Contents

Foreword xv
Preface xvii
Acknowledgement xix

Introduction 1
0.1 Why Innovation? 1
0.2 The Challenge of Wind 2
0.3 The Specification of a Modern Wind Turbine 2
0.4 The Variability of the Wind 4
0.5 Early Electricity-Generating Wind Turbines 4
0.6 Commercial Wind Technology 6
0.7 Basis of Wind Technology Evaluation 7
  0.7.1 Standard Design as Baseline 7
  0.7.2 Basis of Technological Advantage 7
  0.7.3 Security of Claimed Power Performance 8
  0.7.4 Impact of Proposed Innovation 8
0.8 Competitive Status of Wind Technology 8
References 9

Part I  Design Background 11

1 Rotor Aerodynamic Theory 13
  1.1 Introduction 13
  1.2 Aerodynamic Lift 14
  1.3 Power in the Wind 16
  1.4 The Actuator Disc Concept 17
  1.5 Open Flow Actuator Disc 19
  1.5.1 Power Balance 19
  1.5.2 Axial Force Balance 20
  1.5.3 Froude’s Theorem and the Betz Limit 20
  1.5.4 The Power Extraction Process 22
  1.5.5 Relativity in a Fluid Flow Field 23
  1.6 Why a Rotor? 25
  1.7 Actuator Disc in Augmented Flow and Ducted Rotor Systems 26
## Contents

1.7.1 Fundamentals 26  
1.7.2 Generalised Actuator Disc 28  
1.7.3 The Force on a Diffuser 36  
1.7.4 Generalised Actuator Disc Theory and Realistic Diffuser Design 37  
1.8 Blade Element Momentum Theory 38  
1.8.1 Introduction 38  
1.8.2 Momentum Equations 38  
1.8.3 Blade Element Equations 40  
1.8.4 Non-dimensional Lift Distribution 40  
1.8.5 General Momentum Theory 41  
1.8.6 BEM in Augmented Flow 42  
1.8.7 Closed-Form BEM Solutions 44  
1.9 Optimum Rotor Design 46  
1.9.1 Optimisation to Maximise \( C_p \) 46  
1.9.2 The Power Coefficient, \( C_p \) 48  
1.9.3 Thrust Coefficient 51  
1.9.4 Out-of-Plane Bending Moment Coefficient 52  
1.9.5 Optimisation to a Loading Constraint 54  
1.9.6 Optimisation of Rotor Design and Hub Flow 56  
1.10 Limitations of Actuator Disc and BEM Theory 57  
1.10.1 Actuator Disc Limitations 57  
1.10.2 Inviscid Modelling and Real Flows 58  
1.10.3 Wake Rotation and Tip Effect 58  
1.10.4 Optimum Rotor Theory 59  
1.10.5 Skewed Flow 59  
1.10.6 Summary of BEM Limitations 59  

References 60

2 Rotor Aerodynamic Design 65  
2.1 Optimum Rotors and Solidity 65  
2.2 Rotor Solidity and Ideal Variable Speed Operation 66  
2.3 Solidity and Loads 68  
2.4 Aerofoil Design Development 68  
2.5 Sensitivity of Aerodynamic Performance to Planform Shape 73  
2.6 Aerofoil Design Specification 74  
2.7 Aerofoil Design for Large Rotors 75  

References 77

3 Rotor Structural Interactions 79  
3.1 Blade Design in General 79  
3.2 Basics of Blade Structure 80  
3.3 Simplified Cap Spar Analyses 82  
3.3.1 Design for Minimum Mass with Prescribed Deflection 83  
3.3.2 Design for Fatigue Strength: No Deflection Limits 83  
3.4 The Effective \( t/c \) Ratio of Aerofoil Sections 84  
3.5 Blade Design Studies: Example of a Parametric Analysis 85  
3.6 Industrial Blade Technology 91
3.6.1 Design 91
3.6.2 Manufacturing 92
3.6.3 Design Development 94
References 94

4 Upscaling of Wind Turbine Systems 97
4.1 Introduction: Size and Size Limits 97
4.2 The ‘Square-Cube’ Law 100
4.3 Scaling Fundamentals 100
4.4 Similarity Rules for Wind Turbine Systems 102
4.4.1 Tip Speed 102
4.4.2 Aerodynamic Moment Scaling 103
4.4.3 Bending Section Modulus Scaling 103
4.4.4 Tension Section Scaling 103
4.4.5 Aeroelastic Stability 103
4.4.6 Self-Weight Load Scaling 103
4.4.7 Blade (Tip) Deflection Scaling 104
4.4.8 More Subtle Scaling Effects and Implications 104
4.4.8.1 Size Effect 104
4.4.8.2 Aerofoil Boundary Layer 104
4.4.8.3 Earth’s Boundary Layer, Wind Shear and Turbulence 104
4.4.9 Gearbox Scaling 105
4.4.10 Support Structure Scaling 105
4.4.11 Power/Energy Scaling 105
4.4.12 Electrical Systems Scaling 106
4.4.13 Control Systems Scaling 106
4.4.14 Scaling Summary 106
4.5 Analysis of Commercial Data 107
4.5.1 Blade Mass Scaling 108
4.5.2 Shaft Mass Scaling 111
4.5.3 Scaling of Nacelle Mass and Tower Top Mass 112
4.5.4 Tower Top Mass 114
4.5.5 Tower Scaling 114
4.5.5.1 Height versus Diameter 114
4.5.5.2 Mass versus Diameter 115
4.5.5.3 Normalised Mass versus Diameter 116
4.5.6 Gearbox Scaling 118
4.6 Upscaling of VAWTs 119
4.7 Rated Tip Speed 120
4.8 Upscaling of Loads 121
4.9 Violating Similarity 123
4.10 Cost Models 124
4.11 Scaling Conclusions 125
References 126

