

Contents

Preface	xi
Notation	xiii
1 Wind Energy Power Plants	1
1.1 Wind Turbine Structures	1
1.2 A Brief History	4
1.3 Milestones of Development	5
1.4 Functional Structures of Wind Turbines	20
References	30
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>	31
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>Modeling turbine characteristics</i>	40
2.2 Turbines	46
2.2.1 <i>Hub and turbine design</i>	50
2.2.2 <i>Rotor blade geometry</i>	51
2.3 Power Control by Turbine Manipulation	57
2.3.1 <i>Turbine yawing</i>	57
2.3.2 <i>Rotor blade pitch variation</i>	67
2.3.3 <i>Limiting power by stall control</i>	97
2.3.4 <i>Power control using speed variation</i>	100
2.4 Mechanical Drive Trains	102
2.5 System Data of a Wind Power Plant	108
2.5.1 <i>Turbine and drive train data</i>	108
2.5.2 <i>Machine and tower masses</i>	110
2.5.3 <i>Machine costs</i>	111
References	116

3	Generating Electrical Energy from Mechanical Energy	119
3.1	Constraints and Demands on the Generator	119
3.2	Energy Converter Systems	122
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	126
3.4	Static and Dynamic Torque	132
3.4.1	<i>Static torque</i>	133
3.4.2	<i>Dynamic torque</i>	147
3.5	Generator Simulation	154
3.5.1	<i>Synchronous machines</i>	155
3.5.2	<i>Asynchronous machines</i>	160
3.6	Design Aspects	161
3.6.1	<i>Asynchronous generators</i>	162
3.6.2	<i>Synchronous generators for gearless plants</i>	174
3.6.3	<i>Multi-generator concept (Dissertation A. Ezzahraoui)</i>	187
3.6.4	<i>Ring generator with magnetic bearings (Dissertation K. Messol)</i>	194
3.6.5	<i>Compact superconductive and other new generator concepts</i>	197
3.7	Machine Data	199
3.7.1	<i>Mass and cost relationships</i>	200
3.7.2	<i>Characteristic values of asynchronous machines</i>	202
3.7.3	<i>Characteristic values of synchronous machines</i>	204
	References	208
4	The Transfer of Electrical Energy to the Supply Grid	210
4.1	Power Conditioning and Grid Connection	210
4.1.1	<i>Converter systems</i>	212
4.1.2	<i>Power semiconductors for converters</i>	215
4.1.3	<i>Functional characteristics of power converters</i>	218
4.1.4	<i>Converter designs</i>	222
4.1.5	<i>Indirect converter</i>	223
4.1.6	<i>Electromagnetic compatibility (EMC)</i>	236
4.1.7	<i>Protective measures during power conditioning</i>	237
4.2	Grid Protection	238
4.2.1	<i>Fuses and grid disconnection</i>	239
4.2.2	<i>Short-circuiting power</i>	239
4.2.3	<i>Increase of short-circuit power</i>	242
4.2.4	<i>Isolated operation and rapid auto-reclosure</i>	245
4.2.5	<i>Overvoltages in the event of grid faults</i>	247
4.3	Grid Effects	247
4.3.1	<i>General compatibility and interference</i>	247
4.3.2	<i>Output behavior of wind power plants</i>	248
4.3.3	<i>Voltage response in grid supply</i>	260

