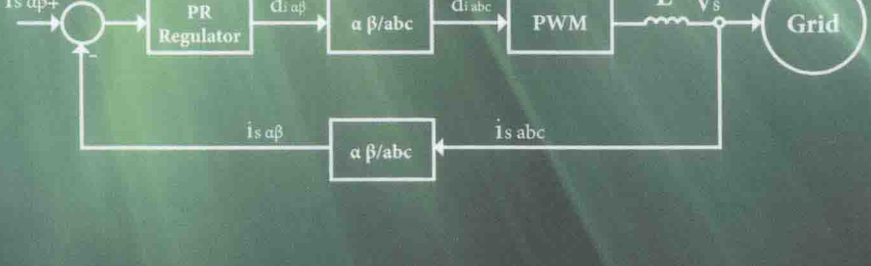
Modeling Power Electronics and Interfacing Energy Conversion Systems

M. Godoy Simões

Felix A. Farret



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

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Library of Congress Cataloging-in-Publication Data:

Names: Simões, M. Godoy, editor. | Farret, Felix A., editor.
Title: Modeling power electronics and interfacing energy conversion systems / edited by Marcelo G. Simões, Felix A. Farret.
Description: Hoboken, New Jersey : John Wiley & Sons, 2017. | Includes bibliographical references and index.
Identifiers: LCCN 2016026094 | ISBN 9781119058267 (cloth) | ISBN 9781119058472 (epub)
Subjects: LCSH: Power electronics–Mathematical models. | Energy conversion–Mathematical models.
Classification: LCC TK7881.15 .M58 2016 | DDC 621.31/7–dc23
LC record available at https://lccn.loc.gov/2016026094

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

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

FOREWORD

This book is an excellent support to a computer-based course for power electronics, power systems, and alternative energy. All of which are extremely important topics nowadays in electrical engineering. Students and practicing engineers with basic knowledge of transient analysis of electric circuits, energy conversion (electric machinery and transformers), and fundamentals of power electronics or power systems can also benefit by studying this book. The chapters follow a progressive complexity. Every chapter has a brief introduction on the background for the particular content in that chapter; some simple problems are solved; a comprehensive laboratory project is discussed with materials and simulation files available for the reader through a Google Group; and suggested problems can be further developed by instructors, which will enhance the understanding of the chapter topics.

The authors seem to have extensive experience in modeling, simulation, and integration of power electronics in very diverse applications, from circuits to power systems; from machines to generators and turbines; and from renewable energy based on wind, photovoltaics (PVs), hydropower, fuel cells, and geothermal to smart-grid applications. Their expertise made possible the innovative presentation of the advanced topics in the book, from the background knowledge of electric circuits, control of DC/DC converters and inverters, energy conversion, and power electronics. The book prepares readers in applying numerical, analytical, and computational methods for multi-domain simulation of energy systems and power electronics engineering problems.

The sequence in the book starts from an introduction to electrical engineering simulation with analysis of electrical circuits, developing modeling of electrical circuits with linear algebra, block diagrams and circuit analysis, and giving hands-on computational experience for the transient response by Laplace transform-based methodologies. Power electronics circuits are modeled based on electrical circuits and on block diagrams, with examples using PSIM, Matlab®, Matlab/Simulink® and Matlab/Power Systems Toolbox, which has been recently renamed to Simscape Power Systems (and it was before called as SimPowerSystems). Practical implementation of control systems will show students and engineers how to use a computer-oriented approach to design a feedback control for DC/DC converters, DC motors, and stand-alone/grid-connected inverters for wind turbines and PV applications.

The book presents an interesting approach on instrumentation and sensor circuits and systems, with examples using PSIM-based simulations. I enjoyed reading the chapter on modeling electrical machines using equivalent circuits with examples of doubly fed induction machines (DFIMs), self-excited induction generators (SEIGs), permanent magnet synchronous machines and a Simulink-based study on transient modeling of single-phase nonideal transformers with distorted sources. I also appreciated their coverage of modeling alternative sources of energy with several examples of typical plants, such as PV, IG, SEIG, doubly fed induction generator (DFIG), permanent magnet synchronous generator (PMSG), fuel cells, lead acid battery storage, and a case study on modeling an integrated power plant with detailed suggested problems alternative sources of energy. The authors have three complex topics, very well organized in stand-alone and grid-connected inverters with their typical control schemes, discussion of IEEE 1547, PI-resonant control, phase-locked-loop (PLL) for synchronization, with a detailed laboratory project with a comprehensive simulation of a grid-connected/stand-alone inverter.