5 Wind Energy Conversion Concepts 127
References 129
## Drive-Train Design 131

6.1 Introduction 131
6.2 Definitions 131
6.3 Objectives of Drive-Train Innovation 132
6.4 Drive-Train Technology Maps 132
6.5 Direct Drive 136
6.6 Hybrid Systems 139
6.7 Geared Systems – the Planetary Gearbox 140
6.8 Drive Trains with Differential Drive 144
6.9 Hydraulic Transmission 145
6.10 Efficiency of Drive-Train Components 148
6.10.1 Introduction 148
6.10.2 Efficiency over the Operational Range 150
6.10.3 Gearbox Efficiency 151
6.10.4 Generator Efficiency 152
6.10.5 Converter Efficiency 153
6.10.6 Transformer Efficiency 153
6.10.7 Fluid Coupling Efficiency 153
6.11 Drive-Train Dynamics 154
6.12 The Optimum Drive Train 155
6.13 Innovative Concepts for Power Take-Off 157

## Offshore Wind Technology 163

7.1 Design for Offshore 163
7.2 High-Speed Rotor 164
7.2.1 Design Logic 164
7.2.2 Speed Limit 164
7.2.3 Rotor Configurations 165
7.2.4 Design Comparisons 167
7.3 ‘Simpler’ Offshore Turbines 170
7.4 Rating of Offshore Wind Turbines 171
7.5 Foundation and Support Structure Design 172
7.5.1 Foundation Design Concepts 172
7.5.2 Support Structure Design Concepts 173
7.5.3 Loads, Foundations and Costs 174
7.6 Electrical Systems of Offshore Wind Farms 175
7.6.1 Collection System for an Offshore Wind Farm 175
7.6.2 Integration of Offshore Wind Farms into Electrical Networks 177
7.6.2.1 High-Voltage Alternating Current (HVAC) 177
7.6.2.2 Current-Source Converter (CSC) 179
7.6.2.3 Voltage-Source Converter for Offshore Wind Farm Integration 180
7.7 Operations and Maintenance (O&M) 180
7.7.1 Introduction 180
7.7.2 Modelling 181
7.7.3 Inspection of Wind Turbines 182
7.8 Offshore Floating Wind Turbines 183
References 188

8 Future Wind Technology 191
8.1 Evolution 191
8.2 Present Trends – Consensus in Blade Number and Operational Concept 193
8.3 Present Trends – Divergence in Drive-Train Concepts 194
8.4 Future Wind Technology – Airborne 194
8.4.1 Introduction 194
8.4.2 KPS – Cable Tension Power Take-Off 198
8.4.2.1 Earth Axes 198
8.4.2.2 Kite Axes 198
8.4.2.3 BEM Application to the Kite as an Aerofoil Section (No Tip Loss Applied) 199
8.4.3 Daisy Kite – Rotary Power Transmission 202
8.4.4 Omnidea – Rotating Cylindrical Balloon as a Lifting Body 203
8.4.5 Makani 203
8.4.6 Airborne Conclusions 204
8.5 Future Wind Technology – Energy Storage 204
8.5.1 Types of Energy Storage 204
8.5.2 Battery Storage 204
8.5.3 Gas Pressure Storage 205
8.5.4 Compressed Air Storage 205
8.5.5 Flywheel Energy Storage 206
8.5.6 Thermal Energy Storage 206
8.6 Innovative Energy Conversion Solutions 207
8.6.1 Electrostatic Generator 207
8.6.2 Vibrating Column 208
References 208

Part II Technology Evaluation 211

9 Cost of Energy 213
9.1 The Approach to Cost of Energy 213
9.2 Energy: the Power Curve 216
9.3 Energy: Efficiency, Reliability, Availability 222
9.3.1 Efficiency 222
9.3.2 Reliability 222
9.3.3 Availability 223
9.4 Capital Costs 224
## Contents

9.5 Operation and Maintenance 225  
9.6 Overall Cost Split 226  
9.7 Scaling Impact on Cost 227  
9.8 Impact of Loads (Site Class) 228  
References 232  

