Contents

1	Windmills and Windwheels	1			
	1.1 The Origins of Windmills	1			
	1.2 European Windmills	4			
	1.3 Economic Importance of Historical Windmills	11			
	1.4 Scientific and Technical Development of Windmills	13			
	1.5 The American Wind Turbine	17			
	References	21			
2	Electrical Power from the Wind - The First Attempts	23			
	2.1 Poul La Cour - A Pioneer in Denmark				
	2.2 Large Wind Power Plants - Ambitious Projects in Germany				
	2.3 1250 kW from the Wind - The First Large Wind Turbine in the US				
	2.4 Wind Turbines in the Fifties - Before the "Energy Crisis"				
	2.5 After the Energy Crisis - A New Start toward Modern Wind Power				
	2.6 The Large Experimental Turbines of the Eighties	46			
	2.7 First Successes with the Small Wind Turbines in Denmark				
	2.8 The Wind Farms in the United States				
	References	63			
3	Basic Concepts of Wind Energy Converters	65			
	3.1 Rotors with a Vertical Axis of Rotation	66			
	3.2 Horizontal Axis Rotors	69			
	3.3 Wind Energy Concentrators	72			
	3.4 Terms and Expressions	77			
	References	78			
4	Physical Principles of Wind Energy Conversion	79			
	4.1 Betz's Elementary Momentum Theory	79			
	4.2 Wind Energy Converters Using Aerodynamic Drag or Lift				
	References	87			
5	Rotor Aerodynamics				
	5.1 Mathematical Models and Calculations	90			
	5.1.1 Blade Element Theory	91			
	5.1.2 Vortex Model of Rotor Flow	96			



		5.1.3	Numeric Flow Simulation	97	
		5.1.4	The Rotor Wake	99	
	5.2	Rotor	Power Characteristics	102	
		5.2.1	Power and Torque Characteristics	102	
		5.2.2	Power Characteristics of Various Rotor Configurations	104	
	5.3	Aerod	lynamic Power Control		
		5.3.1	Power Control by Rotor Blade Pitching	107	
		5.3.2	Passive Stall Control with Fixed Blade Pitch	111	
		5.3.3	Active Stall Control	115	
		5.3.4	Transient Aerodynamic Effects and Boundary-Layer Control	117	
		5.3.5	Turning the Rotor Out of the Wind	119	
	5.4	The A	Aerodynamic Airfoil		
		5.4.1	Characteristic Properties		
		5.4.2	Airfoil Geometry and Classification		
		5.4.3	Laminar Airfoils		
		5.4.4	Influence on the Power Coefficient of the Rotor		
	5.5	Rotor	-Design Features and Power Characteristics	134	
		5.5.1	Number of Rotor Blades		
		5.5.2	Optimum Shape of the Rotor Blades		
		5.5.3	Rotor Blade Twist		
		5.5.4	Blade Thickness		
		5.5.5	Design Tip-Speed Ratio of the Rotor	146	
	5.6	Existi	ng Rotor Blade Designs		
	5.7	Yaw (Control of the Rotor		
	5.8	.8 Aerodynamics of Vertical-Axis Rotors			
	5.9	Exper	rimental Rotor Aerodynamics		
		5.9.1	Measurements on Models in the Wind Tunnel		
		5.9.2	Measurements on Site		
	Ref	erences			
6	Loa	ds and	l Structural Stresses	167	
v	6.1	Loads	s on the Wind Turbine		
	6.2	 Coordinate Systems and Terminology 			
	6.3	Sourc	es of Loading		
	0.2	631	Gravity and Inertial Loads	172	
		632	Uniform and Steady-State Air Flow	173	
		633	Vertical Wind Shear and Cross Winds	177	
		634	Cross Wind on the Rotor	178	
		635	Tower Interference	179	
		6.3.6	Wind Turbulence and Gusts		
	64	Desig	n Load Assumptions	187	
	0. 1	641	International and National Design Standards	188	
		642	IEC Classes of Wind Turbines and German Wind Zones		
		643	Normal Wind Conditions	193	
		5			