There is a very authoritative discussion in how to convert PSIM-based simulations in TI-DSP-based hardware co-simulation. The authors gave an in-depth presentation of power quality, Fourier Series, and design of power quality-based scripts for evaluation and designing filters for power systems using discrete Fourier transform (DFT) and Matlab with a very interesting chapter on digital processing techniques applied to power electronics, with several DSP techniques, filters, total harmonic distortion (THD) calculation, single- and three-phase PLLs, and maximum power point tracking (MPPT) techniques with a laboratory project in islanding detection based on IEEE 1547.

The book can be used after an introductory course on power electronics, but it might also be used in a one-semester course with intensive lectures plus laboratory. All the problems, projects, and topics can also be implemented in other computational environments. The theory and methodology presented in the chapters can be easily adapted for other simulation software packages, such as Modelica, PLECS, CASPOC, Simplorer, Saber, Mathematica, or Maple.

I believe that the approach in the book is very innovative. There is no other book available in the market that covers such multi-universe of multi-domain analysis for understanding the computational modeling and analysis of the multidisciplinary topics relevant to power electronics. The book is very modern, and it should be adopted by instructors looking to a new way to teach those advanced concepts.

DR. BIMAL K. BOSE
EMERITUS CHAIR PROFESSOR
DEPARTMENT OF EECS
UNIVERSITY OF TENNESSEE, KNOXVILLE

PREFACE

The book started a few years ago when one of us (M. Godoy Simões) was discussing with Prof. B.K. Bose about the need for an integrated companion textbook for analysis and simulation studies in power electronics, power systems, power quality and renewable energy systems, which is typically a very diverse universe. Our approach could contemplate in just one book the most useful techniques in teaching computational and modeling techniques for those topics. Nowadays, students must be trained and have a multidisciplinary understanding to work in advanced power electronics, and learn to integrate power systems with power electronics, electromechanical systems with energy conversion, thermal systems, signal processing, control systems, advanced real-time hardware, DSP, signal processing, mechatronics, renewable energy, and smart-grid applications. Prof. Bose was a great inspiration to us. He strongly motivated us to work in this project.

Both of us decided to cover in this first edition the foundation of topics that are relevant for a computer-based course for students who have some basic knowledge of power systems and/or power electronics, on modeling power electronics, and interfacing energy conversion systems. Both of us have a solid experience in simulation on practical and theoretical power electronics and energy systems. We have intensive laboratory projects, using Matlab®, Simulink®, Power Systems Toolbox, and PSIM, but the problems can be solved in other simulation environments as well. Chapters 11 and 12 were written by our colleagues who are experts on specific subjects, such as hardware-in-the-loop simulation using PSIM, and applications of digital processing techniques.

The book can support a computer-based laboratory for power electronics, power systems, and alternative energy, as well as serve as a self-study material for readers with background in electrical power who wants to understand how to apply mathematical and engineering tools for modeling, simulation, and control design for energy systems and power electronics. The sequence of chapters follows a progressive complexity, serving as a point of departure for other more complex and detailed power electronics and electrical systems projects. Nevertheless, it is possible to change the order or skip material in order to customize a sequence that fits a combination of the fundamental topics (power electronics, power systems, and renewable energy).

The book was written based on problem-based learning strategies, with a few more complex chapters with project-based learning methodologies. Each chapter has a brief introduction on the theoretical background, a description of the problems to be solved, and objectives to be achieved. Block diagrams, electrical circuits, mathematical analysis, or computer code are discussed with very didactical background lines. Computer solutions for the laboratory projects are discussed, and the simulation files are available for readers who register with the Google Group: Power Electronics Interfacing Energy Conversion Systems, the email address is power-electronics-interfacing-energy-conversion-systems@googlegroups.com. After your registration, you will receive information on how to access the simulation files; the Google Group can also be used to communicate among registered readers of the book.

