THIRD EDITION

WIND ENERGY EXPLAINED

ON LAND AND OFFSHORE

JAMES F. MANWELL ▪ EMMANUEL BRANLARD
JON G. McGOWAN ▪ BONNIE RAM

WILEY

Wind Energy Explained

Wind Energy Explained

On Land and Offshore

Third Edition

James F. Manwell
University of Massachusetts
Amherst, United States

Emmanuel Branlard
University of Massachusetts
Amherst, United States

Jon G. McGowan
University of Massachusetts
Amherst, United States

Bonnie Ram
University of Delaware
Delaware, United States

WILEY

This edition first published 2024
© 2024 John Wiley & Sons Ltd

Edition History
John Wiley & Sons Ltd (1e, 2009); John Wiley & Sons Ltd (2e, 2010)

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by law. Advice on how to obtain permission to reuse material from this title is available at http://www.wiley.com/go/permissions.

The right of James F. Manwell, Emmanuel Branlard, Jon G. McGowan and Bonnie Ram to be identified as the authors of this work has been asserted in accordance with law.

Registered Offices
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Trademarks: Wiley and the Wiley logo are trademarks or registered trademarks of John Wiley & Sons, Inc. and/or its affiliates in the United States and other countries and may not be used without written permission. All other trademarks are the property of their respective owners. John Wiley & Sons, Inc. is not associated with any product or vendor mentioned in this book.

Limit of Liability/Disclaimer of Warranty
While the publisher and authors have used their best efforts in preparing this work, they make no representations or warranties with respect to the accuracy or completeness of this work and specifically disclaim all warranties, including without limitation any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives, written sales materials or promotional statements for this work. This work is sold with the understanding that the publisher is not engaged in rendering professional services. The advice and strategies contained herein may not be suitable for your situation. You should consult with a specialist where appropriate. The fact that an organization, website, or product is referred to in this work as a citation and/or potential source of further information does not mean that the publisher and authors endorse the information or services the organization, website, or product may provide or recommendations it may make. Further, readers should be aware that websites listed in this work may have changed or disappeared between when this work was written and when it is read. Neither the publisher nor authors shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

Library of Congress Cataloging-in-Publication Data
Names: James F. Manwell, author. | Branlard, Emmanuel, author. | McGowan, J. G., author. | Ram, Bonnie, author.
Title: Wind energy explained : on land and offshore / James F. Manwell, University of Massachusetts, Amherst, United States, Emmanuel Branlard, University of Massachusetts, Amherst, United States, Jon G. McGowan, University of Massachusetts, Amherst, United States, Bonnie Ram, University of Delaware, Newark, United States.
Description: Third edition. | Hoboken, NJ, USA: Wiley, 2024. | Includes index.
Identifiers: LCCN 2023055131 (print) | LCCN 2023055132 (ebook) | ISBN 9781119367451 (cloth) | ISBN 9781119367468 (adobe pdf) | ISBN 9781119367475 (epub)
Subjects: LCSH: Wind power.
Classification: LCC TJ820 M374 2024 (print) | LCC TJ820 (ebook) | DDC 621.31/2136–dc23/eng/20231221
LC record available at https://lccn.loc.gov/2023055131
LC ebook record available at https://lccn.loc.gov/2023055132

Cover Design: Wiley
Cover Images: © NREL /Alamy Stock Photo, sah/Getty Images

Set in 9.5/12.5pt STIXTwoText by Straive, Pondicherry, India

Contents

About the Authors *xxxii*
Preface *xxxiii*
Acknowledgments *xxxv*

1 Introduction: Modern Wind Energy and Its Origins *1*
1.1 Modern Wind Turbines *2*
1.1.1 Modern Wind Turbine Design *3*
1.1.1.1 Rotor *4*
1.1.1.2 Drivetrain *4*
1.1.1.3 Generator *5*
1.1.1.4 Nacelle and Yaw System *5*
1.1.1.5 Support Structure and Stationkeeping System *5*
1.1.1.6 Controls *6*
1.1.1.7 Balance of Electrical System *7*
1.1.2 Power Output Prediction *7*
1.1.3 Other Wind Energy Concepts *8*
1.2 History of Wind Energy *8*
1.2.1 A Brief History of Windmills *10*
1.2.2 Early Wind Generation of Electricity *14*
1.2.3 The Re-Emergence of Wind Energy *15*
1.2.4 Technological Underpinnings of Modern Wind Turbines *18*
1.2.5 Trends *18*
1.2.6 Wind Farms/Wind Power Plants *18*
1.3 Rationale for Wind Energy *19*
1.4 Offshore Wind Energy *19*
1.5 Reference Wind Turbine *21*
1.6 Layout of the Book *22*
References *22*

2 Wind Characteristics and Resources *25*
2.1 Introduction *25*
2.2 General Characteristics of the Wind Resource *26*
2.2.1 Wind Resource: Global Origins *26*
2.2.1.1 Overall Global Patterns *26*
2.2.1.2 Mechanics of Wind Motion *26*

2.2.1.3 Other Atmospheric Circulation Patterns *28*
2.2.2 Temporal and Spatial Characteristics of the Wind *28*
2.2.3 Estimation of Potential Wind Resource *32*
2.2.3.1 Available Wind Power *32*
2.2.3.2 Estimates of Worldwide Resource *33*
2.3 Characteristics of the Atmospheric Boundary Layer *34*
2.3.1 Atmospheric Density and Pressure *34*
2.3.2 Stability of the Atmospheric Boundary Layer *35*
2.3.2.1 Lapse Rate *35*
2.3.2.2 Monin–Obukov Stability Length *36*
2.3.3 The Steady Wind: Wind Speed Variation with Height *36*
2.3.3.1 Logarithmic Profile (Log Law) *37*
2.3.3.2 Power Law Profile *38*
2.3.3.3 Vertical Wind Shear Offshore *39*
2.3.4 Wind Shear and Stability *39*
2.3.5 Effect of Terrain on Wind Characteristics *40*
2.3.5.1 Classification of Terrain *40*
2.3.5.2 Flow Over Flat Terrain with Obstacles *41*
2.3.5.3 Flow in Flat Terrain with a Change in Surface Roughness *42*
2.3.5.4 Characteristics of Non-flat Terrain: Small-scale Features *42*
2.3.5.5 Characteristics of Non-flat Terrain: Large-scale Features *43*
2.4 Wind Data Analysis and Resource Estimation *44*
2.4.1 General Aspects of Wind Turbine Energy Production *44*
2.4.2 Direct Methods of Data Analysis, Resource Characterization, and Turbine Productivity *45*
2.4.2.1 Direct Use of Data *45*
2.4.2.2 Method of Bins *45*
2.4.2.3 Velocity and Power Duration Curves from Data *46*
2.4.3 Statistical Analysis of Wind Data *47*
2.4.3.1 Probability Density Function *48*
2.4.3.2 Cumulative Distribution Function *49*
2.4.3.3 Commonly Used Probability Distributions *49*
2.5 Wind Turbine Energy Production Estimates Using Statistical Techniques *51*
2.5.1 Productivity of an Idealized Turbine Using the Rayleigh Distribution *51*
2.5.2 Productivity of a Realistic Turbine Using the Weibull Distribution *52*
2.6 Regional Wind Resource Assessment *53*
2.6.1 Overview *53*
2.6.2 World Wind Resource Information *54*
2.6.3 United States Resource Information *55*
2.7 Wind Forecasting and Modelling from Data *55*
2.7.1 Wind Forecasting Overview *55*
2.7.2 Wind Modeling from Data via Reanalysis *58*
2.8 Wind Measurement and Instrumentation *58*
2.8.1 Overview *58*
2.8.2 Wind Speed Measuring Instrumentation *59*
2.8.2.1 Cup Anemometers *59*
2.8.2.2 Propeller Anemometers *60*
2.8.2.3 Sonic Anemometers *60*

