



TAMER KHATIB | WILFRIED ELMENREICH

SIMPLIFIED GREEN CODES

— *Modeling of* —  
PHOTOVOLTAIC  
SYSTEMS  
— *Using* —  
MATLAB®

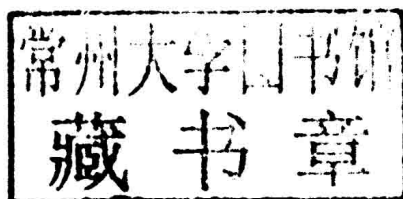
WILEY

# MODELING OF PHOTOVOLTAIC SYSTEMS USING MATLAB®

---

**Simplified Green Codes**

**TAMER KHATIB  
WILFRIED ELMENREICH**



**WILEY**

Copyright © 2016 by John Wiley & Sons, Inc. All rights reserved

Published by John Wiley & Sons, Inc., Hoboken, New Jersey  
Published simultaneously in Canada

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at [www.wiley.com](http://www.wiley.com).

The right of the author to be identified as the author of this work has been asserted in accordance with the Copyright, Designs and Patents Act 1988.

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 the UK Copyright, Designs and Patents Act 1988, without the prior permission of the publisher.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The publisher is not associated with any product or vendor mentioned in this book.

**Limit of Liability/Disclaimer of Warranty:** While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. It is sold on the understanding that the publisher is not engaged in rendering professional services and neither the publisher nor the author shall be liable for damages arising herefrom. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

MATLAB® is a trademark of The MathWorks, Inc. and is used with permission. The MathWorks does not warrant the accuracy of the text or exercises in this book. This book's use or discussion of MATLAB® software or related products does not constitute endorsement or sponsorship by The MathWorks of a particular pedagogical approach or particular use of the MATLAB® software.

*Library of Congress Cataloging-in-Publication Data*

Names: Khatib, Tamer, 1985– | Elmenreich, Wilfried.

Title: Modeling of photovoltaic systems using MATLAB® : simplified green codes / by Tamer Khatib, Wilfried Elmenreich.

Description: Hoboken, New Jersey : John Wiley & Sons, Inc., [2016] | Includes bibliographical references and index.

Identifiers: LCCN 2016015707 | ISBN 9781119118107 (cloth) | ISBN 9781119118121 (epub)

Subjects: LCSH: Photovoltaic power generation—Design and construction—Data processing. | MATLAB.

Classification: LCC TK1087 .K53 2016 | DDC 621.31/244028553—dc23

LC record available at <https://lccn.loc.gov/2016015707>

Set in 10/12pt Times by SPi Global, Pondicherry, India

# **MODELING OF PHOTOVOLTAIC SYSTEMS USING MATLAB®**



## ABOUT THE AUTHORS

Dr. Tamer Khatib, Energy Engineering and Environment Department, An-Najah National University, Nablus, Palestine

Tamer is a photovoltaic power systems professional. He holds a B.Sc. degree in electrical power systems from An-Najah National University, Palestine, as well as a M.Sc. and a Ph.D. degrees in photovoltaic power systems from National University of Malaysia, Malaysia. In addition, he holds a habilitation degree in renewable and sustainable energy from the University of Klagenfurt, Austria. Currently he is an assistant professor at Energy Engineering and Environment Department, An-Najah National University, Nablus, Palestine. So far, he has published over 85 published research articles, meanwhile his current h-index is 14. Moreover, he has supervised six Ph.D. and four M.Sc. researches. He is a senior member of IEEE Power and Energy Society and member of the International Solar Energy Society.

Professor Dr. Wilfried Elmenreich, Smart Grids Group, Alpen-Adria-Universität Klagenfurt, Klagenfurt, Austria

Wilfried Elmenreich studied computer science at the Vienna University of Technology where he received his master's degree in 1998. He became a research and teaching assistant at the Institute of Computer Engineering at Vienna University of Technology in 1999. He received his doctoral degree on the topic of time-triggered sensor fusion in 2002 with distinction. From 1999 to 2007 he was the chief developer of the time-triggered fieldbus protocol TTP/A and the Smart Transducer Interface standard. Elmenreich was a visiting researcher at Vanderbilt University, Nashville, Tennessee, in 2005 and at the CISTER/IPP-HURRAY Research Unit at the Polytechnic Institute of Porto in 2007. By the end of 2007, he moved to the Alpen-Adria-Universität Klagenfurt to become a senior researcher at the Institute of Networked and Embedded Systems. Working in the area of cooperative relaying, he published two patents

together. In 2008, he received habilitation in the area of computer engineering from Vienna University of Technology. In winter term 2012/2013 he was professor of complex systems engineering at the University of Passau. Since April 2013, he holds a professorship for Smart Grids at Alpen-Adria-Universität Klagenfurt. His research projects affiliate him also with the Lakeside Labs research cluster in Klagenfurt. He is a member of the senate of the Alpen-Adria-Universität Klagenfurt, senior member of IEEE, and counselor of Klagenfurt's IEEE student branch. In 2012, he organized the international Advent Programming Contest. Wilfried was editor of four books and published over 100 papers in the field of networked and embedded systems.

