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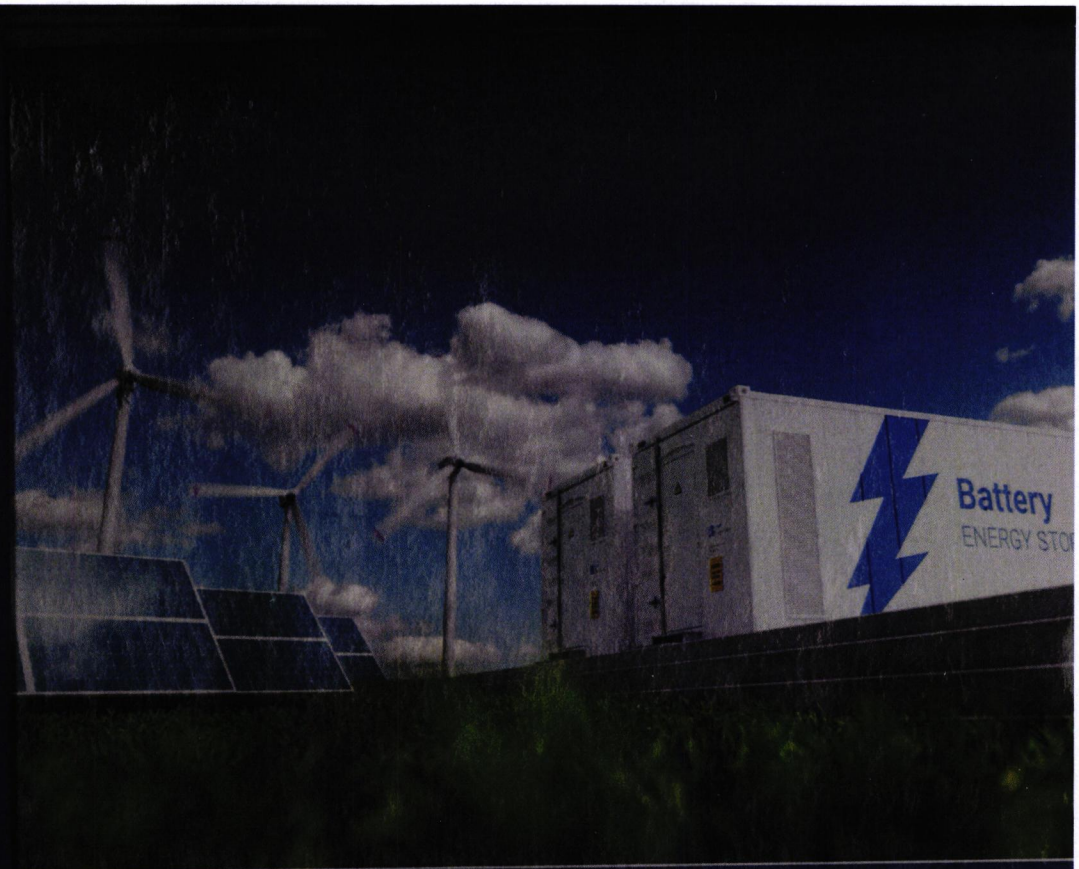
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