2.8.2.4 Acoustic Doppler Sensors (Sodar) *61*
2.8.2.5 Laser Doppler Sensors (Lidar) *62*
2.8.3 Wind Direction Instrumentation *63*
2.8.4 Instrumentation Towers *63*
2.8.5 Data Recording Systems *64*
2.8.6 Wind Data Processing *64*
2.8.7 Overview of a Wind Monitoring Program *65*
2.9 Additional Topics *65*
2.9.1 Use of Numerical or Computational Fluid Dynamic Models for Flow Characterization *66*
2.9.2 Micrositing *66*
2.9.3 Mesoscale to Microscale Flow Modeling *66*
2.9.4 Statistically Based Resource Assessment Techniques/Measure-Correlate Predict Approach *66*
References *68*

3 Aerodynamics of Wind Turbines *71*
3.1 General Overview *71*
3.2 Idealized Wind Turbine Rotor and Actuator Disc Theory *72*
3.2.1 One-dimensional Momentum Theory and the Betz Limit *72*
3.2.1.1 Assumptions *72*
3.2.1.2 Results of the 1D Momentum Theory *73*
3.2.1.3 Maximum Power Production – the Betz–Joukowski Limit *76*
3.2.1.4 *Discussion on the Assumptions *77*
3.2.2 Simplified Two-Dimensional Momentum Theory (with wake rotation) *77*
3.2.2.1 Introduction and Main Assumptions *77*
3.2.2.2 Main Equations of the 2D Momentum Theory *78*
3.2.2.3 Maximum Power Coefficient *80*
3.2.3 *General 2D Momentum Theory *82*
3.2.3.1 Momentum Theory Equations for Arbitrary Control Volumes *82*
3.2.3.2 The General 2D Momentum Theory *83*
3.2.4 *Actuator Disc Vorticity Formulation and Link to Momentum Theory *84*
3.2.4.1 Velocity–Pressure and Vorticity Formulations *84*
3.2.4.2 Vorticity Formulation of the Ideal Actuator Disc without Wake Rotation *85*
3.2.4.3 Approximate Solution Using a Vortex Cylinder *86*
3.2.4.4 Vorticity Formulation of an Actuator Disc with Wake Rotation *87*
3.2.4.5 Approximate Formulation and Relation to Strip Theory *88*
3.3 Airfoils and General Concepts of Aerodynamics *88*
3.3.1 Airfoil Terminology *88*
3.3.2 Lift, Drag, and Nondimensional Parameters *90*
3.3.3 Flow Over an Airfoil *91*
3.3.4 Airfoil Behavior *92*
3.3.4.1 Attached Flow Regime *95*
3.3.4.2 High Lift/Stall Development Regime *95*
3.3.4.3 Flat Plate/Fully Stalled Regime *97*
3.3.4.4 Modeling of Post-stall Airfoil Characteristics *97*
3.3.5 Airfoils for Wind Turbines *97*
3.3.6 Lift vs. Drag Machines *98*
3.3.6.1 Drag Machines *98*

3.3.6.2 Lift Machines *100*
3.3.7 Blade Element Theory *100*
3.3.7.1 Assumptions of the Blade Element Theory *100*
3.3.7.2 General Relations of the Blade Element Theory *101*
3.3.7.3 Blade Element Theory for a Rotor with Straight Blades *102*
3.3.7.4 Results Using the Induction Factors *104*
3.4 Aerodynamic Blade Design for Modern Horizontal Axis Wind Turbines *104*
3.4.1 Simple Aerodynamic Design *104*
3.4.2 Design Requirements *104*
3.4.3 Load Case Simulations *104*
3.4.4 Multidisciplinary Design *105*
3.5 Steady-State Performance Prediction: The Blade Element Momentum Method *105*
3.5.1 The Blade Element Momentum Equations *105*
3.5.1.1 Summary of Blade Element Theory Results *105*
3.5.1.2 Summary of Momentum Theory Results *106*
3.5.1.3 Momentum Theory for a Finite Number of Blades – Tip Losses *106*
3.5.1.4 Blade Element Momentum Theory Equations *107*
3.5.1.5 *BEM Equations with Coning and Prebend *107*
3.5.1.6 Blade Element Momentum Theory Equations Without Drag *107*
3.5.2 BEM Algorithm – Solution Methods *108*
3.5.2.1 Method 1 – Iterative Solution for a and a' *108*
3.5.2.2 Method 2 – Solving for C_l and α *109*
3.5.3 Computing the Rotor Performances *109*
3.5.3.1 Power Coefficient without Drag in the Induction Factors *110*
3.5.4 Effect of Drag and Blade Number on Optimum Performance *110*
3.5.5 Performance Curves for a Given Design – $C_P - \lambda$ Curves *111*
3.5.6 Advanced Flow Configurations and Aerodynamic Challenges *113*
3.5.6.1 Multiple Solutions to Blade Element Momentum Equations *113*
3.5.6.2 Wind Turbine Flow States *113*
3.5.6.3 Rotor Modeling for the Turbulent Wake State *113*
3.5.6.4 Blade Coning, Advanced Flows, and Aerodynamic Challenges *114*
3.6 Simplified Performance Analyses and Designs *115*
3.6.1 Blade Shape for Ideal Rotor without Wake Rotation *116*
3.6.2 Blade Shape for Optimum Rotor with Wake Rotation *118*
3.6.3 Linearized HAWT Rotor Performance Calculation Procedure *120*
3.6.4 Aerodynamic Rotor Design Procedure Using the Steady BEM *121*
3.6.4.1 Determine Basic Rotor Parameters *122*
3.6.4.2 Define the Blade Shape *122*
3.6.4.3 Solve the BEM Equations *123*
3.6.4.4 Calculate Rotor Performance and Modify Blade Design *125*
3.7 *Advanced Methods of Rotor Analysis *125*
3.7.1 The General Structure of Lifting-Line-Based Algorithms *126*
3.7.1.1 Introduction *126*
3.7.1.2 Cross-sectional Loads *127*
3.7.1.3 Lifting-line Algorithm *127*
3.7.2 Unsteady Blade Element Momentum Method *128*
3.7.2.1 Introduction *128*

3.7.2.2 Unsteady Aerodynamic Effects *128*
3.7.2.3 Unsteady Relative Velocity: Frozen Turbulence and Rotational Sampling *128*
3.7.2.4 Yaw and Tilt: Skew Model *129*
3.7.2.5 Tower Influence (Tower Shadow and Tower Wake) *130*
3.7.2.6 Nacelle Influence *131*
3.7.2.7 Unsteady Airfoil Aerodynamics *131*
3.7.2.8 Dynamic Inflow *132*
3.7.2.9 Modified Steady-State BEM Equations *133*
3.7.2.10 Overall Structure of an Unsteady BEM Algorithm *134*
3.7.3 Vortex Methods and Vortex Theory *135*
3.7.3.1 Introduction to Vortex Methods *135*
3.7.3.2 Velocity Fields from a Vorticity Distribution – Biot–Savart Law and Poisson Equation *136*
3.7.3.3 Vortex Lattice Method *137*
3.7.3.4 Advanced Vortex Methods *138*
3.7.3.5 Advantages and Limitations of Vortex Methods *138*
3.7.4 Computational Fluid Dynamics (CFD) *139*
3.7.4.1 Introduction *139*
3.7.4.2 Challenges of CFD *139*
3.7.4.3 Actuator-Disc and Actuator-Line Methods *140*
3.7.4.4 Blade-Resolved CFD *140*
3.7.5 Validation and Modelling Challenges *140*
3.8 Aerodynamics of Vertical Axis Wind Turbines *141*
3.8.1 General Overview *141*
3.8.2 Aerodynamics of a Straight-blade Vertical Axis Wind Turbine *141*
3.8.2.1 Single Stream Tube Analysis *142*
3.8.2.2 Multiple Stream Tube Momentum Theory *145*
3.8.2.3 Double Multiple Stream Tube Momentum Theory *146*
3.8.3 Aerodynamics of the Darrieus Rotor *146*
3.8.4 Savonius Rotor *147*
References *147*

