
Contents

Notation	xix
1 Wind Energy	1
1.1 Introduction.....	1
1.2 State of the Art and Trends in Wind Energy Conversion Systems.....	1
1.2.1 Issues in WECS Technology.....	2
1.2.2 Wind Turbines.....	3
1.2.3 Low-power WECS.....	5
1.2.4 Issues in WECS Control.....	5
1.3 Outline of the Book.....	6
2 Wind Energy Conversion Systems	9
2.1 Wind Energy Resource.....	9
2.2 WECS Technology.....	13
2.3 Wind Turbine Aerodynamics.....	15
2.3.1 Actuator Disc Concept.....	15
2.3.2 Wind Turbine Performance.....	16
2.4 Drive Train.....	19
2.5 Power Generation System.....	19
2.5.1 Fixed-speed WECS.....	20
2.5.2 Variable-speed WECS.....	21
2.6 Wind Turbine Generators in Hybrid Power Systems.....	23
2.7 Control Objectives.....	25
3 WECS Modelling	29
3.1 Introduction and Problem Statement.....	29
3.2 Wind Turbine Aerodynamics Modelling.....	30
3.2.1 Fixed-point Wind Speed Modelling.....	30
3.2.2 Wind Turbine Characteristics.....	37
3.2.3 Wind Torque Computation Based on the Wind Speed Experienced by the Rotor.....	42

3.3	Electrical Generator Modelling	46
3.3.1	Induction Generators	47
3.3.2	Synchronous Generators	51
3.4	Drive Train Modelling	54
3.4.1	Rigid Drive Train	55
3.4.2	Flexible Drive Train	56
3.5	Power Electronics Converters and Grid Modelling	57
3.6	Linearization and Eigenvalue Analysis	60
3.6.1	Induction-generator-based WECS	60
3.6.2	Synchronous-generator-based WECS	66
3.7	Case Study (1): Reduced-order Linear Modelling of a SCIG-based WECS	69
4	Basics of the Wind Turbine Control Systems	71
4.1	Control Objectives	71
4.2	Physical Fundamentals of Primary Control Objectives	72
4.2.1	Active-pitch Control	73
4.2.2	Active-stall Control	73
4.2.3	Passive-pitch Control	74
4.2.4	Passive-stall Control	74
4.3	Principles of WECS Optimal Control	75
4.3.1	Case of Variable-speed Fixed-pitch WECS	75
4.3.2	Case of Fixed-speed Variable-pitch WECS	78
4.4	Main Operation Strategies of WECS	80
4.4.1	Control of Variable-speed Fixed-pitch WECS	80
4.4.2	Control of Variable-pitch WECS	86
4.5	Optimal Control with a Mixed Criterion: Energy Efficiency – Fatigue Loading	90
4.6	Gain-scheduling Control for Overall Operation	92
4.7	Control of Generators in WECS	95
4.7.1	Vector Control of Induction Generators	95
4.7.2	Control of Permanent-magnet Synchronous Generators	100
4.8	Control Systems for Grid-connected Operation and Energy Quality Assessment	101
4.8.1	Power System Stability	101
4.8.2	Power Quality	106
5	Design Methods for WECS Optimal Control with Energy Efficiency Criterion	109
5.1	General Statement of the Problem and State of the Art	109
5.1.1	Optimal Control Methods Using the Nonlinear Model	110
5.1.2	Optimal Control Methods Using the Linearized Model	113
5.1.3	Concluding Remarks	115
5.2	Maximum Power Point Tracking (MPPT) Strategies	116
5.2.1	Problem Statement and Literature Review	116
5.2.2	Wind Turbulence Used for MPPT	119