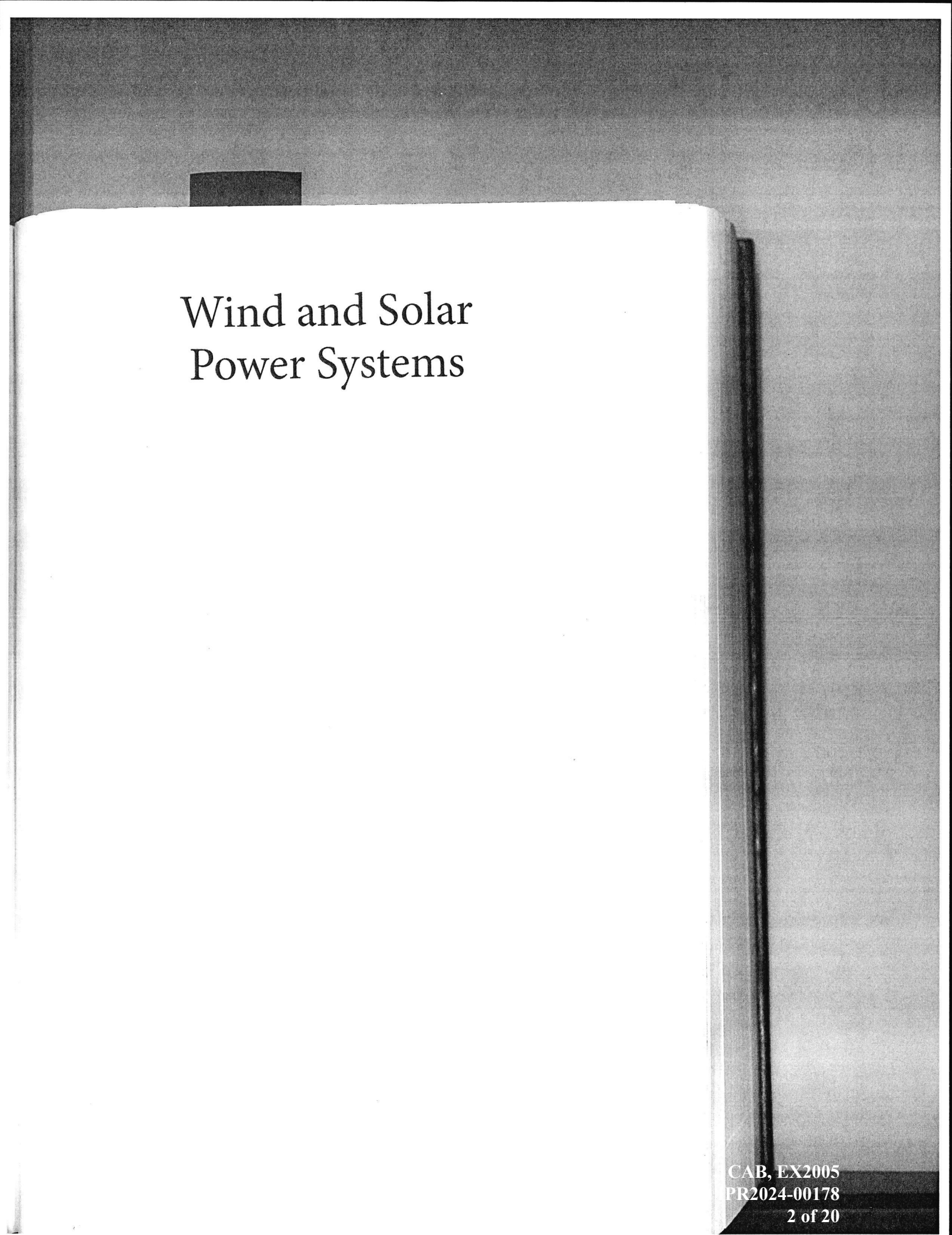
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Third Edition

