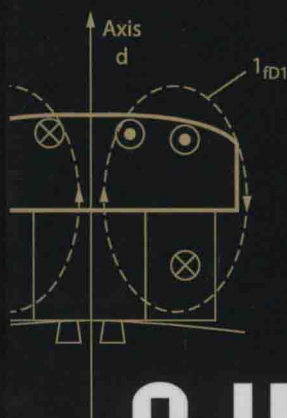
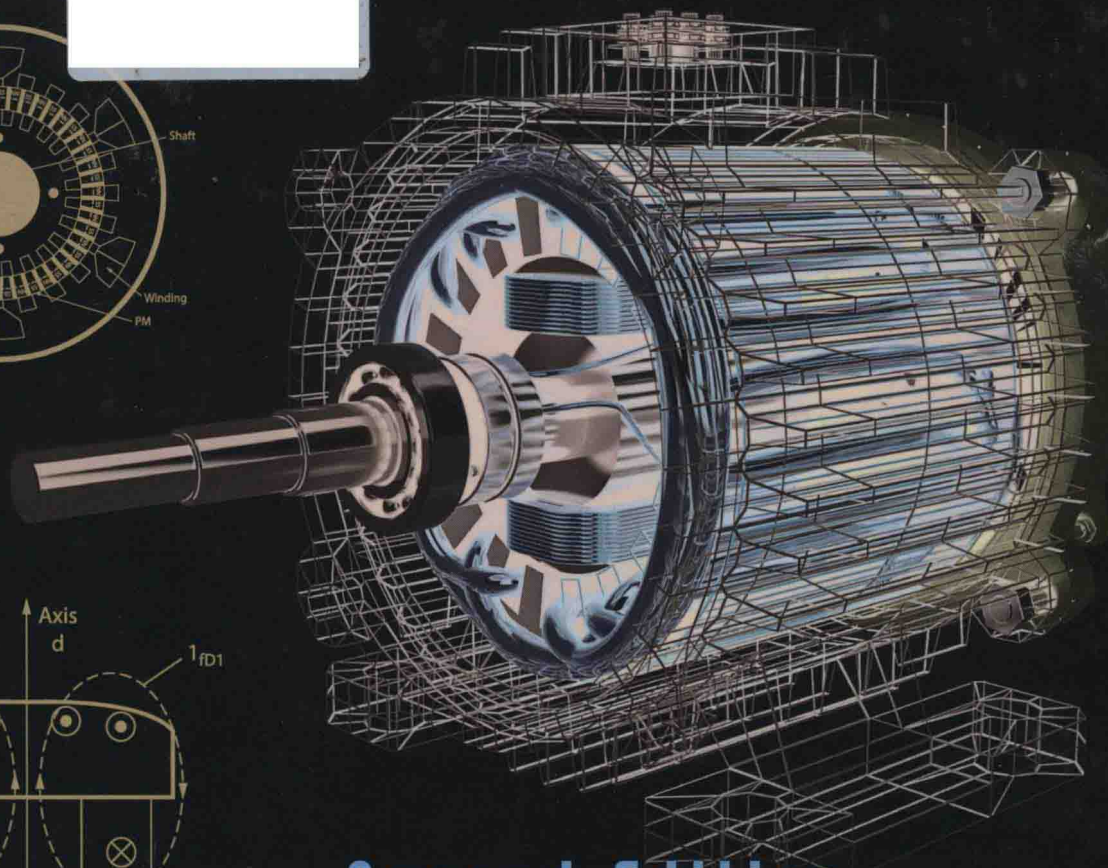
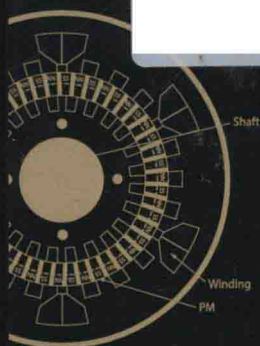
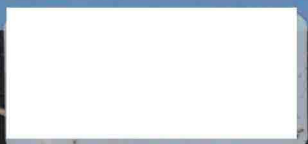