We build the concepts in the book on the background knowledge of electric circuits, control of DC/DC converters and inverters, energy conversion, and power electronics preparing readers in applying the computational methods for multi-domain simulation of energy systems and power electronics engineering problems. The book can be used for a laboratory with lectures on mathematical analysis and theoretical understanding of several relevant electrical energy conversion systems modeling issues plus laboratory experience in simulation implementation through specific software platforms typically used by industries and research institutions, such as Matlab/Simulink, Power Systems Toolbox, and PSIM, but other computational environments could be used, such as PLECS, CASPOC, Simplorer, Mathematica, and MapleSim.

Chapter 1 gives an introduction to electrical engineering simulation, Chapter 2 covers analysis of electrical circuits with mesh and nodal analysis, and Chapter 3 develops modeling and analysis of electrical circuits with block diagrams, with a laboratory project on the transient response study of Laplace transform-based block diagram systems. Introduction to power electronics is covered in Chapter 4, where an electrical circuit simulation is developed using PSIM and Power Systems Toolbox from Matlab, with Matlab analysis. An in-depth coverage of designing power electronics control systems is made in Chapter 5, with discussions of two projects, how to design a DC/DC boost converter and derive their small signal and transfer function with control implementation plus the study of a discrete control system in Matlab and Simulink of a PI-controlled DC motor drive. Chapter 6 covers detailed instrumentation and sensor circuits and systems, with examples of PSIM-based studies; those circuits can also be implemented in electronics-oriented simulators such as NI/MultiSim, Saber, or Matlab/Simscape. Chapter 7 introduces modeling of electrical machines using equivalent circuits, considering satured magnetic core, with examples of DFIG and DFIM, SEIGs, permanent magnet synchronous machines, and a Simulink-based study on transient modeling of a single-phase nonideal transformers with distorted sources. Chapter 8 covers stand-alone and grid-connected inverters typically used for integrating renewable energy sources, with their typical control schemes, discussion of IEEE 1547, PI-resonant control, PLL for synchronization, with a detailed laboratory project with a comprehensive simulation of a grid-connected/stand-alone inverter. Chapter 9 has an extensive coverage of modeling alternative sources of energy with several examples of typical plants, such as PV, IG, SEIG, DFIG, PMSG, fuel cells, lead acid battery storage, and a case study on modeling an integrated power plant with detailed suggested problems alternative sources of energy. Power quality is a very important topic, important in both power systems and power electronics approaches. Therefore, Chapter 10 goes in the details of how to use Fourier series, DFT, and fast Fourier transform (FFT), and how to use Matlab for electrical power and power factor computation of distorted conditions. Chapter 11 shows how to use PSIM simulation for hardware implementation in DSP, with several details of using DSP peripheral blocks with PSIM, code generation and processor-in-the-loop (PIL) simulation. Chapter 12 has a comprehensive coverage of digital processing techniques applied to power electronics, with several DSP techniques, filters, calculation of negative and zero-sequence components with their THD calculation. There are discussions on single-phase and three-phase PLLs, and MPPT techniques with a laboratory project in islanding detection based on IEEE 1547.

The real motivation to write this book is that we are living in the twenty-first century and we need to understand how distributed energy and integration of renewable energy to the utility grid can be advanced with information technology, Internet of Things, and artificial intelligence, in a worldwide requirement for renewable energy sources for a sustainable future. The book will prepare students, engineers, and interested readers to contribute to our society with more smart-grid-based applications, more automation, and more control of energy conversion systems.

We thank our colleagues: Dr. Hua Jin (Powersim Inc.), who collaborated with invited Chapter 11 as well as the Brazilian professors, Dr. Danilo Iglesias Brandão (UFMG, Brazil) and Dr. Fernando Pinhabel Marafão (UNESP, Brazil), who collaborated with invited Chapter 12. Dr. Tiago Davi Curi Busarello helped in several case studies and simulations. We acknowledge and are very grateful with the strong support given by Farnaz Harirchi, who developed several simulation cases and prepared many drawings and figures for the book.

We could not have completed this project without the amazing, continued support and encouragement of our friends; the love of our family; and, of course, motivation provided by our dear students.