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Dedications

Dedicated to my parents Shakariba and Ranchhodbhai who practiced ingenuity, and to my grandchildren Rayna, Dhruv, Naiya, Sevina, Viveka and Mira for keeping me young
Mukund Patel

Dedicated to my family
Omid Beik

AB, EX2005
R2024-00178
5 of 20

Contents

Preface xiii
Acknowledgements xv
Author Biographies xvii
List of Abbreviations and Conversion of Units xix
Glossary xxi

PART A Wind Power Systems

Chapter 1 Introduction 3

1.1 Industry Overview 3
1.2 History of Renewable Energy Development 4
1.3 Utility Perspective 7
Further Reading 8

Chapter 2 Wind Power 9

2.1 Wind Power in the World 9
2.2 U.S. Wind Power Development 12
References 13

Chapter 3 Wind Speed and Energy 15

3.1 Speed and Power Relation 15
3.2 Power Extracted from the Wind 17
3.3 Rotor-Swept Area 19
3.4 Air Density 20
3.5 Wind Speed Distribution 21
3.6 Wind Speed Prediction 34
References 34

Chapter 4 Wind Power Systems 37

4.1 System Components 37
4.2 Turbine Rating 45
4.3 Power vs. Speed and TSR 47
4.4 Maximum Energy Capture 49
4.5 Maximum Power Operation 50
4.6 System-Design Trade-offs 52
4.7 System Control Requirements 55

CAB, EX2005
. IPR2024-00178
6 of 20

4.8 Environmental Aspects 57
4.9 Potential Catastrophes 60
4.10 System-Design Trends 61
References 62

Chapter 5 Electrical Generators 63
5.1 Turbine Conversion Systems 63
5.2 Synchronous Generator 66
5.3 Induction Generator 70
5.4 Doubly Fed Induction Generator 82
5.5 Direct-Driven Generator 83
5.6 Unconventional Generators 85
5.7 Multiphase Generators 87
References 89

Chapter 6 Generator Drives 91
6.1 Speed Control Regions 92
6.2 Generator Drives 95
6.3 Drive Selection 98
6.4 Cutout Speed Selection 99
References 100

Chapter 7 Offshore Wind Farms 101
7.1 Environmental Impact 102
7.2 Ocean Water Composition 103
7.3 Wave Energy and Power 105
7.4 Ocean Structure Design 106
7.5 Corrosion 108
7.6 Foundation 108
7.7 Materials 111
7.8 Maintenance 112
References 113

Chapter 8 AC Wind Systems 115
8.1 Overview 115
8.2 Wind Turbine and Wind Farm Components 118
8.3 System Analyses 120
8.4 Challenges 123
References 123

CAB, EX2005
Case No. IPR2024-00178
7 of 20

Chapter 9 DC Wind Systems 125

9.1 Making a Case for All-DC Wind System 125
9.2 Overview 125
9.3 All-DC System Components 128
9.4 System Analyses 133
9.5 Variable Voltage Collector Grid 136
References 139

PART B Photovoltaic Power Systems

Chapter 10 Photovoltaic Power 143

10.1 Building-Integrated PV System 145
10.2 PV Cell Technologies 147
References 153

Chapter 11 Photovoltaic Power Systems 155

11.1 PV Cell 155
11.2 Module and Array 156
11.3 Equivalent Electrical Circuit 157
11.4 Open-Circuit Voltage and Short-Circuit Current 159
11.5 I-V and P-V Curves 160
11.6 Array Design 162
11.7 Peak-Power Operation 171
11.8 System Components of Stand-Alone System 172
References 174

Chapter 12 Solar Power Conversion Systems 175

12.1 Overview 175
12.2 Solar Power Electronics Systems 175
12.3 Challenges 182
12.4 Trend and Future 183
References 184

CAB, EX2005
IPR2024-00178
8 of 20

PART C System Integration

Chapter 13 Energy Storage 189

13.1 Battery 189
13.2 Types of Battery 191
13.3 Equivalent Electrical Circuit 193
13.4 Performance Characteristics 195
13.5 More on Lead-Acid Battery 204
13.6 Battery Design 206
13.7 Battery Charging 207
13.8 Charge Regulators 208
13.9 Battery Management 209
13.10 Flywheel 212
13.11 Superconducting Magnet 217
13.12 Compressed Air 220
13.13 Technologies Compared 222
13.14 More on Lithium-Ion Battery 223
References 226

Chapter 14 Power Electronics 229

14.1 Basic Switching Devices 229
14.2 AC-DC Rectifier 232
14.3 AC-DC Inverter 233
14.4 IGBT/MOSFET-Based Converters 235
14.5 Control Schemes 237
14.6 Multilevel Converters 239
14.7 HVDC Converters 241
14.8 Matrix Converters 243
14.9 Cycloconverter 244
14.10 Grid Interface Controls 244
14.11 Battery Charge/Discharge Converters 246
14.12 Power Shunts 249
References 251