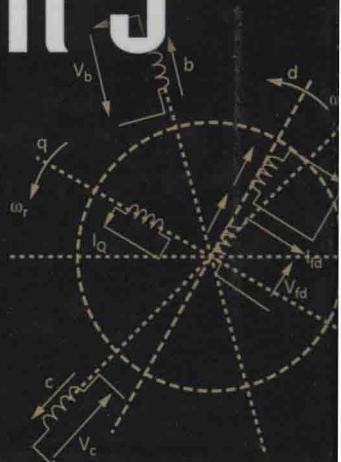
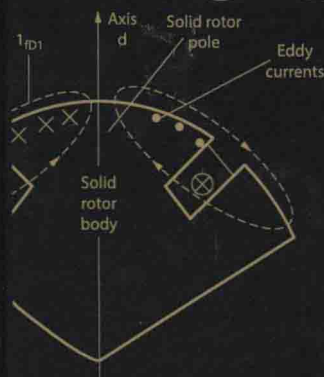
ELECTRIC GENERATORS HANDBOOK



Second Edition

SYNCHRONOUS GENERATORS

Ion Boldea



CRC Press
Taylor & Francis Group

Second Edition

SYNCHRONOUS GENERATORS

Ion Boldea

IEEE Life Fellow
University Politehnica Timisoara
Timisoara, Romania



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Second Edition

SYNCHRONOUS GENERATORS

Preface to the Second Edition

The first edition of this single-author, two-book set was published in 2006. Since then, electric energy, “produced” mostly via electric generators, has become one of the foremost activities in our global economy world. The subject of Electric Generators (*Synchronous Generators* and *Variable Speed Generators* as two books) attracted special attention worldwide both from industry and academia in the last decade. Electric generators’ design and control may constitute a new graduate course in universities with electric power programs.

Also, in the design and control of electric generators for applications ranging from energy conversion to electric vehicles (transportation) and auxiliary power sources, new knowledge and developments have been published in the last ten years. In the last ten years, in wind generators alone, the installed power has increased from some 40,000 MW to 300,000 MW (in 2014).

In view of these developments, we decided to come up with a new edition that

- Keeps the structure of the first edition to avoid confusion for users
- Keeps the style with many numerical worked-out examples of practical interest, together with more complete case studies
- Includes text and number corrections
- Adds quite a few new paragraphs in both books, totaling around 100 pages, to illustrate synthetically the progress in the field in the last decade

The new additions in the second edition are

Synchronous Generators

- Chapter 2 (Section 2.9): High Power Wind Generators, with less or no PM—an overview
- Chapter 4 (Section 4.15): PM-Assisted DC-Excited Salient Pole Synchronous Generators
(Section 4.16): Multiphase Synchronous Machine Inductances via Winding Function Method
- Chapter 6 (Section 6.17): Note on Autonomous Synchronous Generators’ Control
- Chapter 7 (Section 7.21): Optimization Design Issues
(Section 7.21.1): Optimal Design of a Large Wind Generator by Hooke–Jeeves Method
(Section 7.21.2): Magnetic Equivalent Circuit Population-Based Optimal Design of Synchronous Generators
- Chapter 8 (Section 8.10): Online Identification of SG Parameters
(Section 8.10.1): Small-Signal Injection online Technique
(Section 8.10.2): Line Switching (On or Off) Parameter Identification for Isolated Grids
(Section 8.10.3): Synthetic Back-to-Back Load Testing with Inverter Supply

