Figure 2.5 shows, for a range of wind speeds, the available power of the wind flow, the Betz-Joukowsky power limit and the maximum mechanical power that can be extracted from the wind by the NREL 5 MW Wind Turbine. Above 11.4 m/sec, the turbine reaches its rated power of 5 MW and blade pitch control is used to maintain the power at this level.

### 2.4 Operating Regions

This thesis focuses on the control of variable pitch, variable speed Horizontal Axis Wind Turbines. These turbines have different operating regions with respect to the wind speed and their power curve. Conventionally, wind turbine operate in two main regions which are determined by the
current mean wind speed. At very low wind speeds, less than 4 \( m/sec \) in this case, the kinetic energy of wind is too low. That it is referred as Region 1 where the wind turbine does not operate. This speed is called cut-in wind speed and for greater than cut-in wind speeds the turbine begins to operate. The higher the wind speed, the higher the energy that can be harvested by the blades.

At above cut-in wind speeds, also referred as Region 2, one of the main objectives of controller design is to convert as much as wind energy into mechanical energy. This means operating the wind turbine at its highest power co-efficient \( C_{p,\text{max}} \). The \( C_p \) ratio is a function of two key variables; blade pitch angle \( \theta \) and tip speed ratio \( \lambda \) and often written in the form of \( C_p(\lambda, \theta) \). The tip speed ratio (TSR) can be represented by

\[
\lambda(\Omega_r, v_x) := \frac{\Omega_r R}{v_x},
\]

in which the \( \Omega \) and \( R \) are respectively the rotor’s rotational velocity and radius. In Region 2, in order to extract the most possible energy from the wind, blade pitch angle is kept at a fixed minimum and TSR is maintained at the optimal \( \lambda^* \), which maximizes the \( C_p \) therefore,

\[
\max C_p(\lambda, \theta) = C_p(\lambda^*, 0).
\]

According to Table 3.1, the \( \lambda^* \) for the 5MW reference wind turbine is approximately 7.55 which
maximizes $C_p$ with $\theta = 0$. From $\lambda_*$, we can compute $\Omega_*$ and use it as a reference for the rotor speed that delivers optimal power for each given wind speed.

As is evident from (2.3), the wind’s kinetic energy is proportional to the cube of wind speed. This implies that after a certain wind speed, the converted energy $P_{\text{mech}}$ in (2.6) becomes larger than the wind turbine’s rated power. The rated power of the wind turbine is specified by several factors such as the mechanical load capacity of the components as well as the limits on the electrical power and current deliverable by the generator. This specific wind speed is called the *rated wind speed* and the region above that is referred as *Region 3* as depicted in Figure 2.6. Therefore, in this region the power extraction objective is to keep the power at the rated level. This means that the power co-efficient of the turbine is reduced by pitching the blades with feedback controller related to the wind speed. In other words, the main control objective in this region is to keep the wind turbine states such as rotor speed at their rated values, while reducing the mechanical fatigue loads induced by the variations of turbulent wind.

According to Figure 2.6, Region 3 ends after the wind speed reaches a safety limit known as the *cut-out wind speed*. As Table 3.1 illustrates, the 5-MW reference wind turbine has the cut-out wind speed of 25m/sec. Due to safety reasons, the controllers shut down the power generation and place the wind turbine in a safe operating state.

### 2.5 Wind Turbine Components

Although this thesis focuses only on horizontal axis wind turbines which only one of the possible type of wind energy conversion methods, there exists still a large variety machine configurations and control approaches in case of HAWTs. There are several design parameters which determine the capacity and specifications of the wind turbines. The most important of these parameters are rotor diameter (blade length), rotor nominal speed and electrical machine rating which have to be determined for each particular wind turbine design.

#### 2.5.1 Rotor and Blades

The first components of the wind turbine to interact with the passing wind are the blades. Blades are airfoils which create lift when the wind passes around the foils. This lift appears as torque in
the roots of the blades and turns the hub which the blade roots are connected to. In most large scale wind turbines, the blade angle can be changed (pitched) in order to increase or decrease the lift and consequently allows control of the induced aerodynamic torque. In multi-megawatt wind turbines blades can reach up to 100 meters long and are made of strong composite materials similar to aircraft wings. Two types of configurations can be found for horizontal axis wind turbines which are upwind and down wind configuration. In up-wind configuration which is the more common configuration, the rotor plane is in front of the wind turbine and in the down-wind configuration it stands in the opposite direction.

2.5.2 Drive Train

The drive train of the wind turbine is comprised of the rotating parts of the wind turbine. The main shaft which is connected to the rotor transfers the low speed and high torque of the rotor into the gearbox. The gearbox increases the rotational speed to match the nominal values of the generator which are often are higher speed AC machines. Generators are in the high speed side of the gearbox and convert the transferred mechanical energy into electrical energy. AC generators are also of different types, such as doubley-fed, full-variable speed and variable slip. Some wind turbines use multiple pole generators which have extremely low nominal speeds and can work synchronously with the wind turbine rotor without the requirement for a gearbox. These type of wind turbines are called direct drive wind turbines. Usually the drive-train components are enclosed in the nacelle of the wind turbines and located on top of the tower. The yaw mechanism on top of the tower can rotate the whole system of nacelle and blades in order to align the rotor axis with the wind direction to ensure the maximum energy capture.

2.5.3 Tower

The tower of a wind turbine may not affect the energy conversion, but its properties play an important role in the performance of the wind turbine and even it’s economical viability. Obviously, the first function of the tower is to provide ground clearance for the rotor. However, the height of the tower has some other impact on the energy production. A taller tower ensures the rotating disk of the rotor is exposed to less turbulent winds, since the turbulence intensity of the wind decreases
with higher altitude. On the other hand, a taller tower is more flexible and should be made from stronger materials which increases the final cost of the wind turbine.

\section*{2.6 Analysis of Structural Loads}

This section provides required background on the load analysis on the wind turbines as it is one of the main objectives of the controller design in this thesis. Wind turbines are subject to various types of loads depending on the cause \cite{11}:

- \textbf{Aerodynamic loads}: The effect of the wind flow in normal turbulent or extreme conditions on the blades and the tower.

- \textbf{Inertial loads}: The effect of centrifugal or gyroscopic motions of the components such as the high speed rotation of the generator.

- \textbf{Gravitational loads}: The effect of gravity on the moving parts of the wind turbine such as blades are subject to gravitational force direction change due to their rotation.

- \textbf{Operation loads}: Caused by the control, actuation commands or fault events such as blade angle pitching, yawing, braking, grid loss and etc.

Although the primary objective of any wind turbine controller is to steer wind turbine states to achieve the maximum possible energy harvesting, in practice, it is necessary to operate the turbine in a manner that the aforementioned loads do not exceed their desirable levels. In the next Section different Design Load Cases (DLC) will be briefly introduced according to IEC 61400-1 \cite{49}. Then, definitions of the fatigue and extreme loads are provided respectively.

\subsection*{2.6.1 Design Load Cases}

For wind turbine design process and certification there are several protocols and guidelines provided by available standards such as IEC 61400-1, Danish Standard DS 472 \cite{17} and Germanischer Lloyd \cite{67} according which the performance analysis of the wind turbines must be assessed in relation to some standard scenarios defined as Design Load Cases (DLCs).
2.6 Analysis of Structural Loads

<table>
<thead>
<tr>
<th>Design Load Case Number</th>
<th>Performance Assessments at</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Normal power production conditions</td>
</tr>
<tr>
<td>2</td>
<td>Power production plus the occurrence of fault</td>
</tr>
<tr>
<td>3</td>
<td>Start-up conditions</td>
</tr>
<tr>
<td>4</td>
<td>Normal wind turbine shut-down conditions</td>
</tr>
<tr>
<td>5</td>
<td>Emergency shut-down conditions</td>
</tr>
<tr>
<td>6</td>
<td>Stand still or idling conditions</td>
</tr>
<tr>
<td>7</td>
<td>Parked and fault conditions</td>
</tr>
<tr>
<td>8</td>
<td>Wind turbines in transport, assembly, maintenance, and repair</td>
</tr>
</tbody>
</table>

Table 2.2: List of IEC 61400-1 design load cases

These case consists of realistic operating conditions for fatigue and extreme load analysis such as the air density, wind flow characteristics and ambient temperature. Also, state and actuation constraints are applied to replicate operational limitations of the wind turbines.

According to the standard there are three class of wind turbines of I, II and III. Class I wind turbines are designed for the average annual wind speed of 10 m/sec. Class II is designed for 8.5 m/sec and the Class III is for 7.5 m/sec annual wind speed. For instance, the IEC 61400-1 design loads has 22 cases in total categorized in 8 different groups as shown in Table 2.2.

In this thesis the simulation scenarios will consist of fatigue analysis for normal power production modes under turbulent wind situations as well as extreme load analysis for EOG events. Therefore, the relevant DLCs associated with the scenarios according to IEC 61400-1 are DLC case number 1 (Normal Power Production) and DLC case number 3 (Extreme Operating Gust). For detailed description of DLCs see [11].

2.6.2 Fatigue Load Analysis

Flexible components of the wind turbines such as tower and blades are subject to the fatigue loads and are susceptible to crack development which may be caused by the repetitive variations of loads. Such cyclic loads have two major origins which firstly stem from the natural oscillations of the wind turbine structure due to the wind speed variation and secondly stem from the harmonic excitations induced by the rotor motion. For example, at each revolution of the wind turbine rotor, the gravity loads change sign on the blade roots and in case of asymmetrical blade weight distribution, on the low speed shaft. Such loads may vary by a frequency up to the 3 times the rotor
frequency (3P). Other sources of harmonic oscillations also may originate from tower shadow and wind shear [60].

In order to increase the life-span of the wind turbines and to ensure their safe operation, it is essential to take fatigue load analysis into account during the controller design. During the life time of a wind turbine, it withstands a set of load cycles known as the loads collective [60]. To calculate the individual and cumulative fatigue loads, we would need carry out measurements that are not very practical or even feasible. Therefore, to represent the impact of a collective loads during the life-time on each component a single equivalent load is calculated and regarded as the measure for the fatigue loads on that component. This measure is called the Damage Equivalent Load (DEL) and represents the damage of loads collective of all existing frequencies induced to the components by a single amplitude. Such single amplitude load with a specific frequency would cause the same amount of damage during the life span of the wind turbine.

2.6.3 Extreme Load Analysis

Beside the normal operation situations, wind turbine structure must be able to withstand the extreme loads which might happen to the wind turbine during its life span. In this regard, the choice of material types and component specifications should correspond to the extreme load requirements. A well designed controller can have a substantial effect on the extreme loads imposed on the wind turbines, as will be shown in Chapter 7 of this thesis. In order to assess the performance of the controller in extreme events based on the definitions of the extreme load analysis, extreme wind conditions (with 50 years recurrence frequency) are considered while turbine in running at the normal operating condition. The maximum and minimum loads on the blades, tower and the drive train shaft during an extreme event is a determining factor in the design and therefore, the final cost of the wind turbine.

2.7 Definition of Matrix Norms in the Thesis

This section provides a very brief description of norms in linear algebra which will be applied in this thesis to some extent. In functional analysis and Linear Algebra, a norm is defined as a function in a vector space that for each vector in that space assigns a strictly positive value (except
for the zero vector). The most important norms which will be used in this thesis is the Frobenius norm which is defined as

\[ \|A\|_F = \sqrt{\sum_{i=1}^{m} \sum_{j=1}^{n} |a_{ij}|^2} = \sqrt{\text{trace}(A^*A)}. \]  

(2.9)

where \(A\) is a \(n \times m\) matrix. For model validation and comparing linearized models of the plant obtained by two different methods, the matrix norm is required for which we will use the Frobenius Norm. We will also use condition number of matrices in order to observe the variation of their singular value during the simulation. The condition number is defined as

\[ \kappa(A) = \frac{\sigma_{\text{max}}(A)}{\sigma_{\text{min}}(A)} \]  

(2.10)

in which \(A\) is a square matrix, \(\sigma_{\text{max}}\) and \(\sigma_{\text{min}}\) are the largest and smallest singular values of the matrix respectively.

## 2.8 State Space Representation of Dynamic Systems

This section briefly restates the state space representation of dynamic systems in the nonlinear and its linearized format. All modeling and controller design in this thesis is carried out in the state space form.

Generally, a \(n^{th}\) order dynamic system consists of state variables \(x \in \mathbb{R}^n\), input variables \(u\) in the input space \(\mathbb{R}^m\) and output variables \(y\) in the output space \(\mathbb{R}^p\) which can be represented with the following equation [102]:

\[ \dot{x}(t) = f(x(t), u(t)), \]  

(2.11)

\[ y(t) = g(x(t), u(t)), \]  

(2.12)

where, \(f : \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}^n\) and \(g : \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}^p\).

The system given in (2.11) and (2.12) can be linearized about the origin if \(f(0,0) = 0\) and \(f\) is continuously differentiable in the origin \((x = 0, u = 0)\) [59] to the form of
\[
\dot{x}(t) = Ax(t) + Bu(t), \quad y(t) = Cx(t) + Du(t),
\]

where \(A, B, C\) and \(D\) can be obtained by the Jacobian matrices

\[
A = \frac{\partial f}{\partial x}(x, u) \big|_{x=0,u=0}, \quad B = \frac{\partial f}{\partial u}(x, u) \big|_{x=0,u=0},
\]

\[
C = \frac{\partial g}{\partial x}(x, u) \big|_{x=0,u=0}, \quad D = \frac{\partial g}{\partial u}(x, u) \big|_{x=0,u=0}.
\]

The system is considered stable at the origin if the eigenvalues of \(A\) are all in the left half of the complex plane. If either of the eigenvalues has positive real parts the system is unstable in the origin however, if the pair \(A, B\) are stabilisable, then a state feedback can be used to relocate the poles of the closed loop system at desired locations in the left half plane. State feedback has the following form of

\[
u = Fx(t),
\]

where \(F\) is a matrix such \(A + BF\) has its poles on the desired locations.

In systems with disturbance inputs, equation (2.13) can be extended in the form of

\[
\dot{x}(t) = Ax(t) + Bu(t) + Hd(t), \quad y(t) = Cx(t) + Du(t) + Gd(t),
\]

in which \(d(t) \in R^q\) is the disturbance input of the system. Although \(d(t)\) manipulates the systems states similar to \(u(t)\), it can not be changed by the controller and most cases is an arbitrary input from the environment, loads or uncertainties.

Not in all cases all of the system states are accessible via \(y(t)\). The output which is available for measurements and the states which are desired to be controlled or track a reference trajectory might be different in some systems. Therefore, in a more generalized form (2.17), \(y(t)\) is defined as the system measurement output and \(z(t)\) as the controller output [90] such that
2.8 State Space Representation of Dynamic Systems

\[ \Sigma : \begin{cases} 
\dot{x}(t) &= Ax(t) + Bu(t) + Hd(t), \\
y(t) &= C_yx(t) + D_yu(t) + G_yd(t), \\
z(t) &= C_zx(t) + Du(t). 
\end{cases} \tag{2.18} \]

2.8.1 State Estimation of Dynamic Systems

In order to apply the state feedback control law in (2.16) on the system, all state variables should be available for the controller. However, for practical reasons this is not the case in most real applications due to several reasons such as cost or the infeasibility of measuring some state variables. Therefore, control methodologies should be still implementable based on the information obtained from a sub-space of the entire state space.

There are two approaches to control the systems via incomplete state variable information. The first is to design, construct, and use dynamic feedback methods such as PID controllers. The second method is to reconstruct (estimate) the unknown state variables based on the available information and a model of the controlled system. Then, the static feedback control of (2.16) becomes again implementable using the constructed estimate of the state variables.

A dynamic system is called **observable** if the initial state of the system is deducible by observation of a subset of state variables for a finite time period. In a mathematical form, the system (2.13) is observable if the **observability matrix**

\[ O(A, C_y) = \begin{bmatrix} C_y \\ C_yA \\ C_yA^2 \\ \vdots \\ C_yA^{n-1} \end{bmatrix} \tag{2.19} \]

has rank equal to the order of system.

In order to construct the unknown state variables a copy of the system should be created as

\[ \dot{x}(t) = A\hat{x} + Bu, \tag{2.20} \]
where \( \hat{x} \) is the state variable of the copy system. The idea here is to give the same inputs to the copy system, and make it behave the same way as the plant if the initial state of the copy (which will be called the observer from now on) is identical to the plant, i.e. \( \hat{x}_0 = x_0 \). Therefore, we can have a replicated state vector which represents the real values of state variables hidden inside the plant. However, this is not the case for two obvious reasons. First, initial values of the state variables should be known, and the second is that the plant model might have some discrepancy with the actual plant dynamics which will cause deviations from the actual values. Therefore, a correction mechanism has to be applied by comparing the plant output and their associated state variables on the observer and exert corrective input signals on the observer. In (2.13), the output \( y(t) \) gives a subset of information about the state variables of the system. A *Luenberger observer* defines the correction mechanism as follows:

\[
\dot{\hat{x}}(t) = A\hat{x}(t) + K[y(t) - C_y\hat{x}(t)] + Bu(t),
\]

in which \( K \) is called the *observer gain*. The term \( K[y(t) - C_y\hat{x}(t)] \) in (2.21) ensures that the observer states converges to the plant states. If we derive an error for the difference between the plant output and the observer we will have

\[
\dot{e}(t) = \dot{\hat{x}}(t) - \dot{x}(t) = [A - KC_y]e(t).
\]

It is obvious that if \( A - KC_y \) is Hurwitz, i.e. all of its eigenvalues have strictly negative real part, the error will converge to zero and the observer states converge to the actual plant state. Since \( A \) and \( C_y \) are known and pre-defined, error dynamics can only be adjusted by the observer gain \( K \). Therefore, \( K \) can be chosen such that \( A - KC_y \) has much larger negative eigenvalues than \( A \), which ensures the observer dynamics are much faster than the plant dynamics.

### 2.9 Exact Output Regulation

This section provides a relatively detailed background on the Exact Output Regulation which is the main method investigated in this thesis.
2.9 Exact Output Regulation

2.9.1 The Output Regulation Problem

EOR is a multi-variable LTI control architecture in which the plant is subject to known input disturbances that are to be rejected, and the plant outputs are required to track a known reference signal. The aim of EOR is to design a feedback control law which ensures that the plant is internally stable, and the output asymptotically converges to a desired reference signal while rejecting the disturbances [90].

