

Contents

Preface	ix
Notation	xi
1 Wind Energy Power Plants	1
1.1 Wind Turbine Structures	1
1.2 A Brief History	4
1.3 Milestones of Development	6
1.4 Functional Structures of Wind Turbines	19
2 Wind Energy Conversion Systems	31
2.1 Drive Torque and Rotor Power	31
2.1.1 <i>Inputs and outputs of a wind turbine</i>	32
2.1.2 <i>Power extraction from the airstream</i>	32
2.1.3 <i>Determining power or driving torque by the blade element method</i>	34
2.1.4 <i>Simplifying the computation method</i>	38
2.1.5 <i>Modelling turbine characteristics</i>	43
2.2 Turbines	47
2.2.1 <i>Hub and turbine design</i>	50
2.2.2 <i>Rotor blade geometry</i>	52
2.3 Power Control by Turbine Manipulation	59
2.3.1 <i>Turbine yawing</i>	59
2.3.2 <i>Rotor blade pitch variation</i>	69
2.3.3 <i>Limiting power by stall control</i>	98
2.3.4 <i>Power control using speed variation</i>	102
2.4 Mechanical Drive Trains	104
2.5 System Data of a Wind Power Plant	109
2.5.1 <i>Turbine and drive train data</i>	110
2.5.2 <i>Machine and tower masses</i>	110
2.5.3 <i>Machine costs</i>	117
3 Generating Electrical Energy from Mechanical Energy	119
3.1 Constraints and Demands on the Generator	119
3.2 Energy Converter Systems	123

3.2.1	<i>Asynchronous generator construction</i>	125
3.2.2	<i>Synchronous generator construction</i>	126
3.3	Operational Ranges of Asynchronous and Synchronous Machines	128
3.4	Static and Dynamic Torque	133
3.4.1	<i>Static torque</i>	134
3.4.2	<i>Dynamic torque</i>	147
3.5	Generator Simulation	155
3.5.1	<i>Synchronous machines</i>	155
3.5.2	<i>Asynchronous machines</i>	159
3.6	Design Aspects	162
3.6.1	<i>Asynchronous generators</i>	162
3.6.2	<i>Synchronous generators for gearless plants</i>	175
3.7	Machine Data	188
3.7.1	<i>Mass and cost relationships</i>	189
3.7.2	<i>Characteristic values of asynchronous machines</i>	191
3.7.3	<i>Characteristic values of synchronous machines</i>	193
4	The Transfer of Electrical Energy to the Supply Grid	199
4.1	Power Conditioning and Grid Connection	201
4.1.1	<i>Converter systems</i>	201
4.1.2	<i>Power semiconductors for converters</i>	204
4.1.3	<i>Functional characteristics of power converters</i>	207
4.1.4	<i>Converter designs</i>	212
4.1.5	<i>Indirect converter</i>	214
4.1.6	<i>Electromagnetic compatibility (EMC)</i>	225
4.1.7	<i>Protective measures during power conditioning</i>	226
4.2	Grid Protection	228
4.2.1	<i>Fuses and grid disconnection</i>	228
4.2.2	<i>Short-circuiting power</i>	229
4.2.3	<i>Increase of short-circuit power</i>	231
4.2.4	<i>Isolated operation and rapid auto-reclosure</i>	234
4.2.5	<i>Overvoltages in the event of grid faults</i>	236
4.3	Grid Effects	236
4.3.1	<i>General compatibility and interference</i>	237
4.3.2	<i>Output behaviour of wind power plants</i>	237
4.3.3	<i>Voltage response in grid supply</i>	249
4.3.4	<i>Harmonics and subharmonics</i>	260
4.4	Resonance Effects in the Grid During Normal Operation	269
4.5	Remedial Measures against Grid Effects and Grid Resonances	274
4.5.1	<i>Filters</i>	274
4.5.2	<i>Filter design</i>	276
4.5.3	<i>Function of harmonic absorber filters and compensation units</i>	277
4.5.4	<i>Grid-specific filter layout</i>	278
4.5.5	<i>Utilizing compensating effects</i>	281
4.6	Grid Control and Protection	284
4.6.1	<i>Supply by wind turbines</i>	284
4.6.2	<i>Grid support and grid control with wind turbines and other renewable systems</i>	285
4.7	Grid Connection Rules	291

5	Control and Supervision of Wind Turbines	297
5.1	System Requirements and Operating Modes	299
5.2	Isolated Operation of Wind Turbines	300
5.2.1	<i>Turbines without a blade pitch adjustment mechanism</i>	302
5.2.2	<i>Plants with a blade pitch adjustment mechanism</i>	303
5.2.3	<i>Plants with load management</i>	303
5.2.4	<i>Turbine control by means of a bypass</i>	304
5.3	Grid Operation of Wind Turbines	304
5.4	Control Concepts	309
5.4.1	<i>Control in isolated operation</i>	309
5.4.2	<i>Regulation of variable-speed turbines</i>	316
5.4.3	<i>Regulation of variable-slip asynchronous generators</i>	316
5.4.4	<i>Regulation of turbines with a rigid connection to the grid</i>	331
5.5	Controller Design	331
5.5.1	<i>Adjustment processes and torsional moments at the rotor blades</i>	334
5.5.2	<i>Standardizing and linearizing the variables</i>	338
5.5.3	<i>Control circuits and simplified dimensioning</i>	342
5.5.4	<i>Improving the control characteristics</i>	346
5.6	Management System	352
5.6.1	<i>Operating states</i>	353
5.6.2	<i>Faults</i>	363
5.6.3	<i>Determining the state of system components</i>	364
5.7	Monitoring and Safety Systems	365
5.7.1	<i>Wind measuring devices</i>	365
5.7.2	<i>Oscillation monitoring</i>	366
5.7.3	<i>Grid surveillance and lightning protection</i>	366
5.7.4	<i>Surveillance computer</i>	367
5.7.5	<i>Fault prediction</i>	368
6	Using Wind Energy	371
6.1	Wind Conditions and Energy Yields	371
6.1.1	<i>Global wind conditions</i>	371
6.1.2	<i>Local wind conditions and annual available power from the wind</i>	373
6.1.3	<i>Calculation of site-specific and regional turbine yields</i>	375
6.1.4	<i>Wind atlas methods</i>	379
6.2	Potential and Expansion	383
6.3	Economic Considerations	387
6.3.1	<i>Purchase and maintenance costs</i>	388
6.3.2	<i>Power supply and financial yields</i>	388
6.3.3	<i>Electricity generation costs</i>	390
6.3.4	<i>Commercial calculation methods</i>	391
6.4	Legal Aspects and the Installation of Turbines	395
6.4.1	<i>Immission protection</i>	396
6.4.2	<i>Nature and landscape conservation</i>	398
6.4.3	<i>Building laws</i>	400
6.4.4	<i>Planning and planning permission</i>	401
6.4.5	<i>Procedure for the erection of wind turbines</i>	403
	References	405
	Index	417