# Contents

## Notation

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Control of Wind Energy Conversion Systems</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Gain Scheduling Techniques</td>
<td>3</td>
</tr>
<tr>
<td>1.3 Robust Control of WECS</td>
<td>3</td>
</tr>
<tr>
<td>1.4 Outline of the Book</td>
<td>4</td>
</tr>
<tr>
<td>2 The Wind and Wind Turbines</td>
<td>7</td>
</tr>
<tr>
<td>2.1 The Wind</td>
<td>7</td>
</tr>
<tr>
<td>2.1.1 The Source of Winds</td>
<td>7</td>
</tr>
<tr>
<td>2.1.2 Mean Wind Speed</td>
<td>9</td>
</tr>
<tr>
<td>2.1.3 Energy in the Wind</td>
<td>10</td>
</tr>
<tr>
<td>2.1.4 Turbulence</td>
<td>11</td>
</tr>
<tr>
<td>2.2 The Wind Turbines</td>
<td>12</td>
</tr>
<tr>
<td>2.2.1 Types of Rotors</td>
<td>12</td>
</tr>
<tr>
<td>2.2.2 Wind Turbine Aerodynamics</td>
<td>13</td>
</tr>
<tr>
<td>2.2.3 Force, Torque and Power</td>
<td>19</td>
</tr>
<tr>
<td>2.3 Wind Speed Experienced by the Turbine</td>
<td>21</td>
</tr>
<tr>
<td>2.3.1 Deterministic Component</td>
<td>24</td>
</tr>
<tr>
<td>2.3.2 Stochastic Component</td>
<td>27</td>
</tr>
<tr>
<td>3 Modelling of WECS</td>
<td>29</td>
</tr>
<tr>
<td>3.1 WECS Description</td>
<td>29</td>
</tr>
<tr>
<td>3.2 Mechanical Subsystem</td>
<td>31</td>
</tr>
<tr>
<td>3.3 Aerodynamic Subsystem</td>
<td>36</td>
</tr>
<tr>
<td>3.4 Electrical Subsystem</td>
<td>37</td>
</tr>
<tr>
<td>3.4.1 Directly Coupled Squirrel-cage Induction Generator</td>
<td>37</td>
</tr>
<tr>
<td>3.4.2 Stator-controlled Squirrel-cage Induction Generator</td>
<td>39</td>
</tr>
<tr>
<td>3.4.3 Rotor-controlled Doubly-fed Induction Generator</td>
<td>40</td>
</tr>
<tr>
<td>3.5 Pitch Subsystem</td>
<td>42</td>
</tr>
</tbody>
</table>
# Contents

3.6 Model of the Entire WECS ................................. 43
3.7 Effective Wind Model ..................................... 45
  3.7.1 Mean Wind Speed Model ............................ 45
  3.7.2 Turbulence Model .................................. 46
  3.7.3 Effective Wind Speed .............................. 47
  3.7.4 Effective Wind Speed Simulations ................. 47

4 Control Objectives and Strategies .......................... 49
  4.1 Control Objectives ..................................... 50
  4.1.1 Energy Capture .................................... 50
  4.1.2 Mechanical Loads .................................. 52
  4.1.3 Power Quality .................................... 53

4.2 Modes of Operation ...................................... 54

4.3 Control Strategies ...................................... 56
  4.3.1 Fixed-speed Fixed-pitch ............................ 56
  4.3.2 Fixed-speed Variable-pitch ......................... 60
  4.3.3 Variable-speed Fixed-pitch ......................... 64
  4.3.4 Variable-speed Variable-pitch ..................... 68
  4.3.5 Some Options to the Previous Control Strategies .. 69

5 Control of Variable-speed Fixed-pitch Wind Turbines ...... 81
  5.1 Introduction to LPV Gain Scheduling Techniques ....... 81
  5.2 LPV Model of Fixed-pitch WECS ........................ 83
  5.3 Open-loop Characteristics .............................. 88
  5.4 LPV Gain Scheduling Control ........................... 91
  5.4.1 Controller Objectives ................................ 91
  5.4.2 Controller Schemes .................................. 93
  5.4.3 The Controller Design Issue ......................... 97
  5.4.4 Preliminary Control ................................ 99
  5.4.5 Control with Damping Injection ................. 102
  5.4.6 Dealing with Uncertainties ....................... 106
  5.4.7 Performance Assessment of other Variable-speed
       Fixed-pitch Control Strategies .................... 111

6 Control of Variable-speed Variable-pitch Wind Turbines .. 115
  6.1 LPV Model of Variable-pitch WECS .................... 116
  6.2 Open-loop Characteristics ............................ 121
  6.3 LPV Gain Scheduling Control .......................... 125
  6.3.1 Controller Schemes .................................. 125
  6.3.2 Modified Control Strategy for Improved Controllability 130
  6.3.3 The Controller Design Issue ......................... 131
  6.3.4 Control in the High Wind Speed Region ............ 134
  6.3.5 Control in the Low Wind Speed Region............... 144
  6.3.6 Control over the Full Range of Operational Wind Speeds146
  6.3.7 Effects of Uncertainties .......................... 148
## Contents

### A Linear Matrix Inequalities
- A.1 Definition .............................................. 151
- A.2 Semidefinite Programming ................................ 153
- A.3 Properties .............................................. 155

### B Gain Scheduling Techniques and LPV Systems
- B.1 Gain Scheduling Techniques .............................. 159
- B.2 LPV Systems ........................................... 162
  - B.2.1 Stability ............................................. 163
  - B.2.2 Performance ........................................... 164
- B.3 Synthesis of LPV Gain Scheduling Controllers ............ 167
  - B.3.1 Synthesis Procedures ................................. 168
  - B.3.2 Computational Considerations ........................ 173
  - B.3.3 Problem Setup ........................................ 177
- B.4 LPV Descriptions of Nonlinear Systems .................... 179
- B.5 Robust LPV Gain Scheduling Control ....................... 182
  - B.5.1 Robust Stability ...................................... 185
  - B.5.2 Robust Performance ................................... 188
  - B.5.3 Synthesis with Scaling Matrices ..................... 188

### C Quasi-LPV Model and Control .............................. 191

### References ................................................................ 195

### Index .................................................................... 203
Wind Turbine Control Systems
Principles, Modelling and Gain Scheduling Design
Bianchi, F.D.; de Battista, H.; Mantz, R.J.
2007, XX, 208 p., Hardcover