The problem has an extensive literature (see [81, 90, 102]), and the numerous references contained therein. The following summary of EOR is taken from [90], which was adapted from [81].

The EOR control architecture considers a linear time-invariant multivariable system $\Sigma$ shown in the block diagram of Figure 2.7. The plant $\Sigma$ is assumed to be described by state equations in the form of (3.16)-(3.18), with $x$ denoting the plant state, and $z$ and $y$ are the regulated and measured outputs of the plant.

A known linear time-invariant exosystem $\Sigma_{exo}$ generates the autonomous time-varying reference signal $r$ and input disturbance signal $d$. The error signal $e = z - r$ gives the difference between the regulated output and the reference. The exosystem can be written in the form of:

\[
\Sigma_{exo} : \begin{cases}
\dot{w}(t) = Sw(t), & w(0) = w_0 \\
d(t) = L_d w(t), \\
r(t) = L_r w(t).
\end{cases}
\]  

(2.23)

Here $S$ represents the exo-system dynamics and $w$ is the state vector of the exo-system. Output signals $d(t)$ and $r(t)$ are the disturbance and reference signals respectively which can be constructed
by multiplying the output matrices $L_d$ and $L_r$ into the exosystem state vector $w$. By defining

\begin{align}
E_w &= H L_d, \\
D_w &= -L_r,
\end{align}

we may replace $\Sigma$ with the error system $\Sigma_e$:

\[
\Sigma_e : \begin{cases}
\dot{x}(t) &= Ax(t) + Bu(t) + E_w w(t), \\
y(t) &= C_x x(t) + D_y u(t) + C_y d(t), \\
\dot{w}(t) &= Sw(t), \\
e(t) &= C_z x(t) + D_w w(t).
\end{cases}
\tag{2.26}
\]

A feedback controller $u$ for the system $\Sigma_e$ is said to achieve exact output regulation [81] if the closed-loop system is internally stable and, for all initial states $x_0$ and $w_0$ of the plant and exosystem, the system satisfies $\lim_{t \to \infty} e = 0$.

Ensuring the error signal vanishes means that the input disturbance is fully rejected, and the system regulated output $z$ asymptotically tracks the desired reference signal $r$. For the case where all states are measurable, we have $y = x$ and state feedback may be used to achieve exact output regulation as follows:

**Theorem 2.9.1** [81]. Assume system $\Sigma_e$ in (2.26) satisfies the following assumptions

(A.1) The pair $(A, B)$ is stabilisable.

(A.2) The matrix $S$ is anti-Hurwitz-stable.

(A.3) There exists matrices $\Gamma$ and $\Pi$ satisfying

\begin{align}
\Pi S &= A \Pi + B \Gamma + E_w, \\
0 &= C \Pi + D \Gamma + D_w.
\end{align}

Let $F$ be any matrix such that $A + BF$ is Hurwitz-stable, and let $G = \Gamma - F \Pi$. Then the state feedback control law

\[u = Fx + Gw,
\tag{2.29}\]
achieves exact output regulation for $\Sigma_e$.

Equations (2.27)-(2.28) are known as Regulator Equations and solvability conditions are given in [81].

In practice it is not always possible to measure all states of the plant, and an estimate $\hat{x}$ of the plant state must be constructed using the measured output $y$. The following theorem gives conditions under which exact output regulation may be achieved with a dynamic measurement feedback controller.

**Theorem 2.9.2** [81] Assume the system $\Sigma_e$ in (2.26) satisfies the assumptions (A.1)-(A.3). Further assume the matrix pair

$$( [C_y \ 0], \begin{bmatrix} A & E_w \\ 0 & S \end{bmatrix} )$$

is detectable. Then the exact output regulation problem is solvable by a dynamic measurement feedback controller of the form

$$\Sigma_c : \begin{cases} 
\dot{\hat{x}}(t) \\
\dot{w}(t)
\end{cases} = \begin{bmatrix} A & E_w \\ 0 & S \end{bmatrix} \begin{bmatrix} \hat{x}(t) \\ w(t) \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u(t)$$

$$+ \begin{bmatrix} K \\ C_y \end{bmatrix} \begin{bmatrix} \hat{x}(t) \\ w(t) \end{bmatrix} - y(t)$$

$$(2.30)$$

where $F$ and $K$ are such that $A + BF$ and $A + KC_y$ are both Hurwitz stable matrices.

In Chapter 5, we will discuss the application of EOR in a LIDAR-equipped wind turbine by showing that the availability of wind preview information enables the wind to be modeled as a known exo-system generating input disturbances and reference signals. Disturbance rejection means that the effect of wind variations on the desired rotor speed is rejected, and successful reference tracking means that the turbine achieves the optimal tip speed ratio to ensure the maximum power generation. By modeling the wind with a low-order linear system, output regulation may be achieved with smooth variations in the plant state, leading to load reductions, as will be demonstrated in the experimental results shown in the Chapter 7. Two different approaches can be taken to model the dynamics of wind speed variations as a known exo-system. The first is
the continuous-time approach in which an ordinary differential equation (ODE) is assumed to describe the exo-system. The second is the discrete-time approach in which auto regressive models are used to find the matching difference equation which will be described in Chapter 5.
Chapter 3
Wind Turbine Modeling

This thesis uses two different types of models for simulation and controller design. The simulation model aims to capture most of the dynamics and nonlinearities of a real wind turbine. To this end we have used the FAST (Fatigue, Aerodynamics, Structures, and Turbulence) code [55] with a Simulink interface. It is developed by NREL as an open source code for industrial grade simulations. FAST is able to simulate different on and off-shore wind turbines under realistic wind conditions. Throughout this thesis, the NREL 5MW reference wind turbine is used for simulation by FAST with the platform DOFs (associated with off-shore wind turbines) disabled according the specifications of the NREL 5-MW reference turbine given in [54].

Simulation models are typically highly complicated and therefore not suitable for controller design. Hence, a lower (reduced) order model is required for model-based control methods. Although a reduced model should be simple enough to be suitable for stability analysis and controller design, it should include the essential dynamics of the wind turbine. Excessively simplified models may yield under-performing or even unstable systems. Therefore, choosing the model order is often a trade-off between simplicity in design and model accuracy.

3.1 Properties of NREL 5MW Reference Wind Turbine

To support the studies in wind technology, the NREL has developed a utility-scale multi-megawatt wind turbine which is known as the "NREL 5-MW reference wind turbine". This wind turbine is a three-bladed variable-speed variable blade-pitch-to-feather-controlled upwind HAWT. To create the model, NREL has designed this turbine, based on the REpower 5M machine along with the publicly available properties from the conceptual designs in various projects such as the Wind-
PACT [24], RECOFF [34], and DOWEC [39]. The model is widely used as a reference by researchers across the world to assess the benefits of advanced wind turbine technologies. A schematic representation of LIDAR equipped NREL 5-MW reference wind turbine is shown in the Figures 3.1 and 3.2.

![Figure 3.1: Schematic diagram of a Horizontal axis Wind Turbine with LIDAR](image)

In [54] the specifications of the wind turbine such as the structural, aerodynamics, and control-system properties are documented. A summary of the specifications is also presented at Table 3.1.

### 3.1.1 Blade Properties

The NREL offshore 5-MW baseline wind turbine has three blades. The structural properties of each blade are based on the properties of the 63-m long LM-Glasfiber blades in the DOWEC study. Table 3.2 lists the blade properties of the rotor.
3.1 Properties of NREL 5MW Reference Wind Turbine

3.1.2 Hub and Nacelle Properties

The hub of the NREL 5-MW reference wind turbine is located at an elevation of 90 m above ground level when the system is at rest with a shaft tilt of 5°. The specified hub mass is 56,780 kg with the center of mass at the hub center, while the given hub inertia about the shaft is 115,926 kg.m². The nacelle mass and its inertia about the yaw axis are 240,000 kg and 2,607,890 kg.m² respectively. The nacelle-yaw actuator has a natural frequency of 3 Hz. Table 3.3 summarizes the nacelle and hub properties as discussed.

3.1.3 Drive-train Properties

The NREL 5-MW baseline wind turbine to has a rated rotor speed of 12.1 rpm, rated generator speed (1173.7 rpm), and gearbox ratio (97:1). The gearbox is assumed to have no frictional losses. The efficiency of the electrical generator is taken to be 94.4, which is roughly the same as the DOWEC turbine. The generator is assumed to be fully speed controllable thought the whole speed range with inertia of 534.116 kg.m² about the high-speed shaft which is assumed to be rigid. A driveshaft connects the gearbox to the rotor axis with linear-spring constant of 867,637 kN.m/rad and a linear-damping constant of 6,215 kN.m/(rad/s). The high-speed shaft is equipped with a brake with maximum brake torque equal to the maximum generator torque and time lag of 0.6 seconds. This is the time required for the brake to fully engage after deployment command. Table
Table 3.1: The NREL 5-MW Wind Turbine Specifications

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>$P_{\text{rated}}$</td>
<td>5 MW</td>
</tr>
<tr>
<td>Rated rotor speed</td>
<td>$\Omega_{\text{rated}}$</td>
<td>12.1 rpm</td>
</tr>
<tr>
<td>Rated wind speed</td>
<td>$V_{\text{rated}}$</td>
<td>11.4 m/sec</td>
</tr>
<tr>
<td>Cut-in wind speed</td>
<td>$V_{\text{in}}$</td>
<td>3 m/sec</td>
</tr>
<tr>
<td>Cut-out wind speed</td>
<td>$V_{\text{out}}$</td>
<td>25 m/sec</td>
</tr>
<tr>
<td>Rotor radius</td>
<td>$R$</td>
<td>63 m</td>
</tr>
<tr>
<td>Hub height</td>
<td>$h_H$</td>
<td>90 m</td>
</tr>
<tr>
<td>Rotor moment of inertia</td>
<td>$J_r$</td>
<td>$11.77 \times 10^6$ kg/m$^2$</td>
</tr>
<tr>
<td>Generator moment of inertia</td>
<td>$J_g$</td>
<td>534 kg/m$^2$</td>
</tr>
<tr>
<td>Generator Electrical Efficiency</td>
<td>$\eta_g$</td>
<td>94.4 %</td>
</tr>
<tr>
<td>Drive-train Stiffness</td>
<td>$K_d$</td>
<td>$867 \times 10^6$ Nm/Rad</td>
</tr>
<tr>
<td>Drive-train Damping</td>
<td>$C_d$</td>
<td>$6.2 \times 10^6$</td>
</tr>
<tr>
<td>Gearbox ratio</td>
<td>$i$</td>
<td>1/97</td>
</tr>
<tr>
<td>Tower equivalent modal mass</td>
<td>$m_{\text{Te}}$</td>
<td>$4.36 \times 10^3$ kg</td>
</tr>
<tr>
<td>Tower structural damping</td>
<td>$c_{\text{Te}}$</td>
<td>17782</td>
</tr>
<tr>
<td>Bending stiffness</td>
<td>$k_{\text{Te}}$</td>
<td>$1.81 \times 10^6$ N/m</td>
</tr>
<tr>
<td>Static tower-top displacement in absence of thrust forces</td>
<td>$x_{T0}$</td>
<td>-0.0140 m</td>
</tr>
<tr>
<td>Undamped natural frequency of the blade pitch actuator</td>
<td>$\omega$</td>
<td>$2\pi$ rad/s</td>
</tr>
<tr>
<td>Damping factor of the blade pitch actuator</td>
<td>$\zeta$</td>
<td>0.70</td>
</tr>
<tr>
<td>Optimal tip speed ratio</td>
<td>$\lambda_*$</td>
<td>7.55</td>
</tr>
<tr>
<td>Peak power coefficient</td>
<td>$c_{p,\text{max}}$</td>
<td>0.482</td>
</tr>
</tbody>
</table>

Table 3.2: Undistributed Blade Structural Properties

<table>
<thead>
<tr>
<th>Property Name</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (w.r.t. Root Along Pre-coned Axis)</td>
<td>61.5</td>
<td>m</td>
</tr>
<tr>
<td>Mass Scaling Factor</td>
<td>4.53</td>
<td>%</td>
</tr>
<tr>
<td>Overall (Integrated) Mass</td>
<td>17,740</td>
<td>kg</td>
</tr>
<tr>
<td>First Mass Moment of Inertia (w.r.t. Root)</td>
<td>363,231</td>
<td>kg.m</td>
</tr>
<tr>
<td>CM Location (w.r.t. Root along Pre-coned Axis)</td>
<td>20.47</td>
<td>m</td>
</tr>
<tr>
<td>Structural-Damping Ratio (All Modes)</td>
<td>0.47</td>
<td>%</td>
</tr>
</tbody>
</table>

3.4 summarizes the drive-train properties as discussed.

### 3.1.4 Tower Properties

Depending on the type of support structure, the properties of the tower for the NREL reference 5-MW wind turbine will differ. In [54] the land-based tower for the wind turbine is assumed to have a base diameter of 6 m and thickness of 0.027 m, top diameter of 3.87 m and thickness of
### Table 3.3: Nacelle and Hub Properties

<table>
<thead>
<tr>
<th>Property Name</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation of Yaw Bearing above Ground</td>
<td>87.6</td>
<td>m</td>
</tr>
<tr>
<td>Vertical Distance along Yaw Axis from Yaw Bearing to Shaft</td>
<td>1.96</td>
<td>m</td>
</tr>
<tr>
<td>Distance along Shaft from Hub Center to Yaw Axis</td>
<td>5.01</td>
<td>m</td>
</tr>
<tr>
<td>Distance along Shaft from Hub Center to Main Bearing</td>
<td>1.91</td>
<td>m</td>
</tr>
<tr>
<td>Hub Mass</td>
<td>56,780</td>
<td>kg</td>
</tr>
<tr>
<td>Hub Inertia about Low-Speed Shaft</td>
<td>115,926</td>
<td>kg.m²</td>
</tr>
<tr>
<td>Nacelle Mass</td>
<td>240</td>
<td>Ton</td>
</tr>
<tr>
<td>Nacelle Inertia about Yaw Axis</td>
<td>2,607,890</td>
<td>kg.m²</td>
</tr>
<tr>
<td>Nacelle CM Location Downwind of Yaw Axis</td>
<td>1.9</td>
<td>m</td>
</tr>
<tr>
<td>Nacelle CM Location above Yaw Bearing</td>
<td>1.75</td>
<td>m</td>
</tr>
<tr>
<td>Equivalent Nacelle-Yaw-Actuator Linear-Spring Constant</td>
<td>9,028</td>
<td>MNm/rad</td>
</tr>
<tr>
<td>Equivalent Nacelle-Yaw-Actuator Linear-Damping Constant</td>
<td>19,160</td>
<td>KNm/(rad/s)</td>
</tr>
<tr>
<td>Nominal Nacelle-Yaw Rate</td>
<td>0.3</td>
<td>deg/s</td>
</tr>
</tbody>
</table>

### Table 3.4: Drive-train Properties

<table>
<thead>
<tr>
<th>Property Name</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Rotor Speed</td>
<td>12.1</td>
<td>rpm</td>
</tr>
<tr>
<td>Rated Generator Speed</td>
<td>1173.7</td>
<td>rpm</td>
</tr>
<tr>
<td>Gearbox Ratio</td>
<td>97:1</td>
<td>–</td>
</tr>
<tr>
<td>Electrical Generator Efficiency</td>
<td>94.4</td>
<td>%</td>
</tr>
<tr>
<td>Generator Inertia about High-Speed Shaft</td>
<td>534.1</td>
<td>kg.m²</td>
</tr>
<tr>
<td>Equivalent Drive-Shaft Torsional-Spring Constant</td>
<td>867,637</td>
<td>KNm/rad</td>
</tr>
<tr>
<td>Equivalent Drive-Shaft Torsional-Damping Constant</td>
<td>6,215,000</td>
<td>Nm/(rad/s)</td>
</tr>
<tr>
<td>Fully-Deployed High-Speed Shaft Brake Torque</td>
<td>28,116.2</td>
<td>Nm</td>
</tr>
<tr>
<td>High-Speed Shaft Brake Time Constant</td>
<td>0.6</td>
<td>sec</td>
</tr>
</tbody>
</table>

0.019 m. The material of the tower is chosen to be from steel similar to DOWEC study. The radius and thickness of the tower are designed to linearly reduce from the tower base to the tower top.

The tower structure is designed to ensure the first fore-aft and side-to-side tower natural frequencies are between the 1P and 3P frequencies throughout the operational range of the wind turbine. Table 3.5 summarizes the tower properties as discussed.

### Table 3.5: Tower Properties

<table>
<thead>
<tr>
<th>Property Name</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height above Ground</td>
<td>87.6</td>
<td>m</td>
</tr>
<tr>
<td>Overall (Integrated) Mass</td>
<td>347,460</td>
<td>kg</td>
</tr>
<tr>
<td>CM Location (w.r.t. Ground along Tower Centerline)</td>
<td>38.2</td>
<td>m</td>
</tr>
<tr>
<td>Structural-Damping Ratio (All Modes)</td>
<td>1</td>
<td>%</td>
</tr>
</tbody>
</table>
3.2 Full aero-elastic model of the NREL-5MW in FAST

Utility scale wind turbines are expensive machines and it is essential to model their behavior during the design process. To this end, many sophisticated simulation tools have been developed to model the aero-servo-elasticity of the wind turbines, such as ADAMS [37], AeroDyn [72], BLADED [6] and FAST [55]. Wind turbine manufacturers often use these codes to analyze and type certify their turbines. Therefore, they need to use simulation codes which have been approved by the relevant certifying agencies. In this work, the FAST code, developed by NREL is used for simulations. In a 2006 agreement between the NREL and Germanischer Lloyd (GL)\(^1\) the world's foremost certifying body for wind turbines, a comparison between FAST and two other high fidelity simulation codes was conducted. After a variety of exercises and case studies, GL issued a statement that using the NREL FAST code by manufacturers for their on-shore wind turbine certification is acceptable [10].

The FAST code is publicly available as an open source code package and has been constantly updated with new versions and feature since its publication in 2002. It is also provided along with a Simulink S-function interface which makes it ideal for academic use, especially for controller design and load analysis. FAST consists of aerodynamic and structural sub-routines for nonlinear aero-elastic modeling of on-shore and off-shore turbine dynamics. Usually, it is interfaced with AeroDyn for aerodynamic loads computations on the flexible structures. In the following section, FAST will be presented with more details.

