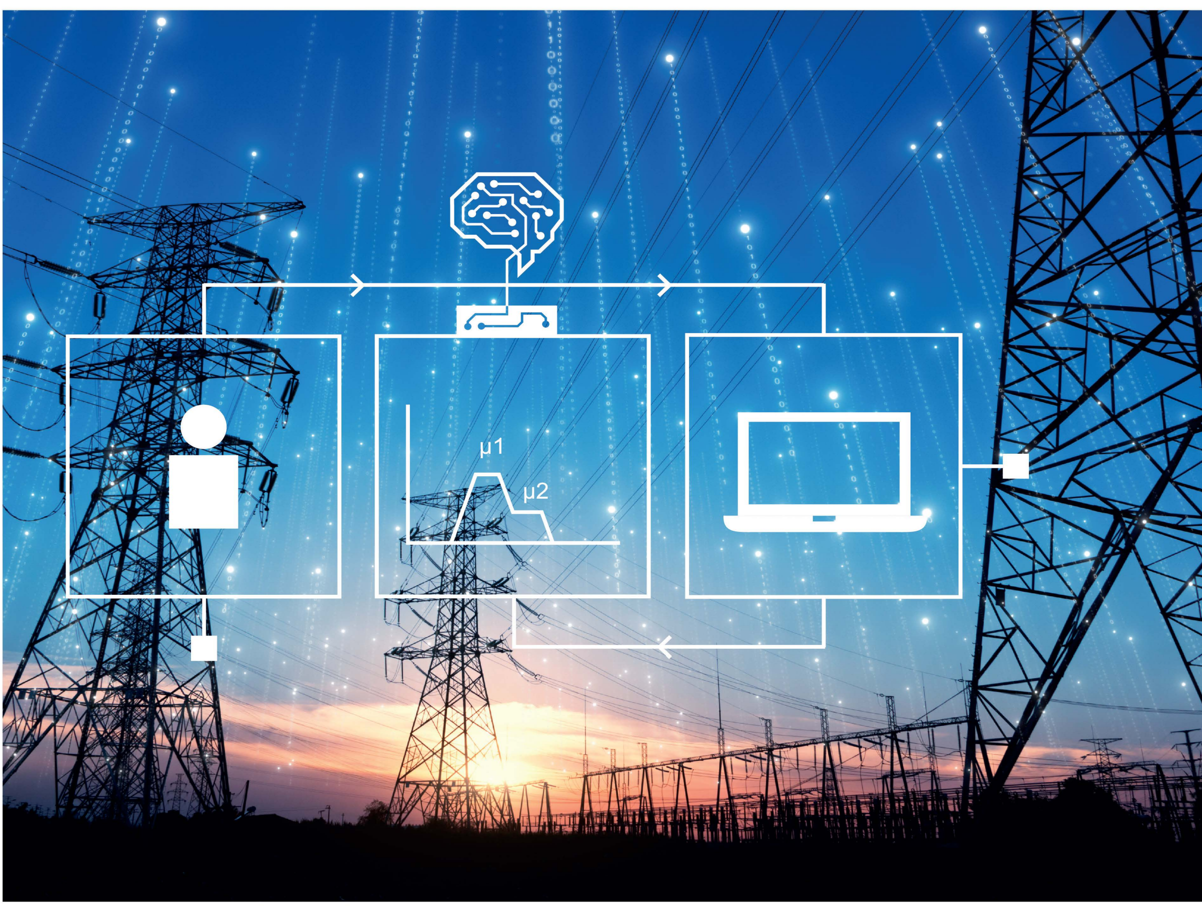
Artificial Intelligence for Smarter Power Systems
Fuzzy logic and neural networks

Marcelo Godoy Simões



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The Institution of Engineering and Technology

Published by The Institution of Engineering and Technology, London, United Kingdom

The Institution of Engineering and Technology is registered as a Charity in England & Wales (no. 211014) and Scotland (no. SC038698).

