

WIND ENERGY GENERATION

MODELLING AND CONTROL

OLIMPO ANAYA-LARA | NICK JENKINS | JANAKA EKANAYAKE
PHILL CARTWRIGHT | MIKE HUGHES

 WILEY

Contents

About the Authors	xi
Preface	xiii
Acronyms and Symbols	xv
1 Electricity Generation from Wind Energy	1
1.1 Wind Farms	2
1.2 Wind Energy-generating Systems	3
1.2.1 <i>Wind Turbines</i>	3
1.2.2 <i>Wind Turbine Architectures</i>	7
1.3 Wind Generators Compared with Conventional Power Plant	10
1.3.1 <i>Local Impacts</i>	11
1.3.2 <i>System-wide Impacts</i>	13
1.4 Grid Code Regulations for the Integration of Wind Generation	14
References	17
2 Power Electronics for Wind Turbines	19
2.1 Soft-starter for FSIG Wind Turbines	21
2.2 Voltage Source Converters (VSCs)	21
2.2.1 <i>The Two-level VSC</i>	21
2.2.2 <i>Square-wave Operation</i>	24
2.2.3 <i>Carrier-based PWM (CB-PWM)</i>	25
2.2.4 <i>Switching Frequency Optimal PWM (SFO-PWM)</i>	27
2.2.5 <i>Regular and Non-regular Sampled PWM (RS-PWM and NRS-PWM)</i>	28
2.2.6 <i>Selective Harmonic Elimination PWM (SHEM)</i>	29
2.2.7 <i>Voltage Space Vector Switching (SV-PWM)</i>	30
2.2.8 <i>Hysteresis Switching</i>	33
2.3 Application of VSCs for Variable-speed Systems	33
2.3.1 <i>VSC with a Diode Bridge</i>	34

2.3.2	<i>Back-to-Back VSCs</i>	34
	References	36
3	Modelling of Synchronous Generators	39
3.1	Synchronous Generator Construction	39
3.2	The Air-gap Magnetic Field of the Synchronous Generator	39
3.3	Coil Representation of the Synchronous Generator	42
3.4	Generator Equations in the dq Frame	44
3.4.1	<i>Generator Electromagnetic Torque</i>	47
3.5	Steady-state Operation	47
3.6	Synchronous Generator with Damper Windings	49
3.7	Non-reduced Order Model	51
3.8	Reduced-order Model	52
3.9	Control of Large Synchronous Generators	53
3.9.1	<i>Excitation Control</i>	53
3.9.2	<i>Prime Mover Control</i>	55
	References	56
4	Fixed-speed Induction Generator (FSIG)-based Wind Turbines	57
4.1	Induction Machine Construction	57
4.1.1	<i>Squirrel-cage Rotor</i>	58
4.1.2	<i>Wound Rotor</i>	58
4.2	Steady-state Characteristics	58
4.2.1	<i>Variations in Generator Terminal Voltage</i>	61
4.3	FSIG Configurations for Wind Generation	61
4.3.1	<i>Two-speed Operation</i>	62
4.3.2	<i>Variable-slip Operation</i>	63
4.3.3	<i>Reactive Power Compensation Equipment</i>	64
4.4	Induction Machine Modelling	64
4.4.1	<i>FSIG Model as a Voltage Behind a Transient Reactance</i>	65
4.5	Dynamic Performance of FSIG Wind Turbines	70
4.5.1	<i>Small Disturbances</i>	70
4.5.2	<i>Performance During Network Faults</i>	73
	References	76
5	Doubly Fed Induction Generator (DFIG)-based Wind Turbines	77
5.1	Typical DFIG Configuration	77

5.2	Steady-state Characteristics	77
5.2.1	<i>Active Power Relationships in the Steady State</i>	80
5.2.2	<i>Vector Diagram of Operating Conditions</i>	81
5.3	Control for Optimum Wind Power Extraction	83
5.4	Control Strategies for a DFIG	84
5.4.1	<i>Current-mode Control (PVdq)</i>	84
5.4.2	<i>Rotor Flux Magnitude and Angle Control</i>	89
5.5	Dynamic Performance Assessment	90
5.5.1	<i>Small Disturbances</i>	91
5.5.2	<i>Performance During Network Faults</i>	94
	References	96
6	Fully Rated Converter-based (FRC) Wind Turbines	99
6.1	FRC Synchronous Generator-based (FRC-SG) Wind Turbine	100
6.1.1	<i>Direct-driven Wind Turbine Generators</i>	100
6.1.2	<i>Permanent Magnets Versus Electrically Excited Synchronous Generators</i>	101
6.1.3	<i>Permanent Magnet Synchronous Generator</i>	101
6.1.4	<i>Wind Turbine Control and Dynamic Performance Assessment</i>	103
6.2	FRC Induction Generator-based (FRC-IG) Wind Turbine	113
6.2.1	<i>Steady-state Performance</i>	113
6.2.2	<i>Control of the FRC-IG Wind Turbine</i>	114
6.2.3	<i>Performance Characteristics of the FRC-IG Wind Turbine</i>	119
	References	119
7	Influence of Rotor Dynamics on Wind Turbine Operation	121
7.1	Blade Bending Dynamics	122
7.2	Derivation of Three-mass Model	123
7.2.1	<i>Example: 300 kW FSIG Wind Turbine</i>	124
7.3	Effective Two-mass Model	126
7.4	Assessment of FSIG and DFIG Wind Turbine Performance	128
	Acknowledgement	132
	References	132
8	Influence of Wind Farms on Network Dynamic Performance	135
8.1	Dynamic Stability and its Assessment	135
8.2	Dynamic Characteristics of Synchronous Generation	136

