Alternative Energy in POWER ELECTRONICS

Muhammad H. Rashid

Alternative Energy in Power Electronics

Edited by

Muhammad H. Rashid
Fellow IET (UK), Life Fellow IEEE (USA)
Department of Electrical and Computer Engineering
University of West Florida
USA

AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO
Butterworth-Heinemann is an imprint of Elsevier

Butterworth-Heinemann is an imprint of Elsevier
225 Wyman Street, Waltham, MA 02451, USA
The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, UK

Library of Congress Cataloging-in-Publication Data
Alternative energy in power electronics / [edited by] Muhammad H. Rashid.
pages cm
ISBN 978-0-12-416714-8 (pbk.)
1. Power electronics. I. Rashid, Muhammad H. (Muhammad Harunur), 1945- editor.
TK7881.15.A48 2015
621.31′7–dc23
2014035517

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN: 978-0-12-416714-8

For information on all Butterworth-Heinemann publications visit our web site at http://store.elsevier.com

Alternative Energy in Power Electronics

Contributors

Noradlina Abdullah Transmission and Distribution, TNB Research, Malaysia

Benjamin Blunier Universite de Technologie de Belfort-Montbeliard, Belfort Cedex, France

Juan M. Carrasco Department of Electronic Engineering, Engineering School, Seville University, Spain

Pablo A. Cassani Power Electronics and Energy Research (PEER) Group, P. D. Ziogas Power Electronics Laboratory, Department of Electrical and Computer Engineering, Concordia University, Montreal, QC, Canada

Lana El Chaar Electrical Engineering Department, The Petroleum Institute, Abu Dhabi, UAE

H. Dehbonei Department of Electrical and Computer Engineering, Curtin University of Technology, Perth, Western Australia, Australia

Eduardo Galván Department of Electronic Engineering, Engineering School, Seville University, Spain

Ir. Zahrul Faizi bin Hussien Transmission and Distribution, TNB Research, Malaysia

S. M. Islam Department of Electrical and Computer Engineering, Curtin University of Technology, Perth, Western Australia, Australia

Alireza Khaligh Electrical and Computer Engineering Department, University of Maryland at College Park, College Park, MD, USA

Srdjan Lukic Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC, USA

S.K. Mazumder, Sr. Department of Electrical and Computer Engineering, Laboratory for Energy and Switching-Electronics Systems (LESES), University of Illinois, Chicago, IL, USA

C. V. Nayar Department of Electrical and Computer Engineering, Curtin University of Technology, Perth, Western Australia, Australia

Omer C. Onar Power Electronics and Electric Machinery Group, National Transportation Research Center, Oak Ridge National Laboratory, Oak Ridge, TN, USA

Ramón Portillo Department of Electronic Engineering, Engineering School, Seville University, Spain

Azlan Abdul Rahim Transmission and Distribution, TNB Research, Malaysia

H. Sharma Research Institute for Sustainable Energy, Murdoch University, Perth, Western Australia, Australia

K. Tan Department of Electrical and Computer Engineering, Curtin University of Technology, Perth, Western Australia, Australia

Sheldon S. Williamson Power Electronics and Energy Research (PEER) Group, P. D. Ziogas Power Electronics Laboratory, Department of Electrical and Computer Engineering, Concordia University, Montreal, QC, Canada

Preface

Electric power generated from renewable energy sources is getting increasing attention and supports for new initiatives and developments in order to meet the increased energy demands around the world. The availability of computer–based advanced control techniques along with the advancement in the high-power processing capabilities is opening new opportunity for the development, applications and management of energy and electric power. Power Electronics is integral part of the power processing and delivery from the energy sources to the utility supply and the electricity consumers.

The demand for energy, particularly in electrical forms, is ever-increasing in order to improve the standard of living. Power electronics helps with the efficient use of electricity, thereby reducing power consumption. Semiconductor devices are used as switches for power conversion or processing, as are solid state electronics for efficient control of the amount of power and energy flow. Higher efficiency and lower losses are sought for devices used in a range of applications, from microwave ovens to high-voltage dc transmission. New devices and power electronic systems are now evolving for even more effective control of power and energy.