4 Mechanics and Dynamics *153*
4.1 Background *153*
4.2 Wind Turbine Motions and Loads *153*
4.2.1 Motions *153*
4.2.1.1 Blade Motions *154*
4.2.1.2 Nacelle and Shaft Motions *154*
4.2.1.3 Tower Motions *154*
4.2.1.4 Offshore Support Structure/Platform Motions *155*
4.2.2 Types of Loads *155*
4.2.2.1 Steady Loads *155*
4.2.2.2 Cyclic Loads *155*
4.2.2.3 Transient Loads *155*
4.2.2.4 Stochastic Loads *156*
4.2.2.5 Resonance-Induced Loads *156*
4.2.3 Sources of Loads *156*
4.2.3.1 Aerodynamics *157*

4.2.3.2 Gravity *157*
4.2.3.3 Dynamic Interactions *157*
4.2.3.4 Mechanical Control *157*
4.2.4 Effects of Loads *157*
4.2.5 Expressions for the Loads Acting on a Rigid Wind Turbine *157*
4.2.5.1 General Integration of Loads on a Component *157*
4.2.5.2 Aerodynamic Thrust and Torque on the Rotor *158*
4.2.5.3 Bending Moments and Stresses on the Rotor *159*
4.2.5.4 Drivetrain Loads *160*
4.2.5.5 Tower Loads *160*
4.2.5.6 Offshore Wind Turbine Substructure Loads *160*
4.3 General Principles of Mechanics *161*
4.3.1 Selected Topics from Basic Mechanics *161*
4.3.1.1 Coordinate Transformations and Rotations *161*
4.3.1.2 Inertial Forces *161*
4.3.1.3 Area Moment of Inertia *162*
4.3.1.4 Mass Moment of Inertia *164*
4.3.1.5 *Inertia Tensor for Three-bladed and Multibladed Rotors *164*
4.3.2 Bending of Cantilevered Beams *165*
4.3.2.1 Deflection of a Tapered, Hollow Cylinder *166*
4.3.2.2 Mass of a Tapered, Hollow Cylinder *167*
4.3.2.3 Finite Difference Calculations for a Cantilever *167*
4.3.3 Rigid Body Planar Rotation *168*
4.3.3.1 Two-Dimensional Rotation *168*
4.3.3.2 Rotational Power/Energy *168*
4.3.4 Gears and Gear Ratios *169*
4.3.5 Gyroscopic Motion *169*
4.3.6 Vibrations: Single Degree of Freedom *170*
4.3.6.1 Undamped Vibrations *170*
4.3.6.2 Damped Vibrations *171*
4.3.6.3 Forced Harmonic Vibrations *171*
4.3.6.4 *Equation of Motion for an Arbitrary Forcing, and Its Linearization *172*
4.3.7 Rotational Equations of Motion and Vibration *173*
4.3.8 Introduction to Vibration of Cantilevered Beams *173*
4.3.8.1 Modes and Mode Shapes *173*
4.3.8.2 General Equation for Vibration of Beams *174*
4.3.8.3 Vibration of Uniform Cantilevered Beams *174*
4.3.8.4 Vibration of Nonuniform Cantilevered Beams *175*
4.4 Methods for Modeling Wind Turbine Structural Response *175*
4.4.1 Lumped Parameter Method *176*
4.4.2 Modal Analysis Method and Shape Function Approach *176*
4.4.3 Finite Element Method *177*
4.4.4 Multibody Analysis *177*
4.4.5 Multi-Physics (Aeroelastic) Wind Turbine Models *178*
4.5 *Equations of Motion of a Wind Turbine – Discrete and Continuous systems *178*
4.5.1 Derivation of the Equations of Motion *178*
4.5.2 Equations of Motion for Multiple Degrees of Freedom System *178*

4.5.3 Examples of Rigid Body Wind Turbine Models with Few Degrees of Freedom *179*
4.5.3.1 Example: Two-DOF Model of an Onshore Wind Turbine (Shaft and Tower-top) *179*
4.5.3.2 Example: Two-DOF Drivetrain Model *180*
4.5.3.3 Example: Two-DOF Model of a Floating Wind Turbine *180*
4.5.4 Solution of the System of Equations *180*
4.5.5 Continuous Systems *181*
4.5.5.1 Equations of Motion *181*
4.5.5.2 Discretization Techniques *181*
4.5.5.3 Solution *181*
4.5.5.4 Myklestad Method *181*
4.6 *Wind Turbine Models Using the Assumed Shape Function Approach *183*
4.6.1 Equations of Motion for an Isolated Beam Described Using One Shape Function *184*
4.6.2 Illustration of the Tower Softening Effect Using a Beam and a Top Mass *185*
4.6.3 Illustration of Centrifugal Stiffening *186*
4.6.4 The Assumed Shape Function Approach with Multiple Shape Functions *188*
4.6.4.1 General Principle of the Assumed Shape Function Approach *188*
4.6.4.2 Equations for an Isolated Beam *188*
4.7 Linearized Hinge Spring Blade Model *190*
4.7.1 Sources of Loads *190*
4.7.2 Modeling of Blade Motion *191*
4.7.3 Coordinate System *191*
4.7.3.1 Flapping Equation *191*
4.7.3.2 Lead–lag Equation *193*
4.7.4 Solutions of the Flapping Equation *194*
4.7.5 Tower Loads *196*
4.7.5.1 Aerodynamic Tower Loads *196*
4.7.5.2 Tower Vibration *196*
4.7.5.3 Dynamic Tower Loads *196*
4.7.6 Yaw Stability *197*
4.7.7 Applicability and Limitations of the Linearized Hinge–Spring Dynamic Model *197*
4.7.7.1 Comparison of LHSBM with *OpenFAST* *198*
4.8 Linearization and Stability *200*
4.8.1 *Linearization of Equations of Motions *200*
4.8.2 Aerodynamic Damping *201*
4.8.3 Multibladed Transformation, Campbell Diagram, and Stability *202*
References *204*

5 Electrical Aspects of Wind Turbines *205*
5.1 Overview *205*
5.2 Basic Concepts of Electrical Power *205*
5.2.1 Fundamentals of Electricity *205*
5.2.2 Alternating Current *206*
5.2.2.1 Capacitors in AC Circuits *207*
5.2.2.2 Inductors in AC Circuits *207*
5.2.2.3 Phasor Notation *207*
5.2.2.4 Complex Impedance *209*
5.2.2.5 Power in AC Circuits *209*

5.2.2.6 Three-phase AC Power *211*
5.2.2.7 Voltage Levels *213*
5.2.3 Fundamentals of Electromagnetism *213*
5.2.3.1 Ampere's Law *213*
5.2.3.2 Flux Density and Magnetic Flux *213*
5.2.3.3 Faraday's Law *214*
5.2.3.4 Induced Force *214*
5.2.3.5 Reluctance *215*
5.2.3.6 Additional Considerations *215*
5.3 Power Transformers *216*
5.4 Electrical Machines *217*
5.4.1 Basic Electrical Machines *218*
5.4.2 Rotating Magnetic Fields *219*
5.4.3 Electrically Excited Synchronous Generators (EESG) *219*
5.4.3.1 Overview of Synchronous Machines *219*
5.4.3.2 Theory of Synchronous Machine Operation *220*
5.4.3.3 Starting Synchronous Machines *222*
5.4.3.4 Pole Numbers and Operational Speed *222*
5.4.4 Permanent Magnet Synchronous Generators (PMSGs) *223*
5.4.5 Squirrel Cage Induction Generators (SCIG) *223*
5.4.5.1 Overview of Induction Machines *223*
5.4.5.2 Theory of Squirrel Cage Induction Machine Operation *224*
5.4.5.3 Starting Wind Turbines with Squirrel Cage Induction Generators *229*
5.4.5.4 Squirrel Cage Induction Machine Dynamic Analysis *229*
5.4.5.5 Off-design Operation of Squirrel Cage Induction Generators *229*
5.4.6 Wound Rotor Induction Generators (WRIG) *230*
5.4.7 Other Types of Generators *231*
5.4.7.1 Shunt Wound DC Generator *231*
5.4.7.2 Switched Reluctance Generators *231*
5.4.8 Generator Mechanical Design *231*
5.4.9 Generator Specification *232*
5.5 Power Converters *233*
5.5.1 Overview of Power Converters *233*
5.5.2 Rectifiers *233*
5.5.2.1 Controlled Rectifiers *234*
5.5.3 Inverters *235*
5.5.3.1 Overview of Inverters *235*
5.5.3.2 Voltage Source Inverters *236*
5.5.4 Harmonics *237*
5.5.4.1 Quantifying Harmonic Distortion *239*
5.5.4.2 Harmonic Filters *240*
5.6 Electrical Aspects of Variable-Speed Wind Turbines *242*
5.6.1 Variable-speed Operation of Synchronous Generators *242*
5.6.2 Variable-speed Operation of Squirrel Cage Induction Generators *242*
5.6.3 Variable-speed Operation with Wound Rotor Induction Generators *243*
5.6.3.1 High Slip Operation *243*
5.6.3.2 Slip Power Recovery *245*
5.6.3.3 True Variable-Speed Operation *246*