8.3	A Synchronizing Power and Damping Power Model of a Synchronous Generator	137
8.4	Influence of Automatic Voltage Regulator on Damping	139
8.5	Influence on Damping of Generator Operating Conditions	141
8.6	Influence of Turbine Governor on Generator Operation	143
8.7	Transient Stability	145
8.8	Voltage Stability	147
8.9	Generic Test Network	149
8.10	Influence of Generation Type on Network Dynamic Stability	150
	8.10.1 <i>Generator 2 – Synchronous Generator</i>	151
	8.10.2 <i>Generator 2 – FSIG-based Wind Farm</i>	152
	8.10.3 <i>Generator 2 – DFIG-based Wind Farm (PVdq Control)</i>	152
	8.10.4 <i>Generator 2 – DFIG-based Wind Farm (FMAC Control)</i>	152
	8.10.5 <i>Generator 2 – FRC-based Wind Farm</i>	152
8.11	Dynamic Interaction of Wind Farms with the Network	153
	8.11.1 <i>FSIG Influence on Network Damping</i>	153
	8.11.2 <i>DFIG Influence on Network Damping</i>	158
8.12	Influence of Wind Generation on Network Transient Performance	161
	8.12.1 <i>Generator 2 – Synchronous Generator</i>	161
	8.12.2 <i>Generator 2 – FSIG Wind Farm</i>	162
	8.12.3 <i>Generator 2 – DFIG Wind Farm</i>	163
	8.12.4 <i>Generator 2 – FRC Wind Farm</i>	165
	References	165
9	Power Systems Stabilizers and Network Damping Capability of Wind Farms	167
9.1	A Power System Stabilizer for a Synchronous Generator	167
	9.1.1 <i>Requirements and Function</i>	167
	9.1.2 <i>Synchronous Generator PSS and its Performance Contributions</i>	169
9.2	A Power System Stabilizer for a DFIG	172
	9.2.1 <i>Requirements and Function</i>	172
	9.2.2 <i>DFIG-PSS and its Performance Contributions</i>	178
9.3	A Power System Stabilizer for an FRC Wind Farm	182
	9.3.1 <i>Requirements and Functions</i>	182

9.3.2	<i>FRC–PSS and its Performance Contributions</i>	186
	References	191
10	The Integration of Wind Farms into the Power System	193
10.1	Reactive Power Compensation	193
10.1.1	<i>Static Var Compensator (SVC)</i>	194
10.1.2	<i>Static Synchronous Compensator (STATCOM)</i>	195
10.1.3	<i>STATCOM and FSIG Stability</i>	197
10.2	HVAC Connections	198
10.3	HVDC Connections	198
10.3.1	<i>LCC–HVDC</i>	200
10.3.2	<i>VSC–HVDC</i>	201
10.3.3	<i>Multi-terminal HVDC</i>	203
10.3.4	<i>HVDC Transmission – Opportunities and Challenges</i>	204
10.4	Example of the Design of a Submarine Network	207
10.4.1	<i>Beatrice Offshore Wind Farm</i>	207
10.4.2	<i>Onshore Grid Connection Points</i>	208
10.4.3	<i>Technical Analysis</i>	210
10.4.4	<i>Cost Analysis</i>	212
10.4.5	<i>Recommended Point of Connection</i>	213
	Acknowledgement	214
	References	214
11	Wind Turbine Control for System Contingencies	217
11.1	Contribution of Wind Generation to Frequency Regulation	217
11.1.1	<i>Frequency Control</i>	217
11.1.2	<i>Wind Turbine Inertia</i>	218
11.1.3	<i>Fast Primary Response</i>	219
11.1.4	<i>Slow Primary Response</i>	222
11.2	Fault Ride-through (FRT)	228
11.2.1	<i>FSIGs</i>	228
11.2.2	<i>DFIGs</i>	229
11.2.3	<i>FRCs</i>	231
11.2.4	<i>VSC–HVDC with FSIG Wind Farm</i>	233
11.2.5	<i>FRC Wind Turbines Connected Via a VSC–HVDC</i>	234
	References	237
	Appendix A: State–Space Concepts and Models	241

Appendix B: Introduction to Eigenvalues and Eigenvectors	249
Appendix C: Linearization of State Equations	255
Appendix D: Generic Network Model Parameters	259
Index	265