Chapter 15 Stand-Alone Systems 253

15.1 PV Stand-Alone 253
15.2 Electric Vehicle 254
15.3 Wind Stand-Alone 256
15.4 Hybrid Systems 257
15.5 System Sizing 267
15.6 Wind Farm Sizing 271
References 273

CAB, EX2005
Case No. IPR2024-00178
9 of 20

Chapter 16 Grid-Connected Systems 275

16.1 Interface Requirements 276
16.2 Synchronizing with the Grid 278
16.3 Operating Limit 282
16.4 Energy Storage and Load Scheduling 286
16.5 Utility Resource Planning Tools 286
16.6 Wind Farm–Grid Integration 287
16.7 Grid Stability Issues 288
16.8 Distributed Power Generation 290
References 292

Chapter 17 Electrical Performance 295

17.1 Voltage Current and Power Relations 295
17.2 Component Design for Maximum Efficiency 296
17.3 Electrical System Model 298
17.4 Static Bus Impedance and Voltage Regulation 299
17.5 Dynamic Bus Impedance and Ripples 300
17.6 Harmonics 301
17.7 Quality of Power 303
17.8 Renewable Capacity Limit 312
17.9 Lightning Protection 316
References 318

Chapter 18 Plant Economy 319

18.1 Energy Delivery Factor 319
18.2 Initial Capital Cost 320
18.3 Availability and Maintenance 320
18.4 Energy Cost Estimates 323
18.5 Sensitivity Analysis 323
18.6 Profitability Index 326
18.7 Project Finance 327
References 327

Chapter 19 The Future 329

19.1 World Electricity to 2050 329
19.2 Future of Wind Power 331
19.3 PV Future 334
19.4 Declining Production Cost 335
19.5 Market Penetration 337
References 340

CAB, EX2005
o. IPR2024-00178
10 of 20

PART D Ancillary Power Technologies

Chapter 20 Solar Thermal System 343

20.1 Energy Collection 344
20.2 Solar-II Power Plant 345
20.3 Synchronous Generator 347
20.4 Commercial Power Plants 354
20.5 Recent Trends 355
References 355

Chapter 21 Ancillary Power Systems 357

21.1 Heat-Induced Wind Power 357
21.2 Marine Current Power 357
21.3 Ocean Wave Power 361
21.4 Jet-Assisted Wind Turbine 362
21.5 Bladeless Wind Turbine 363
21.6 Solar Thermal Microturbine 363
21.7 Thermophotovoltaic System 365
References 366

Index 369

CAB, EX2005
Case No. IPR2024-00178
11 of 20

Preface

The 3rd edition of this book is an expanded, revised, and updated version of the 2nd edition with new chapters such as AC wind systems, HVDC and all-DC wind systems, multiphase and DC wind turbine conversion systems, and solar power electronics for on-grid and off-grid systems. The new edition is the result of teaching the course to inquisitive students and short courses to professional engineers that enhanced the contents in many ways. The book is designed and tested to serve as textbook for a semester course for university seniors in electrical and mechanical engineering fields. The practicing engineers will get detailed treatment of this rapidly growing segment of the power industry. The government policy makers would benefit by overview of the material covered in the book. The book is divided into four parts in 21 chapters.

Part A covers the wind power technologies. It includes the engineering fundamentals, the probability distributions of the wind speed, the annual energy potential of a site, and the wind power system operation and the control requirements. Since most wind plants use induction generators for converting the turbine power into electrical power, the theory of the induction machine performance and operation is reviewed. The electrical generator speed control for capturing the maximum energy under wind fluctuations over the year is presented. The rapidly developing offshore wind farms with their engineering and operational aspects are covered in detail. Included in Part A are also new chapters on AC wind systems and DC wind systems.

Part B covers the solar photovoltaic technologies and the current developments around the world. It starts with the energy conversion characteristics of the photovoltaic cell, and then the array design, the effect of the environment variables, the sun-tracking methods for the maximum power generation, the controls, and the emerging trends are discussed. A new chapter on modern power electronics needed for solar power conversion for on-grid and off-grid systems is included in Part B.