5.7 Ancillary Electrical Equipment *247*
5.7.1 Power Cables *247*
5.7.2 Slip Rings *247*
5.7.3 Soft Start *248*
5.7.4 Contactors *248*
5.7.5 Circuit Breakers and Fuses *248*
5.7.6 Main Disconnect *248*
5.7.7 Power Factor Correction Capacitors *248*
5.7.8 Turbine Electrical Loads *249*
References *249*

6 Environmental External Design Conditions *251*
6.1 Overview of External Design Conditions *251*
6.1.1 Wind Turbine Design Basis and External Conditions *251*
6.2 Wind as an External Design Condition *252*
6.2.1 Normal Wind Conditions *252*
6.2.1.1 Fundamental Considerations *252*
6.2.2 Wind Profile (Wind Shear) *253*
6.2.3 Stability *253*
6.2.4 Turbulence *253*
6.2.4.1 Gusts *254*
6.2.4.2 Turbulence Intensity *254*
6.2.4.3 Turbulent Wind Probability Density Function *255*
6.2.4.4 Autocorrelation *256*
6.2.4.5 Integral Time Scale/Length Scale *256*
6.2.4.6 Crosscorrelation *257*
6.2.4.7 Power Spectral Density Function *257*
6.2.4.8 Coherence *258*
6.2.5 Turbulent Data Synthesis *259*
6.2.6 Extreme Wind Speeds *260*
6.2.6.1 Return Period *260*
6.2.6.2 Models for Extreme Events *261*
6.2.7 Joint Occurrence of Environmental Conditions *261*
6.2.7.1 Environmental Contours *262*
6.2.8 Design Wind Conditions Offshore *265*
6.2.8.1 Stability Offshore *265*
6.2.8.2 Offshore Wind Shear *265*
6.2.8.3 Surface Roughness Offshore *265*
6.2.8.4 Turbulence Offshore *267*
6.3 Waves as External Design Condition *268*
6.3.1 Overview of Wind-Driven Waves *268*
6.3.2 Regular (Airy) Waves *268*
6.3.2.1 Dispersion Relation *269*
6.3.2.2 Wave Velocity and Acceleration *269*
6.3.3 Random Waves *270*
6.3.4 Wave Spectra *271*
6.3.4.1 Spectral Parameters *271*
6.3.4.2 Pierson–Moskowitz Spectrum *272*

6.3.4.3 JONSWAP Spectrum *272*
6.3.4.4 Wind and Wave Spectra *273*
6.3.4.5 Occurrences of Wave Heights in a Sea State *274*
6.3.4.6 Maximum Wave in a Sea State *274*
6.3.4.7 Overall Maximum Wave Height *275*
6.3.4.8 Illustrative Example of Modelling Real Waves *275*
6.3.5 Breaking Waves *277*
6.3.6 Other Types of Waves *277*
6.3.7 Synthetic Waves *277*
6.4 Forces Due to Waves *278*
6.4.1 Wave Loads on a Monopile *279*
6.5 Wind and Waves: Combined Effects *280*
6.5.1 *Environmental Contours of Sea States *280*
6.6 Currents *282*
6.6.1 Subsurface Currents *282*
6.6.2 Wind Generated, Near-Surface Currents *282*
6.6.3 Breaking Wave-Induced Surf Currents *283*
6.7 Floating Sea/Lake Ice *283*
6.7.1 Forces Due to Floating Ice *284*
6.8 Exceptional Conditions *284*
6.8.1 Hurricanes/Tropical Cyclones *284*
6.8.2 Extratropical Cyclones *285*
6.9 Other Marine Conditions *286*
6.9.1 Tides *286*
6.9.2 Salinity *286*
6.9.3 Marine Growth *286*
6.9.4 Additional Conditions *287*
6.10 Offshore Metocean Data Collection *287*
6.10.1 Platform and Tower Options *287*
6.10.2 Instrument Options *287*
6.10.3 Available Offshore Data in the United States *288*
6.10.4 Buoy Measurement Issues *288*
6.10.5 Wave Data Estimation *288*
6.11 External Conditions in Wind Turbine Design Standards *288*
6.11.1 IEC Design Wind Conditions *289*
6.11.1.1 Normal Wind Conditions *289*
6.11.1.2 Extreme Wind Conditions *289*
6.11.2 IEC Design Conditions Offshore *291*
6.11.2.1 IEC Wind Conditions Offshore *291*
6.11.2.2 Marine Conditions *291*
6.11.2.3 Other Conditions *292*
References *292*

7 Wind Turbine Materials and Components of the Rotor Nacelle Assembly *295*
7.1 Overview *295*
7.1.1 Review of Basic Mechanical Properties of Materials *295*
7.2 Material Fatigue *295*

7.2.1 Fatigue in Wind Turbines *296*
7.2.2 Assessment of Fatigue *296*
7.2.2.1 Fatigue Life Characterization *296*
7.2.2.2 Fatigue Damage Model *300*
7.2.2.3 Damage Equivalent Loads *304*
7.2.3 Statistical Methods in Fatigue Estimation *304*
7.2.3.1 Damage Equivalent Load Using the Weibull Distribution *305*
7.2.3.2 $^{*}S$–N curve with Two Segments *307*
7.3 Wind Turbine Materials *307*
7.3.1 Steel *308*
7.3.2 Composites *308*
7.3.2.1 Glass Fibers *308*
7.3.2.2 Matrix (Binder) *309*
7.3.2.3 Carbon Fiber Reinforcing *309*
7.3.2.4 Wood–Epoxy Laminates *309*
7.3.2.5 Fatigue Damage in Composites *310*
7.3.3 Copper *310*
7.3.4 Concrete *310*
7.3.5 Materials for Offshore Applications *311*
7.3.5.1 Corrosion Prevention *311*
7.3.5.2 Floating Systems – Lightweight Designs *312*
7.4 Machine Elements *312*
7.4.1 Shafts *312*
7.4.2 Couplings *313*
7.4.3 Bearings *313*
7.4.4 Gears *314*
7.4.4.1 Gear Terminology *315*
7.4.4.2 Gear Speed Relations *316*
7.4.4.3 Gear Loading *316*
7.4.4.4 Gear Dynamic Loading *316*
7.4.5 Dampers *317*
7.4.6 Fastening and Joining *317*
7.5 Principal Components of the Rotor Nacelle Assembly (RNA) *317*
7.5.1 Rotor *317*
7.5.1.1 Blades *318*
7.5.1.2 Aerodynamic Control Options *324*
7.5.1.3 Hub *325*
7.5.2 Drivetrain *329*
7.5.2.1 Main Shaft *329*
7.5.2.2 Couplings *330*
7.5.2.3 Gearbox *331*
7.5.2.4 Generator *335*
7.5.2.5 Direct-Drive Generators *335*
7.5.2.6 Brakes *336*
7.5.3 Yaw System *337*
7.5.3.1 Function *337*
7.5.3.2 Types *337*

7.5.3.3 Description *337*
7.5.4 Main Frame and Nacelle *338*
7.5.4.1 Main Frame *338*
7.5.4.2 Nacelle Housing *339*
References *339*