First published 2021

The Institution of Engineering and Technology
Michael Faraday House
Six Hills Way, Stevenage
Herts, SG1 2AY, United Kingdom

www.theiet.org

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

ISBN 978-1-83953-000-5 (hardback)
ISBN 978-1-83953-001-2 (PDF)

Typeset in India by MPS Limited
Printed in the UK by CPI Group (UK) Ltd, Croydon

I dedicate this book to my wife, Deborah Doin, and to my children: Ahriel Godoy, Lira Godoy, Rafael Doin, and Luiz Notari. There is light and happiness in my life, because I have you.

Contents

About the author

Marcelo Godoy Simões is a Professor in Electrical Power Engineering, in Smart and Flexible Power Systems, at the University of Vaasa (Finland), in the School of Technology and Innovations, with the Electrical Engineering Department. He received a National Science Foundation (USA) CAREER Award, a very prestigious award for new faculty members in 2002. He was an US Fulbright Fellow at Aalborg University (Denmark) and worked as a visiting professor in several international institutions. He is an IEEE Fellow, published hundreds of journal papers and conference articles, and authored 12 books. He has pioneered the application of neural networks and fuzzy logic in renewable energy systems, his credential and publications are authority and relevant for advanced wind turbine control, photovoltaics, fuel cells modelling, smart-grid management and power electronics enabled power systems control for integration of renewable energy sources.

Foreword

It is my pleasure and privilege to write a Foreword for this important book on artificial intelligence (AI) techniques, and their applications in power electronics and power systems. It is well known that the AI techniques, particularly fuzzy logic and neural networks, have already established tremendous importance in power electronics and power systems, among many other industrial and nonindustrial applications. Particularly, their applications are very promising in the emerging next generation of smart grid and renewable energy systems. Again, among all the AI disciplines, it is expected that neural networks will have a maximum impact on power electronics and power systems. The area of power electronics, particularly, is very complex and multidisciplinary. The advancing frontier of power electronics with the AI technology will be challenging to the power electronics engineers. The book is authored by Prof. Marcelo Simoes, who is a world-renowned scientist in AI area. I am proud to mention that Dr. Simoes initiated his pioneering AI research in my power electronics laboratory in the University of Tennessee. It is interesting to note that in 1997, I organized a panel discussion session on advances and trends of power electronics in the IEEE Industrial Electronics Society Conference (IECON-1997), where I invited him as a panelist on AI applications in power electronics. He was the youngest panelist in such most important area. In the last 25 years, since his doctorate degree in 1995, he has established himself as a very prominent scientist in this area. The present book authored by Marcelo is very comprehensive. It extensively reviews the state-of-the-art technologies of fuzzy logic and neural network and their applications in power electronics and power systems. In addition, it includes real-time modeling and simulation, hardware-in-loop testing, deep machine learning, etc., which will be important in emerging smart grid and renewable energy systems applications. Of course, one of the nine chapters has been contributed by OPAL-RT engineers, who are specialized in this area. The book will be important for university professors and other professionals, and students who are doing research in this area. Of course, selected portions of the book can be taught in undergraduate and graduate programs. I wish success for this book.

Dr. Bimal K. Bose, *IEEE Life Fellow*
Emeritus Chair Professor in Electrical Engineering
(Formerly Condra Chair of Excellence in Power Electronics)
Member, US National Academy of Engineering
Department of Electrical Engineering and Computer Science
The University of Tennessee, Knoxville

Preface

I started this book many years ago, and it has been paused on and off due so many other professional priorities, personal matters and evolving of my life as a whole. When I just thought that neural networks were saturated in power electronics and power systems, I observed the rapid evolution of deep learning, at the same time the maturity of smart-grid systems as a core in electrical engineering. I am very proud to introduce this book to our professional community. I hope all who read it, or have any brief consultation on any of the topics, will appreciate a solid foundation of artificial intelligence (AI), fuzzy logic, neural networks, and deep-learning for advancing power electronics, power systems, enhancing the integration of renewable energy sources in a smart-grid system.