3.2.1 Aerodynamics in FAST

In FAST the Blade-Element/Momentum (BEM) theory is used in order to model the aerodynamics of horizontal-axis wind turbines [55]. Blade Element Momentum Theory is based on two existing methods of describing turbine operation. The first method uses the momentum balance on a stream tube passing through a cross-section of a turbine. The second method calculates the generated collective forces by the aerofoil lift and drag properties at several smaller segments along the blade. These two methods then can be described by equations which usually can only be solved iteratively [48].

---

\(^1\) GL merged with Norway’s DNV (Det Norske Veritas) in September 2013 and became the present-day DNV GL.
Table 3.6: Available and Enabled DOFs in FAST code

<table>
<thead>
<tr>
<th>Name</th>
<th>Enabled</th>
<th>No. of DOFs</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator</td>
<td>✓</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Drive-train Torsion</td>
<td>✓</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>First and Second fore-aft tower bending</td>
<td>✓</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>First and Second side-side tower bending</td>
<td>✓</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>First edge-wise blade</td>
<td>✓</td>
<td>1 × 3</td>
<td>3</td>
</tr>
<tr>
<td>First flap-wise blade</td>
<td>✓</td>
<td>1 × 3</td>
<td>3</td>
</tr>
<tr>
<td>Second flap-wise blade</td>
<td>✓</td>
<td>1 × 3</td>
<td>3</td>
</tr>
<tr>
<td>Nacelle-yaw-actuator</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Rotor teetering</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Tail furl</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Support platform flexibility modes</td>
<td>-</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

In order to achieve more accurate simulations, FAST has been equipped with additional models in addition to the BEM model in the aerodynamic subroutines. This additions are corrections for the tip and hub losses, dynamic stall, skewed wakes, and tower shadows which are taken into account to achieve a more realistic model of the wind turbine aerodynamics [55].

3.2.2 Structural Dynamics in FAST

The wind turbine structural components are divided into two rigid and flexible bodies. Flexible bodies are the tower, low-speed shaft of the drive-train, and the blades. Other components such as earth, base platform, nacelle, generator shaft, hub and the gearbox are assumed to be rigid.

As shown in Table 3.6, there are up to 24 degrees-of-freedom (DOF) available in FAST for a three-bladed HAWT. Throughout this work we have assumed an on-shore 5-MW NREL reference wind turbine, always facing to the wind with a stand-alone steel tower. Therefore, irrelevant DOFs have been disabled in the FAST settings.

3.2.3 Actuators in FAST

The wind turbine model in FAST accepts four different inputs. The first is the generator torque which acts on the drive train shaft. The next three inputs are the blade pitch angles which can be individually set to arbitrary values. However, custom models can be interfaced deliberately into
FAST in order to accommodate the actuator dynamics. To include custom generator models, FAST can be linked with user-written Dynamic Link Library (DLL) files developed in C or FORTRAN. The second method is to use the MATLAB S-Function interface in which both external generator and pitch actuator models can be developed in Simulink and connected to FAST. Detailed guidelines for compiling the FAST source codes into MATLAB mex files to create the S-function are provided in [55].

3.2.4 FAST Measurement Outputs

For each enabled DOF given in Table 3.6, FAST provides one or more output signals. For example, signals related to the generator DOF provide data on its rotational speed, torque, and generated power during the simulation.

Fatigue loads can also be inferred from the temporal variations of the movements of the associated DOFs. For example, by providing the first and second fore-aft tower bending moment signal to the rain-flow counting algorithm, correlated fatigue loads can be calculated. Accordingly, for each desired signal which represents a time-varying force or torque, this can be carried out as well.

3.3 Simplified Model for Estimation and Control

As mentioned before, simulation models are not suitable for controller and estimator design. Horizontal Axis Wind Turbine can be modeled by the combination of four subsystems which are Aerodynamics, Mechanical, Electrical, and Control/Actuator subsystems. Since the electrical subsystem dynamic is usually much faster than other subsystems, it can be ignored during the controller design provided that it is dynamically uncoupled to the grid by full-size power electronics. Therefore, our simplified model will consist of 3 subsystems.

3.3.1 Simplified Aerodynamics Subsystem Model

The aerodynamic subsystem captures the kinetic energy in the moving air (wind) and converts it into the mechanical torque about the axis of rotation of the turbine rotor. Proportional to the drag
which is created in this process, it induces thrust on the tower which pushes and bends the tower in the direction of wind. For the sake of simplicity in modeling we will ignore the aerodynamic transients and consider the aerodynamic sub-system to be in steady state. This is a common assumption in the wind turbine control literature, including the NREL guidelines for wind turbine controller design [108]. Using the definitions in Section 2.4, the aerodynamic torque $M_a$ and the aerodynamic trust $F_a$ can be represented by

$$M_a(\Omega_r, \theta, v_x) := \frac{1}{2} \rho \pi R^3 \frac{c_P(\lambda, \theta)}{\lambda} v_x^2,$$  

(3.1)

$$F_a(\Omega, \theta, v_x) := \frac{1}{2} \rho \pi R^2 c_T(\lambda, \theta) v_x^2,$$  

(3.2)

where $\theta$ and $\Omega_r$ are the wind turbine blade pitch angle and rotor speed (with the radius $R$), $\rho$ is the air density and the perpendicular wind speed $v_x$ is the magnitude of the component of the wind velocity vector perpendicular to the rotor plane. Both $c_T$ and $c_P$ are the coefficients of thrust and power.

The power and thrust co-efficient function $c_P(\lambda, \theta)$ and $c_T(\lambda, \theta)$ are functions of blade tip speed and pitch angle. Figures 3.3 and 3.4 show the graphical representation of the 2-D lookup table of the NREL-5MW reference wind turbine. The use of this look-up table can be in two forms. The first is to fit a 2-D polynomial to the data points and use a closed form of $c_P(\lambda, \theta)$ in (3.1). The second method is to directly use a 2-D interpolation between the data points. Also for deriving linearized models all Jacobians can be calculated by imposing small perturbations in $\lambda$ and $\theta$ to obtain good approximations of partial derivatives for each of the independent variables. For example, $\frac{\partial c_T}{\partial \lambda}$ at the point of $\lambda = \lambda_*$ and $\theta = \theta_*$ can be approximated by

$$\frac{\partial c_T}{\partial \lambda} \approx \frac{c_T(\theta_*, \lambda_*) - c_T(\theta_*, \lambda_* + \Delta \lambda)}{\Delta \lambda},$$  

(3.3)

$$\frac{\partial c_P}{\partial \lambda} \approx \frac{c_P(\theta_*, \lambda_*) - c_P(\theta_*, \lambda_* + \Delta \lambda)}{\Delta \lambda},$$  

(3.4)

where $\Delta \lambda$ is the deviation from the $\lambda_*$. The same operation can be carried out for the partial derivatives of other variables.
3.3.2 Simplified Mechanical Subsystem Model

The mechanical subsystem consists of the drivetrain and tower dynamics. The drivetrain transfers the aerodynamic torque on the rotor to the generator and electrical sub-systems. The tower is a flexible structure which holds the nacelle and drive-train atop in order to make ground clearance for the blades. The tower is subject to aerodynamic thrust forces.

The rotating part of the wind turbine is comprised of the rotor and drive-train which are modeled by a two-mass spring damper system as depicted in Figure 3.5. Each of the masses located at each end of the drive train and are associated with the rotor $J_r$ and generator moments of inertia $J_g$ respectively. In between stands the gearbox in which the high speed shaft is coupled with the generator and the low speed shaft is coupled with the rotor. The counter-acting torque between the generator and the rotor causes a torsion angle of $\phi$ on the drive train which can be modeled by a rotation spring $K_d$. The torsion is defined as the twisting angle difference between the rotor $\Theta_r$ and gearbox angular position $\Theta_g$ compared to their rest states and can be written as

$$\phi = \Delta \Theta = \Theta_r - \Theta_g.$$  (3.5)
Several bearings which support the low and high speed shafts induce some friction into the system which are modeled by a rotational friction $C_d$.

Applying the second Newton’s law for the motions of rotor and generator mass, we have

$$\dot{\phi} = \Omega_r - \Omega_g, \quad (3.6)$$

$$J_g \dot{\Omega_g} = C_d (\Omega_r - \Omega_g) + K_d \phi - M_g, \quad (3.7)$$

$$J_r \dot{\Omega_r} = M_a (\cdot) - C_d (\Omega_r - \Omega_g) + K_d \phi, \quad (3.8)$$
where generator torque $M_g$ is system control inputs, $\Omega_r$ and $\Omega_g$ are the rotor and generator speeds. Throughout this thesis, for the sake clarity and readability of equations, $\Omega_g$ will represent the rotational speed of generator divided by the gearbox ratio. This allows us to omit the gearbox ratio $i$ in equations. As it was mentioned above, parameters $J_r$ and $J_g$ are the moments of inertia of the rotor and generator while $C_d$ and $K_d$ are the damping and stiffness coefficients of the drive train. Finally, $M_a(.)$ is the aerodynamic torque which is a nonlinear function of system states and given in (3.1). The power coefficient is provided as 2-D lookup tables by the manufacturer.

To represent the dynamics of the flexible tower in its fore-aft motion, a simple mass-spring-damper model is used. Figure 3.6 shows movement of the tower in fore-aft direction lateral to the aerodynamic force $F_a(.)$. The dynamics can be written as

$$m_T \ddot{x}_T + c_T \dot{x}_T + k_T x_T = F_a(.),$$  \hspace{1cm} (3.9)

in which $x_T$ is the tower-top displacement in the fore-aft direction, $m_T$ is the tower mass, $c_T$ is the tower damping, $k_T$ is the tower stiffness and the aerodynamic force $F_a(.)$ is a nonlinear function of system states and the wind speed given by (3.2).
3.3.3 Simplified Electrical Subsystem Model

The electrical subsystem is responsible for converting mechanical energy into electrical energy and transmitting it to the power grid. It is comprised of a generator, power electronics, current transmission cables, transformers, and harmonic filters. The generator is the connection point of the mechanical subsystem into the electrical and is driven with power electronics. We consider the generator as a torque actuator, decoupled from the power grid dynamics.

3.3.4 Simplified Actuator Subsystem Model

Large scale wind turbines have two main actuation mechanisms. The first is the generator torque which can be fully or partially controlled depending on the type of generator. In this thesis, the generators are modeled as fully speed and torque variable. The second actuation system are the blade pitch angle actuators which can be altered collectively or individually depending on the control methodology used. Throughout this thesis, collective pitch actuation is used. Pitch actuation system is a position control loop tracking the reference angle $\theta_c$. Therefore it can be modeled by a second order linear system as

$$\ddot{\theta} + 2\zeta\omega\dot{\theta} = \omega^2(\theta_c - \theta),$$  \hspace{1cm} (3.10)

with parameters $\zeta$ and $\omega$ according to Table 3.1. A block diagram of actuators subsystem model is depicted in Figure 3.7.

3.4 Linearized Model of the Wind Turbine

The controller design introduced in this thesis requires linear state space models of the wind turbine as the internal model. This linearized model can be obtained by different methods such as system identification and linearisation of simplified nonlinear model about the equilibrium point. Additionally FAST is able of extracting linearized representations of the complete nonlinear aeroelastic wind turbine. This capability is useful for determining all of the system modes of a wind turbine by the use of eigenanalysis. However, this capability is able to work offline while the controller introduced in this thesis requires an online method in order to cope with the changing
reference wind speeds. Therefore, we will use the equilibrium point linearisation instead of FAST method. To validate and compare our applied model against the linearized models of the FAST, some eigenanalysis will be carried out and compared against the FAST linearisation methods.

### 3.4.1 Equilibrium Point Linearisation

Linearisation methods can be applied on each of the non-linear dynamic equations discussed in Section 3.3. In this thesis drive train and pitch actuator dynamics are selected for the internal model used by the controller. Therefore, equations (3.6) to (3.8) and (3.10) may be written in the system form of

\[
\dot{x} = f(x, u, d) = \begin{bmatrix} \Omega_r - \Omega_g \\ C_d J_g^{-1}(\Omega_r - \Omega_g) + K_d J_g^{-1}\phi - M_g J_g^{-1} \\ M_d(\dot{\phi}) J_r^{-1} - C_d J_r^{-1}(\Omega_r - \Omega_g) + K_d J_r^{-1}\phi \\ \omega^2(\theta - \theta) - 2\zeta \omega \theta \end{bmatrix}, \quad (3.11)
\]

where \( x = [\Omega_r \ \phi \ \Omega_g \ \theta \ \dot{\theta}]^T \) is the state variable vector, \( u = [\theta_c \ M_g]^T \) is the control input vector and \( d = v_x \) is the input disturbance. The aerodynamic trust function \( M_d(\Omega_r, \theta, v_x) \) is as defined in (3.1) and \( z \) is the controlled output. For a given reference wind speed, \( d* = v_x,\theta \) an
equilibrium point of \((x^*, u^*, d^*)\) must be found which satisfies

\[
\dot{x} = f(x^*, u^*, d^*) = 0, \quad \text{subject to : } \Omega_r = \Omega_r^*,
\]

where \(\Omega_r^* = \lambda_x R^{-1} v_{x,0}\) in Region 2 and \(\Omega_r^* = \Omega_{rated}\) in Region 3 as given in Table 3.1. The solution for (3.13) can be found by two different methods. The first is to directly solve (3.13) numerically (e.g. in MATLAB with the \(f\)minunc function). The second method, finding the associated equilibrium points \(u^*\) and \(x^*\) for a given reference wind speed, \(v_{x,0}\) by simulating the wind turbine in FAST with prolonged and constant wind signals. In this regard, the wind turbine rotor speed should be kept on its nominal values by a PI controller while it is exposed to a constant wind speed until the transient effects fade away on all states. Then, the obtained state vector \(x^*\) and applied input \(u^*\) in this status are the equilibrium point values of the wind turbine in wind speed \(v_{x,0}\). Now, the linearisation method given in Section 2.8 can be achieved by

\[
A = \frac{\partial f}{\partial x}(x, u, d) \bigg|_{x=x^*, u=u^*, d^*=v_{x,0}}, \quad B = \frac{\partial f}{\partial u}(x, u, d) \bigg|_{x=x^*, u=u^*, d^*=v_{x,0}},
\]

\[
C_z = \frac{\partial g}{\partial x}(x, u, d) \bigg|_{x=x^*, u=u^*, d^*=v_{x,0}}, \quad H = \frac{\partial f}{\partial d}(x, u, d) \bigg|_{x=x^*, u=u^*, d^*=v_{x,0}}.
\]

Hence we obtain the following linear state space model in perturbed coordinates

\[
\dot{x}(t) = Ax(t) + Bu(t) + Hd(t),
\]

\[
y(t) = C_y x(t)
\]

\[
z(t) = C_z x(t),
\]

where \(x(t)\) is the system state vector perturbation from \(x^*\), \(u(t)\) is the control input perturbation from \(u^*\) and \(d(t)\) is the input disturbance deviation from \(d^*\). The measured output is \(y(t)\), \(A\), \(B\) and \(H\) represent the system matrices, \(C_y\) is the measurement output matrix and \(C_z\) is the controlled output matrix.

The actual mean wind speed \(v_{x,0}\) can be obtained by cumulative averaging the wind speed for a short period of time. An example is shown in Figure 3.8 for cumulative averaging the wind speed results compared by the 1 hour wind data produced by TurbSim for a reference wind speed.
parameter of $18 \text{ m/sec}$. In less than 100 seconds, the averaging method can produce an accurate estimate which can be used as the reference wind speed. Because of this buffer time, around 100 seconds of the simulation results will be omitted in the result analysis in order to eliminate the initialization effects on the controllers performance. The obtained actual mean wind speed is then used as linearisation point as well as a criteria for model selection between Region 2 and Region 3. We observe the cumulative wind speed for 10 minutes and in case it changes from Region 2 to 3 or vice versa, the model will be switched to the appropriate region of operation accordingly. The selection of one hour simulation time length is also motivated by the wind variation spectrum shown in Figure 2.1, which illustrates that the one hour average wind speed has the least variation frequency. Nevertheless, time intervals as short as 10 minutes can be used according to IEC 61400 [49].

3.4.2 Region 2 Linearized Model

We seek a linearized state space formulation for turbine of the form (3.16) to (3.18). In the Region 2, the blade pitch angle is always kept at zero therefore, (3.10) will not appear in the equations and the input will only be comprised of generator torque. Thus we have $u(t) = M_g$, where $M_g$ is the only control input and the output is the system rotor speed and $v_r(t)$ is the wind speed.
Linearized model has been extracted according to the guidelines in [107] for a third order model with the following state variables

\[ x = \begin{bmatrix} \Omega_r & \phi & \Omega_g \end{bmatrix}^T, \]  

(3.19)

where the states are the perturbed values with respect to the linearisation point \( x^* \). For any given reference wind speed \( v_{x,0} \), the linearisation point \( x^* \) can be obtained by finding the control input \( u^* \) for which the tip speed ratio is kept at the optimal tip speed ratio \( \lambda_* \). The obtained linearized system matrices are constructed as follows:

\[
A = \begin{bmatrix}
\frac{(\gamma - C_d)}{J_r} & -\frac{1}{J_r} & \frac{C_d}{J_r} \\
K_d & 0 & -K_d \\
\frac{C_d}{J_g} & \frac{1}{J_g} & -\frac{C_d}{J_g}
\end{bmatrix},
B = \begin{bmatrix}
0 \\
0 \\
-\frac{1}{J_g}
\end{bmatrix},
H = \begin{bmatrix}
\frac{\alpha}{J_r} \\
0 \\
0
\end{bmatrix},
\]  

(3.20)

where

\[
\gamma = \frac{\partial M_g}{\partial \Omega_r} \bigg|_{x_r,\mu_r,\nu_r,\beta_r}, \quad \alpha = \frac{\partial M_g}{\partial v_x} \bigg|_{x_r,\mu_r,\nu_r,\beta_r},
\]

(3.21)

and the constants \( C_d, K_d, J_r \) and \( J_g \) are given in Table 3.1.

Not all of the states on the wind turbine are measurable directly via sensors. In practice, some of the states are either inaccessible or very expensive to measure. For example, measuring the drive train torsion requires rotational position sensors for each shaft. In case of measuring tower movements, tower acceleration is the only economically viable measurement and therefore, other states are best estimated by state observers. In this thesis, in order to show the ability of EOR to work with estimated signals, estimated signals of drive-train torsion and blade pitch rate will be used instead of direct measurements.