Power electronics has already found an important place in modern technology and has revolutionized control of power and energy. As the voltage and current ratings and switching characteristics of power semiconductor devices keep improving, the range of applications continue to expand in areas, such as lamp controls, power supplies to motion control, factory automation, transportation, energy storage, multi-megawatt industrial drives, and electric power transmission and distribution. The greater efficiency and tighter control features of power electronics are becoming attractive for applications in motion control by replacing the earlier electromechanical and electronic systems. Applications in power transmission and renewable energy include high-voltage dc (VHDC) converter stations, flexible ac transmission system (FACTS), static var compensators, and energy storage. In power distribution, these include dc-to-ac conversion, dynamic filters, frequency conversion, and custom power system.

Audience:
The purpose of *Alternative Energy in Power Electronics* is a derivative of the best-selling *Power Electronics Handbook*, Third Edition. The purpose of *Alternative Energy in Power Electronics* is to provide a reference that is both concise and useful for engineering students and practicing professionals. It

is designed to cover topics that relate to renewable energy processing and delivery. It is designed as advanced textbooks and professional references. The contributors are leading authorities in their areas of expertise. All were chosen because of their intimate knowledge of their subjects, and their contributions make this a comprehensive state-of-the-art guide to the expanding filed energy of energy.

Muhammad H. Rashid, Editor-in-Chief

Any comments and suggestions regarding this book are welcome. They should be sent to

Dr. Muhammad H. Rashid
Professor
Department of Electrical and Computer Engineering
University of West Florida
11000 University Parkway Pensacola.
FL 32514-5754, USA
E-mail: mrashidfl@gmail.com
Web: http://uwf.edu/mrashid

Contents

Contributors xi
Preface xiii

1. **Power Electronics for Renewable Energy Sources** 1
C. V. Nayar, S. M. Islam, H. Dehbonei, K. Tan, and H. Sharma

1.1 **Introduction** 2
1.2 **Power Electronics for Photovoltaic Power Systems** 3
1.2.1 Basics of Photovoltaics 3
1.2.2 Types of PV Power Systems 6
1.2.3 Stand-alone PV Systems 9
1.2.4 Hybrid Energy Systems 25
1.2.5 Grid-connected PV Systems 32
1.3 **Power Electronics for Wind Power Systems** 49
1.3.1 Basics of Wind Power 51
1.3.2 Types of Wind Power Systems 58
1.3.3 Stand-alone Wind Power Systems 58
1.3.4 Wind–diesel Hybrid Systems 59
1.3.5 Grid-connected Wind Energy Systems 60
1.3.6 Control of Wind Turbines 62
References 75

2. **Energy Sources** 81
Omer C. Onar, and Alireza Khaligh

2.1 **Introduction** 82
2.2 **Available Energy Sources** 89
2.2.1 Coal 89
2.2.2 Oil 89
2.2.3 Natural Gas 90
2.2.4 Hydropower 90
2.2.5 Nuclear Power 90
2.2.6 Solar 91
2.2.7 Wind 91
2.2.8 Ocean 91
2.2.9 Hydrogen 92
2.2.10 Geothermal 93
2.2.11 Biomass 93

2.3	**Electric Energy Generation Technologies**		**94**
	2.3.1	Thermoelectric Energy	94
	2.3.2	Hydroelectric Energy	97
	2.3.3	Solar Energy Conversion and Photovoltaic Systems	99
	2.3.4	Wind Turbines and Wind Energy Conversion Systems	111
	2.3.5	Ocean Energy Harvesting	122
	2.3.6	Geothermal Energy Systems	133
	2.3.7	Nuclear Power Plants	136
	2.3.8	Fuel Cell Power Plants	138
2.4	**Other Unconventional Energy Sources and Generation Technologies**		**142**
	Summary		**142**
	References		**143**

