Renewable Energy Systems

Design and Analysis With Induction Generators

M.Godoy Simoes
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For my mother, Cecília, and my sister, Maysa,

who always believed in my idealism.

For my wife, Luzia, and my children, Ahriel and Lira,

who support me now (M.G.S.).

For my family who, with their love and affection.

helped me write every line I put in this work,

Gerry, Matheus, and Patrick (F.A.F.).

Foreword

It is indeed an honor and a privilege to write the foreword for this important and timely book. We are now at a critical crossroad of our global energy scenario. Energy has been the lifeblood of the continual progress of human civilization. Since the industrial revolution of two centuries ago, global energy consumption has increased by leaps and bounds to improve our living standards, particularly in the industrialized nations of the world.

Currently, about 87% of total energy is generated from fossil fuels (coal, oil, and natural gas), 6% is generated in nuclear plants, and the remaining 7% comes from renewable sources (mainly hydro and wind power). Unfortunately, the world has limited amounts of fossil fuel and nuclear power resources. According to current estimates, natural uranium for nuclear power will last only about 50 years; oil will last no more than 100 years; gas, 150 years; and coal, 200 years. Will the wheels of our civilization come to a screeching halt after the 23rd century when fossil and nuclear fuels become totally exhausted?

Not only that, our overdependence on fossil and nuclear fuels is causing environmental pollution and safety problems, which are now becoming dominant issues in our society. There is, in addition, the urban pollution problem due mainly to internal combustion engine vehicles. The impact of environmental pollution on global warming and the resulting climatic changes can have disastrous consequences in the long run.

At this juncture, we are turning more and more to environmentally clean and safe renewable energy sources like wind, photovoltaic, and fuel cells. The world has enormous resources of wind energy. It has been estimated that tapping barely 10% of the wind energy available could supply all the electricity needs of the world. Recent technological advances in variable-speed wind turbines, power electronics, drives, and controls have made wind energy competitive with coal and natural gas power.

One third of the world's population lives outside the power grid system. For them, wind and photovoltaic energy are very important. The U.S. wind energy potential is so large that it can meet more than twice current electricity consumption. Currently, 1% of U.S. power demand is supplied by wind, which will be expanded to 5% by the year 2020. In Denmark, 13% of electricity is provided by wind, which will be expanded to 50% by 2030. Germany is the world leader in wind energy installed capacity (4500 MW), and the United States is the second (2554 MW). Developing countries such as India and China have huge expansion programs in wind generation.

One of the problems of wind energy is that its availability is sporadic, and, therefore, it needs to be backed by other power sources. The concepts of a future hydrogen economy and hydrogen fuel cell cars are based on conversion of wind power and storing energy in the form of hydrogen. This book emphasizes wind generation systems using induction generators (induction machines acting in generating mode). It is the right topic at right time.

Photovoltaic systems have the additional advantage of being static and barely requiring repair and maintenance. However, photovoltaic power is typically five times more expensive than wind power. Currently, there is a tremendous research and development effort to develop low-cost photovoltaic panels for widespread terrestrial applications in the future.

Solar power conversion efficiency is typically 16%, and its availability is also sporadic. The primary fuel for fuel cell energy is hydrogen or a fossil fuel (gasoline or methanol) with a reformer. Only in the former case can it be defined as renewable energy. Fuel cells are static and have high conversion efficiency (60%). Currently, they are bulky and expensive and have poor transient response. Fuel cells show tremendous promise for the future, particularly for electric cars, although a tremendous amount of research and development is needed to arrive at this goal.

This book highlights induction generators, particularly the cage type, for application in renewable energy systems. Although both induction and synchronous machines have been used widely, induction machines appear to be the right choice for variable-speed renewable energy systems because they are robust and economical. They have easily supplied excitation from the stator, good transient behavior, and mild short-circuit fault. Generally, a pulsewidth modulated inverter in the front end supplies the variable-frequency variable-voltage power to the induction generator along with its excitation need.

The drawbacks of induction generators, however, compared to synchronous machine, are slightly lower efficiency and inability to be operated at unity or leading power factor. Doubly fed induction generators with slip power control using cascaded converters or cycloconverter have been used in Scherbius drives. An example of a high-power Scherbius drive is the Kansai Power Company's 400-MW variable-speed pumped-storage hydropower station in Kansai Power (Japan). Toshiba has recently built flywheel energy storage units in the utility system using this principle. Therefore, this timely book enables the reader to comprehend the technology required in the implementation of induction-generator–based renewable energy systems.

Dr. Bimal K. Bose
Condra Chair of Excellence in Power Electronics
The University of Tennessee, USA

Preface

Induction generators have been used since the beginning of the 20th century. However, seemingly abundant fossil fuel production led to their almost complete disappearance by the 1960s. In the last few years, attention to environmental issues and international policy has made people conscious of the importance of distributed generation and the need for development of renewable and alternative energy solutions.

This book is written for the reader whose goal is to understand the technology of induction generators. Topics such as the process of self-excitation, numerical analysis of stand-alone and multiple-induction generators, requirements for optimized laboratory experimentation, application of modern vector control, optimization of power transference, use of doubly fed induction generators, computer-based simulations, and the social and economic impact of induction generators are presented in order to take the subject from the academic realm to the desks of practicing engineers and undergraduate, and graduate students.