In Region 2, it is assumed that only the rotor speed \( \Omega_r \) and generator speed \( \Omega_g \) are measurable and the torsion \( \phi \) has to be estimated by an observer. Therefore, the measurement output matrix \( C_y \) in (2.18) will be

\[
C_y = \begin{bmatrix}
1 & 0 & 0 \\
0 & 0 & 1
\end{bmatrix},
\]

(3.22)

and matrices \( D_y \) and \( G_y \) are not required. Therefore, the estimator state vector will be \( \hat{x} = [\Omega_r \ \phi \ \Omega_g] \), where \( \hat{\phi} \) is the estimated torsion. Finally, the rotor speed is the controlled output
so $C_z$ becomes

$$C_z = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}. \quad (3.23)$$

### 3.4.3 Region 3 Linearized Model

We again develop a linearized model of the form (3.16) to (3.18) applicable in Region 3 where the pitch actuator dynamics are added to the system so state space variables become

$$x = [\Omega_r \ \phi \ \Omega_g \ \theta \ \dot{\theta}]^T, \quad (3.24)$$

which are perturbed values of the rotor speed, torsion, generator speed, pitch angle and pitch angle rate respectively. The linearisation point $(x^*, u^*, d^*)$ can be obtained by finding the control input $u_*$ for which the rotor speed is kept at rated value (see Table 3.1) for the reference wind speed $v_{x,0}$. The system matrices can be constructed by augmenting the system matrix of Region 2 and the pitch actuator system from (3.10):

$$A = \begin{bmatrix} \frac{(\gamma - C_d)}{J_r} & -\frac{1}{J_r} & \frac{C_d}{J_r} & \frac{\dot{\beta}}{J_r} & 0 \\ K_d & 0 & -K_d & 0 & 0 \\ \frac{C_d}{J_g} & \frac{1}{J_g} & -\frac{C_d}{J_g} & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -\omega^2 & -2\zeta\omega \end{bmatrix}, \quad B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & -J_g^{-1} \\ 0 & 0 \\ \alpha f_r^{-1} & 0 \end{bmatrix}, \quad H = \begin{bmatrix} 0 & 0 \end{bmatrix},$$

$$\quad (3.25)$$

where $\beta = \frac{\partial M_a}{\partial \theta}$, $\omega$ and $\zeta$ are the parameters of a canonical second-order pitch actuator system. It is also assumed that only blade pitch angle $\theta$ is measurable and its rate $\dot{\theta}$ must be estimated. Therefore, the measurement output matrix $C_y$ in (2.18) will be

$$C_y = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}. \quad (3.26)$$
Therefore, the estimator state vector will be \( \hat{x} = [\Omega_r \ \dot{\phi} \ \Omega_x \ \theta \ \dot{\theta}] \), where \( \dot{\phi} \) and \( \dot{\theta} \) are the estimated torsion and pitch rate respectively. If the generator torque is kept on the rated value and blade pitch angle is chosen to be tracked, then the input matrix \( B \) and controlled output \( C_z \) will simplify to:

\[
B = [0 \ 0 \ 0 \ 0 \ \omega_r^2]^T, \quad C_z = [0 \ 0 \ 0 \ 1 \ 0].
\] (3.27)

### 3.4.4 Model Validation of the Lower Order Model

In this section, we will compare the results of linearisation about mean wind speed against the FAST linearisation. FAST is able to generate linearized models of desired system order from the wind turbine with offline calculations. However, since we need an online ability for the controller to generate linearized models for a given reference wind speed, the linearisation method given in Sections 3.4.3 and 3.4.2 is used.

Taking FAST as the reference we can assume that the linearisation about mean wind speed is accurate if its results match those of the FAST linearisation. Since there are more than one modes in the models, we need to measure the distance between the system matrix \( A \) in (3.25) for each method. There are many techniques to measure this distance however we will use Frobenius norm to identify the similarity.

![Figure 3.9: Frobenius Distance between two \( A_F \) and \( A_E \) matrices in Region 2](image)

Figure 3.9: Frobenius Distance between two \( A_F \) and \( A_E \) matrices in Region 2
We define $\Delta A$ as

$$\Delta A := A_F - A_E,$$  \hspace{1cm} (3.28)

in which $A_F$ and $A_E$ are the system matrix generated by FAST and the Equilibrium Point Linearisation respectively. We can compare the similarity of $A_F$ and $A_E$ by looking at the ratio of the Frobenius norm of $\Delta A$ to either of the $A_F$ or $A_E$. As it can be seen in Figures 3.9 and 3.10, the ratio between Frobenius norm of the $\Delta A$ and $A_F$ is between 2% to 5% throughout the reference wind speeds from 5 m/sec to 24 m/sec. Therefore, we may safely use Equilibrium Point Linearisation results as our internal model for controller design.
Chapter 4
Wind Turbine Control Objectives and Methods

This chapter discusses the performance objectives in wind turbine control, which are higher energy generation and load reduction. As these two objectives are conflicting ones, a successful control method has to make a desired balance between them. However, by introducing new sensor information such as LIDAR data into the controllers, it can be expected that with the utilization of an effective control architecture that can properly exploit the extra information, the overall performance on one objective may be improved without affecting the other one.

In this thesis, two generic control methods are also presented which will be taken as references to be compared against the method proposed by this thesis. These methods are baseline PI and the DAC method. Baseline PI is presented due to its broad application in the wind turbine industry while DAC is presented due to its structural similarity with EOR. At the end of this chapter where it will be shown how EOR methodology can be adapted and applied for LIDAR assisted wind turbine control.

4.1 Wind turbine Control Objectives

The primary objective of wind turbine control is to extract the maximum possible energy from the wind while protecting the wind turbine from the operational hazards and fatigues and complying with the power grid connection standards. The performance of different controllers differs in satisfying each part of these objectives. Therefore, clear quantitative measures must be set in order to make comparisons between the controllers. In the next subsections these objectives are briefly explained.
4.1.1 Power Generation measures

As mentioned, capturing the maximum power from the wind is essential in lower wind speeds (Region 2), where the harvestable energy is lower than the wind turbine nominal value. The power extraction performance in a time duration of $T$ can be calculated by the mean generated power of the turbine in this time period as

$$P_{\text{mean}} = \frac{1}{T} \int_0^T \eta_g M_g(t) \Omega_g(t) dt,$$

where $\eta_g$ (given in Table 3.1) and $M_g$ are the generator efficiency and torque respectively. Although in Region 2, the rotor speed changes along with the wind speed, the tip speed ratio $\lambda$ should be kept constant at its optimal value $\lambda^*$ to ensure the maximum energy extraction from the wind. Therefore, minimizing the standard deviation of the tip speed ratio $\sigma(\lambda)$ is another measure associated with power production maximization in Region 2.

In higher wind speeds (Region 3), the wind carries more energy than wind turbine is nominal (rated) values. Therefore, maintaining the wind turbine states in rated values such as rated rotor speed and rated power replace the maximum power extraction goal. The measure of success in this is to minimize the standard deviation of these variables. Reducing the standard deviation of rotor speed $\sigma(\Omega_r)$ is a measure of how well the wind variation disturbances are rejected by the controller.

A low standard deviation of power $\sigma(P)$ in Region 3, is another performance objective which is partially dependent upon $\Omega_r$ and therefore $\Omega_g$. It is associated with voltage frequency fluctuations on the power grid side due to the intermittent active power injection into the network by the large wind farms [77], [111]. When a large number of turbines in a wind farm are connected to the grid, a large value of $\sigma(P)$ causes high variations of generated active power which might violate some grid connection requirement standards. The standard deviation for both rotor speed and generated power are calculated based on the generic formula of

$$\sigma(P(t)) = \sqrt{E[P(t)^2] - (E[P(t)])^2},$$

$$\sigma(\Omega_r(t)) = \sqrt{E[\Omega_r(t)^2] - (E[\Omega_r(t)])^2},$$
4.1 Wind turbine Control Objectives

in which $\Omega_r(t)$ and $P(t)$ are the recorded rotor speed or generated power during the simulation, and $E[\cdot]$ is the expected value operator.

4.1.2 Fatigue Load Measurement

Although improvements in energy capture can increase the economical feasibility of the wind energy, it requires an aggressive tracking of the optimal tip speed ratio. This requires large control efforts and invoking high actuator rate in order to perfectly track the wind speed variations with the optimal rotor speed at all times. Therefore, it is not unexpected that maximum power production is a conflicting objective with the goal of reducing mechanical stress and load on the turbine. Additionally, with regards to the produced energy cost, the life-span of the wind turbine should be taken into account. The LCOE of a sub-optimally but smoothly controlled wind turbine might be less than the LCOE of an optimally controlled one. Thus, another major objective of wind turbine control in both operation regions is to reduce fatigue loads on the structure by reducing oscillations induced by the wind and actuator variations. One of the standard metrics in wind industry for measuring fatigue damages is damage equivalent load (DEL) which represents the damages caused by the structural loads accumulated during the life time of the wind turbine.

Three major points of measuring DEL considered in this thesis are drive train low-speed shaft, tower root and blades. These points are under high strain and load variations and also compose the most expensive parts of the wind turbine. Therefore, load mitigation on these points are greatly desirable economically. In this thesis, tower fore-aft bending moment $M_{yT}$, tower side to side bending moment $M_{xT}$, blade edge-wise and flap-wise $M_{yB}$ and $M_{xB}$, low speed shaft torque $LSS$ are the signals which will be used for calculating fatigue loads.

To calculate the DEL for a signal such as blade or tower bending moments, the well known Rain-Flow-Counting method described [20] is used. Rain-flow Counting method is widely used for the purpose of calculating fatigue loads in various research and engineering fields [95]. This type of Rain-flow Counting method is one of the approved methods by ASTM E 1049-85 standard [2]. A Wöhler exponent of 4 for steel such as tower and 10 for composite parts such as blades are assumed for the algorithm which is executed in a MATLAB toolbox freely available at Mathworks File Exchange library [75].

Since the simulation scenarios for normal turbulent condition are based on a reference wind
speed, each simulation will produce an associated DEL amplitude. However, each scenario will happen with a different frequency during the lifetime of the wind turbine depending on the geographical location of the wind turbine. Therefore, in order to calculate the extrapolated \textit{Lifetime-Weighted DEL}, the following averaging function is used \cite{[82]}:

\[
DEL = \sqrt{\sum_{j=1}^{m} f_j A_{ref,j}^m} \quad \text{and} \quad \sum_{j} f_j = 1,
\]

where \( A_{ref,j}^m \) is load amplitude from each simulation \( j \), \( f_j \) is their relative frequency of occurrence and \( m \) is the Wöhler exponent. For the frequency of occurrence a fitted Weibull distribution will be used which is the closest distribution for the wind speed variations. Figure 4.1 represents a sample Weibull distribution of wind speed variation from measured data at the height of 102 m in Bremerhaven recorded during the winter of 2009 \cite{[82]}. This data will be used in calculating the lifetime DEL results in the Chapter 7.

![Figure 4.1: Weibull distribution of wind speed variation from measured data at the height of 102 m in Bremerhaven \cite{[82]}.](image)

### 4.1.3 Actuator Saturation and Measures

According to the NREL 5MW wind turbine definitions and specifications in \cite{[54]}, certain limitations must be maintained on the actuators of the wind turbine. Since there are two control inputs
in the collective pitch control mode (Blade pitch angle and Generator Torque), in total there are 4 distinctive limitations for the absolute values and rate of the actuation which are summarized in Table 4.1

<table>
<thead>
<tr>
<th>Blade-Pitch Angle</th>
<th>Blade-Pitch Rate</th>
<th>Generator Torque</th>
<th>Generator Torque Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Limit</td>
<td>90°</td>
<td>47,402</td>
<td>15,000</td>
</tr>
<tr>
<td>Min Limit</td>
<td>0°</td>
<td>-47,402</td>
<td>-15,000</td>
</tr>
<tr>
<td>Unit</td>
<td>°</td>
<td>N.m</td>
<td>N.m/sec</td>
</tr>
</tbody>
</table>

Within these limitations, two different measures for evaluating the performance on the actuation level will be considered as following:

**Commanded Torque Rate**

Similar to most of other control applications, reducing control effort is also a design objective. In Region 2, where the wind turbine is only controlled by the generator torque, it is desirable to reduce the commanded torque rate (CTR) which can be shown by the RMS of the torque variations:

\[
CTR = \sqrt{\frac{1}{T} \int_0^T \left( \frac{dM_g(t)}{dt} \right)^2 dt},
\]

(4.5)

where \( T \) is the measurement time length. The amplitude of CTR shows how often the torque is changed which is an indirect indicator of the load on the drive-train shaft.

**Pitch Travel**

Pitch actuation is the second actuation measure to be considered when comparing different controllers. Pitch Travel measures the sum of the pitch angle changes [71] and is calculated by:

\[
PT = \int_0^T \left| \frac{d\theta}{dt} \right| dt.
\]

(4.6)

Pitch travel is associated with the life span of the actuator, particularly the bearings in servo-mechanisms.
4.1.4 Spectral Performance Measures: Power Spectral Density

Finally, since the effect of using different controllers along with LIDAR is more suitable for visualization in the frequency domain[87], power spectral density (PSD) of some of the measurements represents how different controllers behave in different frequencies. Normally, higher attenuation in high frequencies is desirable as it represents reduced vibrations on the actuators. However, due to the random nature of the disturbance (wind), a conventional Fourier Transform analysis is not suitable for analysing the output signal from the turbine. Therefore, Power Spectral Density in a given frequency $f_0$ as the average of Fourier Transform magnitude squared is calculated over a large time interval as

$$S_y(f_0) = \lim_{T \to \infty} \frac{1}{2T} E \left[ \int_{-T}^{+T} y(t) e^{-j2\pi f_0 t} dt \right]^2,$$  \hspace{1cm} (4.7)

where $y(t)$ is the measured signal and $T$ is the time duration. Since (4.7) does not produce accurate numbers for finite time signals, a Welch approximation of the PSD will be used in thesis which is described in [106]. The time length $T$ in (4.7) is set as equal to the simulation time which is approximately one hour.

4.2 Widely used Control Methodologies

In this section two mainstream methods are presented for wind turbine control which will be used for comparison against the proposed methodology of the thesis. The first method is the baseline method which is comprised of a simple torque control for Region 2 and a PI controller for blade pitch angle in Region 3. The second method is the Disturbance Accommodation Control which is a more advanced wind turbine control method consisting of state feedback and feedforward control. Both controllers and their design are described in the NREL guideline documentations [108]. The DAC controller is particularly chosen since it has been augmented with LIDAR recently to achieve load mitigation on the large wind turbines [103]. DAC also uses a similar architecture to EOR which is a point of interest for structural comparison.
4.2 Widely used Control Methodologies

4.2.1 Baseline Control

Since the power production objectives in Region 2 and 3 are different, the torque control schemes applied in each region are also different. At below rated wind speed, pitch angles of the blades are always kept at the minimum angle to maintain the most interaction between the wind and the blades. Therefore, the system is a SISO system and the power is controlled via the generator torque only. To keep the tip speed ratio in (2.7) at its optimal value, the standard (Baseline) regulator for Region 2 is a torque reference proportional to square of the rotational speed of the rotor:

\[ M_g = k\Omega_r^2, \]  

where \( k \) is given by

\[ k = \frac{1}{2}\rho\pi R^2 \frac{C_{P_{\text{max}}}}{\lambda_*}, \]  

and \( \lambda_* \) as mentioned, is the optimal tip speed ratio which imposes \( C_P = C_{P_{\text{max}}} \) [79].

Although (4.8) might look nonintuitive since it is a nonlinear controller, it is quite successful in keeping the tip speed ratio at \( \lambda_* \). When the wind speed changes to a higher value, the aerodynamic torque increases which causes an acceleration on rotor speed. Therefore, an increase of rotor speed, according to (4.8) will cause a squared increase in the generator torque until the generator torque becomes equal to the new aerodynamic torque and a new equilibrium of state is achieved.

In wind speeds above rated value (Region 3), objectives are different. The primary objective is to maintain the rotor wind speed and torque at nominal values by pitching the blades. In case of any change in the wind speed, blade pitch angles are adjusted to match the aerodynamic torque with the turbine’s rated values. In this region, baseline controller is a PI regulator which is set to eliminate rotor speed error by generating required references for blade pitch angle. The feedback information is taken from the rotor speed \( \Omega_r \) and compared against the rated rotor speed. The rotor speed error is then fed into a conventional PI controller to generate the pitch command \( \theta_c \) in the following form

\[ \Delta\Omega = \Omega_r - \Omega_{\text{rated}}, \]  

\[ \theta_c = K_P\Delta\Omega + K_I \int_0^t \Delta\Omega dt. \]
The $K_p$ and $K_i$ gains in (4.10) are obtained by using the linearized model of the wind turbine to place the system poles in a desired location in the complex plane. The NREL guidelines for designing the PI gains can be found in [107].

The generator torque $M_g$ in Region 3 can be chosen to be controlled by two methods. The first is to lock it to the rated value while the second more common approach is to follow a constant power policy such that

$$M_g = \frac{P_{\text{rated}}}{\Omega_g \eta_g},$$

(4.12)

in which $\eta_g$ is the electrical efficiency of the generator. This policy will ensure that the produced power during the turbulent wind conditions will be better kept on the rated value since the generator will adjust the torque to compensate for rotor speed variations. Figure 4.2 shows the block diagram of the baseline controller for both torque and pitch angle control. The design procedure of baseline Region 3 controller for determining proportional and integral gains $K_p$ and $K_i$ and gain scheduling is described at [108].
4.2 Widely used Control Methodologies

4.2.2 Disturbance Accommodation Control

Disturbance Accommodation Control method assumes the wind (disturbance) and the wind turbine plant as an aggregated system. Via this assumed wave form model, DAC counteracts or cancels persistent wind (disturbance) effects. The following description of DAC is taken from [105] with notation adjusted to the notations of this thesis. The disturbance $d$ is produced by a waveform generator in the following form of

$$
\begin{align*}
\dot{x}_d(t) &= Sx_d(t), \\
d(t) &= Lx_d(t),
\end{align*}
$$

(4.13)

The wave-form model is commonly assumed to take a constant value ([4, 103, 107, 108]) that can be represented in the form

$$
\begin{align*}
x_d(t) &= 0, \\
d(t) &= x_d(t),
\end{align*}
$$

(4.14)

(4.15)

where $S = 0, L = 1$ and $x_d(t)$ is the state of the disturbance.