3. Photovoltaic System Conversion 155

Lana El Chaar

3.1	**Introduction**		**155**
3.2	**Solar Cell Characteristics**		**156**
3.3	**Photovoltaic Technology Operation**		**160**
3.4	**Maximum Power Point Tracking Components**		**161**
	3.4.1	Voltage Feedback Control	162
	3.4.2	Power Feedback Control	162
3.5	**MPPT Controlling Algorithms**		**162**
	3.5.1	Perturb and Observe (PAO)	162
	3.5.2	Incremental Conductance Technique (ICT)	163
	3.5.3	Constant Reference	164
	3.5.4	Current-Based Maximum Power Point Tracker	164
	3.5.5	Voltage-Based Maximum Power Point Tracker	165
	3.5.6	Other Methods	165
3.6	**Photovoltaic Systems' Components**		**166**
	3.6.1	Grid-Connected Photovoltaic System	166
	3.6.2	Stand-Alone Photovoltaic Systems	169
3.7	**Factors Affecting PV Output**		**170**
	3.7.1	Temperature	171
	3.7.2	Dirt and Dust	171
	3.7.3	DC–AC Conversion	171
3.8	**PV System Design**		**171**
	3.8.1	Criteria for a Quality PV System	171
	3.8.2	Design Procedures	171
	3.8.3	Power-Conditioning Unit	172
	3.8.4	Battery Sizing	172
	Summary		**172**
	References		**172**

4. **Wind Turbine Applications** 177

Juan M. Carrasco, Eduardo Galván, and Ramón Portillo

4.1 **Wind Energy Conversion Systems** 178
4.1.1 Horizontal-axis Wind Turbine 178
4.1.2 Simplified Model of a Wind Turbine 183
4.1.3 Control of Wind Turbines 185
4.2 **Power Electronic Converters for Variable Speed Wind Turbines** 188
4.2.1 Introduction 188
4.2.2 Full Power Conditioner System for Variable Speed Turbines 189
4.2.3 Rotor Connected Power Conditioner for Variable Speed Wind Turbines 198
4.2.4 Grid Connection Standards for Wind Farms 208
4.3 **Multilevel Converter for Very High Power Wind Turbines** 211
4.3.1 Multilevel Topologies 211
4.3.2 Diode Clamp Converter (DCC) 211
4.3.3 Full Converter for Wind Turbine Based on Multilevel Topology 213
4.3.4 Modeling 214
4.3.5 Control 216
4.3.6 Application Example 218
4.4 **Electrical System of a Wind Farm** 220
4.4.1 Electrical Schematic of a Wind Farm 220
4.4.2 Protection System 222
4.4.3 Electrical System Safety: Hazards and Safeguards 222
4.5 **Future Trends** 222
4.5.1 Semiconductors 222
4.5.2 Power Converters 224
4.5.3 Control Algorithms 224
4.5.4 Offshore and Onshore Wind Turbines 225
References 228

5. **High-Frequency-Link Power-Conversion Systems for Next-Generation Smart and Micro Grid** 231

S.K. Mazumder, Sr.

5.1 **Introduction** 232
5.2 **Low-Cost Single-Stage Inverter** 234
5.2.1 Operating Modes 234
5.2.2 Analysis 236
5.2.3 Design Issues 237
5.3 **Ripple-Mitigating Inverter** 241
5.3.1 Zero-Ripple Boost Converter (ZRBC) 242
5.3.2 HF Two-Stage DC–AC Converter 247

5.4 **Universal Power Conditioner** 247
5.4.1 Operating Modes 250
5.4.2 Design Issues 254
5.5 **Hybrid-Modulation-Based Multiphase HFL High-Power Inverter** 259
5.5.1 Principles of Operation 260
Acknowledgement 265
Copyright Disclosure 265
References 265