8 Wind Turbine Design and Testing *343*
8.1 Overview *343*
8.1.1 Overview of Design Issues *343*
8.2 Design Basis for Wind Turbines *344*
8.2.1 Wind Turbine Design Philosophy *344*
8.2.2 Guiding Considerations for Wind Turbine Design *344*
8.2.2.1 Operating Conditions *345*
8.3 Design Process *345*
8.3.1 Determine Application *345*
8.3.2 Review Previous Experience *346*
8.3.3 Select Topology *346*
8.3.4 Preliminary Loads Estimate *346*
8.3.5 Develop Tentative Design *347*
8.3.6 Predict Performance *347*
8.3.7 Evaluate Design *347*
8.3.8 Estimate Costs and Levelized Cost of Energy *348*
8.3.9 Refine Design *348*
8.3.10 Build Prototype *348*
8.3.11 Test Prototype *348*
8.3.12 Design Production Turbine *348*
8.4 Wind Turbine Topologies *348*
8.4.1 Rotor Axis Orientation: Horizontal or Vertical *349*
8.4.2 Rotor Power Control: Stall, Pitch, Yaw, or Aerodynamic Surfaces *349*
8.4.3 Rotor Position: Upwind of Tower or Downwind of Tower *350*
8.4.4 Yaw Control: Free or Active *350*
8.4.5 Rotor Speed: Constant or Variable *351*
8.4.6 Design Tip-Speed Ratio and Solidity *351*
8.4.7 Hub: Rigid, Teetering, Hinged Blades, Gimballed *351*
8.4.8 Rigidity: Flexible or Stiff *351*
8.4.9 Number of Blades *352*
8.4.10 Generator Speed *352*
8.4.11 Support Structure *352*
8.4.12 Design Constraints *352*
8.4.12.1 Climatic Factors Affecting Design *353*
8.4.12.2 Site-specific Factors Affecting Design *353*
8.4.12.3 Social and Environmental Factors Affecting Design *353*
8.4.13 Unconventional Wind Turbines *354*
8.5 Wind Turbine Design Standards, Technical Specifications, and Certification *354*
8.5.1 Wind Turbine Standards and Technical Specifications *354*
8.5.2 Certification *355*

8.6 Wind Turbine Design Loads *356*
8.6.1 Overview *356*
8.6.2 Wind Turbine Design Loads and the IEC 61400-1 Design Standard *356*
8.6.2.1 The IEC 61400-1 Design Standard *357*
8.6.3 Design Environmental Conditions *357*
8.6.4 Design Load Cases *357*
8.7 Design Values, Safety Factors, and Probabilistic Design *358*
8.7.1 Conventional Strength Assessment *359*
8.7.2 Varying Loads and Material Properties *359*
8.7.2.1 Accounting for Uncertainties *359*
8.7.3 Design Values, Characteristic Values, and Partial Safety Factors *360*
8.7.3.1 Consequence of Failure *361*
8.7.3.2 Characteristic Values *362*
8.7.4 Method of Partial Safety Factors *362*
8.7.5 *Probabilistic Design and the Probability of Failure *363*
8.7.5.1 Multiple Linearly Related Normally Distributed Random Variables *364*
8.7.5.2 Reliability and the Standard Normal Distribution *364*
8.7.5.3 First Order Reliability Method (FORM) *365*
8.7.5.4 First Order Reliability Method (FORM) for Nonlinear Limit State Equations *366*
8.7.5.5 Inverse First Order Reliability Method (IFORM) *369*
8.7.5.6 Monte Carlo Methods *369*
8.7.5.7 Probabilistic Load Extrapolation *369*
8.8 Scaling Relations *369*
8.8.1 Load Scaling Relations *370*
8.8.2 Power *370*
8.8.3 Rotor Speed *370*
8.8.4 Torque *371*
8.8.5 Aerodynamic Moments *371*
8.8.6 Rotor Weight *371*
8.8.7 Maximum Stresses *371*
8.8.7.1 Stresses Due to Aerodynamic Moments *371*
8.8.7.2 Stresses Due to Blade Weight *371*
8.8.7.3 Stresses Due to Centrifugal Force *372*
8.8.8 Blade Natural Frequencies *372*
8.9 Computer Codes for Wind Turbine Design *373*
8.9.1 Overview of the Use of Computer Codes in the Wind Industry *373*
8.9.2 Categories of Models Used in the Wind Industry *373*
8.9.3 Examples of Computer Codes Used in Wind Turbine Design *374*
8.9.3.1 OpenFAST *374*
8.9.3.2 TurbSim *375*
8.9.3.3 HydroDyn *375*
8.9.3.4 IECWind *375*
8.9.3.5 AirfoilPrep *375*
8.9.3.6 PropID *375*
8.9.3.7 PreComp *375*
8.9.3.8 BModes *375*

8.9.3.9 Aerodyn *375*
8.9.3.10 MoorDyn *376*
8.9.3.11 NuMAD *376*
8.9.3.12 Bladed *376*
8.9.3.13 HAWC2 *376*
8.9.3.14 ROSCO *376*
8.9.3.15 MLife *376*
8.9.4 Verification and Validation of Computer Codes *376*
8.10 Power Curve Prediction *376*
8.10.1 Simplified Power Curve Prediction of Directly Connected, Fixed Pitch Wind Turbines *377*
8.11 Design Evaluation *379*
8.11.1 Wind and Metocean Inputs *379*
8.11.2 Model of Turbine *379*
8.11.3 Simulation *380*
8.11.4 Converting Simulation Outputs to Load Effects *380*
8.11.5 Damage Assessment *380*
8.12 Wind Turbine and Component Testing *380*
8.12.1 A Wind Turbine Test Program *380*
8.12.1.1 Overview *380*
8.12.2 Full-scale Wind Turbine Testing *381*
8.12.2.1 Sensors for Wind Turbine Testing *381*
8.12.2.2 Modal Testing *382*
8.12.2.3 Example of Full-scale Wind Turbine Testing *382*
8.12.3 Component Testing *382*
8.12.3.1 Material Tests *382*
8.12.3.2 Testing of Drivetrain Components *383*
8.12.3.3 Full-scale Testing of Blades *384*
8.12.4 Turbine Testing for Certification *387*
8.12.4.1 Load Measurements *387*
8.12.4.2 Power Performance Testing *388*
8.12.4.3 Sound Emission Tests *388*
8.13 Design of Offshore Wind Turbines *388*
8.13.1 Important Considerations for the Design of the Offshore RNA *389*
8.13.1.1 Rotor – Offshore *389*
8.13.1.2 Drivetrain – Offshore *390*
8.13.1.3 Generator – Offshore *390*
8.13.1.4 Power Control System – Offshore *390*
8.13.1.5 Yaw System – Offshore *390*
8.13.1.6 Nacelle – Offshore *390*
8.13.2 Trends in the Design of Offshore Wind Turbines *390*
8.13.3 Additional Considerations for the Design of Offshore Wind Turbines *391*
References *391*

9 Wind Turbine Control *395*
9.1 Wind Turbine Control Overview *395*
9.1.1 Levels of Control Systems in Wind Turbines *395*
9.1.2 Active and Passive Control *397*
9.1.3 Power Curve and Power Regions *397*