M. Godoy Simões, Denver, Colorado, USA
Felix A. Farret, Santa Maria, Brazil

CONTENTS

1

INTRODUCTION TO ELECTRICAL ENGINEERING SIMULATION

Theoretical modeling-based analysis is a process where a model is set up based on laws of nature and logic, using mostly mathematics, physics, and engineering—initially with simplified assumptions about their processes and aiming at finding an input/output model. The following basic procedures and formulations are usually used in supporting a theoretical or an experimental model:

1. Balance equations, for stored masses, energies, and impulses
2. Physical–chemical constitutive equations
3. Phenomenological equations of irreversible processes (thermal conductivity, diffusion, chemical reaction)
4. Entropy balance equations, if several irreversible processes are interrelated
5. Connection equations, describing the interconnection of process elements

Using such formulation principles, a system can be understood in terms of their ordinary differential equations, or their algebraic equations, and then a physical device or a computer simulation or an emulation can be devised in order to obey such equations. The physical system is initialized with their proper initial values, and their development over time mimics the differential equations.

Integrators and function generation can accomplish simulation of an ordinary differential equation (ODE). It has been discussed by Ragazzini in 1947 that the continuous functions of several variables could be approximated by a combination of

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scalar products, scalar functions, and their time derivatives. We have to find first suitable state variables, i.e. variables that account for energy storage. Typically those variables appear differentiated in the ordinary differential equations.

Several computer-based simulations depend on the principles of analog computing, where a differential equation such as Equation 1.1 must be represented in terms of fundamental operations such as integration, addition, multiplication, and function generation. The old analog computer circuitry required scaling of variables, but in a modern computer, floating-point numbers represents the variables and scaling is not required. Higher precision, flexibility for modifications, better stability, reporting facilities, and lower costs are the main advantages of the digital processing. The analog computing may have an advantage for high-speed online data processing, for example, a voltage across a resistor has immediate response. A function such as the one represented by Equation 1.1 requires several interconnections to represent the required calculations.

$$\frac{dx}{dt} = f\left(t,x\right) \tag{1.1}$$

Numerical solution techniques and algorithms to solve differential equation are essential and used in digital computers. There are many ways to find approximate numerical solutions to ordinary differential equations such as the one represented by Equation 1.1. The methods are based on replacing the differential equations by a difference equation. Euler's method is based on the approximation of the derivative by a first-order difference, but there are more efficient techniques such as Runge–Kutta and multistep methods. These methods were well known when digital simulators emerged in the 1960s, but several contributions made them better and more stable when solving difference approximations, for example, the automatic step length adjustment was a very important contribution. A more mathematical-oriented model for dynamical systems can be based on differential–algebraic equations (DAEs), that is, a mixture of differential and algebraic equations, such as those represented by Equation 1.2:

$$g\left(t, x, \dot{x}\right) = 0 \tag{1.2}$$

It is not always possible to convert such an equation to an ODE because the Jacobian $\frac{\partial g}{\partial x}$ may not be invertible. Numerical methods for DAEs appeared during the 1970s. However, even until today, the algorithms for DAEs are still not so well developed as the ones for ordinary differential equations. Most of the reliable computer simulators and emulators are based on numerical solution of ODES. So, a DAE is mostly a mathematical exploration, and usually the engineering and physics problems are modeled using ODEs.

When a system is formulated based on DAEs, the derivatives are not usually expressed explicitly. In addition, some derivatives of some dependent variables may not appear in the equations. A system of DAEs can be converted to a system of ODEs by differentiating it with respect to the independent variable. The index of a DAE is effectively the number of times you need to differentiate the DAEs to get a system of ODEs. Even though the differentiation is possible, it is not generally used as a computational technique because properties of the original DAEs are often lost in numerical simulations of the differentiated equations.