6. **Energy Storage** 267
Sheldon S. Williamson, Pablo A. Cassani, Srdjan Lukic, and Benjamin Blunier

6.1 **Introduction** 268
6.2 **Energy Storage Elements** 269
6.2.1 Battery Storage 269
6.2.2 Ultracapacitor (UC) 271
6.2.3 Flow Batteries and Regenerative Fuel Cells (RFC) 273
6.2.4 Fuel Cells (FC) 274
6.3 **Modeling of Energy Storage Devices** 276
6.3.1 Battery Modeling 276
6.3.2 Electrical Modeling of Fuel Cell Power Sources 278
6.3.3 Electrical Modeling of Photovoltaic (PV) Cells 280
6.3.4 Electrical Modeling of Ultracapacitors (UCs) 282
6.3.5 Electrical Modeling of Flywheel Energy Storage Systems (FESS) 286
6.4 **Hybridization of Energy Storage Systems** 288
6.5 **Energy Management and Control Strategies** 290
6.5.1 Battery State Monitoring 291
6.5.2 Cell Balancing 293
6.6 **Power Electronics for Energy Storage Systems** 296
6.6.1 Advantages and Disadvantages of Li-Ion Battery Packs for HEV/PHEV Applications 297
6.6.2 Operational Characteristics of Classic and Advanced Power Electronic Cell Voltage Equalizers 298
6.7 **Practical Case Studies** 302
6.7.1 Hybrid Electric and Plug-in Hybrid Electric Vehicles (HEV/PHEV) 302
6.7.2 Fuel Cells for Automotive and Renewable Energy Applications 306
6.7.3 Fuel-Cell-Based Hybrid DG Systems 311
Summary 313
References 314

7. Electric Power Transmission 317

Ir. Zahrul Faizi bin Hussien, Azlan Abdul Rahim, and Noradlina Abdullah

7.1 Elements of Power System 317
7.2 Generators and Transformers 318
7.3 Transmission Line 322
7.3.1 Aluminum Conductor Steel-Reinforced, ACSR 323
7.4 Factors That Limit Power Transfer in Transmission Line 323
7.4.1 Static and Dynamic Thermal Rating 323
7.4.2 Thermal Rating 324
7.4.3 Convection Heat Loss 325
7.4.4 Radiative Heat Loss 326
7.4.5 Solar Heat Gain 327
7.4.6 Ohmic Losses ($I^2R(T_C)$) Heat Gain 328
7.5 Effect of Temperature on Conductor Sag or Tension 328
7.5.1 Conductor Temperature and Sag Relationship 328
7.6 Standard and Guidelines on Thermal Rating Calculation 332
7.7 Optimizing Power Transmission Capacity 333
7.7.1 Overview of Dynamic Thermal Current Rating of Transmission Line 333
7.7.2 Example of Dynamic Thermal Current Rating of Transmission Line 337
7.8 Overvoltages and Insulation Requirements of Transmission Lines 338
7.8.1 Overvoltage Phenomena by Lightning Strikes 340
7.8.2 Switching Surges 343
7.8.3 Temporary Overvoltage 344
7.9 Methods of Controlling Overvoltages 344
7.10 Insulation Coordination 345
References 347

Index 349

Chapter 1

Power Electronics for Renewable Energy Sources

C. V. Nayar, S. M. Islam, H. Dehbonei, and K. Tan

Department of Electrical and Computer Engineering, Curtin University of Technology, Perth, Western Australia, Australia

H. Sharma

Research Institute for Sustainable Energy, Murdoch University, Perth, Western Australia, Australia