9.2 Key Aspects of Dynamic Control *398*
9.2.1 Control Objectives *399*
9.2.2 Wind Turbine Sensors *400*
9.2.3 Control Actuators *400*
9.2.3.1 Generator Torque Control *401*
9.2.3.2 Pitch Control *401*
9.2.3.3 Yaw Orientation Control *402*
9.2.4 Turbine Power Production and Efficiency *402*
9.2.5 Control Theory with Application to a Pitch Actuator System *403*
9.2.5.1 The Physical System *403*
9.2.5.2 Model Development and Linearization *404*
9.2.5.3 Open-loop and Closed-loop Response to Disturbances *404*
9.2.5.4 Example of Open-loop system *404*
9.2.5.5 Equation Solution Using Laplace Transform – Transfer Function *405*
9.2.5.6 Example of Closed-loop System Using a PID-controller *407*
9.2.5.7 Typical Control Issues – Resonances *408*
9.3 Main Regions of Dynamic Control *409*
9.3.1 Power Curve – Power vs. Wind Speed *409*
9.3.2 Equation of Motion of the Drivetrain *411*
9.3.3 Region 2 Control *412*
9.3.3.1 Overview *412*
9.3.3.2 Derivation of the Proportionality Constant in Region 2 *413*
9.3.4 Region 3 Control *415*
9.3.4.1 Overview *415*
9.3.4.2 Generator Torque Control Strategies in Region 3 *416*
9.3.4.3 *Closed-loop Equations for the Pitch Controller *417*
9.3.4.4 *Open-loop Linearized Drivetrain Equation of Motion *417*
9.3.4.5 *Closed-loop Linearized Drivetrain Equation of Motion *418*
9.3.4.6 *Gain Scheduling of the Pitch Controller *419*
9.3.5 Region Matching *421*
9.3.6 Example Behaviors *421*
9.4 Advanced Control Strategies *423*
9.4.1 Thrust Peak Shaving *423*
9.4.2 Speed Constraints in Region 2 *423*
9.4.3 Controlling Structural Vibrations *424*
9.4.3.1 Controlling Tower Vibrations *425*
9.4.3.2 Controlling Drivetrain Vibrations *425*
9.4.3.3 Additional Structural Dampers *425*
9.4.4 Individual Pitch Control *425*
9.4.5 Smart Rotors *426*
9.4.6 Frequency Control and Grid Integration *427*
9.4.7 Signal Processing and Filtering *427*
9.4.8 Lidar Feedforward *427*
9.4.9 Control of Floating Systems *427*
9.4.10 Wind Farm Control *428*
9.5 Design, Implementation, and Challenges of Dynamic Control *428*
9.5.1 Design of a Dynamic Control System *428*

9.5.1.1 Classic Control System Design Methodology *428*
9.5.1.2 Other Control Design Approaches *428*
9.5.1.3 Wind Turbine System Models *429*
9.5.2 Summary of Control Issues in Wind Turbine Design *430*
9.5.3 Dynamic Control System Implementation *431*
9.5.3.1 Mechanical Control Systems *431*
9.5.3.2 Analog Electrical Circuit Control Systems *431*
9.5.3.3 Digital Control Systems *431*
9.6 Supervisory Control *432*
9.6.1 Operating States *432*
9.6.2 Fault and Component Health Diagnosis *433*
9.6.3 Fail-safe and Fault-tolerant Systems *433*
References *433*

10 Soils, Foundations, and Fixed Support Structures *435*
10.1 Overview *435*
10.2 Soil *435*
10.2.1 Soil Properties *436*
10.2.1.1 Soil Types and Soil Grain Size *437*
10.2.1.2 Types of Soil Based on Moisture Content *437*
10.2.1.3 Specific Weight of Soil *437*
10.2.1.4 Unconfined Compressive Strength *438*
10.2.1.5 Undrained Shear Strength *438*
10.2.1.6 Shear Strength Values from Test Data *438*
10.2.1.7 Friction Angle *438*
10.2.1.8 Cohesion of Soil *439*
10.2.1.9 Modulus of Elasticity of Soil *439*
10.2.2 Assessment of Soil Conditions *439*
10.3 Foundations and Soil Reaction *440*
10.3.1 Bearing Capacity and Foundations *440*
10.3.1.1 Estimation of Ultimate Bearing Capacity for Shallow Foundations *441*
10.3.1.2 Correction Factors *442*
10.3.1.3 Bearing Capacity Factors for Other Types of Foundations *443*
10.3.2 Gravity Foundations *443*
10.3.2.1 Required Weight and Dimensions of Gravity Foundation *443*
10.3.2.2 Gravity Foundation Above Rock *445*
10.3.2.3 Examples of Foundation Design *445*
10.3.3 Pile Foundations and *p–y* Curves *447*
10.3.3.1 *P–y* Method for Piles *447*
10.3.3.2 *P–y* Calculation Example *448*
10.3.4 Suction Caissons (Buckets) *448*
10.4 Support Structure Requirements *449*
10.4.1 Stress *449*
10.4.1.1 Stresses Due to Combined Axial Forces and Moments *450*
10.4.2 Deflection *450*
10.4.3 Natural Frequency *450*
10.4.3.1 Calculation of Natural Frequencies *451*

10.4.3.2 Damping *451*
10.4.4 Buckling *452*
10.4.5 Resistance to Environmental Degradation *453*
10.5 Loads on the Support Structure *453*
10.5.1 Aerodynamic Loading from the Rotor *453*
10.5.2 Tower Drag *453*
10.5.3 Gravity Loads *454*
10.5.4 Wave Loads *454*
10.5.5 Currents *454*
10.5.6 Floating Ice Loads *454*
10.5.7 Soil Loads *454*
10.5.8 Combined Wind and Wave Load Loading *454*
10.6 Towers *454*
10.6.1 General Tower Issues *455*
10.6.2 Tower Materials *456*
10.6.3 Tower Climbing Safety *456*
10.6.4 Tower Top *456*
10.6.5 Tower Erection *456*
10.6.6 Optimization of Tower Design *456*
10.6.7 Tower Optimization Example *458*
10.7 Substructures for Fixed Offshore Wind Turbines *459*
10.7.1 Monopiles *459*
10.7.1.1 Transition Piece *460*
10.7.1.2 Appurtenances *461*
10.7.1.3 Design Variables *461*
10.7.1.4 Monopiles for Deeper Water *461*
10.7.1.5 Example for a Turbine on a Monopile *461*
10.7.2 Gravity-Based Structures *462*
10.7.3 Jackets and Other Multimember Substructures *463*
10.8 Environmental Considerations Regarding Substructures and Foundations *465*
References *465*

11 Floating Offshore Wind Turbines *467*
11.1 Historical Precedents *467*
11.2 Definitions *469*
11.2.1 Main Components *469*
11.2.2 Generic Description of a Vessel and a Floating Substructure *469*
11.2.3 Definitions for Stationkeeping Systems *470*
11.2.4 Main Types of Technologies for Floating Offshore Wind Turbines *471*
11.2.5 Important Geometric Definition for the Study of Vessels *472*
11.3 Topology Options for Floating Offshore Wind Turbines *472*
11.3.1 Overview of Key Features *472*
11.3.2 Barge *473*
11.3.3 Spar *473*
11.3.4 Semisubmersible Platform *475*
11.3.5 Tension Leg Platform *475*
11.4 Fundamental Principles *476*

11.4.1 Buoyancy *476*
11.4.2 Floating Stability *477*
11.4.2.1 Ballast Stabilization *477*
11.4.2.2 Buoyancy Stabilization *477*
11.4.2.3 Mooring Line Stabilization *477*
11.4.2.4 Metacentric Height *478*
11.4.2.5 Maintenance of Near Verticality During Operation *479*
11.4.2.6 Other Considerations *479*
11.5 Floating Substructure/Hulls *479*
11.5.1 Hull Design *479*
11.6 Hydrostatics of Floating Offshore Wind Turbines *480*
11.6.1 General Considerations and Assumptions *480*
11.6.2 Barges *481*
11.6.2.1 Displaced Volume *481*
11.6.2.2 Mass *481*
11.6.2.3 Water Plane Area *482*
11.6.2.4 Center of Buoyancy *482*
11.6.2.5 Center of Gravity *482*
11.6.2.6 Area Moment of Inertia *482*
11.6.2.7 Metacentric Height *482*
11.6.2.8 Platform Pitch Angle *482*
11.6.2.9 Mass Moment of Inertia *483*
11.6.3 Spars *483*
11.6.3.1 Displaced Volume *484*
11.6.3.2 Mass *484*
11.6.3.3 Water Plane Area *484*
11.6.3.4 Center of Buoyancy *484*
11.6.3.5 Center of Gravity *485*
11.6.3.6 Area Moment of Inertia *485*
11.6.3.7 Metacentric Height *485*
11.6.3.8 Platform Pitch Angle *485*
11.6.3.9 Mass Moments of Inertia *486*
11.6.4 Semisubmersibles *486*
11.6.4.1 Displaced Volume *487*
11.6.4.2 Mass *487*
11.6.4.3 Water Plane Area *487*
11.6.4.4 Center of Buoyancy *487*
11.6.4.5 Center of Gravity *487*
11.6.4.6 Area Moment of Inertia *487*
11.6.4.7 Metacentric Height *487*
11.6.4.8 Platform Pitch Angle *488*
11.6.4.9 Mass Moments of Inertia *488*
11.6.5 Tension Leg Platforms *489*
11.6.5.1 Displaced Volume *489*
11.6.5.2 Mass *489*
11.6.5.3 Water Plane Area *490*
11.6.5.4 Center of Buoyancy *490*