10 Evaluation Methodology 235  
10.1 Key Evaluation Issues 235  
10.2 Fatal Flaw Analysis 235  
10.3 Power Performance 236  
10.3.1 The Betz Limit 236  
10.3.2 The Pressure Difference across a Wind Turbine 237  
10.3.3 Total Energy in the Flow 238  
10.4 Structure and Essential Mass 239  
10.5 Drive-Train Torque 241  
10.6 Representative Baseline 241  
10.7 Design Loads Comparison 242  
10.8 Evaluation Example: Optimum Rated Power of a Wind Turbine 244  
10.9 Evaluation Example: the Carter Wind Turbine and Structural Flexibility 246  
10.10 Evaluation Example: Concept Design Optimisation Study 249  
10.11 Evaluation Example: Ducted Turbine Design Overview 251  
10.11.1 Extreme Loads 251  
10.11.2 Drive-Train Torque 252  
10.11.3 Energy Capture 252  
References 253  

### Part III Design Themes 255

11 Optimum Blade Number 257  
11.1 Energy Capture Comparisons 257  
11.2 Blade Design Issues 258  
11.3 Operational and System Design Issues 260  
11.4 Multi-bladed Rotors 265  
References 266  

12 Pitch versus Stall 267  
12.1 Stall Regulation 267  
12.2 Pitch Regulation 269  
12.3 Fatigue Loading Issues 270  
12.4 Power Quality and Network Demands 272  
12.4.1 Grid Code Requirements and Implications for Wind Turbine Design 272  
References 274  

13 HAWT or VAWT? 277  
13.1 Introduction 277  
13.2 VAWT Aerodynamics 277
13.3 Power Performance and Energy Capture 282
13.4 Drive-Train Torque 284
13.5 Niche Applications for VAWTs 286
13.6 Status of VAWT Design 286
13.6.1 Problems 286
13.6.2 Advances in VAWT Understanding and Technology 287
References 289

14 Free Yaw 291
14.1 Yaw System COE Value 291
14.2 Yaw Dynamics 291
14.3 Yaw Damping 293
14.4 Main Power Transmission 293
14.5 Operational Experience of Free Yaw Wind Turbines 294
14.6 Summary View 295
References 295

15 Multi-rotor Systems (MRS) 297
15.1 Introduction 297
15.2 Standardisation Benefit and Concept Developments 297
15.3 Operational Systems 298
15.4 Scaling Economics 298
15.5 History Overview 300
15.6 Aerodynamic Performance of Multi-rotor Arrays 300
15.7 Recent Multi-rotor Concepts 301
15.8 MRS Design Based on VAWT Units 304
15.9 MRS Design within the Innwind.EU Project 306
15.9.1 Loads, Structure and Yaw System Design 306
15.9.2 Operations and Maintenance 308
15.9.3 Cost of Energy Evaluation 309
15.10 Multi-rotor Conclusions 311
References 311

16 Design Themes Summary 313

Part IV Innovative Technology Examples 315

17 Adaptable Rotor Concepts 317
17.1 Rotor Operational Demands 317
17.2 Management of Wind Turbine Loads 319
17.3 Control of Wind Turbines 320
17.4 LiDAR 321
17.4.1 Introduction 321
17.4.2 The LiDAR Operational Principle 321
17.4.3 Evaluation of LiDAR for Control of Wind Turbines 322
17.4.4 An Example of Future Innovation in LiDAR 323
17.5 Adaptable Rotors 323
17.6 The Coning Rotor 326
17.6.1 Concept 326
17.6.2 Coning Rotor: Outline Evaluation – Energy Capture 328
17.6.3 Coning Rotor: Outline Evaluation – Loads 329
17.6.4 Concept Overview 330
17.7 Variable Diameter Rotor 330
References 332

18 Ducted Rotors 335
18.1 Introduction 335
18.2 The Katru Shrouded Rotor System 336
18.3 The Wind Lens Ducted Rotor 340
References 344

19 The Gamesa G10X Drive Train 345

20 DeepWind Innovative VAWT 349
20.1 The Concept 349
20.1.1 Blades 349
20.1.2 Controls 351
20.1.3 Generator Concepts 351
20.1.4 Torque Absorption 353
20.1.5 Anchoring Part 353
20.2 DeepWind Concept at 5 MW Scale 353
20.3 Marine Operations Installation, Transportation and O&M 353
20.4 Testing and Demonstration 353
20.5 Cost Estimations 355
References 356

21 Gyroscopic Torque Transmission 357
References 362

22 The Norsetek Rotor Design 363
References 365

23 Siemens Blade Technology 367

24 Stall-Induced Vibrations 371
References 374

25 Magnetic Gearing and Pseudo-Direct Drive 377
25.1 Magnetic Gearing Technology 377
25.2 Pseudo-Direct-Drive Technology 380
References 382

26 Summary and Concluding Comments 383

Index 385