Part C starts with large-scale energy storage technologies often required to augment non-dispatchable energy sources, such a wind and PV, to improve the availability of power to the users. It covers characteristics of various batteries, their design methods using the energy balance analysis, factors influencing their operation, and the battery management methods. The energy density and the life and operating cost per kWh delivered are presented for various batteries, such as lead-acid, nickel-cadmium, nickel-metal-hydride, and lithium-ion. The energy storage by the flywheel, compressed air, the superconducting coil, and their advantages over the batteries are reviewed. The basic theory and operation of the power electronic converters and inverters used in the wind and solar power systems are then presented. The grid-connected renewable power systems are covered with voltage and frequency control methods needed for synchronizing the generator with the grid. The theory and the operating characteristics of the interconnecting transmission line, the voltage regulation, the maximum power transfer capability, and the static and dynamic stability are covered. About two billion people in the world not yet connected to the utility grid

CAB, EX2005
IPR2024-00178
12 of 20

are the largest potential market of stand-alone power systems using wind and photovoltaic systems in hybrid with diesel generators or fuel cells which are also covered.

Part C continues with the overall electrical system performance, the method of designing system components to operate at their maximum possible efficiency, the static and dynamic bus performance, the harmonics, and the increasingly important quality of power issues applicable to the renewable power systems. The total plant economy and the costing of energy delivered to the paying customers are presented. It also shows the importance of a sensitivity analysis to raise confidence level of the investors. The past and present trends of the wind and PV power, the declining price model based on the learning curve, and the Fisher-Pry substitution model for predicting the future market growth of the wind and PV power based on historical data on similar technologies are presented.

Part D covers the ancillary power system derived from the sun, the ultimate source of energy on the earth. It starts with the utility-scale solar thermal power plant using concentrating heliostats and molten salt steam turbine. It then covers the solar-induced wind power, the marine current power, and the ocean wave power.

List of acronyms and conversion of units are given at the Starting of the book.

CAB, EX2005
Case No. IPR2024-00178
13 of 20

Acknowledgements

Any book of this nature on emerging technologies such as wind and photovoltaic power systems cannot possibly be written without help from many sources. We have been extremely fortunate to receive support from many organizations and individuals. They not only encouraged us to write on this timely subject but also provided valuable suggestions and comments during the development of the book.

The 3rd edition of this book is the extension of the successful 1st and 2nd editions. Therefore, our gratitude remains to Dr. Nazmi Shehadeh, Head of the EE Department at the University of Minnesota, Duluth, who gave Dr. Patel an opportunity to develop and teach this course as a Visiting Professor. Dr. Elliott Bayly of the World Power Technologies in Duluth shared with us his long experience in pioneering wind power systems in the USA. For the 2nd edition, we remain grateful to Prof. Jose Femenia, Head of Marine Engineering at the U.S. Merchant Marine Academy, Kings Point, New York, for supporting our research and publications in this field. For the 3rd edition, as was for the 1st and 2nd editions, several institutions worldwide provided current data and reports on these rather rapidly developing technologies. They are the American Wind Energy Association, the Canadian Wind Energy Association, the American Solar Energy Association, the European Wind Energy Association, the National Renewable Energy Laboratory, the Riso National Laboratory in Denmark, the Tata Energy Research Institute in India, the California Energy Commission, and many corporations engaged in the wind and solar power technologies.

We wholeheartedly acknowledge the valuable support that we have received from all during the course of preparing the book.