When I graduated from Poli/USP in 1985 in Electrical Engineering, my expertise was electronic systems, high frequency circuits, and I was just starting to learn the basics of power electronics. Computer simulation was still based on mainframes, electrical circuit simulation in Spice, software was written in compiled languages, such as Pascal, C, FORTRAN. Designing and implementing a switching power supply required me to understand analog circuits of TVs, reading application notes of semiconductor companies, reverse engineering circuits from computers, taking notes on a notebook to document the design, and eventually burning and destroying many transistors and diodes during the workbench prototyping. I first learned to use MATLAB® in an IBM PC AT in 1988, and when I joined University of Tennessee for my Ph.D. program, I witnessed an evolution in how computer-simulation-based design and digital signal processing (DSP)-based hardware would enhance very complex control algorithms in real-life applications. From 1991 to 1995, I started to study, learn, and to apply fuzzy logic and neural networks in power electronics, enhancing wind energy systems, PV solar systems, and power quality diagnosis and energy management.

In my career, I have been writing books and publishing several papers; I saw how power electronics evolved and became a key enabling technology for the twenty-first century with the technology of smart-grids for the integration of renewable energy resources. The revolution in power electronics was introduced with solid-state power semiconductor devices in the 1950s. AI, initially on the first generation of neural networks, started about the same time, a few years earlier. During the 1960s, fuzzy logic was introduced by Lotfi Zadeh. With the emergence of microprocessors and later DSP controllers, there was a widespread application of power electronics in industrial, commercial, residential, transportation, aerospace, military, and utility systems. From the 1990s to now, we have had the age of industry automation, high efficiency energy systems that include modern renewable energy systems, integration of transmission, and distribution with bulk energy storage, electric and hybrid vehicles, and energy efficiency improvement of electrical equipment.

With the popularization of the backpropagation algorithm in 1985, a second wave of neural network research was made possible with so many topologies and architectures of neural networks, also many expert system shells, fuzzy logic systems for microcontrollers, and PLCS, eventually making the use of AI in power electronics and power systems a reality.

Power electronics is the most important technology in the twenty-first century, and our power systems, utility integration, and distribution systems became a power-electronics-enabled power system, with added intelligence to be a smart-grid system. In such a vision of smart grid, the role of power electronics in high-voltage DC systems, static VAR compensators, flexible AC transmission systems, fuel cell energy conversion systems, uninterruptible power systems, besides the renewable energy and bulk energy storage systems, has tremendous opportunities. In the current trend of our energy scenario, the renewable energy segment is continuously growing, and our dream of 100% renewables in the long run (with the complete demise of fossil and nuclear energy) is genuine. Therefore, the social impact of power electronics in our modern society is undeniable, and this book contributes with nine specialized chapters. After a general introduction in Chapter 1, there is a discussion on Chapter 2 of how hardware-in-the-loop, real-time simulation, and digital twins are enabling future smart-grid applications, with a strong need for AI. Chapters 3, 4, and 5 present everything necessary for an engineer to develop, implement, and deploy fuzzy systems, with all sorts of engine implementations, and how to design fuzzy logic control systems. Chapters 6 and 7 focus on feedforward neural networks and feedback, competitive and associative neural networks, with methods, procedures, and equations, discussed in an agnostic and scientific perspective, so the reader can adopt and adapt the discussions into any modern computer language. Chapter 8 discuss the applications of fuzzy logic and neural networks in power electronics and power systems.

During the twentieth century, particularly after the advent of computers and advances in mathematical control theory, many attempts were made for augmenting the intelligence of computer software with further capabilities of logic, models of uncertainty, and adaptive learning algorithms that made possible the initial developments in neural networks in the 1950s. However, a very radical and fruitful of such foundations was initiated by Lotfi Zadeh in 1965 with publication of his paper "Fuzzy Sets." In such paper, the idea of membership function with a foundation on such a multivalued logic, properties, and calculus became a solid theory and technology that bundled together thinking, vagueness, and imprecision. Every design starts from the process of thinking, i.e., a mental creation, and people will use their own linguistic formulation, with their own analysis and logical statements about their ideas. Then, vagueness and imprecision are considered here as empirical phenomena. Scientists and engineers try to remove most of the vagueness and imprecision of the world by making clear mathematical formulation of laws of physics, chemistry, and the nature in general. Sometimes it is possible to have precise mathematical models, with strong constraints on non-idealities, parameter variation, and nonlinear behavior. However, if the system becomes complex, the lack of ability to measure or to evaluate features, has a lack of definition of precise modeling, in addition to many other uncertainties and incorporation of human expertise, making almost impossible to explore such a very precise model for a complex real-life system. Fuzzy logic and neural network became the foundation for the newly advanced twenty-first century of smart control, smart modeling, intelligent behavior, and AI. This book presents the basics and foundation for fuzzy logic and neural network, with some applications in the area of energy systems, power electronics, power systems, and power quality.