5.2.3	Case Study (2): Classical MPPT vs. MPPT with Wind Turbulence as Searching Signal.....	124
5.2.4	Conclusion	128
5.3	PI Control.....	129
5.3.1	Problem Statement.....	129
5.3.2	Controller Design.....	130
5.3.3	Case Study (3): 2 MW WECS Optimal Control by PI Speed Control	132
5.3.4	Case Study (4): 6 kW WECS Optimal Control by PI Power Control	134
5.4	On–Off Control	135
5.4.1	Controller Design.....	135
5.4.2	Case Study (5).....	140
5.5	Sliding-mode Control.....	142
5.5.1	Modelling.....	143
5.5.2	Energy Optimization with Mechanical Loads Alleviation	143
5.5.3	Case Study (6).....	146
5.5.4	Real-time Simulation Results	147
5.5.5	Conclusion	150
5.6	Feedback Linearization Control.....	150
5.6.1	WECS Modelling.....	151
5.6.2	Controller Design.....	152
5.6.3	Case Study (7).....	156
5.7	QFT Robust Control.....	158
5.7.1	WECS Modelling.....	158
5.7.2	QFT-based Control Design.....	158
5.7.3	Case Study (8).....	160
5.8	Conclusion	166
6	WECS Optimal Control with Mixed Criteria	169
6.1	Introduction.....	169
6.2	LQ Control of WECS.....	170
6.2.1	Problem Statement.....	170
6.2.2	Input–Output Approach.....	170
6.2.3	Case Study (9): LQ Control of WECS with Flexibly-coupled Generator Using R-S-T Controller	173
6.3	Frequency Separation Principle in the Optimal Control of WECS.....	176
6.3.1	Frequency Separation of the WECS Dynamics.....	176
6.3.2	Optimal Control Structure and Design Procedure (2LFSP)	177
6.3.3	Filtering and Prediction Algorithms for Wind Speed Estimation.....	180
6.4	2LFSP Applied to WECS with Rigidly-coupled Generator	182
6.4.1	Modelling.....	182
6.4.2	Steady-state Optimization Within the Low-frequency Loop.....	185
6.4.3	LQG Dynamic Optimization Within the High-frequency Loop.....	185
6.4.4	LQ Dynamic Optimization Within the High-frequency Loop.....	187
6.4.5	Case Study (10).....	190
6.4.6	Global Real-time Simulation Results	193

- 6.5 2LFSP Applied to WECS with Flexibly-coupled Generator 197
 - 6.5.1 Modelling..... 197
 - 6.5.2 Steady-state Optimization Within the Low-frequency Loop..... 199
 - 6.5.3 Dynamic Optimization Within the High-frequency Loop 199
 - 6.5.4 Case Study (11)..... 201
- 6.6 Concluding Remarks on the Effectiveness of 2LFSP 204
- 6.7 Towards a Multi-purpose Global Control Approach 205
 - 6.7.1 Control Objectives in Large Wind Power Plants..... 205
 - 6.7.2 Global Optimization vs. Frequency Separation Principle
for a Multi-objective Control..... 206
 - 6.7.3 Frequency-domain Models of WECS..... 208
 - 6.7.4 Spectral Characteristics of the Wind Speed Fluctuations 209
 - 6.7.5 Open-loop Bandwidth Limitations of WECS Control Systems . 211
 - 6.7.6 Frequency Separation Control of WECS..... 214
- 7 Development Systems for Experimental Investigation
of WECS Control Structures 219**
 - 7.1 Introduction..... 219
 - 7.2 Electromechanical Simulators for WECS..... 220
 - 7.2.1 Principles of Hardware-in-the-loop (HIL) Systems..... 220
 - 7.2.2 Systematic Procedure of Designing HIL Systems 223
 - 7.2.3 Building of Physical Simulators for WECS 223
 - 7.2.4 Error Assessment in WECS HIL Simulators..... 225
 - 7.3 Case Study (12): Building of a HIL Simulator for a DFIG-based
WECS 229
 - 7.3.1 Requirements Imposed to the WECS Simulator..... 230
 - 7.3.2 Building of the Real-time Physical Simulator (RTPS)..... 230
 - 7.3.3 Building of the Investigated Physical System (IPS) and
Electrical Generator Control..... 233
 - 7.3.4 Global Operation of the Simulated WECS 236
 - 7.4 Conclusion 237
- 8 General Conclusion..... 239**
- A Features of WECS Used in Case Studies 243**
- B Elements of Theoretical Background and Development 247**
 - B.1 Sliding-mode Control..... 247
 - B.2 Feedback Linearization Control..... 249
 - B.3 QFT Robust Control..... 255
- C Photos, Diagrams and Real-time Captures..... 261**
- References..... 269**
- Index..... 281**