621.312136 WINd

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 Wind Turbines 3
1.2.2 Wind Turbine Architectures 7
1.3 Wind Generators Compared with Conventional Power Plant 10
1.3.1 Local Impacts 11
1.3.2 System-wide Impacts 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 The Two-level VSC 21
2.2.2 Square-wave Operation 24
2.2.3 Carrier-based PWM (CB-PWM) 25
2.2.4 Switching Frequency Optimal PWM (SFO-PWM) 27
2.2.5 Regular and Non-regular Sampled PWM (RS-PWM and NRS-PWM) 28
2.2.6 Selective Harmonic Elimination PWM (SHEM) 29
2.2.7 Voltage Space Vector Switching (SV-PWM) 30
2.2.8 Hysteresis Switching 33
2.3 Application of VSCs for Variable-speed Systems 33
2.3.1 VSC with a Diode Bridge 34

	2.3.2 Back-to-Back VSCs	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 Generator Electromagnetic Torque	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 Excitation Control	53
	3.9.2 Prime Mover Control	55
	References	56
4	**Fixed-speed Induction Generator (FSIG)-based Wind Turbines**	**57**
4.1	Induction Machine Construction	57
	4.1.1 Squirrel-cage Rotor	58
	4.1.2 Wound Rotor	58
4.2	Steady-state Characteristics	58
	4.2.1 Variations in Generator Terminal Voltage	61
4.3	FSIG Configurations for Wind Generation	61
	4.3.1 Two-speed Operation	62
	4.3.2 Variable-slip Operation	63
	4.3.3 Reactive Power Compensation Equipment	64
4.4	Induction Machine Modelling	64
	4.4.1 FSIG Model as a Voltage Behind a Transient Reactance	65
4.5	Dynamic Performance of FSIG Wind Turbines	70
	4.5.1 Small Disturbances	70
	4.5.2 Performance During Network Faults	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 Active Power Relationships in the Steady State	80
	5.2.2 Vector Diagram of Operating Conditions	81
5.3	Control for Optimum Wind Power Extraction	83
5.4	Control Strategies for a DFIG	84
	5.4.1 Current-mode Control (PVdq)	84
	5.4.2 Rotor Flux Magnitude and Angle Control	89
5.5	Dynamic Performance Assessment	90
	5.5.1 Small Disturbances	91
	5.5.2 Performance During Network Faults	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 Direct-driven Wind Turbine Generators	100
	6.1.2 Permanent Magnets Versus Electrically Excited Synchronous Generators	101
	6.1.3 Permanent Magnet Synchronous Generator	101
	6.1.4 Wind Turbine Control and Dynamic Performance Assessment	103
6.2	FRC Induction Generator-based (FRC-IG) Wind Turbine	113
	6.2.1 Steady-state Performance	113
	6.2.2 Control of the FRC-IG Wind Turbine	114
	6.2.3 Performance Characteristics of the FRC-IG Wind Turbine	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 Example: 300 kW FSIG Wind Turbine	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 Generator 2 – Synchronous Generator 151
8.10.2 Generator 2 – FSIG-based Wind Farm 152
8.10.3 Generator 2 – DFIG-based Wind Farm (PVdq Control) 152
8.10.4 Generator 2 – DFIG-based Wind Farm (FMAC Control) 152
8.10.5 Generator 2 – FRC-based Wind Farm 152
8.11 Dynamic Interaction of Wind Farms with the Network 153
8.11.1 FSIG Influence on Network Damping 153
8.11.2 DFIG Influence on Network Damping 158
8.12 Influence of Wind Generation on Network Transient Performance 161
8.12.1 Generator 2 – Synchronous Generator 161
8.12.2 Generator 2 – FSIG Wind Farm 162
8.12.3 Generator 2 – DFIG Wind Farm 163
8.12.4 Generator 2 – FRC Wind Farm 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 Requirements and Function 167
9.1.2 Synchronous Generator PSS and its Performance Contributions 169
9.2 A Power System Stabilizer for a DFIG 172
9.2.1 Requirements and Function 172
9.2.2 DFIG-PSS and its Performance Contributions 178
9.3 A Power System Stabilizer for an FRC Wind Farm 182
9.3.1 Requirements and Functions 182

9.3.2 FRC–PSS and its Performance Contributions 186
References 191

10 The Integration of Wind Farms into the Power System **193**
10.1 Reactive Power Compensation 193
10.1.1 Static Var Compensator (SVC) 194
10.1.2 Static Synchronous Compensator (STATCOM) 195
10.1.3 STATCOM and FSIG Stability 197
10.2 HVAC Connections 198
10.3 HVDC Connections 198
10.3.1 LCC–HVDC 200
10.3.2 VSC–HVDC 201
10.3.3 Multi-terminal HVDC 203
10.3.4 HVDC Transmission – Opportunities and Challenges 204
10.4 Example of the Design of a Submarine Network 207
10.4.1 Beatrice Offshore Wind Farm 207
10.4.2 Onshore Grid Connection Points 208
10.4.3 Technical Analysis 210
10.4.4 Cost Analysis 212
10.4.5 Recommended Point of Connection 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 Frequency Control 217
11.1.2 Wind Turbine Inertia 218
11.1.3 Fast Primary Response 219
11.1.4 Slow Primary Response 222
11.2 Fault Ride-through (FRT) 228
11.2.1 FSIGs 228
11.2.2 DFIGs 229
11.2.3 FRCs 231
11.2.4 VSC–HVDC with FSIG Wind Farm 233
11.2.5 FRC Wind Turbines Connected Via a VSC–HVDC 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