Fuzzy control has a lot of advantages when used for optimization of alternative and renewable energy systems. The parametric fuzzy algorithm is inherently adaptive, because the coefficients can be altered for system tuning. Thus, a real-time adaptive implementation of the parametric approach is feasible by dynamically changing the linear coefficients by means of a recursive least-square algorithm repeatedly on a recurrent basis. Adaptive versions of the rule-based approach, changing the rule weights (Degree of Support) or the membership functions recurrently is possible. The disadvantage of the parametric fuzzy approach is the loss of the linguistic formulation of output consequents, sometimes important for industrial plant/process control environment.

Fuzzy and neuro-fuzzy techniques became efficient tools in modeling and control applications. There are several benefits in optimizing cost effectiveness because fuzzy logic is a methodology for handling inexact, imprecise, qualitative, fuzzy, verbal information such as temperature, wind speed, humidity, and pressure in a systematic and rigorous way. A neuro-fuzzy controller generates, or tunes, the rules or membership functions of a fuzzy controller with an artificial neural network approach.

For applications of alternative and renewable energy systems, it is very important to use AI techniques because the installation costs are high, the availability of the alternative power is by its nature intermittent, and the system must be supplemented by additional sources to supply the demand curve. There are efficiency constraints, and it becomes important to optimize the efficiency of the electric power transfer, even for relatively small incremental gains, in order to amortize installation costs within the shortest possible time. Smart-grid systems must be evaluated in comprehensive case studies, engineering analysis, big databases, with detailed modeling, and simulation techniques.

In this third decade of the twenty-first century, we want young students and junior engineers to become motivated by the third-wave of research in neural networks, i.e., big data analytics, data science, and deep learning. Chapter 9 is extensive in discussing deep learning and big data applications in electrical power systems. The approach is comprehensive, clear, allowing implementation in any hardware and software. The reader will learn what is a deep-learning neural network, how it can be used for classification, regression, clustering, and modeling. How convolutional neural networks can be used for smart-grid applications, and how the previous paradigm of recurrent neural networks has been modernized in the twenty-first century with long short-term memory neural networks (LSTM) and how fuzzy parametric CMAC neural networks can also be applied for current deep-learning AI revolution.

All the chapters review the state of the art, presenting advanced material and application examples. The reader will become familiarized with AI, fuzzy logic, neural networks, and deep learning in a very coherent and clear presentation. I want to convey my sincere enthusiasm with this hopeful timeliness book in your hands. I am very confident that this book fulfills the curiosity and eagerness for knowledge in AI for making power systems, power electronics, renewable energy systems, and smart grid, a legacy for generations to come in this century.

I am grateful to all my past undergraduate and graduate students, most of them are currently working in high technology and advanced in their careers; we became colleagues and professional fellows. I am grateful to all faculty and researchers who have been working with me in this professional journey in the past a little more than three decades in my life. There are so many of you, important in my life, that it is not fair to list names, but we know each other and we support each other.

Specifically, I am very thankful to the support of Dr. Tiago D.C. Busarello who reviewed the manuscript and gave me suggestions for improvements. I am grateful to Alexandre Mafra who kept his professional dream in working with neural networks and gave me valuable feedback. To the group of colleagues and engineers in OPAL-RT and the guest authors of Chapter 2, I show my strong appreciation and gratitude for the collaboration, I am especially grateful to Prof. Bimal K. Bose, my former Ph.D. adviser, who motivated me a few years ago to write this book.

I am grateful, *in memoriam*, to Dr. Paulo E.M. Almeida; he was my Ph.D. student, he became a successful professor and a leader in intelligent automation.

I dedicate this book to you, reader, such a knowledge is for you to advance, for you to make our world better, for you to make our society more prosperous. Thank you for reading this book.

—Marcelo Godoy Simões, Ph.D., IEEE Fellow,
Professor in Electrical Power Engineering, in Smart and Flexible Power Systems, at the University of Vaasa (Finland), in the School of Technology and Innovations, with the Electrical Engineering Department.

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