Chapter Outline

1.1 Introduction 2
1.2 Power Electronics for Photovoltaic Power Systems 3
1.2.1 Basics of Photovoltaics 3
1.2.2 Types of PV Power Systems 6
1.2.3 Stand-alone PV Systems 9
1.2.3.1 Battery Charging 9
1.2.3.2 Inverters for Stand-alone PV Systems 15
1.2.3.3 Solar Water Pumping 18
1.2.4 Hybrid Energy Systems 25
1.2.4.1 Series Configuration 26
1.2.4.2 Switched Configuration 27
1.2.4.3 Parallel Configuration 28
1.2.4.4 Control of Hybrid Energy Systems 30
1.2.5 Grid-connected PV Systems 32
1.2.5.1 Inverters for Grid-connected Applications 33
1.2.5.2 Inverter Classifications 33
1.2.5.3 Inverter Types 34
1.2.5.4 Power Control through PV Inverters 40
1.2.5.5 System Configurations 45
1.2.5.6 Grid-compatible Inverters Characteristics 47
1.3 Power Electronics for Wind Power Systems 49
1.3.1 Basics of Wind Power 51
1.3.1.1 Types of Wind Turbines 53
1.3.1.2 Types of Wind Generators 54
1.3.2 Types of Wind Power Systems 58

Alternative Energy in Power Electronics

1.3.3 Stand-alone Wind Power Systems 58
1.3.3.1 Battery Charging with Stand-alone Wind Energy System 58
1.3.3.2 Wind Turbine Charge Controller 58
1.3.4 Wind–diesel Hybrid Systems 59
1.3.5 Grid-connected Wind Energy Systems 60
1.3.5.1 Soft Starters for Induction Generators 61
1.3.6 Control of Wind Turbines 62
1.3.6.1 Fixed Speed Wind Turbines 62
1.3.6.2 Variable Speed Wind Turbines 65
1.3.6.3 Discretely Variable Speed Systems 66
1.3.6.4 Continuously Variable Speed Systems 67
1.3.6.5 Types of Generator Options for Variable Speed Wind Turbines Using Power Electronics 70
1.3.6.6 Isolated Grid Supply System with Multiple Wind Turbines 73
1.3.6.7 Power Electronics Technology Development 74
References **75**

1.1 INTRODUCTION

The Kyoto agreement on global reduction of greenhouse gas emissions has prompted renewed interest in renewable energy systems worldwide. Many renewable energy technologies today are well developed, reliable, and cost competitive with the conventional fuel generators. The cost of renewable energy technologies is on a falling trend and is expected to fall further as demand and production increases. There are many renewable energy sources (RES) such as biomass, solar, wind, mini hydro and tidal power. However, solar and wind energy systems make use of advanced power electronics technologies and, therefore the focus in this chapter will be on solar photovoltaic and wind power.

One of the advantages offered by (RES) is their potential to provide sustainable electricity in areas not served by the conventional power grid. The growing market for renewable energy technologies has resulted in a rapid growth in the need of power electronics. Most of the renewable energy technologies produce DC power and hence power electronics and control equipment are required to convert the DC into AC power.

Inverters are used to convert DC to AC. There are two types of inverters: (a) stand-alone or (b) grid-connected. Both types have several similarities but are different in terms of control functions. A stand-alone inverter is used in off-grid applications with battery storage. With back-up diesel generators (such as photovoltaic (PV)/diesel/hybrid power systems), the inverters may have additional control functions such as operating in parallel with diesel generators and bi-directional operation (battery charging and inverting). Grid interactive inverters must follow the voltage and frequency characteristics of the utility generated power presented on the distribution line. For both types of inverters, the conversion efficiency is a very important consideration. Details of stand-alone and grid-connected inverters for PV and wind applications are discussed in this chapter.

Section 1.2 covers stand-alone PV system applications such as battery charging and water pumping for remote areas. This section also discusses power electronic converters suitable for PV-diesel hybrid systems and grid-connected PV for rooftop and large-scale applications. Of all the renewable energy options, the wind turbine technology is maturing very fast. A marked rise in installed wind power capacity has been noticed worldwide in the last decade. Per unit generation cost of wind power is now quite comparable with the conventional generation. Wind turbine generators are used in stand-alone battery charging applications, in combination with fossil fuel generators as part of hybrid systems and as grid-connected systems. As a result of advancements in blade design, generators, power electronics, and control systems, it has been possible to increase dramatically the availability of large-scale wind power. Many wind generators now incorporate speed control mechanisms like blade pitch control or use converters/inverters to regulate power output from variable speed wind turbines. In Section 1.3, electrical and power conditioning aspects of wind energy conversion systems were included.