# FOREWORD

Recently, photovoltaic system theory became an important aspect that is considered in educational and technical institutions. Therefore, the theory of photovoltaic systems has been assembled and introduced in a number of elegant books. In the meanwhile, the modeling methodology of these systems must be also given a focus as the simulation of these systems is an essential part of the educational and the technical processes in order to understand the dynamic behavior of these systems. Thus, this book aims to present simplified coded models for these systems' component using Matlab. The choice of Matlab codes stands behind the desire of giving the student or the engineer the ability of modifying system configuration, parameters, and rating freely. This book comes with five chapters covering system's component from the solar source until the end user including energy sources, storage, and power electronic devices. Moreover, common control methodologies applied to these systems are also modeled. In addition to that auxiliary components to these systems such as wind turbine, diesel generators and pumps are considered as well.

In general the readership of this book includes researchers, students, and engineers who work in the field of renewable energy and specifically in photovoltaic system. Moreover, the book can be used mainly or partially as a textbook for the following courses:

- Modeling of photovoltaic systems
- Modeling of solar radiation components
- Computer application for photovoltaic systems
- Photovoltaic theory



The authors of this book believe that this book will be helpful for any researcher who is interested in developing Matlab codes for photovoltaic systems, whereas many of the basic parts of system models are provided.

## ACKNOWLEDGMENT

The authors would like to thank Wiley publishing house's editorial team including but not limited to Brett Kurzman, Kathleen Pagliaro, and Divya Narayanan for their kind cooperation. In addition to that, the authors would like to acknowledge the valued contribution of Dr. Ammar Mohammed Ameen, Dr. Dhiaa Halboot Muhsen, Eng. Ibrahim A. Ibrahim, Dr. Aida Fazliana Abdul Kadir, Dr. Manfred Rabl-Pochacker, Dr. Andrea Monacchi, Dr. Dominik Egarter, Ms. Kornelia Lienbacher, and Professor Dr. Azah Mohamed to this book.



*To my daughter Rayna who will be in a dire need for green energy when she understands the contents of this book and to my wife Aida.*

***Tamer Khatib***

*To my daughters Gretchen and Viviane and to my wife Claudia.*

***Wilfried Elmenreich***



# CONTENTS

<b>About the Authors</b>	<b>vii</b>
<b>Foreword</b>	<b>ix</b>
<b>Acknowledgment</b>	<b>xi</b>
<b>1 Modeling of the Solar Source</b>	<b>1</b>
1.1 Introduction, 1	
1.2 Modeling of the Sun Position, 2	
1.3 Modeling of Extraterrestrial Solar Radiation, 8	
1.4 Modeling of Global Solar Radiation on a Horizontal Surface, 13	
1.5 Modeling of Global Solar Radiation on a Tilt Surface, 17	
1.6 Modeling of Solar Radiation Based on Ground Measurements, 21	
1.7 AI Techniques for Modeling of Solar Radiation, 26	
1.8 Modeling of Sun Trackers, 32	
Further Reading, 37	
<b>2 Modeling of Photovoltaic Source</b>	<b>39</b>
2.1 Introduction, 39	
2.2 Modeling of Solar Cell Based on Standard Testing Conditions, 39	
2.3 Modeling of Solar Cell Temperature, 48	
2.4 Empirical Modeling of PV Panels Based on Actual Performance, 48	
2.5 Statistical Models for PV Panels Based on Actual Performance, 49	

2.6	Characterization of PV Panels Based on Actual Performance,	51
2.7	AI Application for Modeling of PV Panels,	52
	Further Reading,	84
<b>3</b>	<b>Modeling of PV System Power Electronic Features and Auxiliary Power Sources</b>	<b>87</b>
3.1	Introduction,	87
3.2	Maximum Power Point Trackers,	87
3.3	DC–AC Inverters,	96
3.4	Storage Battery,	102
3.5	Modeling of Wind Turbines,	107
3.6	Modeling of Diesel Generator,	107
3.7	PV Array Tilt Angle,	108
3.8	Motor Pump Model in PV Pumping System,	113
	Further Reading,	123
<b>4</b>	<b>Modeling of Photovoltaic System Energy Flow</b>	<b>125</b>
4.1	Introduction,	125
4.2	Energy Flow Modeling for Stand-Alone PV Power Systems,	125
4.3	Energy Flow Modeling for Hybrid PV/Wind Power Systems,	129
4.4	Energy Flow Modeling for Hybrid PV/Diesel Power Systems,	129
4.5	Current-Based Modeling of PV/Diesel Generator/Battery System Considering Typical Control Strategies,	136
	Further Reading,	157
<b>5</b>	<b>PV Systems in the Electrical Power System</b>	<b>159</b>
5.1	Overview of Smart Grids,	159
5.2	Optimal Sizing of Grid-Connected Photovoltaic System's Inverter,	161
5.3	Integrating Photovoltaic Systems in Power System,	164
5.4	RAPSim,	168
	Further Reading,	174
<b>6</b>	<b>PV System Size Optimization</b>	<b>175</b>
6.1	Introduction,	175
6.2	Stand-Alone PV System Size Optimization,	176
6.3	Hybrid PV System Size Optimization,	190
6.4	PV Pumping System Size Optimization,	196
	Further Reading,	211
	<b>Index</b>	<b>213</b>