The system described in (4.14)-(4.15) is then augmented in the linearized state-space model of the wind turbine in the form of

$$
\begin{align*}
\dot{x}(t) &= Ax(t) + Bu(t) + Hd(t), \\
y(t) &= Cx(t).
\end{align*}
$$

(4.16)

In order to construct a complete DAC controller as depicted in the Figure 4.3 several steps have to be taken:

**Step 1:** A linearized model of (4.16) should be generated at a specific operation point (for example mean wind speed). Determine the state matrices of $A$, $B$, $C$ and $H$.

**Step 2:** Examine the controllability of the system in (4.16) to ensure the feasibility of pole placement.

**Step 3:** Design a state feedback matrix $F$ to place the poles of $A + BF$ in step 2 in the desired locations.
Step 3: In the control law

\[ u(t) = Fx(t) + G_{DAC}x_d(t), \]  

(4.17)

if possible, choose \( G \) to cancel the wind disturbance. Such possibility exists if by choosing \( G \) the following equation is satisfied:

\[ BG_{DAC} + HL = 0. \]  

(4.18)

The feed-forward gain \( G_{DAC} \) which satisfies (4.18) cancels all the disturbance effects on the output of the system. However, this equation is not generally solvable if the vector \( B \) has zero elements. In such cases we may choose \( G_{DAC} \) from the following minimization equation

\[ \arg\min_{G_{DAC}} \|BG_{DAC} + HL\|_2. \]  

(4.19)

In such cases DAC will not be able to exactly cancel the disturbances which is the case in most of DAC applications in wind turbine control. Once \( G_{DAC} \) calculated we construct the augmented

Figure 4.3: Block Diagram of the DAC
gain vector of
\[ \bar{G} = \begin{bmatrix} F & G_{DAC} \end{bmatrix}. \] (4.20)

**Step 4:** Augment \( x_d \) into \( x \) and form an aggregated state vector of \( [x \ x_d]^T \). Form the augmented state matrices and assess the observability of the augmented system:
\[
\bar{A} = \begin{bmatrix} A & H \bar{L} \\ 0 & S \end{bmatrix}, \quad \bar{B} = \begin{bmatrix} B \\ 0 \end{bmatrix} \quad \text{and} \quad \bar{C} = \begin{bmatrix} C & 0 \end{bmatrix}.
\] (4.21)

**Step 5:** If the system (4.21) is observable, choose the estimator gains in order to achieve the desired behavior. Within the aggregated state vector \( [x \ x_d]^T \), \( x_d \) can be used to estimate the wind speed.

**Step 6:** This step is only necessary when (4.19) does not have a non-zero solution for \( G_{DAC} \).

Below the rated wind speed in Region 2, the control input for DAC is limited to the generator torque. The controller aims to track the optimal tip speed ratio of the rotor which requires the knowledge of the wind speed which is provided by the augmented disturbance state in the state space model.

Above the rated wind speed in Region 3, the generator torque is either kept constant or in a constant power manner similar to the baseline controller. Therefore, the control input used by DAC is the blade pitch angle where the controller aims to cancel the effects of the wind disturbance on the rotor speed. In this case since the \( B \) matrix is linearly independent from the \( H \) in (4.19), the answer to the minimization problem is always zero. Therefore, in order to avoid this problem, the pitch actuator dynamics are ignored to achieve a dependent pair of \( B \) and \( H \) vectors and a non-zero answer for \( G_{DAC} \). Never the less, omitting the pitch actuator dynamics may result in delayed pitch commands and degrade the overall performance of the wind turbine.

### 4.2.3 LIDAR Variant of the DAC

Wind speed estimation in DAC requires a good internal model of the wind turbine. However, due to the model simplifications and linearisation, the wind speed estimation will include errors if the wind turbine operates far from the linearisation point. It is possible to replace the wind speed estimator with a LIDAR system which measures the effective wind speed in front of the wind turbine.
before it hits the blades. Such a replacement can roll out the model reduction and linearisation effects on the wind speed estimation and improve the overall performance. LIDAR can be mounted on top of the nacelle or on the ground in front of the tower. It can scan a relatively large area in front of the rotor face depending on the focal distance and beam angle by measuring its Line of Sight (LOS) wind speed. This LOS measurements can be translated by some geometrical translations into the effective wind speed perpendicular to the rotor plane which is the active component the wind vector on the blades. Therefore the control law in 4.17 becomes

\[ u(t) = Fx(t) + G_{DAC} v_{LIDAR}(t), \]

in which \( v_{LIDAR}(t) \) is the LIDAR measured wind speed corrected for the look ahead time regarding the mean wind speed and the LIDAR focal distance.

Since LIDAR measures the wind speed ahead of its interaction time with the blades, it provides some reaction time for the controller. In order to allow the controller to use the LIDAR data as the instantaneous wind speed, such data should be included in the controller with some artificial delay corresponding to the time required the moving air mass to reach the wind turbine from the point of measurement (See Figure 4.4). Therefore, the delayed pitch actuation arising from ignoring the
blade blade pitch actuator dynamics can be compensated by manually tuning the artificial delay time $\Delta T$ in (4.23). However, the exact tuning method remains empirical.

$$u(t) = Fx(t) + G_{DAC} v_{LIDAR}(t + \Delta T), \quad (4.23)$$

where $\Delta T$ is the tuning value for the time delay.
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Chapter 5
Utilization of Exact Output Regulation for Wind Turbines

In this chapter, an adaption of the Exact Output Regulation scheme into wind turbine control is presented. The key part for this adaptation is how to construct exo-systems in which the disturbance exo-system represents the wind and reference exo-system represents the outputs that the wind turbine is desired to track. As a reminder, we repeat the (2.26) here again along with the description of each parameter.

\[ \Sigma_e : \begin{align*}
\dot{x}(t) &= Ax(t) + Bu(t) + E_w w(t), \\
y &= C_y x(t), \\
\dot{w}(t) &= Sw(t), \\
e(t) &= C_z x(t) + D_w w(t).
\end{align*} \tag{5.1} \]

It should be noted that all of the linearized equations such as plant model and the exosystem have been homogenized around a critical point \([x^* \quad u^* \quad d^*]\). Therefore, all the state variables, inputs and disturbance values represent the perturbation around the critical point. The system matrix \(A\) in (5.1) represents the linearized dynamics of the wind turbine around the mean wind speed and \(x\) is the states of the wind turbine model in perturbed coordination. The input gain \(B\) and control input signal \(u\) vary in the Region 2 to Region 3, from a torque input to the blade pitch reference signal. The vector \(w\) consists the states of exo-system, \(E_w\) is the input disturbance and \(D_w\) is the reference output.

Figure 5.1 provides a block diagram representation for equation (5.1). The wind exosystem represents the deviation of the wind speed from the mean value of \(\hat{v}_x\). The reference signal \(r\) is rotor speed \(\Omega_r\) in Region 2 and in Region 3 the pitch angle \(\theta\) is the reference. Therefore,
disturbance and references can obtained as the outputs of the exosystem where $w$ is a vector containing the dynamics of the wind variation signal. Also $L_d$ and $L_r$ matrices yield $d$ and $r$ from $w$. The dynamics of the exosystem in (5.1) represent the wind variations. The order of $S$ determines how accurately the exosystem dynamics captures the main spectral components.

5.1 Synthesis of Exo-systems for EOR

In this part we describe how to effectively use LIDAR information in output regulation controller scheme in the wind turbines. First, we consider how to synthesize exo-system dynamics in (2.23) to represent the very short-term wind evolution with a high fidelity by the aid of LIDAR provided data. Since LIDAR can provide several seconds preview information of the wind, the controller has enough time to construct a good approximation of the required subsystems. To this end, the matrices and vectors $S$, $L_d$ and $L_r$ have to be constructed by which the homogeneous system $\Sigma_{exo}$ (with state variables $w$) oscillates similar to the wind deviations from the mean wind speed provided that the same initial conditions is given to it. By a successful modeling of wind deviations by $\Sigma_{exo}$, solving the regulator equations (2.27) and (2.28) can be done by various methods. Consequently, the turbine actuators can be performed without their associated time constants having a negative effect on the turbine’s reaction to the variation of the wind.

5.1.1 Parameter Estimation in Discrete Time

In favor of computational simplicity in parameter estimation we have used discrete time form of exo-systems. Therefore, a recursive discrete form is introduced [69]. In order to find a discrete
form exo-system, an auto-regressive model is fitted on the wind speed signal provided by the LIDAR (LIDAR model will also be discussed in section 6.3).

The output of the LIDAR is sampled with the same sampling time of the discrete exo-systems and then fed into a shift register as shown in Figure 5.2. The shift register is used to create time delays and constructing the state vector of the wind exo-system. The state of the shift register is then given to a Recursive Least Square (RLS) estimator to estimate the $S$ matrix. Therefore, exo-systems are constructed in discrete time to be compatible with the sampled data. Consequently, in the simulations, EOR is used in discrete-time form with dynamics modeled by the linear difference equation

$$w_x[n] = a_1w_x[n - 1] + a_2w_x[n - 2] + \cdots + a_Nw_x[n - N], \quad (5.2)$$

in which $w_x[n] = \dot{v}_{x,0}$ is the deviation of measured wind speed’s horizontal component $\dot{v}_x$ from the average wind speed at the current sampling instant $n$. Also $a_k$ is the system coefficients vector and $N$ is the order of exo-system dynamics to be chosen. A least square problem to find $[a_0^*, \ldots, a_{N-1}^*]$ is to minimize the residual of following sum

$$s = \sum_{n=N}^{N+m} (w_x[n] - a_1w_x[n - 1] + a_2w_x[n - 2] + \cdots + a_Nw_x[n - N])^2 \quad (5.3)$$

in which $m$ is the number of sampled signal length. A larger $m$ yields more accurate estimation of the parameters however, increasing the computation time and slowing down the control loop. Hence, (5.3) will be solved recursively every time a new sample comes from the LIDAR.

Choosing higher values of $N$ yields better representation of the actual wind variations which gives a better disturbance rejection and reference tracking. But it should be noted that an aggressive disturbance rejection and reference tracking is contradictory to load reduction. A perfect disturbance rejection requires all the states to precisely track their equilibrium value against the wind speed, which in case of tower deflection or drive-train torsion contributes to high stress loads. Higher order difference equations also provide information on higher derivatives of the disturbance as well although it requires more computational power. When disturbances and the control inputs are unmatched, (i.e, when $d(t)$ enters from a channel where there is no direct access with $u(t)$), higher derivatives of the $d(t)$ are necessary for disturbance rejection. Thus, a trade-off
needs to be made between higher fidelity modeling of the wind (for larger $N$ values) and reducing the fluctuation in the control input signal (for lower $N$ values). Throughout this work, $N = 2$ is empirically chosen in both regions to generate smooth exo-system outputs. Moreover, a moderately chosen $N$ reduces the computation time for calculations and therefore makes it easier to construct the controller for real-time application.

In order to choose suitable exo-system coefficients $a_k$ in real time, the LIDAR measurements will be sampled and passed into a Recursive Least Square (RLS) Estimator to obtain coefficients $a^*_k$ in (5.2) for $1 \leq k \leq N$. The reason for using recursive least square method is to make the control algorithm applicable in real time and avoid large matrix inversions used in batch least square methods. As a result, simulation times are 3 times faster than real-time. For example a one hour simulation takes around 20 minutes. At each time step, optimal values of $a^*_k$ are used to update the matrix $S$ in (wind) exo-system as following

$$w[n + 1] = \begin{bmatrix}
a^*_0 & a^*_1 & a^*_2 & \ldots & a^*_N \\
1 & 0 & 0 & \ldots & 0 \\
0 & 1 & 0 & \ldots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & \ldots & 1 & 0
\end{bmatrix} w[n]$$

where $w[n] = [w_x[n], w_x[n - 1], \ldots, w_x[n - N]]^T$ is the state vector of the exo-system and the matrix $S$ represents its dynamics. When the optimal values $a^*_k$ are found, the discrete version of exo-system dynamics can be represented by
\[ w_{n}[n + 1] = Sw_{n}[n]. \]  

After the construction of \( S \) and \( L \) matrices, there are two possibilities for obtaining the state variables of the exo-systems. If the measurements are low in noise, the values recorded in the shift register are equivalent to the state variables of the exo-system. However, if the LIDAR measurements are affected by noise, a discrete Kalman filter must be used in order to optimally estimate the exo-system states. Finally the wind exo-system state variable \( w \), disturbance \( d \) and reference \( r \) are provided to the EOR controller \( \Sigma_c \) in order to calculate feed-forward gain \( G \) and consequently the control variable.

### 5.1.2 Computation of the disturbance and reference signals

In order to make the full exo-system in (2.23), output matrices \( L_d, L_r \) should also be determined. If \( S \) represents the wind dynamics then we should have

\[
L_d = [1 \ 0 \ \ldots \ \ 0]_{1 \times N_r},
\]

therefore, the disturbance perturbation \( d \) can be obtained by

\[
d = L_d w_x = w_x.
\]

To determine the reference output matrix \( L_r \), equilibrium locus of the controlled states versus wind speed is used. In Region 2, the slope of tangent is also \( \lambda_s / R \) and in Region 3 it is \( \theta_s = f(v_x) \)

where \( f(\cdot) \) is the equilibrium locus of blade pitch angle for a constant wind speed \( v_x \). This function can be obtained numerically for given \( v_x \) and \( \Omega_{rated} \), by solving the equation

\[
M_a(\Omega_{rated}, v_x, 0, \theta) - M_{rated} = 0,
\]

for \( \theta \) in the range of Region 3 wind speeds \( 11.4 < v_{x,0} < 24 \), where \( M_{rated} = \frac{P_{rated}}{\Omega_{rated}} \) is the rated aerodynamical torque of the rotor. Figure 5.3 shows the \( \theta^* = f(v_x) \) in Region 3 for wind speeds from 11.4 to 24 m/sec. Since \( f(v_x) \) is a nonlinear function, to obtain \( L_r \), we need a
Figure 5.3: Equilibrium locus of the controlled outputs of $\theta^*$ Region 3 wind speed (Blue line). Tangent line slope is the output gain of $L_r$ (Red)

linearized form of $f(\cdot)$ around the reference wind speed $v_{x,0}$. Therefore, in Region 3 the reference $r$ for blade pitch angle will be $r = \frac{d\theta^*}{dv_{x,0}}w_x$ which means we can obtain $L_r$ in each region in the form of

$$L_r = \begin{cases} \frac{\Lambda_r}{R} & 0 & 0 \quad : \text{Region 2} \\ \frac{d\theta^*}{dv_{x,0}} & 0 & 0 \quad : \text{Region 3}. \end{cases}$$

(5.9)

where the region of operation will be selected based on 10-minutes observation intervals of the cumulative mean wind speed. We produced $L_r$ with the same dynamics as wind but with a different output gain. Therefore to similarly construct the reference exo-system to the disturbance, we should use $r[n] = L_r w[n]$. Combining $S$, $L_r$ and $L_d$ yields the exo-system $\Sigma_{exo}$ in (2.23) that will be used to develop the EOR dynamic measurement feedback controller $\Sigma_c$ according to Theorem 3.2. Finally, the system

$$\begin{align*}
w[n+1] &= Sw[n], \\
d[n] &= L_d w[n], \\
r[n] &= L_r w[n],
\end{align*}$$

(5.10)
Figure 5.4: Actual wind speed vs discrete exo-system output. The measured wind speed is shown by red line while the fitted exo-systems are shown in black.

represents fully the disturbance exo-system which is associated with the wind and reference variations. Figure 5.4 illustrates an actual hub height wind speed versus discrete exo-systems output and the LIDAR output for a sample 200 seconds wind signal with an average of 8 m/sec.

With the use of discrete-time form for the exo-systems, we must transform the state space matrices into discrete-time form as well. In this thesis, \( A, B, C \) and \( H \) are obtained from linearisation and then transformed into discrete equivalent values using the Tustin method with the sampling rate of 0.1 seconds.

### 5.1.3 EOR Controller Design

As it was mentioned in section 2.9, the full state feedback EOR controller generates the control signal as

\[
u = Fx + Gw,
\]

in which \( F \) is the state feedback matrix, \( x \) is the plant state vector, \( G \) is the feed-forward gain and \( w \) is the exo-system state vector. Therefore, the design process in EOR involves the determination of suitable \( F \) and \( G \) matrices. The state feedback matrix is responsible for pole placement of the close loop system and there are multiple ways of locating the desired locations for the close loop poles. In this thesis the state feedback matrix \( F \) is chosen by the linearquadratic regulator.
algorithm with $Q = C_z^T C_z$ where $C_z$ is given by either (3.22) or (3.26) appropriate for the current operating region and $R$ is chosen to avoid control input saturation.

The feed-forward gain vector $G$ is determined by solving the regulator equations (2.27) and (2.28). There is a unique solution for (2.27) if matrices $S$ and $A$ are disjoint (have no common eigenvalues). Different solutions can be used for solving the equation for $\Pi$ and $\Gamma$ among which the Schur’s method [57] and [5] can be pointed out. Finally, as mentioned before, the $G$ matrix can be obtained from $G = \Gamma - F \Pi$. In case of using a dynamic observer instead of a full state feedback, the calculation for $F$ and $G$ will remain unchanged however, the observer gain $K$ should be determined in (2.30) for both Region 2 and 3. This can be done by choosing the $K$ such that $A - KC_y$ has stable poles with an order of magnitude larger than poles of the plant. Alternatively, a Kalman filter can be used for an optimal determination of $K$.

### 5.2 Mathematical Relationships Between DAC and EOR

It is worth noting that the DAC control methodology may be viewed as a special case of the EOR control methodology. In the following, it will be shown how DAC can be synthesized from the EOR methodology by some simplifying assumptions.