		6.4.4	Extreme Wind Conditions	194
		6.4.5	Other Climatic and Environmental Influences	195
		6.4.6	Other External Conditions	197
		6.4.7	Safety Factors	198
	6.5	Opera	tional Status and Load Cases	199
		6.5.1	Normal Operation	199
		6.5.2	Technical Faults	201
	6.6	Struct	tural Stresses in the Wind Turbine	203
		6.6.1	Kind of Stressing	203
		6.6.2	Load Spectra	205
	6.7	Mathe	ematical Models of Structural Dynamics	208
		6.7.1	Functional and Structural Modelling of the Wind Turbine	208
		6.7.2	Representation of the Wind Turbulence	209
		6.7.3	Analytical Approaches and Numerical Computer Codes	213
	6.8	Conce	eptual Design Features and Structural Stresses	215
		6.8.1	Number of Rotor Blades	215
		6.8.2	Rotor Hub Hinges in Two-Blade Rotors	217
		6.8.3	Stiffness of the Rotor Blades	220
		6.8.4	Power Control System	221
		6.8.5	Rotor Speed Flexibility and Variable-Speed Operation	223
	6.9	Meas	uring the Structural Stresses	226
		6.9.1	Rotor Blade Testing	227
		6.9.2	Data Acquisition Systems and Field Measurements	228
	Ref	erences	5	230
7	Vib	ration	Characteristics	233
	7.1	Excit	ing Forces and Vibrational Degrees of Freedom	234
	7.2	Aeroe	elastic Stability of Rotor Blades	236
		7.2.1	Static Divergence	236
		7.2.2	Natural Frequencies and Vibration Modes	237
		7.2.3	Typical Rotor Blade Vibrations	239
	7.3	Torsi	onal Vibration of the Drive Train	242
		7.3.1	Mathematical Model	242
		7.3.2	Equivalent Mechanical Models for the Electrical Grid Coupling	246
		7.3.3	Natural Frequencies and Vibration Modes	247
		7.3.4	Excitations and Resonances	249
	7.4	Dyna	mics of the Yaw System	252
		7.4.1	Modelling and Moments Around the Yaw Axis	252
		7.4.2	Excitation and Resonances	254
	7.5	Vibra	tion of the Whole Wind Turbine	256
		7.5.1	Tower Stiffness	256
		7.5.2	Vibrational Characteristics of Existing Wind Turbines	258
	7.6	Math	ematical Simulation	264
	Ref	erence	s	267

8	Rot	or Bla	des	
	8.1	Mater	rials	270
	8.2	Aircra	aft Wings as Model	272
	8.3	Exper	imental Designs of Rotor Blades in the Past	274
		8.3.1	Revited Aluminium Construction	275
		8.3.2	Steel Designs	277
		8.3.3	Traditional Wood Construction	
		8.3.4	Previous Designs with Fibre-Reinforced Composites	
		8.3.5	Wood/Epoxy Composites	
	8.4	Mode	rn Fibre-Reinforced Composite Blades	
		8.4.1	Fibre Composites Technology	
		8.4.2	Structural Design of the Rotor Blades	
		8.4.3	Manufacturing Methods	290
	8.5	Blade	Connection to the Rotor Hub	293
	8.6	Comp	parison of Rotor Blade Designs	296
	8.7	Aeroc	lynamic Brakes on Stall-Controlled Rotors	
	8.8	Light	ning Protection	
	8.9	Ice W	/arning and De-icing	
	Ref	erences	S	
n	Мо	ahania	al Drive Train and Nacolla	305
9	0.1	Funde	amontal Considerations of Power Transmission	306
	9.1 0.2	Dravia	anomal Considerations of Fower Transmission	309
	9.2	021	Generator in the Tower Base	310
		9.2.1	Vertically Positioned Generator in the Tower Head	310
	03	Gurra	we standard Designs	312
	9.5	031	Gearbox between Rotor and Generator	312
		9.3.1	Direct Potor Driven Generator	314
	0.4	Potor	- Hub	318
	9.4	0.11	Cast Steel Rotor Hubs for Three-Blade Rotors	320
		0/7	Rotor Hub Concepts for Two-Bladed Rotors	321
	95	Blade	Pitch Mechanism	325
	1.5	951	Rotor Blade Bearings	327
		9.5.1	Blade Pitch Systems with Hydraulic Drive	329
		9.5.2	Electrically Driven Blade Pitch Systems	333
		954	Passive Blade Pitching	335
		055	Redundancy and Safety Issues	336
	96	Rotor	r Shaft and Bearing Assembly	338
	9.0	961	Bearing Technology	338
		962	Rotor Shaft with Separate Bearings	341
		962	Three-Point Suspension of Rotor Shaft and Gearbox	343
		9.0.5	Rotor Shaft Integrated into the Gearbox	344
		965	The "Single-Bearing" Concept	345
		9.0.5	Rotor Support on a Fixed Axle	346
		2.0.0	Rotor Support on a linear the maintain and the second	