---

# 1

---

## MODELING OF THE SOLAR SOURCE

### 1.1 INTRODUCTION

Solar energy is the portion of the Sun's radiant heat and light, which is available at the Earth's surface for various applications of generating energy, that is, converting the energy form of the Sun into energy for useful applications. This is done, for example, by exciting electrons in a photovoltaic cell, supplying energy to natural processes like photosynthesis, or by heating objects. This energy is free, clean, and abundant in most places throughout the year and is important especially at the time of high fossil fuel costs and degradation of the atmosphere by the use of these fossil fuels. Solar energy is carried on the solar radiation, which consists of two parts: extraterrestrial solar radiation, which is above the atmosphere, and global solar radiation, which is at surface level below the atmosphere. The components of global solar radiation are usually measured by pyranometers, solarimeters, actinography, or pyrheliometers. These measuring devices are usually installed at selected sites in specific regions. Due to high cost of these devices, it is not feasible to install them at many sites. In addition, these measuring devices have notable tolerances and accuracy deficiencies, and consequently wrong/missing records may occur in a measured data set. Thus, there is a need for modeling of the solar source considering solar astronomy and geometry principles. Moreover, the measured solar radiation values can be used for developing solar radiation models that describe the mathematical relations between the solar radiation and the meteorological variables such as ambient temperature,



humidity, and sunshine ratio. These models can be later be used to predict solar radiation at places where there is no solar energy measuring device installed.

### 1.2 MODELING OF THE SUN POSITION

As a fact, the Earth rotates around the Sun in an elliptical orbit. Figure 1.1 shows the Earth rotation orbit around the Sun. The length of each rotation the Earth makes around the Sun is about 8766 h, which approximately stands for 365.242 days.

From the figure, it can be seen that there are some unique points at this orbit. The winter solstice occurs on December 21, at which the Earth is about 147 million km away from the Sun. On the other hand, at the summer solstice, which occurs on June 21, the Earth is about 152 million km from the Sun. However, to provide more accurate points, the Earth is closest to the Sun (147 million km) on January 2, and this point is called perihelion. The point where the Earth is furthest from the Sun (152 million km) is called aphelion and occurs on July 3.

For an observer standing at specific point on the Earth, the Sun position can be determined by two main angles, namely, *altitude angle* ( $\alpha$ ) and *azimuth angle* ( $\theta_s$ ), as seen in Figure 1.2.

From Figure 1.2 the altitude angle is the angular height of the Sun in the sky measured from the horizontal. The altitude angle can be given by

$$\sin \alpha = \sin L \sin \delta + \cos L \cos \delta \cos \omega \tag{1.1}$$

where  $L$  is the latitude of the location,  $\delta$  is the angle of declination, and  $\omega$  is the hour angle.

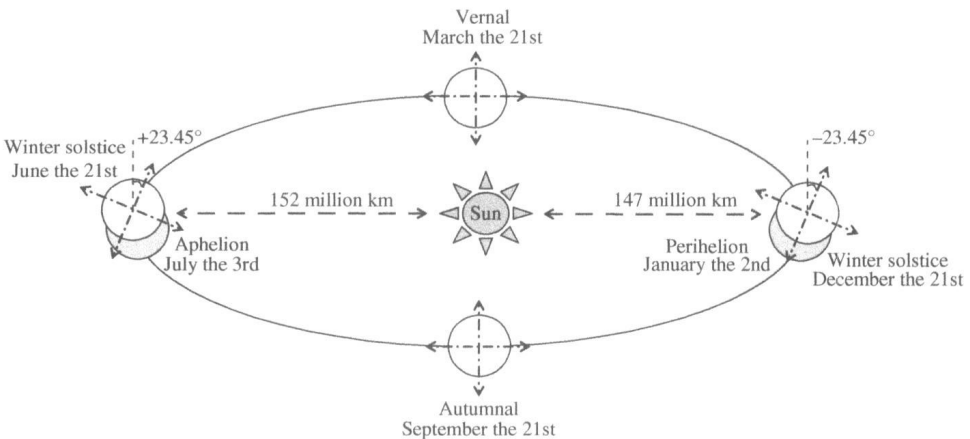


FIGURE 1.1 Earth rotation orbit around the Sun.