4.3.4	<i>Harmonics and subharmonics</i>	271
4.3.5	<i>Voltage faults and the fault-ride-through (FRT)</i>	279
4.4	Resonance Effects in the Grid During Normal Operation	284
4.5	Remedial Measures against Grid Effects and Grid Resonances	290
4.5.1	<i>Filters</i>	290
4.5.2	<i>Filter design</i>	292
4.5.3	<i>Function of harmonic absorber filters and compensation units</i>	293
4.5.4	<i>Grid-specific filter layout</i>	294
4.5.5	<i>Utilizing compensating effects</i>	297
4.6	Grid Control and Protection	300
4.6.1	<i>Supply by wind turbines</i>	300
4.6.2	<i>Grid support and grid control with wind turbines and other renewable systems</i>	301
4.6.3	<i>Central reactive power control</i>	305
4.6.4	<i>System services and operation</i>	308
4.6.5	<i>Connection of wind turbine to the transmission grid</i>	310
4.7	Grid Connection Rules	311
4.8	Grid Connection in the Offshore Region	317
4.8.1	<i>Offshore wind farm properties</i>	317
4.8.2	<i>Stationary and dynamic behavior of offshore wind farms</i>	319
4.8.3	<i>Wind farm and cluster formation at sea and grid connection</i>	319
4.8.4	<i>Electrical energy transmission to the mainland</i>	323
4.8.5	<i>Reactive power requirement and reactive power provision in the offshore grid</i>	325
4.8.6	<i>Flexible AC transmission systems (FACTS)</i>	330
4.9	Integration of the Wind Energy into the Grid and Provision of Energy	333
4.9.1	<i>Grid extension</i>	333
4.9.2	<i>Provision of energy</i>	335
4.9.3	<i>Control and reserve power</i>	337
4.9.4	<i>Power reserve provision with wind farms (Dissertation A. J. Gesino)</i>	338
4.9.5	<i>Intercontinental grid connections</i>	346
	References	346
5	Control and Supervision of Wind Turbines	355
5.1	System Requirements and Operating Modes	356
5.2	Isolated Operation of Wind Turbines	358
5.2.1	<i>Turbines without a blade pitch adjustment mechanism</i>	359
5.2.2	<i>Plants with a blade pitch adjustment mechanism</i>	360
5.2.3	<i>Plants with load management</i>	362
5.2.4	<i>Turbine control by means of a bypass</i>	362
5.3	Grid Operation of Wind Turbines	363
5.4	Control Concepts	367
5.4.1	<i>Control in isolated operation</i>	367
5.4.2	<i>Regulation of variable-speed turbines</i>	371

5.4.3	<i>Regulation of variable-slip asynchronous generators</i>	373
5.4.4	<i>Regulation of turbines with a rigid connection to the grid</i>	388
5.4.5	<i>Wind turbine control using hydrodynamic variable-speed superimposing gears</i>	390
5.5	Controller Design	390
5.5.1	<i>Adjustment processes and torsional moments at the rotor blades</i>	392
5.5.2	<i>Standardizing and linearizing the variables</i>	395
5.5.3	<i>Control circuits and simplified dimensioning</i>	400
5.5.4	<i>Improving the control characteristics</i>	404
5.5.5	<i>Control design for wind turbines</i>	410
5.6	Management System	411
5.6.1	<i>Operating states</i>	412
5.6.2	<i>Faults</i>	423
5.6.3	<i>Determining the state of system components</i>	424
5.7	Monitoring and Safety Systems	424
5.7.1	<i>Wind measuring devices</i>	425
5.7.2	<i>Oscillation monitoring</i>	425
5.7.3	<i>Grid surveillance and lightning protection</i>	426
5.7.4	<i>Surveillance computer</i>	426
5.7.5	<i>Fault prediction</i>	427
5.7.6	<i>Voltage limitation</i>	429
	References	430
6	Using Wind Energy	436
6.1	Wind Conditions and Energy Yields	436
6.1.1	<i>Global wind conditions</i>	436
6.1.2	<i>Local wind conditions and annual available power from the wind</i>	438
6.1.3	<i>Calculation of site-specific and regional turbine yields</i>	440
6.1.4	<i>Wind atlas methods</i>	444
6.2	Potential and Expansion	449
6.2.1	<i>Wind energy use on land</i>	449
6.2.2	<i>Offshore wind energy use</i>	451
6.2.3	<i>Repowering</i>	453
6.3	Economic Considerations	455
6.3.1	<i>Purchase and maintenance costs</i>	457
6.3.2	<i>Power supply and financial yields</i>	457
6.3.3	<i>Blue section</i>	460
6.3.4	<i>Commercial calculation methods</i>	461
6.4	Legal Aspects and the Installation of Turbines	463
6.4.1	<i>Immission protection</i>	464
6.4.2	<i>Nature and landscape conservation</i>	467
6.4.3	<i>Building laws</i>	468
6.4.4	<i>Planning and planning permission</i>	469
6.4.5	<i>Procedure for erecting a wind turbine</i>	470
6.4.6	<i>Offshore utilization of wind energy</i>	472

6.5	Ecological Balance	474
6.5.1	<i>Contribution to climate protection</i>	474
6.5.2	<i>Landscape utilization</i>	475
6.5.3	<i>Bird strike</i>	475
6.5.4	<i>Bats</i>	475
6.5.5	<i>Recycling of wind turbines</i>	475
6.5.6	<i>Energetic amortization time and harvest factor</i>	476
	References	476
Index		483