	9.7 H	Rotor Brake	347
	9.8 0	Gearbox	350
	ç	9.8.1 Gearbox Configurations	350
	9	9.8.2 External Load Specifications for the Gearbox	354
	ç	9.8.3 Internal Gearbox Dimensioning and Design	357
	9	9.8.4 Efficiency and Noise Emission	358
	9.9	Variable-Speed Power-Splitting Gearboxes	361
	9.10	Torsional Flexibility in the Mechanical Drive Train	363
	9.11	Installation of the Electric Generator	366
	9.12	Nacelle	368
		9.12.1 Auxiliary Systems	368
		9.12.2 Load Carrying Concept	371
		9.12.3 External Shape - Aesthetic Aspects	374
	9.13	Yaw System	377
	9.14	Assembly and Functional Testing	380
	Refer	ences	382
10	Elec	trical System	. 385
	10.1	Synchronous and Asynchronous Generator	386
		10.1.1 Synchronous Generator	386
		10.1.2 Induction Generator	390
		10.1.3 Generator with Permanent Excitation	394
	10.2	Assessment Criteria for Using Generators in Wind Turbines	398
	10.3	Fixed-Speed Generator Systems	401
		10.3.1 Synchronous Generator Directly Coupled to the Grid	401
		10.3.2 Induction Generator Directly Coupled to the Grid	403
		10.3.3 Variable-Slip Induction Generator	405
		10.3.4 Multi-Speed Generator Systems	406
	10.4	Variable Speed Generator Systems with Inverter	408
		10.4.1 Frequency Inverters	409
		10.4.2 Synchronous Generator with Inverter	411
		10.4.3 Induction Generator with Oversynchronous Cascade	413
		10.4.4 Double-Fed Induction Generator	414
	10.5	Directly Rotor-Driven Variable-Speed Generators	417
		10.5.1 Synchronous Generator with Electric Excitation	417
		10.5.2 Direct-Drive Generators with Permanent-Magnet Excitation	419
	10.6	Complete Electrical System of a Wind Turbine	421
		10.6.1 Large Turbines	421
·		10.6.2 Small Wind Turbines	424
	10.7	Comparison of Electrical Concepts	426
	Refe	erences	428
	C		400
П		Iroi Systems and Operational Sequence	429
	111	Input Data Measurement	430
	11.1	11.1.1. Wind Measuring Constant	421
	11.1	11.1.1 Wind Measuring System	431
	11.1	11.1.1 Wind Measuring System	431 434

	11.2	Basic Technology of Controllers	435
	11.3	Yaw Control	437
	11.4	Power Control with Rotor Blade Pitching	438
		11.4.1 System Characteristics and Analytical Design Methods	440
		11.4.2 Fixed-Speed Generators Directly Coupled to the Grid	443
		11.4.3 Variable-Speed Operation with Frequency Converter	448
		11.4.4 Isolated Operation without Grid	450
	11.5	Power Limiting by Aerodynamic Stall	452
		11.5.1 Parallel-Grid Operation	452
		11.5.2 Isolated Operation	453
		11.5.3 Active Stall Control	454
	11.6	Operational Sequence and Safety System	457
		11.6.1 Operational States	457
		11.6.2 Safety System	459
	11.7	Control System Implementation	460
	11.8	Interaction with the Grid	462
	Refe	rences	465
12	The	Tower	467
	12.1	Tower Configurations	468
	12.2	Strength and Stiffness Design	471
	12.3	Tower Demensioning Conforming to German Building Regulations	473
	12.4	Free-Standing Tubular-Steel Towers	474
		12.4.1 Stiffness and Structural Mass	474
		12.4.2 Manufacturing Techniques and Construction	477
		12.4.3 Climbing Aids and Internal Installations	480
	12.5	Lattice Towers	483
	12.6	Concrete Towers	487
	12.7	Concrete-Steel Hybrid Towers	492
	12.8	Comparison of Different Tower Concepts	494
	12.9	Increasing the Height with Different Tower Concepts	496
	12.10	0 The Foundation	499
	Refe	rences	503
			505
13	The	Wind Kesource	303 505
	13.1	Clauses of the wind and of the Power in the wind	500
	13.2	Global Distribution of wind Resources	508 مراجع
	13.3	Wind Kesources in Europe	סוכ דו =
	13.4	Unaracteristic Parameters of the Wind	
		13.4.1 Intean Annual wind Speed and wind Speed Frequency	517
		Distribution	/ 13 520
		13.4.2 Increase in white Speed with Attitude	520 524
		13.4.5 SteadIness of the williams and Custa	324 520
		15.4.4 wind 1 urbulence and Gusts	