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CAB, EX2005
PR2024-00178
14 of 20

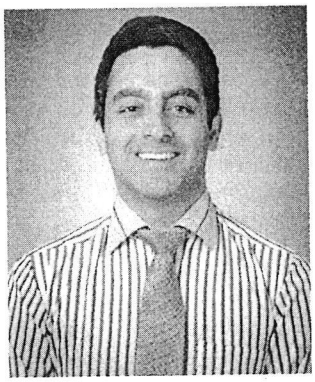
Author Biographies



Mukund R. Patel, PhD, PE, has served as a Professor at the U.S. Merchant Marine Academy in Kings Point, NY; Principal Engineer at General Electric Space Division in Valley Forge, PA; Fellow Engineer at Westinghouse Research Center in Pittsburgh, PA; Senior Staff Engineer at Lockheed Martin in Princeton, NJ; Development Manager at Bharat Bijlee (Siemens) in Mumbai, India; and 3M McKnight Distinguished Visiting Professor at the University of Minnesota, Duluth. He has over 50 years of internationally recognized experience in research, development, design, and education of the state-of-the-art electrical power equipment and systems.

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CAB, EX2005
IPR2024-00178
15 of 20

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CAB, EX2005
Case No. IPR2024-00178
16 of 20

List of Abbreviations and Conversion of Units

AC	Alternating Current
ASES	American Solar Energy Society
AWEA	American Wind Energy Association
Ah	Ampere-hour of the battery capacity
BIPV	Building-integrated photovoltaics
BWEA	British Wind Energy Association
Cp	Rotor energy conversion efficiency
C/D	Charge/discharge of the battery
CTP	Constant power
DC	Direct current
DOD	Depth of discharge of the battery
DOE	Department of Energy
DWIA	Danish Wind Industry Association
ECU	European currency unit
EDF	Energy delivery factor
EPRI	Electric Power Research Institute
EWEA	European Wind Energy Association
GW	Gigawatts (10^9 watts)
GWh	Gigawatthours
HV	High voltage
HVDC	High-voltage direct current (transmission)
IEA	International Energy Agency
IEC	International Electrotechnical Commission
ISES	International Solar Energy Society
kW	Kilowatts
kWh	Kilowatthours
LV	Low voltage
LVRT	Low voltage ride-through
MVDC	Medium voltage DC
MVA	Mega volt amperes
MPPT	Maximum power point tracking
MW	Megawatts
MWa	Megawatts accumulated
MWe	Megawatts electric
MWh	Megawatthours
NEC	National Electrical Code®
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
NWTC	National Wind Technology Center

CAB, EX2005
IPR2024-00178
17 of 20

PM	Permanent Magnet
PV	Photovoltaic
PWM	Pulse width modulation
QF	Qualifying facility
RPM	Revolutions per minute
SiC	Silicon Carbide
SOC	State of charge of the battery
SRC	Specific rated capacity (kW/m^2)
THD	Total harmonic distortion in quality of power
THM	Top head mass (nacelle + rotor)
TPV	Thermophotovoltaic
TSR	Tip speed ratio (of rotor)
TWh	Trillion (10^{12}) watthours
UCE	Unit cost of energy
VSC	Voltage source converter
WF	Wound field
Wp	Watt peak

PREFIXES

k	kilo (10^3)
M	Mega (10^6)
G	Giga (10^9)
T	Trillion (10^{12})