1.2 POWER ELECTRONICS FOR PHOTOVOLTAIC POWER SYSTEMS

1.2.1 Basics of Photovoltaics

The density of power radiated from the sun (referred as "solar energy constant") at the outer atmosphere is 1.373 kW/m^2. Part of this energy is absorbed and scattered by the earth's atmosphere. The final incident sunlight on earth's surface has a peak density of 1 kW/m^2 at noon in the tropics. The technology of photovoltaics (PV) is essentially concerned with the conversion of this energy into usable electrical form. Basic element of a PV system is the solar cell. Solar cells can convert the energy of sunlight directly into electricity. Consumer appliances used to provide services such as lighting, water pumping, refrigeration, telecommunication, television, etc. can be run from PV electricity.

Solar cells rely on a quantum-mechanical process known as the "photovoltaic effect" to produce electricity. A typical solar cell consists of a p–n junction formed in a semiconductor material similar to a diode. Figure 1.1 shows a schematic diagram of the cross section through a crystalline solar cell [1]. It consists of a 0.2–0.3 mm thick monocrystalline or polycrystalline silicon wafer having two layers with different electrical properties formed by "doping" it with other impurities (e.g. boron and phosphorous). An electric field is established at the junction between the negatively doped (using phosphorous atoms) and the positively doped (using boron atoms) silicon layers. If light is incident on the solar cell, the energy from the light (photons) creates free charge carriers, which are separated by the electrical field. An electrical voltage is generated at the external contacts, so that current can flow when a load is connected. The photocurrent (I_{ph}), which is internally generated in the solar cell, is proportional to the radiation intensity.

A simplified equivalent circuit of a solar cell consists of a current source in parallel with a diode as shown in Fig. 1.2a. A variable resistor is connected to the solar cell generator as a load. When the terminals are short-circuited, the output voltage and also the voltage across the diode is zero. The entire photocurrent (I_{ph}) generated by the solar radiation then flows to the output. The solar cell current has its maximum (I_{sc}). If the load resistance is increased, which results in an increasing voltage across the p–n junction of the diode, a portion of the current flows through the diode and the output current decreases by the same amount. When the load resistor is open-circuited, the output current is zero and the entire photocurrent flows through the diode. The relationship between current and voltage may be determined from the diode characteristic equation

$$I = I_{ph} - I_0(e^{qV/kT} - 1) = I_{ph} - I_d \tag{1.1}$$

where q is the electron charge, k is the Boltzmann constant, I_{ph} is photocurrent, I_0 is the reverse saturation current, I_d is diode current, and T is the solar cell operating temperature (°K). The current vs voltage (I–V) of a solar cell is thus equivalent to an "inverted" diode characteristic curve shown in Fig. 1.2b.

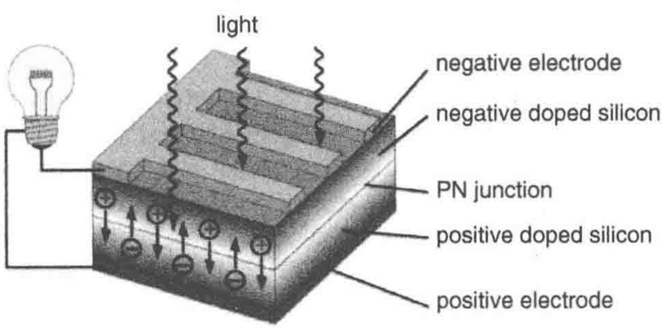

FIGURE 1.1 Principle of the operation of a solar cell [2].