	13.5	Topogr	aphy and Local Wind Flow	532
	13.6	Measur	ing and Determining the Wind Speed	534
		13.6.1	Measuring Techniques	534
		13.6.2	Ascertaining the Wind Data and the Energy Yield	
			from the European Wind Atlas	539
		13.6.3	Numeric Models of Three-Dimensional Wind Fields	542
	13.7	About	the Wind Energy Potential	543
	Refe	rences		547
14	Powe	er Outp	ut and Energy Yield	549
	14.1	From R	Rotor Power Characteristics to Turbine Power Curve	550
		14.1.1	Installed Generator Power and Rotor Speed	550
		14.1.2	Losses due to Power Control and Operational Sequence	554
		14.1.3	Efficiencies in the Mechanical-Electrical Energy Conversion	557
		14.1.4	Power Coefficients of Today's Turbines	559
	14.2	Determ	ination of the Power Curve	560
		14.2.1	Definitions, Characteristics and Warranty	561
		14.2.2	Measuring the Power Curve	563
	14.3	Site-Re	elated Influences on the Power Curve	569
		14.3.1	Complex Terrain	569
		14.3.2	Air Density	570
		14.3.3	Turbulence	573
		14.3.4	Other Weather-Related Influences	575
		14.3.5	Soiling of the Rotor Blades	575
	14.4	Unifor	mity of Power Output	576
	14.5	Annual	Energy Yield	579
		14.5.1	Method of Calculation	579
		14.5.2	Approximate Calculation of the Energy Yield	581
		14.5.3	Technical Availability	584
		14.5.4	Safety Deductions for Economic Calculations	588
	14.6	Wind F	Regime and Energy Yield	589
	14.7	Major	Design Features and Energy Yield	591
		14.7.1	Rotor Power Coefficient	592
		.14.7.2	Rotor Diameter	593
		14.7.3	Optimal Rotor Speed and Variable Rotor Speed	
			Operation	594
		14.7.4	Power Control: Blade Pitch Contra Stall	597
		14.7.5	Installed Generator Power	598
		14.7.6	Rotor Hub Height	600
		14.7.7	Operational Wind Speed Range	601
		14.7.8	Efficiency of a Wind Turbine as Energy Converter	602
	Refe	rences		603

•

15	Envi	ronmental Impact	605
	15.1	Hazards for the Environment	606
		15.1.1 How Far Can a Rotor Blade Fly?	.606
		15.1.2 Safety Risks	.609
	15.2	Wind Turbine Noise	610
		15.2.1 Acoustic Parameters and Permissible Noise Levels	610
		15.2.2 Noise Sources in Wind Turbines	613
		15.2.3 Noise Emission of Current Wind Turbines	617
	15.3	Shadow Effects	622
	15.4	Interference with Radio and Television Signals	625
	15.5	Impact on Bird Life	628
	15.6	Land Use	629
	15.7	Visual Impact on the Landscape	631
	15.8	Utilisation of Wind Energy and Climate Protection	633
		15.8.1 Effect on the Local Climate	633
		15.8.2 Utilisation of Wind Power and CO ₂ Emissions	634
	Refe	rences	636
	G		()=
16		mercial Applications of Wind Turbines	. 657
	16.1	Stand-Alone wind Turbine Applications	038
		16.1.1 Autonomous Power Supply - Storage Problems	039
		16.1.2 Residential Heating with wind Energy	043
		16.1.3 Pumping water	048
	16.0	10.1.4 Desalination of Sea water	050
	16.2	Small Grids with Dieser Generators and wind Turbines	033 657
	10.3	Wind Turbines Connected with Large Onds	037
		Consumers	657
		16.2.2 Wind Dark Installations	658
	16.4	Integration into the Utility Congretion System	050
	10.4	16.4.1 Operational Strategies and Control Issues	
		16.4.2 Adoption of the Utility Grids to Panawahla Energy Utilisation	005
		16.4.2 Contribution to Firm Dower	005
	16.5	Wind Turbing Industry and Market	000 868
	10.5	16.5.1 Historical Development of the Markets	668
		16.5.2 The Wind Turbine Manufacturers	670
		16.5.2 Components Industry Service Providers and Basic Research	070
	Refe	rences	072
	Reit		
17	Offs	hore Wind Energy Utilisation	. 677
	17.1	Important Technical Issues of Offshore Siting	678
		17.1.1 Technical Requirements for the Wind Turbines	678
		17.1.2 Foundation on the Sea Floor	681
		17.1.3 Electrical Infrastructure	688
		17.1.4 Transportation and Installation	694

.