#### 5.2.1 Generality: DAC as special case of EOR

We note a number of similarities and differences between EOR and DAC. Both use a state feedback law to stabilize the closed-loop dynamics and a feedforward term to cancel input disturbances. If we apply the simplifying assumptions $S = 0$ and $L_d = 1$ to (2.23), we obtain $E_w = H$ and

\begin{align*}
\dot{w}(t) &= 0, \quad (5.12) \\
d(t) &= z_d(t), \quad (5.13)
\end{align*}

which are identical to (4.14) - (4.15) with $w = z_d$. Using $\Pi = 0$ in the EOR control law gives $\Gamma = G$, so the first regulator equation ((2.27)) becomes

\begin{equation}
0 = BG + H, \quad (5.14)
\end{equation}
5.2 Mathematical Relationships Between DAC and EOR

which is (4.18).

Where DAC models the disturbance as a constant, the dynamic exo-system used in EOR enables far greater flexibility in the modeling of the disturbance. These simplifications will be shown to degrade the control performance of DAC compared to EOR, as DAC cannot ensure the output tracks a desired reference.

While (4.18) is not generally solvable, under mild system assumptions of controllability and observability, the regulator equations (2.27) - (2.28) are generically solvable, allowing for exact regulation of the output by EOR. By contrast DAC can generally only achieve approximate solutions for (4.18), leading to only approximate disturbance cancellation. In the next section it will be shown how this approximated solution might affect the performance of the control system.

5.2.2 Solvability of DAC Equations

In some cases, even an approximate solution for (4.18) that satisfies (4.19) does not exist. For example, for the linear model presented in Section 3.4.3, the minimization problem of (4.19) becomes

\[
\arg\min_G \left\| G \right\|_2 \quad \text{subject to} \quad \begin{bmatrix} 0 & \alpha J^{-1} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \alpha J^{-1} \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix},
\]

in which as it is obvious, \( B \) and \( H \) are linearly independent. Therefore, the solution for the minimization problem is only \( G = 0 \) which means that the feed-forward channel should be disconnected. In order to avoid this situation and achieve a non-zero solution for \( G \), it can be helpful to ignore some of the dynamics of the plant model. For example, by ignoring the pitch actuator dynamics and assuming the blade pitch angle as an input, the equation (3.25) becomes
It is now possible to solve (5.15) and we have

\[
\text{argmin}_G \begin{bmatrix} G B \end{bmatrix} + \begin{bmatrix} \alpha J_r^{-1} \end{bmatrix}, \quad (5.17)
\]

which is solvable with

\[
G = -\frac{\alpha}{\beta}. \quad (5.18)
\]

However, ignoring the blade pitch dynamics, causes some performance losses due to the time delays and phase shifts which are created by the pitch actuation system.
Chapter 6
Simulation Environment for Turbine Control Performance Evaluation

For the sake of comprehensive simulations, a software package for simulation of the wind turbine response is developed and will be articulated in this chapter. This toolbox is developed in Simulink® and as mentioned before is called TOR throughout this thesis. TOR is able to simulate a large amount of predefined simulation scenarios and compare the control performance of the EOR, DAC and Baseline control methodologies for the NREL 5MW FAST turbine model. TOR is available for public use at GitHub [68].

6.1 TOR Components

The TOR simulator environment is represented in Figure 6.1 and is comprised of seven subsystems as follows:

1. The TurbSim package [53] for the simulation of realistic wind fields.
2. The LIDAR simulator based on [23].
3. The linear exosystem generator obtained from LIDAR data, as described in Section 5.
4. The high fidelity wind turbine simulator FAST [55].
5. The linearized model of the nonlinear Simplified Low-Order of Wind (SLOW) Turbine model (Section 3.4).
6. The dynamic observer and the controller subsystem $\Sigma_c$. 
7. Performance measurement code to calculate metrics related to the power generation and fatigue loads according to Section 2.6.

Some of these sub-systems are themselves other open source codes which are integrated into the tool box and the rest are the developed codes in Simulink and MATLAB. The signals in this illustration are shown by small letters on black thin arrows. For example, \( v \) is the actual wind signal where \( \hat{v}_x \) is the rotor effective wind speed perpendicular to the rotor plane (or the \( x \) axis). The exo-system state is \( w \) and the plant model input and output signals are shown by \( u \) and \( y \) respectively, according to Section 3.4. On the other hand, parameters and matrices are shown by capital letters on thick gray arrows. Exo-system parameters are shown by \( S, L_d, L_r \) where the plant model parameters are given by \( A, B, H, C_y, C_z \). Finally, \( X \) represents the set of measurement signals produced by the FAST code as log files and used for fatigue load and power generation calculations. We describe each of its component blocks in the following sections.

### 6.2 TurbSim Wind Field Simulator Sub-System

The first block in TOR is the open source TurbSim code. It is a full-field, turbulent-wind simulator developed by NREL using stochastic models to generate realistic three-dimensional wind field vectors \( \tilde{v} \), with components for the longitudinal, crosswise and vertical components of the wind,
Figure 6.2: Three-Dimensional wind fields generated by TurbSim for aero-elastic simulations [100]

TurbSim is widely used for 3-D wind field generation for simulations in the literature e.g. [103], [104] and [87] and many similar works. The detailed parameters of wind input files are the vertical stability parameter $R_i$, shear exponents $\alpha_D$ and the mean friction velocity $u^*_D$ [58] which are set on the default values in TurbSim to generate one hour of wind information.

In order to study the impact of turbulent wind on the performance of controllers, the FAST model of the wind turbine is exposed to Class-A intensity winds generated by TurbSim as wind fields according to IEC-61400-1 standard [47] in the form of a $33 \times 33$ vertical and horizontal grid-point matrix as shown in Figure 6.2. These wind field sets have mean wind speeds from 8 to 24 m/sec with resolution steps of 2 m/secs. We choose Class-A wind profiles since their intensity is the highest in the IEC standard, and hence will challenge the controllers ability to maintain the wind turbine on its nominal values. The first 100 seconds are excluded from the performance
measurements to remove the effects of the initial conditions on the results. The TurbSim output \( \mathbf{v} \) in Figure 6.1 represents the wind field vector which is applied to both the FAST turbine simulator and the CW-LIDAR simulator.

### 6.3 CW-LIDAR Simulator Sub-System

In this work we will use the continuous wave CW-LIDAR model described in [23] to simulate the longitudinal wind speed measurement (perpendicular component of the wind to the rotor plane) at a specific distance by focusing the laser beam at that location. In the linearised model of the wind turbine (3.25), only the longitudinal wind speed \( v_x \) is used. Therefore the LIDAR is assumed to be mounted on the nacelle where it can measure the wind speed along its line of sight to give a good approximation of \( v_x \). Figure 6.3 depicts the coordinate system and geometrics of the LIDAR placement on the wind turbine nacelle.

For simulations, 24 evenly distributed measuring points on a circular cross-section of the wind
vector $v$ generated with TurbSim at focal distance $f$ from the rotor plane are scanned by the LIDAR laser beam to obtain $\hat{v}_x$, an approximation of the effective longitudinal speed $v_x$ of the wind passing through the rotor plane. Due to the physics of focused Gaussian laser beam a length weighting function $W(L)$ affects the measurements along the laser beam according the following integration

$$v(f) = \int_{-\infty}^{\infty} v(L)W(L)dL,$$

(6.1)

where $v(L)$ is the radial velocity at length $L$ along the laser beam [27]. Moreover, the amplitude weighting function $W(L)$ for the focal distance of $f$ is described by

$$W(L) = \frac{K_n}{L^2 + (1 - \frac{f}{L})^2 L_R^2},$$

(6.2)

where $L_R$ is called Rayleigh range and $K_n$ is a constant which normalizes the integration result such that

$$\int_{-\infty}^{\infty} W(L)dL = 1.$$  \hspace{1cm} (6.3)

The Rayleigh range depends on the characteristics of the laser beam such as wave length $\lambda_L$ and the beam waist $w_0$ and defined by

$$L_R = \frac{\pi w_0}{\lambda_L}.$$  \hspace{1cm} (6.4)

The LIDAR used in [23] uses an infrared laser beam with the wavelength of $\lambda_L = 1.565 \, \mu m$ and the $e^{-2}$ intensity radius of 2.8 cm which is characteristic of most commercially available Doppler CW-LIDARS. The effect of spatial averaging described in (6.1) is equivalent to low-pass filtering the signal for which the $3 \, dB$ bandwidth is determined by

$$BW_{3dB} = \frac{87}{f^2},$$

(6.5)

where the constant 87 is based on specific parameters of the LIDAR used in [23]. According to [23], the equivalent low pass filtering effects imposed by LIDAR measurements do not distort the phase as it can be modeled by an equivalent ideal low pass filter. Although such a filter would be non-causal, it can be practically implemented because of the availability of wind preview
Figure 6.4: Finite Length LPF impulse response with the total length of 50 sample information provided by LIDAR. Therefore, CW-LIDAR can be modeled in the simulations by convolving the impulse response of a band limited ideal low pass filter with the TurbSim-generated wind signals such

\[ \text{LPF}[n] \ast g[n] = \sum_{m=-\infty}^{\infty} \text{LPF}[m] v_x[n - m] \]  

(6.6)

in which LPF[n] is the impulse response of the filter (6.5) and \( v_x(n) \) is the sampled wind speed signal at the supposed focal point of the LIDAR in TurbSim output. Due to the limited length of the measured signal \( v_x[n] \), the LPF is approximated with a finite length impulse response proposed in [40] and shown in the Figure 6.4. Averaging Riemannian sums of the 24 measurements in the cross-section yields

\[ \hat{v}_x[n] = \frac{1}{24} \sum_{i=1}^{24} \hat{v}_x[n]_i, \]  

(6.7)

which is a 3D spatial average. In Figure 6.5 the overlay comparison between the real hub-height wind signal and the simulated LIDAR output \( \hat{v}_x \) with a focal distance of 60 meters is shown. Finally, the output \( \hat{v}_x \) will be passed into the exo-system generator in order to construct \( S, L_d \) matrices and \( L_r \).
6.4 Wind Exo-system Generator Sub-System

This sub-system receives the wind signal $\hat{v}_x$ from the simulated LIDAR and uses it to synthesise the matrices $S$, $L_r$, and $L_d$ for the exosystem $\Sigma_{exo}$ given in (2.23), as described in section 5.1. As shown in (5.4), arbitrary order can be assumed for the dynamics of exo-systems and consequently the $S$ matrix. The higher order would deliver a better modeling of the wind signal however it might lead into higher actuation rates. Therefore, the effective wind speed signal $\hat{v}_x$ measured by LIDAR can be low pass filtered with a similar LPF used in LIDAR down to a desired bandwidth in order to avoid high variations in exo-system dynamics. Consequently, a lower order for $N$ in (5.2) can be chosen for the ease of calculation load and reducing actuation rates. Throughout this work $N$ has been chosen to be 2 for the construction the exo-system in discrete-time form.

6.5 FAST Wind Turbine Model Sub-System

In order to predict fatigue loads of three-bladed HAWTs, the open source NREL FAST code is used. A compiled MATLAB S-Function of the FAST 7 code is used to link the designed controllers to FAST in Simulink. According to the specifications of the NREL 5-MW reference turbine given in [54], the DOFs applicable to the on-shore 5MW wind turbine are listed in Table 6.1, and these
Table 6.1: Enabled DOFs in FAST code

<table>
<thead>
<tr>
<th>Enabled mode</th>
<th>No. of DOFs</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Drive-train Torsion</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; &amp; 2&lt;sup&gt;nd&lt;/sup&gt; fore-aft tower bending</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; &amp; 2&lt;sup&gt;nd&lt;/sup&gt; side-side tower bending</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; edge-wise blade</td>
<td>1 × 3</td>
<td>3</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; edge-wise blade</td>
<td>1 × 3</td>
<td>3</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; flap-wise blade</td>
<td>1 × 3</td>
<td>3</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; flap-wise blade</td>
<td>1 × 3</td>
<td>3</td>
</tr>
<tr>
<td>Total DOFs</td>
<td></td>
<td>18</td>
</tr>
</tbody>
</table>

have been activated in FAST for our simulation studies. The FAST code does not include a model for the pitch actuator, so a second order servo-system according to Table 3.1 has been added to the Simulink environment.

The FAST model sub-system receives the wind field vector $\tilde{v}$ from TurbSim, and the control input $u$ from the controller subsystem. It also computes the turbine state vector $x$ and measurable output signal $y = C_y x$, where $C_y$ is given by either (3.22) or (3.26), as appropriate for the current operating region. Signal $y$ is passed to the controller sub-system for computation of the control input $u$. Also, FAST provides an array of output signals (shown by $\mathcal{X}$ in this thesis) which represent physical measurements on each component of the wind turbine. These measurements are finally passed to the performance evaluation subsystem.

### 6.6 Linearized Low Order Model Sub-System

For each reference mean wind speed $\tilde{v}$, a linearized model as described in Section 3.4 is stored in a lookup table. These linearized models are based on the parameters given in Table 3.1 and provide the linearized turbine model $\Sigma$ in (2.26). State matrices $A$, $B$, $H$, $C_y$ and $C_z$ appropriate to the current operating region and the reference wind speed are passed to the controller sub-system. The reference wind speed can be detected by an averaging of the wind speed for a course of 10 to 20 minutes. If a change in the mean wind speed is detected, the linear model in the controller will be update with a new model.
6.7 EOR, DAC and Baseline Controllers Sub-System

The EOR dynamic measurement feedback controller \( \Sigma_c \) is obtained according to Chapter 5. The state feedback matrix \( F \) is chosen by the LQR algorithm with \( Q = C_z^T C_z \), where \( C_z \) is given by either (3.23) or (3.27), as appropriate for the current operating region, and \( R \) is chosen to avoid control input saturation. The estimated state vector \( \hat{x} \) is obtained using the measured outputs \( y \) received from the FAST simulator. The observer feedback gain matrix \( K \) is determined by the Kalman filter. Since the wind turbine model (3.18) does not have a process noise term, and the output measurements obtained from the outputs of the FAST may only contain numerical errors, so the process noise covariance matrix of the Kalman filter can be neglected, and a very small measurement noise covariance matrix is sufficient.

The feed-forward gain vector \( G \) in (2.29) by solving the regulator equation in (2.27)-(2.28) with \( S \) and \( L \) matrices produced by wind exosystem generator subsystem is used.

Although the control inputs are repeatedly computed at every time step, the EOR algorithm is computationally very efficient. For example, one hour of turbine response simulation required 20 minutes of CPU time on a contemporary desktop PC. Moreover, this CPU time includes the computation time of the FAST code for the turbine response, in addition to the computation of the EOR control input. Hence the output regulation control methodology can be expected to be suitable for real-time realization on a wind turbine.

As noted in Section 5.2, a DAC controller is a special case of an EOR controller under the simplifying assumptions (5.12)-(5.14). When simulating DAC controllers we have used the same state feedback matrix \( F \) as for the EOR controllers. Finally, the Baseline controller is designed using the guidelines in [108]. In each case the control input signal \( u \) is passed to the FAST simulator subsystem.

6.8 Performance Measurement Sub-System

This subsystem builds an interface between FAST and Rain-Flow Counting codes and calculates the DELs according to Section 3.2.4, as well as the generated power. The signals logged by the FAST subsystem for the turbine states \( X \) are delivered to the Performance Measurement subsystem. The DELs computed are the tower fore-aft bending moment \( M_{yT} \), tower side-to-side bending...
moment $M_{x,T}$, blade flapwise bending moment $M_{y,B}$, blade edgewise bending moment $M_{x,B}$, and Low Speed Shaft Torque. These are computed using the Rain-Flow-Counting method [20], with DEL computations performed with the Rain-Flow-Counting-Algorithm open source MATLAB® code [75]. This subsystem also computes the average power generated $P_{\text{mean}}$, and for Region 3 operation we compute the power standard deviation $\text{std}(P)$ and rotor speed standard deviation $\text{std}(\Omega_r)$; smaller power standard deviation indicates the power generation is maintained close the rated value of 5 MW. For Region 2 operation we compute the tip speed ratio standard deviation $\text{std}(\lambda)$, smaller values indicating a better tracking of optimal tip speed ratio.

Additionally the measurement subsystem provides a spectral analysis of the tower fore-aft bending moment, tower side-to-side bending moment, blade flap-wise bending moment, low speed shaft torque, pitch rate and the produced power. Reduced high frequency content in the power spectral density of these variables implies reduced fluctuations of the measured variable. For bending moment (tower or blade) signals, the integral of the amplitude of the PSD over the frequency range is an indicator of the energy dissipated within the turbine tower or blade. The consequence of this energy dissipation is fatigue accumulation in the tower or blade, and thus reduced PSD amplitudes are associated with lower lifetime turbine damage.
Chapter 7
Simulation Results and Analysis

This section provides a comprehensive set of simulations and detailed results. The 5MW NREL wind turbine will be exposed to different wind speeds and turbulence for prolonged simulation times and the states are measured. By using these measurements, the oscillation of different components of the wind turbine may be observed and Damage Equivalent Loads can be calculated.

As it was mentioned in Section 4.1, the primary objectives of wind turbine control are to maximize the energy harvesting from the available wind, while also protecting the wind turbine structure from the damages and fatigues and complying to the power grid connection standards. Different controllers perform differently in satisfying each objectives. In order to compare each method definitively, quantitative measures must be established. To obtain the performance of a controller on fatigue load reduction, the life time DEL must be calculated. Every scenario with a specific mean wind speed has a frequency of occurrence during the life time of a wind turbine which is very much dependent to the installation location and geographical aspects of it. Such frequency of occurrence is used to weigh each scenario as given in (4.4).

As the primary objective of wind turbine control is focused on the power production, comparisons need to be made on the controllers according their power generation performance. This objective depends on the operating region. As mentioned in previous chapters, in Region 2, it is translated to harvest as much as energy from the wind since it is under the mechanical and electrical capacity of the turbine. Such power maximization requires a rigid tracking of the optimal tip speed ratio. Also in Region 3, the power production objective is to obtain the rated capacity of the wind turbine. In the other words a controller performs better in Region 3, if it can maintain the rated power under turbulent wind conditions. To this end, two main variables should be kept constant which are the rotor angular velocity and the generator torque.
As discussed before, such rigid control of the plant outputs and fatigue load reduction are contradictory control objectives. Therefore, any load reduction without loss of the power generation can be considered a major improvement.

All simulations are performed for all three types of the controllers: Baseline, DAC and the proposed EOR method. For a recorded oscillation from utilization of each controller the fatigue loads are then calculated. Success of each controller in reducing DELs then can be compared for each mean wind speed. Reduced amplitude of DEL on each turbine component shows the advantage of each controller over the other methods for that specific scenario.