Suppose a linear system is defined by an algebraic, such as Equation 1.3.

$$AX = B \tag{1.3}$$

If A is a $m \times n$ matrix, a numerical solution has the following possible scenarios:

- $m = n$, it is a square system, and it can have a unique solution, as long as there are no rows or columns linearly dependent of the other ones. This is usually a numerical problem of matrix inversion. There are interesting input/output mapping of large systems, where A is not known, and experimental data will support the definition of A, for example, with gradient descent methods for system identification.
- $m > n$, it is an overdetermined (or over identified) system and at least one solution can be defined. Overidentified systems are common in curve fitting to experimental data, and least square methods for minimizing the sum of the data deviation squares from the model are a suitable approach.
- $m < n$, it is an underdetermined system, and a trivial solution with at most m nonzero components can be defined. Undetermined systems involve more unknowns than equations, so the solution is never unique. There is a particular solution computed by the so-called QR factorization with a column pivoting method. This kind of problem may have additional constraints, and the methodology becomes the so-called linear programming.

In this book, we emphasize the applications of ODEs, particularly in their state-space format, for modeling energy systems and power electronics. We can then study their dynamics and transient solutions, or we can use linear algebraic systems to understand static or steady-state solutions for such systems. The approach adopted in this book best fits a senior undergraduate or a first-year graduate course. Differential equation-based systems are developed and simulated from practical examples that focus typical electrical circuit applications, energy conversion, renewable energy sources, interconnection of distributed generation, power electronics, power systems, and power quality problems. The linearization of systems is discussed based on average modeling and the use of Taylor series expansion. Techniques of Fourier expansion are developed for power quality considerations, including the understanding of the discrete Fourier transform (DFT), fast Fourier transform (FFT), and wavelet techniques. MATLAB® will be used for programming, solving several numerical algorithms, and graph plotting. Simulink® is used for block diagram-oriented modeling. Electrical circuit-oriented modeling is analyzed using the Power Systems Toolbox of MATLAB as well as the PSIM circuit simulator.

The analog computing paradigm requires explicit state models and linkage from input towards output. That is a kind of limitation because blocks must have a unidirectional data flow from inputs to outputs, but such paradigm supports the majority of solutions for engineering systems. A consequence is that it is difficult to build physics-based model libraries in the block diagram languages with bidirectional dataflow or bidirectional energy flow. There are other more advanced paradigms for simulation of multiphysics domain in object-oriented programming using software for differential–algebraic systems aiming at noncausal modeling with mathematical equations. Such object-oriented approach facilitates the reuse of modeling knowledge. However, this book is not focused on such advanced hybrid computer simulations. The intention of this book is to support a computer-based laboratory for power electronics, power systems, distributed generation, and alternative energy, as well as to be a self-study material for readers with background in electrical power who want to understand how to apply mathematical and engineering tools for modeling, simulation, and control design of energy systems and power electronics. The sequence of chapters follows a progressive complexity, but it is possible to change the order or skip material in order to customize a sequence that best fits a combination of the fundamental topics (power electronics, power systems, distributed generation, and renewable energy). Most of chapters are centered on a laboratory project as an example, but some chapters are more discursive with practical explanations of how to model a diversity of electrical engineering systems.

This book follows the approach of problem-based learning strategies, with some project-based learning methodologies. Each chapter has a brief introduction on the theoretical background, a description of the problems to be solved, and objectives to be achieved. Block diagrams, electrical circuits, mathematical analysis, or computer code are also discussed. A solution is presented for the problems or the approach of proposed projects. Each chapter helps the reader to understand the theory, modeling, and computational issues approached in that chapter, with suggestions for further studies, work on possible problems, and even to conduct some experimental work.

1.1 FUNDAMENTALS OF STATE-SPACE-BASED MODELING

Most of the electrical systems consisting of a lumped linear network are causal. They can be written in state-space form such as

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{1.4}$$

$$y(t) = Cx(t) + Du(t) \tag{1.5}$$

Such set of first-order differential equations is defined as the state-space equation of the system where $x(t)$ is the state vector, $u(t)$ is the input vector, and $y(t)$ is the output. The second equation is referred to as the output equation. The output is considered a linear combination of states and inputs. The matrix A is called the state matrix, B is the input matrix, C is the matrix of combination of states contributing for the output, and D is the direct transition matrix. One advantage of the state-space formulation is that it is suitable for either analog- or digital-based modeling, control methodology, or mathematical treatment. In addition, the state-space method can be extended to nonlinear systems. State equations can be obtained from a higher-order nth-order differential equation and sometimes from the system model by identifying