	17.2	Operational	Issues of Offshore Wind Turbines	697
		17.2.1 Acce	essibility at Poor Weather Conditions	697
		17.2.2 Serv	icing and Maintenance	699
	17.3	Offshore Wi	nd Energy in the North Sea and in the Baltic Sea	701
		17.3.1 Ocea	nographic Conditions and Wind Resources	701
		17.3.2 Lega	1 Situation	704
		17.3.3 Crite	ria for the Permission	706
		17.3.4 The	First Offshore Wind Parks	708
		17.3.5 Com	mercial Offshore Wind Parks	709
	Refe	ences		718
				- 10
18	Wine	I Turbine In	stallation and Operation	719
	18.1	Project Deve	lopment	720
		18.1.1 Sear	ch for a Site and Acquisition of Land Lease Agreements	720
		18.1.2 Prep	lanning and Building Permission	721
	18.2	Technical La	yout of Wind Park Installations	724
		18.2.1 Win	d Turbine Spacing	725
		18.2.2 Inter	nal Electrical Cabling	729
		18.2.3 Grid	Connection	732
		18.2.4 Site	Preparation and Building Activities	738
	18.3	Transportation	on to the Site	741
	18.4	Erection on t	he Site	745
		18.4.1 Stan	dard Method	745
		18.4.2 Erec	tion without Heavy Lifting Equipment	749
		18.4.3 Extr	emely Large Installations	752
		18.4.4 Larg	e Experimental Turbines with Two-Bladed Rotor	755
	18.5	Commisioni	ng	760
		18.5.1 Com	mercial Wind Turbines	760
		18.5.2 Exp	erimental Turbines and Prototypes	761
	18.6	Operation an	d Monitoring	763
		18.6.1 Acq	uisition of Operational Data	763
		18.6.2 Mon	itoring of Large Wind Parks	767
		18.6.3 Tech	nnical Condition Monitoring	768
	18.7	Safety Aspec		770
		18.7.1 Tech	nnical Safety Systems	770
		18.7.2 Risk	s from Extreme Weather Conditions	775
	18.8	Maintenance	and Repair	779
		18.8.1 Rou	tine Maintenance	780
		18.8.2 Cau	ses of Damage and Repair Risks	781
		18.8.3 Stati	stical Evaluations	785
	Refe	ences		786
46		~		-
19	Win	1 Turbine Co	Osts	789
	19.1	Manufacturi	ng Costs and Selling Prices of Wind Turbines	790
	19.2	Specific Cos	its and Reference Parameters	791

		19.2.1	Structural Masses as a Basis for Determining	
			the Manufacturing Costs	792
		19.2.2	Structural Masses of Present Wind Turbines	798
		19.2.3	Manufacturing Cost Calculation on the Basis	
			of Mass-Related Cost Figures	
		19.2.4	Manufacturing Costs and Price Calculation	803
		19.2.5	Design Features and Manufacturing Costs	809
		19.2.6	Economy of Scale in Series Production	
		19.2.7	Lowering Costs through Further Technical	
			Development	813
		19.2.8	Alternative Technical Concepts and Achievable Costs	814
		19.2.9	On the Development Costs of Wind Turbines	
		19.2.10	Development of Sales Prices for Wind Turbines	817
	19.3	Investr	nent Costs for Turnkey Installations	
		19.3.1	Acquisition of the Project Rights	
		19.3.2	Technical Planning and Application for the Building	
			Permission	
		19.3.3	Procurement of Wind Turbines	
		19.3.4	Technical Infrastructure	
		19.3.5	Organisational Costs	
		19.3.6	Selected Examples for Turn-Key Costs	
	19.4	Operat	ing and Maintenance Costs	
		19.4.1	Maintenance and Repairs	
		19.4.2	Insurances	
		19.4.3	Other Operating Costs	
	10.5	19.4.4	Total Annual Operating Costs	
	19.5	Offsho	re Projects	
		19.5.1	Investment Costs	834
	D C	19.5.2	Operating Costs	841
	Refei	rences		
20	Wine	d Turbi	ne Economics	845
	20.1	Corpor	ate Organisation of the Project and Financing	
	20.2	Power	Production Costs and Repayment Periods	848
		20.2.1	Basics for Calculating the Costs of Electricity	
		20.2.2	Static Annuity Approach	850
		20.2.3	Offshore Installations	854
		20.2.4	Dynamic Calculation of Economic Viability	857
		20.2.5	Cash-Flow Projection	859
	20.3	Compe	etition with Conventional Energy Sources	863
	20.4	Energy	Recovery in Wind Turbines	
	20.5	The Ef	fect of Wind Energy Utilisation on Employment	
	20.6	Macro	economic Framework and Renewable Energies	
	Refe	rences		
Subj	ject In	dex		871