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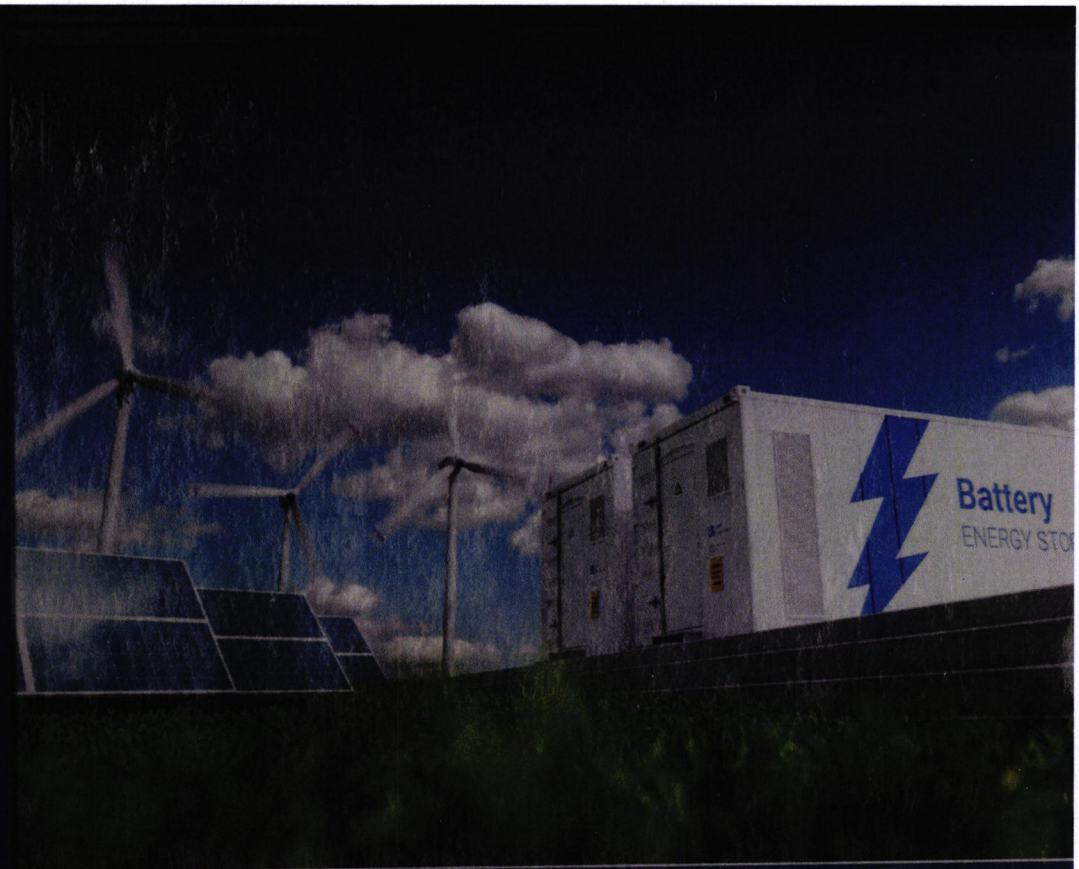
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Wind and Solar Power Systems

Design, Analysis, and Operation

Third Edition

Mukund R. Patel
Omid Beik

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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

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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

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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.

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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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Toronto, Canada

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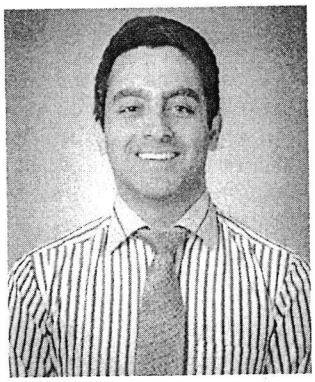
Author Biographies



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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

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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})

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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

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Part A

Wind Power Systems

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