CAB, EX2005
Case No. IPR2024-00178
18 of 20

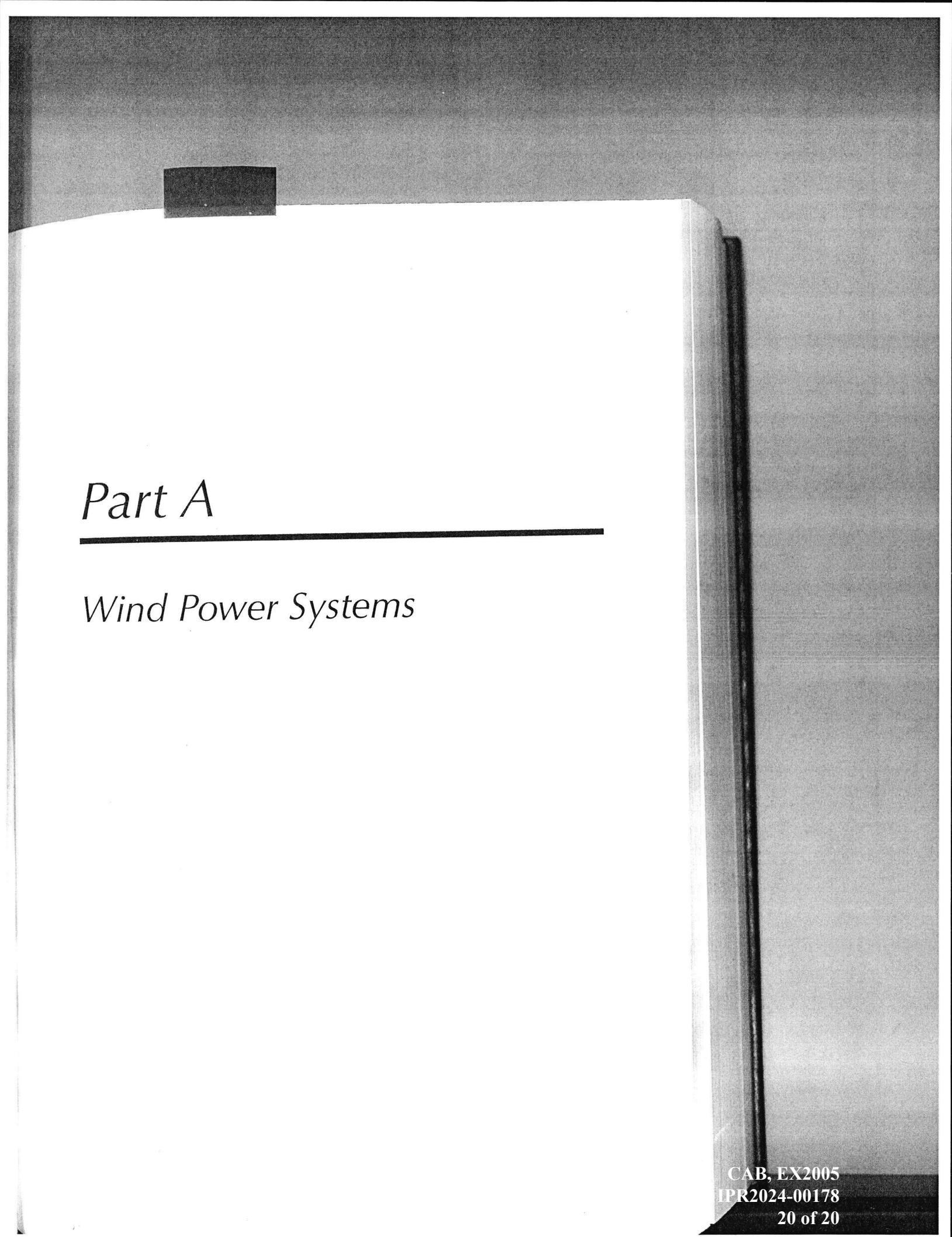
Glossary

CONVERSION OF UNITS

The information contained in the book comes from many sources and many countries using different units in their reports. The data are kept in the form they were received by the authors and were not converted to a common system of units. The following is the conversion table for the most commonly used units in the book:

To Change From	Into	Multiply By
mph	m/sec	0.447
kn	m/sec	0.514
mi	km	1.609
ft	m	0.3048
in.	cm	2.540
lb	kg	0.4535
Btu	W·sec	1054.4
Btu	kW·h	2.93×10^{-4}
Btu/ft^2	W·sec/m^2	11357
Btu/h	W	0.293
Btu/ft^2/h	kW/m^2	3.15×10^{-7}
Btu/h/ft^2/°F	W/m^2/°C	5.678
hp	W	746
gallon of oil (U.S)	kWh	42
gal (U.S.)	liter	3.785
barrel of oil	Btu	6×10^6
barrel	gal (U.S.)	42

CAB, EX2005
No. IPR2024-00178
19 of 20



Part A

Wind Power Systems

CAB, EX2005
IPR2024-00178
20 of 20