On TurbSim, the vertical stability parameter $Ri_L$, shear exponents $\alpha_D$ and the mean friction velocity $u_D^*$ are set on the default values in TurbSim which are 0.02, $0.05 \times v_{x,0}$ and 0.3 respectively [53]. Each generated wind file is 60 minutes for each mean wind speed ranging from 8 to 24 m/sec, with resolution of 2 m/sec.

7.1 Simulation Setup

This section provides information about the settings of the simulation environment (described in Chapter 6) such as general settings which are common for all controllers as well as other settings which are specific for each controller.

7.1.1 FAST and TurbSim settings

The FAST model of the 5 MW NREL wind turbine is configured with the 18 DOFs activated associated with on-shore wind turbines as shown in Table 3.6. For the state estimation and control purposes the output signals from FAST are only rotor speed, generator speed and blade pitch angle (Table 7.1). In order to carry out load and power generation performance analysis, the list of FAST signals and measurable parameters are shown in Table 7.2 which are tower, drive-train shaft, and blades movements and moments. Also all of the three types of the controllers are set to follow the constant power policy given in (4.12) above the rated wind speeds.

Fatigue loads are calculated as DELs for the tower root, the LSS torque, and the blade roots as described in Section 6.8 after each simulation when the output signals are fully generated by FAST as time-series.
### 7.1 Simulation Setup

#### Table 7.1: Available FAST Output Signals for Controller Design

<table>
<thead>
<tr>
<th>Generic Name</th>
<th>Signal Symbol</th>
<th>FAST Output Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Speed Rotor Angular Velocity</td>
<td>$\Omega_r$</td>
<td>RotSpeed</td>
</tr>
<tr>
<td>High Speed Rotor Angular Velocity</td>
<td>$\Omega_g$</td>
<td>GenSpeed</td>
</tr>
<tr>
<td>Collective Blade Pitch Angle</td>
<td>$\theta$</td>
<td>BldPitch1</td>
</tr>
</tbody>
</table>

#### Table 7.2: List of FAST Output Signals for Load and Performance Analysis

<table>
<thead>
<tr>
<th>Generic Name</th>
<th>Signal Symbol</th>
<th>FAST Output Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower base fore-aft bending moment</td>
<td>$M_yT$</td>
<td>TwrBsMyt</td>
</tr>
<tr>
<td>Tower base side to side bending moment</td>
<td>$M_xT$</td>
<td>TwrBsMxt</td>
</tr>
<tr>
<td>Blade 1 flap-wise moment at the blade root</td>
<td>$M_yB$</td>
<td>RootMyb1</td>
</tr>
<tr>
<td>Blade 1 edge-wise moment at the blade root</td>
<td>$M_xB$</td>
<td>RootMxb1</td>
</tr>
<tr>
<td>Low Speed Shaft Torque</td>
<td>$LSS$</td>
<td>LSShtTq</td>
</tr>
<tr>
<td>Electrical generator power</td>
<td>$P$</td>
<td>GenPwr</td>
</tr>
<tr>
<td>Low Speed Rotor Angular Velocity</td>
<td>$\Omega_r$</td>
<td>RotSpeed</td>
</tr>
</tbody>
</table>

### 7.1.2 Baseline Controller and DAC Settings

The Baseline controller has been used as a benchmark for comparing against EOR and DAC controllers. It consists of a torque and PI feedback controller for blade pitch angles. The torque controller in Region 2 is chosen to follow (4.8) and the constant power strategy torque reference computed by (4.12) for Region 3. The pitch controller is only active in Region 3 which is a gain-scheduled PI controller which regulates the rotor speed at the rated value described in Section 4.2.1.

In the DAC setting, similar pole placement and state feedback has been used as EOR. Also the LIDAR variant of the DAC is used in addition to the LIDAR model described at Section 6.3. The feed-forward gain is calculated based on the reference wind speed and solving the minimization given in (4.19). In order to avoid zero feed forward gain in Region 3, actuator dynamics has been ignored in the wind turbine linearized model. The LIDAR delay described in equation (4.23) as been set to a constant value of

$$\Delta T = \frac{f}{\bar{U}},$$

(7.1)

in which $f$ is the focal length of the LIDAR and $\bar{U}$ is the mean wind speed.
7.1.3 EOR Settings

The core calculation in the EOR is the solution of the regulator equations (2.27) and (2.28). These equations have to be solved each time the exo-system dynamics are updated. Although the sampling time for the control loop is high speed (10 Hz), regulator equations, and consequently the feed-forward gain vector $G$, need to be updated occasionally (every 6 seconds) and therefore, do not require a great deal of computational power. As shown in Section 6.7, although the exosystems parameters are constantly updated by RLS parameter estimators, the feed-forward gain vector $G$ does not vary substantially during the operation. Therefore, at any given time, any solution for $G$ is also valid for an extended length backward or forward in time. The update rates for the exosystems is 0.1 seconds while the update rate of the $G$ can be well above several seconds (6 seconds is used in these simulations) up to the point that wind speed short-term dynamics has drastically changed. This difference is due to the use of RLS instead of the batch least square methods for estimating the $S$ matrix in exosystems. A batch least square method has to perform large matrix inversions at every update event of $G$ (6 seconds) which might be not feasible for real-time applications. By using RLS instead, this computation load is distributed evenly for each simulation step. With a forgetting factor of 0.90, the RLS will perform similar to batch least square since after 6 seconds, the weight of each sampled data becomes almost zero as $0.90^{60} \approx 0.001$.

Regarding the fact that TurbSim uses a constant mean wind speed and turbulence intensity for generating wind signals used in the simulations, the spectrum of the wind signal does not change during each simulation scenario. Therefore, after a relatively short amount of time, RLS converges to the true low-order approximated spectrum of the wind used by TurbSim. This approximated lower order spectrum is represented by the $S$ matrix in the disturbance exo-system. Therefore, the EOR controller implemented in TOR toolbox can be safely assumed to be an LTI controller. The order of the exo-system model in (5.4) has taken to be 3 in both Region 2 and 3.

7.2 Time Domain Sample Illustrative in Normal Operation

This section presents some illustrative simulation results from our investigation of the performance of the EOR, DAC and Baseline controllers introduced in Section 4.2 and Chapter 5. A color convention is used to represent the results for different controllers throughout the remainder of
this chapter as follows: green represents outputs from a Baseline controller, blue represents DAC, and EOR is shown by red. Illustrative time-domain comparisons are given in Figures 7.1 and 7.2. They show 800 seconds of turbine response data under the three controllers for 8 and 18 m/sec class-A turbulent wind scenarios which represent sample time domain responses for the wind turbine in Region 2 and Region 3 respectively. These wind speeds have been chosen as since their average wind speeds are safely far from the other region as well as the cut-in and cut-out wind speeds. The figures illustrate tower bending moment, rotor speed, blade edgewise bending moment and LSS torque response respectively. Moreover, the last subplot of Figures 7.1 and 7.2 illustrate command torque rate for Region 2 and pitch rate for Region 3, as they are the main control commands for each region.

The responses from the EOR controller exhibit smaller fluctuations than the two alternative controllers, particularly in the LSS torque variations where EOR exerted a much smoother torque command on the low speed shaft of the wind turbine. In general, it seems that EOR shows a higher correlation with Baseline outputs however, the first derivative of the torque input (command torque rate) shows a much aggressive torque command with Baseline and DAC. Such aggressive control input manifests itself in the LSS torque variations, and as will be shown later, on fatigue loads of the drive-train as well.
Figure 7.1: Comparison of the results from the standard Baseline controller (Blue), Disturbance Accommodation Control (Green) and Exact Output Regulator (Red) for low turbulence wind with mean wind speed of 9 m/sec.
Figure 7.2: Comparison of the results from the standard Baseline controller (Green), Disturbance Accommodation Control (Blue) and Exact Output Regulator (Red) for a sample Class A turbulent wind with mean wind speed of 18 m/sec.
7.3 Power Generation Performance Comparison

To compare the power generation performance of the three controllers, we distinguish between Region 2 and Region 3 performance. In Region 2, the primary controller objective is to harvest the maximum amount of energy from the available wind by keeping the blade TSR at its optimal value $\lambda^*$. In Region 3, the power objective is to reduce fluctuations on the output power by maintaining power generation as closely as possible to the rated power of 5 MW.

Regarding the average generated power, no substantial difference is observed among different controllers. Hence, we consider secondary performance criteria such as the standard deviation of generated power, rotor speed, and tip speed ratio. Figures 7.3 and 7.4 illustrate the standard deviations of rotor speed and generated power, which represent each controller’s ability to maintain rotor speed and generated power at their rated value. Reducing these standard deviations implies less variation in these variables, indicating that the controller gives better performance in maintaining the desired rotor speeds and rated power. These two graphs only contain Region 3 wind speeds, as these objectives only apply in Region 3 operation. Here EOR again outperforms both controllers, with the DAC controller giving significantly worse performance.

![Figure 7.3: Standard deviation of electric power production for Class-A turbulent winds with mean wind speeds from 8 m/sec to 24 m/sec.](image-url)
Figure 7.4: Standard deviation of rotor speed for Class-A turbulent winds with mean wind speeds from 8 m/sec to 24 m/sec.

Table 7.3: Power Generation Performance

<table>
<thead>
<tr>
<th>Region 2 (9 m/sec)</th>
<th>Region 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>std(λ)</td>
<td>P: [MW]</td>
</tr>
<tr>
<td>EOR</td>
<td>0.53</td>
</tr>
<tr>
<td>Baseline</td>
<td>0.41</td>
</tr>
<tr>
<td>DAC</td>
<td>0.64</td>
</tr>
<tr>
<td>EOR cf. BL %</td>
<td>-30.56</td>
</tr>
<tr>
<td>DAC cf. BL %</td>
<td>-56.72</td>
</tr>
</tbody>
</table>

Table 7.3 summarizes the results of the controller performance for power generation. As a convention in comparisons in this thesis, positive numbers will show the percentage of improvement relative to Baseline; for example: \( EOR \text{ cf. BL} := \frac{BL - EOR}{BL} \times 100 \). In Region 2, we have chosen a single wind speed of 9 m/sec to ensure the wind speed signal mostly remains above 7.85 m/sec. For wind speeds below this level, the Baseline controller is not designed to track the optimal TSR, and this would invalidate the controller energy harvesting performance comparison.

The first column of the table shows that in Region 2, both EOR and DAC have considerably higher standard deviation in their TSR \( \lambda \), indicating less rigid control on the rotor speed. While this might have been expected to indicate a failure to achieve the optimal TSR for energy gener-
Column 5 of Table 7.3 show that EOR generated the same amount of power as Baseline, while DAC has some slight loss in power generation, due to more fluctuations on rotor speed. The averaged results for the standard deviations $\text{std}(\Omega_r)$ and $\text{std}(P)$ are shown in columns 3 and 4 of Table 7.3, with wind speeds weighted according to the Weibull distribution in Figure 4.1. The EOR controller achieved a substantial improvement in both rotor speed variation and power regulation by 17.89% and 10.53%, relative to Baseline. Conversely, DAC suffered a performance degradation of 67.15% and 23.39%, relative to Baseline.

Reducing rotor speed standard deviation in Region 3 has benefits beyond power regulation. With reduced standard deviation of $\Omega_r$, it becomes less likely that the rotor speed will violate the safe operational limits on the rotor angular velocity. This reduces the chances of turbine failure and increases the turbine’s operational availability.

### 7.4 Damage Equivalent Load Performance Comparisons

For each enabled DOF given in Table 3.6, FAST provides one or more output signals which is associated by its temporal variation. Fatigue loads are calculated from the temporal variations of the movements of associated DOFs. For example, by passing the first and second fore-aft tower bending moment signal to the rain-flow counting algorithm, induced fatigue loads from these motions can be calculated. Accordingly, for each desired signal which represents a time varying force or torque, this can be carried out as well.

Since DELs are not region specific, the results on DELs can be shown for the whole range of the wind speeds from Region 2 to the cut-out wind speed. Figures 7.5 to 7.8 show fatigue loads for mean wind speeds ranging between 8 m/sec to 24 m/sec. The results are associated with Region 2 are distinguished with a gray background in all of the DEL figures.

In Figure 7.5, tower fore-aft bending moment ($M_{yT}$) shows that DAC and EOR both improve considerably over Baseline in reducing this load. It is also obvious that EOR performs better in the higher wind speeds and DAC has performed better in the lower wind speed.

For tower side-to-side bending moment DELs, Figure 7.6 does not indicate a consistent im-
7.5 Life-Time DELs

In order to compare lifetime DELs under each controller, the DELs applicable at each mean wind speed must be averaged across the operating range, with weighting according to the relative frequency of each mean wind speed. The Weibull distribution used to determine the $f_j$ for each
Figure 7.6: Tower root side to side bending moment DEL for Class-A turbulent winds with mean wind speeds from 8 m/sec to 24 m/sec.

Figure 7.7: Low speed shaft DEL for Class-A turbulent winds with mean wind speeds from 8 m/sec to 24 m/sec.
Figure 7.8: Blade root flap-wise bending moment DEL for Class-A turbulent winds with mean wind speeds from 8 m/sec to 24 m/sec.

Figure 7.9: Blade root edge-wise bending moment DEL for Class-A turbulent winds with mean wind speeds from 8 m/sec to 24 m/sec.
reference wind speed in (4.4) from the recorded wind speed variations in Bremerhaven was previously shown in Figure 4.1.

We have used this wind speed distribution to weight the performance results shown in Figure 7.5 to 7.9, and the calculated lifetime weighted values are shown in the first three rows of Table 7.4. The last two rows of this table show the percentage improvements of EOR and DAC against the Baseline controller. Positive numbers indicate improvement relative to Baseline, while negative values indicate inferior performance.

Table 7.4: Weighted average of DEL and Power results for class A turbulent wind in both regions

<table>
<thead>
<tr>
<th></th>
<th>$M_yT$: [kNm]</th>
<th>$M_xT$: [kNm]</th>
<th>$M_yB$: [kNm]</th>
<th>$M_xB$: [kNm]</th>
<th>LSS: [kNm]</th>
<th>$P_{mean}$: [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>8.86E+04</td>
<td>2.50E+04</td>
<td>1.05E+04</td>
<td>1.96E+04</td>
<td>2.59E+04</td>
<td>3.75</td>
</tr>
<tr>
<td>EOR</td>
<td>5.20E+04</td>
<td>1.98E+04</td>
<td>6.68E+03</td>
<td>1.95E+04</td>
<td>2.28E+04</td>
<td>3.74</td>
</tr>
<tr>
<td>DAC</td>
<td>5.72E+04</td>
<td>3.66E+04</td>
<td>6.07E+03</td>
<td>1.95E+04</td>
<td>2.72E+04</td>
<td>3.74</td>
</tr>
<tr>
<td>EOR cf. BL %</td>
<td>41.3</td>
<td>20.8</td>
<td>33.5</td>
<td>0.5</td>
<td>13.1</td>
<td>$\sim$ 0</td>
</tr>
<tr>
<td>DAC cf. BL %</td>
<td>35.4</td>
<td>-46.4</td>
<td>39.6</td>
<td>0.5</td>
<td>-5.0</td>
<td>$\sim$ 0</td>
</tr>
</tbody>
</table>

Table 7.4 illustrates that, without reducing power generation, both the EOR and DAC controllers have been able to reduce lifetime DEL loads, in comparison with Baseline. However the DAC performance showed deterioration in LSS torque and Tower side-to-side bending moment, relative to the Baseline controller. By contrast, with the exception of $M_yB$, EOR has been able to improve on Baseline for all the DEL metrics by margins of between 13% and 41%.

### 7.6 PSD Analysis of the Fatigue Loads

Figures 7.10 to 7.15 show the power spectral densities (PSD) for $M_yT$, $M_xT$, LSS, $M_yB$, as well as $\dot{\theta}$ and generated power, for a sample class-A turbulent wind scenario with mean speed of 20 m/sec. In very low frequencies all controllers show similar spectral content, but above 0.02 Hz, EOR has superior attenuation. As can be seen in Figure 7.10 for the tower fore-aft bending moment $M_yT$, EOR shows the most reduction around 0.05 Hz while for higher frequencies EOR performs the same as DAC. For the tower side-to-side bending moment $M_xT$ shown in Figure 7.11, similar improvements can be seen for EOR. The excitation around 0.32 Hz represents the first tower side-to-side natural frequency [54]. Since the tower model is not considered in the reduced model (3.6)-
(3.10), this frequency is not attenuated by any of the controllers. For LSS torque in Figure 7.12, DAC falls short of two other controllers below 0.05 Hz while EOR maintains better attenuation across the spectrum.

![Power Spectral Density Graphs](image)

Figure 7.10: Power Spectral Density Graphs of Tower root fore-aft bending moment $M_{yT}$ with mean wind speed of 20 m/sec.

Blade flap-wise moments $M_{yB}$ in Figure 7.13 show a peak at 0.2 Hz which is the 1P frequency (1 times the rotor frequency) for all controllers. However both EOR and DAC manage to improve similarly over Baseline on the other parts of the spectrum. The most noticeable performance difference happens on the pitch rate illustrated by Figure 7.14. EOR manages to substantially reduce the high frequency commands on the pitch actuator at the cost of negligible increase in lower frequencies indicating smoother control actuation. Finally, EOR shows slightly better performance on the smoothness of generated power (Figure 7.15). Comparing the results from the PSD analysis shows consistency with the DEL results presented in Figures 7.3 to 7.8 as PSD shows reduced signal power for fatigue measurements over a wide frequency range when EOR controller is used.

### 7.7 Pitch Actuation and Command Torque Rate

Figure 7.16 shows the command torque rate (CTR) calculated by (4.5). CTR measures how much the controller has had to change the torque set point during the 60 minute simulation period. This actuation measure is directly associated with the LSS fatigue loads since any change in generator
Figure 7.11: Power Spectral Density Graphs of Tower root side to side bending moment $M_{s,T}$ with mean wind speed of 20 m/sec.

Figure 7.12: Power Spectral Density Graphs of LSS torque with mean wind speed of 20 m/sec.
7.7 Pitch Actuation and Command Torque Rate

Figure 7.13: Power Spectral Density Graphs of Blade root flap-wise bending moment $M_{yB}$ with mean wind speed of 20 m/sec.