11.6.5.5 Center of Gravity *490*
11.6.5.6 Area Moment of Inertia *490*
11.6.5.7 Metacentric Height *490*
11.6.5.8 Forces in the Tendons *490*
11.6.5.9 Platform Pitch Angle *491*
11.6.5.10 Mass Moment of Inertia *491*
11.7 Motions of Floating Wind Turbines *491*
11.7.1 Oscillatory Motions of the Floating Platform *492*
11.7.1.1 Added Mass *493*
11.7.2 Natural Frequencies of Floating Offshore Wind Turbines *493*
11.7.2.1 Heave *493*
11.7.2.2 Roll Natural Frequency *494*
11.7.2.3 Pitch *494*
11.7.2.4 Surge/Sway/Yaw *494*
11.8 Stationkeeping Systems for Floating Offshore Wind Turbines *494*
11.8.1 Mooring Lines *494*
11.8.1.1 Mooring Line Connections *495*
11.8.1.2 Catenary Mooring Lines *495*
11.8.1.3 *Catenary Mooring Lines under Differential Loading *497*
11.8.1.4 Semi-taut Mooring Lines *498*
11.8.1.5 Tendons *499*
11.8.2 Anchors *499*
11.9 Sample Calculations for Typical Floating Offshore Wind Turbines *500*
11.9.1 Barge *501*
11.9.2 Spar *501*
11.9.3 Semisubmersible *502*
11.9.4 Tension Leg Platform *503*
11.9.5 Observations on the Platforms *503*
11.10 *Coupled Aero/Hydro/Structural Dynamics of Floating Offshore Wind Turbines *505*
11.10.1 Example: Two-degrees of Freedom Model of a Floating Wind Turbine *505*
References *508*

12 Wind Farms and Wind Power Plants *511*
12.1 Electrical Grids – Overview *512*
12.2 Conventional Electricity Generators *512*
12.2.1 Rated Power *513*
12.2.2 Fuel vs. Power Relations *513*
12.2.3 No-load Fuel Consumption *513*
12.2.4 Minimum Allowed Power Level *514*
12.2.5 Start-up Time *514*
12.2.6 Minimum Operating Time *514*
12.3 Electrical Loads *514*
12.3.1 Grid Control/Power Balancing *516*
12.3.2 Frequency/Voltage Control *516*
12.4 Transmission and Distribution Systems *517*
12.4.1 General Properties of Transmission Systems *518*
12.4.1.1 Resistance *518*

12.4.1.2 Inductance *518*
12.4.1.3 Capacitance *519*
12.4.1.4 Reactance and Impedance *519*
12.4.2 Overhead AC Transmission Systems *520*
12.4.3 High Voltage Direct Current (HVDC) Transmission *520*
12.5 Offshore Electricity Transmission *521*
12.5.1 Submarine Cables *521*
12.5.1.1 Construction of Cables/Cable Components *522*
12.5.1.2 Cable Conductors *523*
12.5.1.3 Cable Insulation *523*
12.5.1.4 Electrical Properties of Submarine Cables *523*
12.5.1.5 Power Losses in Cables *524*
12.5.1.6 Additional Considerations *524*
12.5.1.7 Commercially Available Cables *524*
12.5.1.8 Examples of Electrical and Mechanical Properties *524*
12.5.1.9 Environmental Factors in Submarine Cables *525*
12.5.1.10 Ampacity of Submarine Cables *525*
12.5.1.11 Overload *525*
12.5.2 HVDC Offshore *525*
12.6 Wind Turbines and Wind Power Plants in Power Systems *526*
12.6.1 *Electrical/Technical Aspects of Wind Power Plants *526*
12.6.1.1 Wind Turbines/Steady-State Voltage Levels *526*
12.6.1.2 Wind Turbines/Unsteady Voltage Levels *528*
12.6.1.3 Voltage Flicker *529*
12.6.1.4 Harmonics *530*
12.6.1.5 Grid Capacity Limitations *530*
12.6.2 Grid Connection Equipment *530*
12.6.3 Wind Plant Operational Considerations *531*
12.6.3.1 Net Load *531*
12.6.3.2 Curtailment *532*
12.6.3.3 Ancillary Services *532*
12.6.3.4 Ramp Rates *532*
12.6.3.5 Wind Power Variability and Unit Commitment *532*
12.7 Power from Wind Plants *533*
12.7.1 Moderate Spatial Separation and Power Smoothing *533*
12.7.2 Wind Farm Power Curves *534*
12.7.3 Larger Spatial Separation and Wind Plant Variability *535*
12.8 Wind Power Plants in the Power Market *535*
12.9 Wind Farm Aerodynamics: Overview *536*
12.10 Characteristics of the Wind Turbine Inflow and Wakes *537*
12.10.1 Main Flow Features of the Near Wake and Far Wake *537*
12.10.2 Impact of Wakes on Downstream Turbines *539*
12.11 Array Losses *539*
12.12 Wake Models *541*
12.12.1 Steady-State and Time-Averaged Wake Models *541*
12.12.2 Jensen–Katić Model *543*
12.12.3 Dynamic Wake Models *544*

12.12.4 CFD Models *545*
12.12.5 Challenges for Wake Modeling *545*
12.13 Wake Effect Mitigation *545*
12.14 Wind Farm Wakes and Blockage Effects *546*
References *547*

13 Wind Energy System Economics *551*
13.1 Introduction *551*
13.2 Overview of Economic Assessment of Wind Energy Systems *551*
13.2.1 Generating Costs of Grid-connected Wind Turbines: Overview *552*
13.2.1.1 Availability *552*
13.2.1.2 Lifetime of the System *552*
13.2.1.3 Capital Costs *553*
13.2.1.4 Financing Costs *554*
13.2.1.5 Operation and Maintenance Costs *554*
13.2.2 Value of Grid-Connected Wind Energy: Overview *554*
13.2.3 Economic Analysis Methods: Overview *555*
13.2.4 Market Considerations: Overview *555*
13.3 Capital Cost Estimation of Wind Turbines *555*
13.3.1 General Considerations *555*
13.3.2 Use of Experience (or Learning) Curves to Predict Capital Costs *556*
13.3.3 Detailed Models for Estimation of Wind Turbine Costs *557*
13.3.3.1 Historical Overview *557*
13.3.4 Wind Farm Costs *560*
13.3.4.1 Onshore Wind Farms *560*
13.3.5 Offshore Wind Farms *560*
13.4 Operation and Maintenance Costs *563*
13.4.1 Land-Based Wind Operation and Maintenance Costs *563*
13.4.2 Offshore Wind Operation and Maintenance Costs *563*
13.5 Value of Wind Energy *565*
13.5.1 Power Purchase Agreements (PPA) *565*
13.5.1.1 Traditional Power Purchase Agreement *565*
13.5.1.2 Virtual Power Purchase Agreement (vPPA) *565*
13.5.1.3 Proxy Generation Power Purchase Agreement (Proxy Gen PPA) *565*
13.5.2 Avoided Cost Valuation *565*
13.5.2.1 Fuel Savings *566*
13.5.2.2 Capacity Value *566*
13.5.3 Environmental Value of Wind Energy *568*
13.5.3.1 Sources of Environmental Benefits *569*
13.5.4 Market Value of Wind Energy *569*
13.5.4.1 Market Applications *569*
13.5.4.2 Wind Project Owners or Developers *570*
13.5.4.3 Types of Revenue *571*
13.5.4.4 Examples *572*
13.6 Economic Analysis Methods *573*
13.6.1 Simplified Economic Analysis Methods *573*
13.6.1.1 Simple Payback Period Analysis *573*