Part of our intent is to suggest ideas and point further directions; in several cases the reader is referred to other sources for more detailed development. Much of the material presented here has not appeared in book form before. As teachers and researchers, we realize the importance of feedback, and we appreciate comments and suggestions for improvements and hearing about what might have been valuable in the material we have presented.

This book is organized in 13 chapters.

Chapter 1 presents some definitions and the characteristics of primary sources and industrial, commercial, residential, and remote sites and of rural loads, with highlights for the selection of the suitable electric generator.

Chapter 2 presents the steady-state model of the induction generator with classical steady-state representation, parameter measurements, and peculiarities of the interconnection to the distribution grid.

Chapter 3 expounds on transient modeling of induction generators with a novel numerical representation of state space modeling that permits generalization of the aggregation of generators in parallel, an important subject for wind farms.

Chapter 4 introduces in detail the performance of self-excited induction generators, voltage regulation, and the mathematical description of self-excitation.

Chapter 5 presents some general characteristics of the induction generator with regard to torque vs. speed, power vs. output current, and the relationship of air-gap voltage to magnetizing current.

Chapter 6 discusses the construction features of induction machines, particularly generator sizing, design, and manufacturing aspects.

Chapter 7 presents power electronic devices; requirements for injection of power into the grid; interfacing with renewable energy systems; and AC-DC, DC-DC, DC-AC, and AC-AC conversion topologies as they apply to the control of induction machines used for motoring and generation purposes.

Chapter 8 describes the fundamental principles of scalar control of induction motors/generators and how control of the magnitude of voltage and frequency achieves suitable torque and speed with impressed slip.

Chapter 9 presents vector control techniques in order to calculate stator current components for decoupling of torque and flux for fast-transient closed-loop response.

Chapter 10 presents contemporary optimization techniques for peak-power tracking control of induction generators. In particular, hill-climbing control and fuzzy control are emphasized.

Chapter 11 covers wound-rotor induction generators as applied to high-power renewable energy systems with important pumped-hydro and grid-tied applications.

Chapter 12 describes simulation approaches to transient response of self-excited induction generators in several environments, steady-state analysis, and vector-control–based induction motoring/generating systems.

Chapter 13 discusses economic, social, and impact issues related to alternative sources of energy with appraisal and investment considerations for the decision maker.

The Authors

M. Godoy Simões, Ph.D., earned the B.Sc. and his M.Sc. degrees from the University of São Paulo, Brazil, and his Ph.D. degree from the University of Tennessee, in 1985, 1990 and 1995, respectively. In 1998, he also received a D.Sc. degree (Livre-Docência) from the University of São Paulo.

Dr. Simões joined the faculty of the University of São Paulo from 1989 to 2000 and Colorado School of Mines in April 2000. He has been working to establish research and education activities in the development of intelligent control for high-power electronics applications in renewable and distributed energy systems.

Dr. Simões is currently serving as IEEE Power Electronics Society Intersociety chairman. He is associate editor of *Energy Conversion* as well as editor of *Intelligent Systems of IEEE Transactions on Aerospace and Electronic Systems*. He is also associate editor of *Power Electronics in Drives* of *IEEE Transactions on Power Electronics*. He has been actively involved in the Steering and Organization Committee of the IEEE 2005 International Future Energy Challenge. Dr. Simões is IEEE Senior Member, EPE and IEE Member and was the recipient of a National Science Foundation (NSF) Faculty Early Career Development (CAREER) in 2002. It is the NSF's most prestigious award for new faculty members, recognizing activities of teacher-scholars who are considered most likely to become the academic leaders of the 21st century.

Felix A. Farret, Ph.D., earned his B.Sc. in 1972 and M.Sc. in 1979 in electrical engineering from the Federal University of Santa Maria (UFSM), Brazil. He also received a M.Sc. in electrical engineering from the University of Manchester, England, in 1981, and a Ph.D. degree from Imperial College, University of London, England, in 1984. Dr. Farret's Ph.D. research was concerned with the injection of supplementary control signals to minimize uncharacteristic harmonics in high voltage direct current (HVDC) transmission systems.

After working at the Companhia Estadual de Energia Eléctrica (CEEE) of Rio Grande do Sul, Brazil, during the two years of implantation of the Thermopower Station of Candiota II, in 1974, he moved to UFSM. He did research work in high power and high frequency in the Osaka Prefectural Industrial Research Institute, Japan, in 1975. Since then, he has been teaching in the Department of Electronics and Computing and doing research in the field of micropower plants and industrial electronics, mostly related to power converters for injection of energy into the public network.

Dr. Farret was a visiting professor in 2002/2003 at the Colorado School of Mines, in the area of integration of alternative sources of energy with special emphasis on the use of fuel cells, induction generators and power electronics. Recently, he became coordinator of the Center of Studies in Energy and Environment (CEEMA-UFSM) working in the utilization of fuel cells for load management in distribution networks and stand-alone power generation.

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Marcelo Godoy Simões
Golden, Colorado, USA

Felix Alberto Farret
Santa Maria, Rio Grande do Sul, Brazil

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