Figure 7.14: Power Spectral Density graphs of Pitch Rate $\dot{\theta}$ with mean wind speed of 20 m/sec.
torque might cause variation in low speed shaft torsion. A lower CTR means less torque actuation which is desirable for extending the drive train life span. As it was described in state-space equations (3.6)-(3.8), any change in the system input $M_g$ perturbs the system states and causes changes in the drive train torsion. Such variations in drive train torsion are associated with fatigue on the drive shaft. Therefore, it is desirable for a controller to achieve its control objectives with reduced torque actuation. It is worth mentioning that this also increases the life span of other components that are directly affected by drive train torque variations such as gearbox and generator. The results show that EOR has lowest CTR in most wind speeds (expect 12 m/sec) which means a smoother control input generated by EOR throughout the operation regions. DAC has also lower CTR compared to Baseline except in areas close to transition region (12 to 14 m/sec).

Figure 7.17 shows a comparison between the controllers regarding their total pitch travel (calculated by (4.6)) in Region 3 where pitch actuation is active. Reduced pitch travel is desirable as it reduces the wear and tear on the bearings of the pitch mechanism. Another possible impact of the pitch travel is its indirect effect on the tower fore-aft and blade flap-wise fatigue loads. It is obvious from (3.2) that fast changes in blade pitch angle are also correlated with fast changes in aerodynamic thrust. Such variations cause the amount of pushing force from the wind to change as well as the tower’s fore-aft inclination. This rapid variation in the tower fore-aft bending is a
7.8 Extreme Operating Gust

The results in this section compare the performance of EOR against the Baseline and DAC during Extreme Operating Gusts (EOG). Regarding the intermittent and unpredictable nature of wind in extreme conditions, some very large and sudden variations, however rare, can steer the wind turbine states such as rotor speed out of the safe operation band and saturate the actuators due to the inability of the controller to compensate for such effects. Actuator saturation can cause faults
in the wind turbine’s operation by inducing instability or activating safety measures of the turbine. Furthermore, such sudden variations in wind speed or direction may induce unusually large loads on the wind turbine structure. In case the wind turbine controller is not able to handle such scenarios, it may cause component damage or even structural failure. Therefore, under extreme operating situations, the primary control objective can be to mitigate the maximum occurring loads during such events while maintaining the wind turbine within the operational bounds. This enables the wind turbine to remain operating after the gust event while avoiding structural damage and an emergency shut down.

IEC standard guidelines [49] has considered the EOG events is in different design load cases. In order to evaluate the performance of the EOR controller in mitigating the extreme loads, an EOG with a 50 years period is considered similar to the design load case 2.3 (DLC 2.3), where the wind turbine in the normal power production mode is exposed to EOG events. The simulations are carried out using the TOR toolbox for all three types of controller and the NREL 5MW wind turbine is disturbed by extreme operation gusts. Assuming perfect wind measurements, the hub-height time-series are created with extreme operation gusts according to [49] at $v_{\text{rated}} + 2\text{ m/s} = 13.2\text{ m/s}$ and $v_{\text{out}} = 25\text{ m/sec}$. The wind speeds EOG 13.5 m/sec and EOG 25 m/sec are fed to the FAST model of the NREL 5MW wind turbine as well as the EOR, DAC and Baseline controllers.
Table 7.5: Performance comparison: Peak values derived from the simulations for extreme operation conditions shown in Figure 7.18

<table>
<thead>
<tr>
<th></th>
<th>EOG 13.5 m/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M_y T_{max}$ [K Nm]</td>
</tr>
<tr>
<td>Baseline PI controller</td>
<td>$1.22 \times 10^5$</td>
</tr>
<tr>
<td>EOR-based control</td>
<td>$7.08 \times 10^4$</td>
</tr>
<tr>
<td>DAC controller</td>
<td>$7.99 \times 10^4$</td>
</tr>
<tr>
<td>EOR cf. BL %</td>
<td>41.9</td>
</tr>
<tr>
<td>DAC cf. BL %</td>
<td>34.5</td>
</tr>
</tbody>
</table>

Figures 7.18 and 7.19 summarizes the simulation results and compares the pitch angle, $\theta$, rotor speed $\Omega_r$, and the tower base fore-aft bending moment, $M_y T$ for the Baseline, DAC and the EOR-based controllers.

For both extreme wind speeds at EOG 13.5 m/sec and EOG 25 m/sec, the EOR controller has shown a superior performance in reducing the rotor speed deviation from the rated value compared to the DAC+LIDAR and Baseline controller. The performance of the proposed controllers in mitigating the extreme loads on the wind turbine tower are summarized in Tables 7.5 and 7.6. It can be seen that the performance of the EOR controller in reducing the effects of the extreme gust events on the tower fore-aft bending moment is substantially better than the other two controllers. This is because the EOR is capable of employing more blade pitch actuation during the gust events. Moreover, the EOR controller uses preview information associated with the future disturbances to build the exo-systems for generating disturbance and reference signals. This gives the EOR the capacity for preemptive control actuation which is comparable to Model Predictive Control methods that use numerical optimization methods. This preemptive actuation is visible in Figure 7.18 before the start of the gust event at time $t = 100$. Both DAC and Baseline show substantial delays in responding to the EOG event, while EOR is able to respond promptly. This is not because EOR sends larger control commands, but it is instead due to the ability of EOR to compensate for the delay caused by the pitch actuator mechanism. This explains the superior performance of the EOR compared to DAC, despite the availability of LIDAR information to both controllers.
Table 7.6: Performance comparison: Peak values derived from the simulations for extreme operation conditions shown in Figure 7.19

<table>
<thead>
<tr>
<th></th>
<th>EOG 25 m/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M_{yT,\text{max}}$ [K Nm]</td>
</tr>
<tr>
<td>Baseline PI controller</td>
<td>$6.25 \times 10^4$</td>
</tr>
<tr>
<td>EOR-based control</td>
<td>$3.18 \times 10^4$</td>
</tr>
<tr>
<td>DAC controller</td>
<td>$4.69 \times 10^4$</td>
</tr>
<tr>
<td>EOR cf. BL %</td>
<td>49.1</td>
</tr>
<tr>
<td>DAC cf. BL %</td>
<td>24.9</td>
</tr>
</tbody>
</table>

7.9 Discussion and Evaluation

This section provided detailed performance comparisons of EOR and two other widely used turbine control methods. Results on the fatigue loads showed that EOR is successful in a larger number of scenarios in reducing the mechanical stress on the wind turbine components. This is the result of a combination of more effective use of wind preview information and smoother control inputs. The generation of exo-systems based on the preview information provides EOR with some preemptive actuation capabilities. This advantage eliminates the need for the closed loop section of the control loop to be high in bandwidth. Therefore, control commands can be smoother while contributing to the load reduction.

The same effect can be observed in the power production performance in Region 2. Smoother control commands led to a less rigid tracking of the optimal tip speed ratio and therefore, some increase in the standard deviation of the tip speed ratio although this did not contribute to any power generation loss due to the flatness of the $C_p$ curve at its apex.

As Table 7.3 represented, EOR has reduced standard deviation of the generated power variations as well as the rotor speed variations in Region 3. This also did not compromise the mean value of the power production. This has been achieved by an effective integration of preview information which allows EOR to better cope with the disturbance compared to Baseline which can not accommodate the upcoming wind variations, and acts upon the instantaneous rotor speed measurements. Although DAC has been augmented with LIDAR as well, its simplified structure compared to EOR (according to Section 5.2) hinders it from effectively and preemptively using the LIDAR information. In other words, DAC is only able to use absolute value of the wind speed provided by LIDAR and does not use the preview information to model higher derivatives of the
Finally, PSD analysis of the measured variables further confirms the superiority of EOR in attenuating the oscillations on the structural components of the wind turbine throughout the frequency spectrum.
Figure 7.18: Simulation results for the extreme operation conditions with EOG 13.5 m/sec. Preemptive actuation of EOR is distinguishable before the EOG starts at time $t = 100$. 
Figure 7.19: Simulation results for the extreme operation conditions with EOG 25 m/sec
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Chapter 8
Conclusion and Outlook

8.1 Conclusion

We proposed a new strategy for wind turbines blade pitch angle and generator torque control based on the classical exact output regulation control methodology. Simulations were performed with FAST code of full nonlinear NREL 5MW wind turbine model with multiple realistic wind signals generated by TurbSim. Results showed the EOR controller was able to provide substantial and consistent load reductions compared to the Baseline controller and DAC without loss of generated power in both operating regions. Additionally, the modest computational cost of the output regulation methodology means it can be expected to be suitable for real-time implementation.

Although in Region 2 one of the main objectives is to increase or even maximize the energy production, this requires (2.8) to hold at all times of the turbine operation. This requires the rotor speed controller be designed to precisely track the optimal TSR $\lambda^\ast$. As pointed out in Section 6.1, this requires all other states of the wind turbine to precisely track their equilibrium value for any instantaneous effective wind speed. However, it was shown in [8] that the power co-efficient curve $C_p$ is relatively flat at its maximum and a controller designed to precisely track the optimal TSR probably does not contribute much to the power production, while adding a considerable amount of stress to the structure. Similar results were noted in [103],[104] and [8], where very small increases in power production came at the cost of substantial increases in DELs. This situation suggests that controller design objective should instead be to reduce fatigue loads without compromising power harvesting efficiency.

Our results in Region 2 showed that stress on the structure can be reduced without compromising energy capture. For example, Figure 7.7 shows considerable reduction in low speed shaft
fatigue loads, as well as tower side to side bending moment in Figure 7.6. On the tower for aft and blade flap-wise bending moment EOR is a bit behind DAC but still works better than Baseline.

It should be noted that the ultimate goal in wind energy industry is reducing the LCOE. Therefore, although producing more energy in Region 2 is desirable, it should not come with the higher long term cost of structural fatigue. Moreover, information on the different costs of structural fatigue, maintenance costs and energy prices for every specific wind turbine is needed to determine LCOE and how to balance increases in energy against increases in loads.

Results in Region 3 showed that EOR can substantially reduce variability in the rotor speed and power generation without compromising total energy production almost at every wind speed from 12 m/sec to 24 m/sec. Moreover, as Figures 7.3, 7.4 and Table 7.3 show, EOR has been able to reduce the standard deviations of the rotor speed and the generated power. This required some additional pitch travel compared to DAC in the wind speeds higher than 16 m/sec.

Considering the relative performance of the EOR and DAC controllers, our performance comparisons showed an EOR controller was able to provide superior fatigue load reduction to a DAC controller. The improved performance of EOR may be attributed to its ability to utilise higher derivatives of the wind speed. In fact, the feed-forward gain in DAC does not take the wind dynamics into account which is a restricting assumption when dealing with highly varying disturbances. On the other hand, EOR assumes higher order dynamics for disturbances where the exo-system state $w$ is a vector comprised of the first and higher derivatives of the disturbance. Therefore, EOR is better able to utilise information about the disturbance and has some predictive capability due to its use of time derivative information from the disturbance signal.

The order of exosystem employed within the EOR methodology can be freely chosen depending on the reliability of LIDAR measurements, available computational power and the parameter estimation limitations. Therefore, it is possible to design the EOR controller with regard to different control performance objectives. For example, high-order exosystems yield more precise description of the wind and hence improved disturbance rejection. However, it may increase the structural loads and actuation efforts. Hence, selecting the appropriate order for the exosystem involves a trade-off between increasing the power generation performance and reducing the loads.
8.2 Future Developments

Here we discuss some potential developments for future works.

8.2.1 EOR without LIDAR

By observing variations in the exosystem $S$ matrix during simulations, it can be shown that EOR could possibly be used without the need for LIDAR measurements. Estimations which are performed based on recorded data (past wind measurements) seem to remain valid for the next few seconds as well. This can completely eliminate the need for LIDAR and therefore, opens a gate for a more economic use of EOR only relying on the estimated rotor effective wind speed at each given time.

Figure 8.1 represents the variation of $S$ matrix comparing its condition number against initial estimation during operation with Class-A 20 m/sec average wind speed for one hour of simulation. The following fraction is calculated for the each of six seconds of LIDAR data:

$$ C(S) = \frac{\kappa(S) - \kappa(S_0)}{\kappa(S_0)} $$

(8.1)

where $\kappa(.)$ is the condition number of a square matrix and $S = S_0$ when EOR is activated after 100 seconds of simulation time. As it can be seen, such variations does not exceed around 2-3 percent of the initial value during the operation. Since $S$ is recursively updated, $G$ is also subject to slight variations during the operation which means for every given time step $n$, $G[n]$ may be slightly different than previous $G[n - 1]$. By defining

$$ \Delta G[n] = G[n] - G[n - 1] $$

(8.2)

as the variation of feed-forward gain and

$$ R[n] = \frac{||\Delta G[n]||_{Fro}}{||G[n]||_{Fro}} \times 100 $$

(8.3)

as the rate of change, the variation of $G$ at each time step can be measured as the ratio between the Frobenius norms of $\Delta G$ and $G$. Figure 8.2 shows variations of $R[n]$ (after every 6 seconds) for the linearized wind turbine model and Class-A turbulent wind with the average wind speed of
20 m/sec. The reason for choosing condition number for analyzing $S$ matrix and Frobenius norm for $G$ matrix is that the condition number is a better tool for measuring the variation of $S$ matrix since $S$ represents the approximation of wind spectrum. On the contrary, Frobenius norm is more suitable for measuring variations of $G$ since it is a feed-forward gain and the norm of $G$ has a direct impact on the amplitude of the control input.

It is clear that $R[n]$ is mostly well under 5% all the time with occasional spikes around 10%. In fact the mean value for a 3000 second operation of the wind turbine is 1.604% with the variance of $\sigma = 2.789$. Figure 8.3 represents the statistical representation of $R[n]$ which can address concerns over the possibility of high variations of $G$.

These experiments with TOR shows that the dynamics of the exo-systems constructed to describe the wind speed variations in the next future few seconds of the operation does not vary considerably by the advance of time despite the high turbulence of the wind. Figure 8.1 showed that the condition number of the $S$ matrix from it’s initial value to the final value remains almost constant with some largest variations less than 3%.

Furthermore, the generated feed-forward gain $G$ obtained from solving the regulator equations
8.2 Future Developments

![Figure 8.2: The Ratio of Frobenius norm of the $\Delta G$ and the instantaneous Frobenius norm of feed-forward gain vector $G$](image)

also does not show considerable variations in its Frobenius norm during each update based on the new LIDAR data. This suggests that it can be safely assumed the proposed EOR controller parameters remain approximately time invariant during the operation.

### 8.2.2 Individual Pitch Control

Future developments will also consider the performance of EOR methodology in individual pitch control, when each blade pitch angle can be manipulated exclusively according to LIDAR’s 3D wind field measurements. It is anticipated the EOR methodology will be able to deliver further improvements in rotor speed control with reduced fatigue loads in comparison with Baseline method and DAC.

### 8.2.3 Transition Region for EOR

Although we have developed a comprehensive framework for the application of EOR, it still lacks a transition strategy between Regions 2 and 3. Around the transition wind speeds, there can
be some performance loss or excessive oscillations on the wind turbine. For instance, standard deviation of rotor speed $\text{std}(\Omega_r)$ at the reference wind speed of 12 m/sec, is higher than both other methods which is in contrary with the performance of EOR in the Region 3 wind speed range. Similarly, the command torque ratio at the reference wind speed of 12 m/sec for EOR is higher than Baseline which can clearly be associated with transition region issues as the EOR performance is clearly better than Baseline over all other wind speeds. Therefore, future work can consider developing a transition region method for EOR which enables it to smoothly switch from rotor speed reference to the blade pitch reference control as the wind speed increases from Region 2 into 3 and vice versa.

8.2.4 Robust EOR

The EOR controller design method described in section 5.1 has been extended to accommodate other control problem frameworks, such as the robust output regulation problem, in which the objective is to achieve output regulation in the presence of plant uncertainty, and the nonlinear output regulation problem which considers the problem of regulating the output of a nonlinear plant [42]. Both of these variations on EOR control have the potential to further improve turbine
performance, by accommodating the plant uncertainty introduced by use of the linearised model in (3.25) or else through the use of the reduced nonlinear model in (3.6)-(3.10) for the turbine controller design.

8.2.5 Yaw Control

LIDAR is capable of detecting wind direction as well. In this thesis we assumed that the wind turbine is always in the direction of the wind and there is no yaw error. However, in a more realistic scenario, wind direction should also be tracked as well as the wind speed in order to extract the maximum energy from the wind. The same structure for wind speed tracking can be repeated for the yaw control mechanism using the wind direction data provided by LIDAR. Since yaw actuation in the utility scale wind turbines have very slow dynamics, preemptive actions of the EOR in tracking the upcoming direction changes can provide advantages for a wind turbine equipped with EOR and LIDAR.

8.2.6 Wind Evolution

From the point of the wind speed measurement by LIDAR in from of the wind turbine to the moment that the wind interacts with the blades, the wind speed may be subject to change. In this thesis, the construction of the exo-systems is based on the validity of the Taylor’s Frozen Turbulence Hypothesis which describes the wind as a turbulence box marching towards the wind turbine. The Taylor’s Hypothesis, is valid for relatively flat terrain where the geological features does not interact considerably with the air flow during its journey between the point of measurement and the wind turbine location.

However, on rough terrain, Taylor’s hypothesis might not apply and the wind flow might be subject to the influence of ground features. Therefore, the wind flow may evolve during its short journey and differ substantially from its value at the point of measurement. However, wind evolution can also be modeled in order to predict the variation of the wind after measurement. Such models can also be augmented in the construction of the exo-systems in the EOR without any required major changes in the architecture of the proposed controller.
8.2.7 Wind Farm Control

There is a growing number of publications on distributed and multi agent output regulation in the control systems literature [89] which can be applied for wind farm control. In the wind farms the turbines affect each others performance by creating wakes which has negative impacts on the power generation of the down stream wind turbines. A collective optimization on a wind farm sometimes requires a harmonized set-point tracking among a large number of wind turbines which could be handled by a distributed version of exact output regulation.

8.2.8 Experimental Validation

Although this thesis has used the most realistic assumptions and simulation tools to obtain results, no amount of simulations can replace the value of experimental validation in control engineering practice. Further validations on a real experimental wind turbine such as the works presented in [91] and [83] can increase confidence in reliability and effectiveness of EOR on the LIDAR equipped wind turbines.