13.6.1.2 Cost of Energy Analysis *574*
13.6.2 Life Cycle Costing Methods *574*
13.6.2.1 Overview and Definition of Life Cycle Costing Concepts and Parameters *575*
13.6.2.2 Life Cycle Costing Analysis Evaluation Criteria *577*
13.6.3 Electric Utility-Based Economic Analysis for Wind Farms *579*
13.6.3.1 EPRI TAG Method *580*
13.6.3.2 Cash Flow Method *581*
13.6.3.3 Economic Performance Sensitivity Analysis *581*
13.7 Wind Energy Market Considerations *582*
13.7.1 Overview *582*
13.7.2 The Market for Onshore Utility-scale Wind Systems *582*
13.7.2.1 International Onshore Wind Energy Market *582*
13.7.2.2 United States Onshore Wind Energy Market *583*
13.7.3 International Offshore Wind Energy Market *583*
13.7.4 Barriers to Wind Energy Deployment *583*
13.7.5 Incentives to Wind Energy Development *585*
References *586*

14 Project Development, Permitting, Environmental Considerations, and Public Engagement *589*
14.1 Overview of the Chapter *589*
14.1.1 National Policies Fostering Wind Energy *589*
14.2 Project Development *590*
14.2.1 Project Development Process and the Development Team *590*
14.2.2 Siting of Land-Based Wind Projects: Challenges and Opportunities *592*
14.3 Offshore Project Development *593*
14.3.1 Marine (Maritime) Spatial Planning: Overview *594*
14.3.2 Navigational Risk Characterization *595*
14.3.3 Marine Archeological Resources and Cultural Heritage *596*
14.3.4 Regulatory Structure for Offshore Wind – The US Case *596*
14.3.5 Environmental Impact Statement/Assessment *597*
14.3.6 Public Engagement and Communities *599*
14.4 Environmental Considerations: Overview *601*
14.5 Visual Impact of Wind Turbines *601*
14.5.1 Visual Impacts: Risk Characterization of Offshore Sites *602*
14.5.2 Visual Impacts: Land-Based Risk Characterization *603*
14.5.3 Delineation of Distance Zones or Zone of Theoretical Visibility *604*
14.5.4 Lighting Impacts *604*
14.5.5 Visual Impact Mitigation Strategies – Offshore and Land-Based *604*
14.5.5.1 Audio-Visual Warning System (AVWS) *605*
14.5.6 Insights from the Social Sciences *606*
14.6 Wind Turbine Noise *606*
14.6.1 Noise and Sound Fundamentals *607*
14.6.1.1 Characteristics of Sound and Noise *607*
14.6.1.2 Sound Power and Pressure Measurement Scales *607*
14.6.1.3 Measurement of Sound or Noise *609*
14.6.2 Noise Mechanisms of Wind Turbines *610*
14.6.2.1 Aerodynamic Noise *610*

14.6.2.2 Amplitude Modulation *611*
14.6.2.3 Mechanical Noise *611*
14.6.3 Noise Prediction from Wind Turbines *612*
14.6.3.1 Single Wind Turbines *612*
14.6.3.2 Multiple Wind Turbines *612*
14.6.4 Noise Propagation from Wind Turbines *613*
14.6.5 Noise Reduction Methods for Wind Turbines *613*
14.6.6 Noise Assessment, Standards, and Regulations *614*
14.6.7 Wind Turbine Sound – Example *614*
14.7 Wind Turbines and Effects on Birds and Bats *615*
14.7.1 Avian Interactions with Land-Based Wind Turbines: Overview *615*
14.7.2 Avian Risk Characterization – Land Based *616*
14.7.3 Bat Risk Characterization – Land-Based *617*
14.7.4 Bird and Bat Monitoring Strategies *618*
14.7.5 Avian Mitigation Concepts *620*
14.7.6 Site-Specific Post-construction Monitoring Studies for Birds and Bats *621*
14.7.7 Bat Fatality Mitigation Concepts *622*
14.7.8 Characterizing Offshore Wind Risks *622*
14.8 Aviation Safety *624*
14.9 Shadow Flicker *624*
14.9.1 Mitigation Possibilities *625*
14.10 Marine Mammals *626*
14.10.1 Marine Mammals – Risk Characterization *626*
14.10.2 Sources of Noise Affecting Marine Mammals *627*
14.10.2.1 Pile-Driving Noise *627*
14.10.2.2 In-Air Noise from Pile Driving *627*
14.10.2.3 Underwater Noise from Vessels *628*
14.10.3 The North Atlantic Right Whale (NARW) *629*
14.10.4 Mitigation Strategies *629*
14.11 Commercial Fisheries: Risk Characterization *630*
14.11.1 Mitigation Hierarchy Strategies *631*
14.12 Electromagnetic Fields and Electromagnetic Interference *632*
14.12.1 EMF Impacts on the Subsea Environment and Communities *632*
14.12.2 Electromagnetic Interference *633*
References *634*

15 Installation, Operation, and Maintenance of Wind Turbines *643*
15.1 Installation of Land-Based Wind Turbines *643*
15.1.1 Fabrication *643*
15.1.2 Site Preparation *644*
15.1.3 Roads in Land-Based Wind Plants *644*
15.1.4 Foundation Installation *644*
15.1.4.1 Excavation *644*
15.1.4.2 Form Work *644*
15.1.4.3 Reinforcing Rod *645*
15.1.4.4 Anchor Bolts *645*
15.1.4.5 Mixing and Pouring the Concrete *645*

15.1.5 Turbine Transportation *645*
15.1.5.1 Blades *645*
15.1.5.2 Towers *646*
15.1.5.3 Nacelle Components *646*
15.1.6 Turbine Assembly and Erection *646*
15.1.7 Grid Connection *648*
15.1.8 Commissioning *648*
15.2 Installation of Offshore Wind Turbines *649*
15.2.1 Preparing for Offshore Installation *650*
15.2.1.1 Overall Logistics *650*
15.2.1.2 Supply Chain Constraints *650*
15.2.1.3 Contingency Planning *650*
15.2.1.4 Port Facilities *650*
15.2.1.5 Installation Vessels *650*
15.2.1.6 Substructure Fabrication and Installation *650*
15.2.1.7 Phased Delivery of the Tower Sections, Nacelle, Hub, and Blades *651*
15.2.1.8 Offshore Electrical System *651*
15.2.1.9 Workforce for the Various Aspects of the Project *651*
15.2.2 Fixed Offshore Turbine Substructure Installation *651*
15.2.2.1 Monopile *651*
15.2.2.2 Gravity Base Structure (GBS) *652*
15.2.2.3 Jacket *652*
15.2.2.4 Suction Bucket *654*
15.2.3 Installation of Floating Wind Turbines *654*
15.2.3.1 Spar *654*
15.2.3.2 Semisubmersible *657*
15.2.3.3 Tension Leg Platform (TLP) *657*
15.2.3.4 Anchors and Mooring Lines *659*
15.2.4 Installation of Offshore Turbine Tower and Rotor/Nacelle Assembly *659*
15.2.4.1 Piecewise Installation Offshore *659*
15.2.4.2 Entire Turbine Assembled Onshore *660*
15.3 Installation of Offshore Electrical Systems *660*
15.3.1 Installation of Offshore Substation Transformer Platform *661*
15.3.2 Submarine Cable Installation *661*
15.3.3 Shore-Side Connection of the Main Transmission Cable *663*
15.4 Vessels for Offshore Wind *663*
15.4.1 Important Terms *663*
15.4.2 Carrying Capacity *664*
15.4.3 Stability *664*
15.4.4 Hulls *664*
15.4.5 Vessel Motion *664*
15.4.6 Forward Motion: Resistance and Propulsion *665*
15.4.6.1 Resistance to Forward Motion *665*
15.4.6.2 Propulsion *667*
15.4.7 Commonly Used Vessels for Offshore Wind *667*
15.4.7.1 Barges *667*
15.4.7.2 Dredges *668*