Variable Speed Generators

- Chapter 2 (Section 2.14): Ride-Through Control of DFIG under Unbalanced Voltage Sags
(Section 2.15): Stand-Alone DFIG Control under Unbalanced Nonlinear Loads
- Chapter 5 (Section 5.8): Stand-Alone SCIG with AC Output and Low Rating PWM Converter
(Section 5.10): Twin Stator Winding SCIG with 50% Rating Inverter and Diode Rectifier
(Section 5.11): Dual Stator Winding IG with Nested Cage Rotor
- Chapter 6 (Section 6.8): IPM Claw-Pole Alternator System for More Vehicle Braking Energy
Recuperation: A Case Study
- Chapter 8 (Section 8.12): 50/100 kW, 1350 –7000 rpm (600 N m Peak Torque, 40 kg) PM-Assisted
Reluctance Synchronous Motor/Generator for HEV: A Case Study
- Chapter 9 (Section 9.11): Double Stator SRG with Segmented Rotor
- Chapter 10 (Section 10.16): Grid to Stand-Alone Transition Motion-Sensorless Dual-Inverter
Control of PMSG with Asymmetrical Grid Voltage Sags and Harmonics
Filtering: A Case Study
- Chapter 11 (Section 11.5): High Power Factor Vernier PM Generators

We hope that the second edition will be of good use to graduate students, to faculty, and, especially, to R&D engineers in industry that deal with electric generators, design control, fabrication, testing, commissioning, and maintenance. We look forward to the readers' comments for their confirmation and validation and for further improvement of the second edition of these two books: *Synchronous Generators* and *Variable Speed Generators*.

Professor Ion Boldea

IEEE Life Fellow

Romanian Academy

University Politehnica Timisoara

Timisoara, Romania

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The MathWorks, Inc.

3 Apple Hill Drive

Natick, MA 01760-2098 USA

Tel: 508-647-7000

Fax: 508-647-7001

E-mail: info@mathworks.com

Web: www.mathworks.com

Preface to the First Edition

Electric energy is a key factor for civilization. Natural (fossil) fuels such as coal, natural gas, and nuclear fuel are fired to produce heat in a combustor and then the thermal energy is converted into mechanical energy in a turbine (prime mover). The turbine drives an electric generator to produce electric energy. Water potential and kinetic and wind energy are also converted to mechanical energy in prime movers (turbine) to drive an electric generator.

All primary energy resources are limited, and they have a thermal and chemical (pollutant) effect on the environment.

Currently, much of electric energy is produced in constant-speed-regulated synchronous generators that deliver electric energy with constant AC voltage and frequency into regional and national electric power systems, which further transport and distribute it to consumers.

In an effort to reduce environment effects, electric energy markets have been recently made more open, and more flexible distributed electric power systems have emerged. The introduction of distributed power systems is leading to an increased diversity and growth of a wider range power/unit electric energy suppliers. Stability, quick and efficient delivery, and control of electric power in such distributed systems require some degree of power electronics control to allow lower speed for lower power in electric generators to tap the primary fuel energy.

This is how *variable-speed* electric generators have come into play recently [up to 400 (300) MVA/unit], as for example, pump storage wound-rotor induction generators/motors have been in used since 1996 in Japan and since 2004 in Germany.

This book deals in depth with both constant- and variable-speed generator systems that operate in stand-alone and power grid modes.

Chapters have been devoted to topologies, steady-state modeling and performance characteristics, transients modeling, control, design, and testing, and the most representative and recently proposed standard electric generator systems.

The book contains most parameter expressions and models required for full modeling, design, and control, with numerous case studies and results from the literature to enforce the understanding of the art of electric generators by senior undergraduate and graduate students, faculty, and, especially, industrial engineers who investigate, design, control, test, and exploit electric generators for higher energy conversion ratios and better control. This 20-chapter book represents the author's unitary view of the multifacets of electric generators with recent developments included.

Chapter 1 introduces energy resources and fundamental solutions for electric energy conversion problems and their merits and demerits in terms of efficiency and environmental effects. In Chapter 2, a broad classification and principles of various electric generator topologies with their power ratings and main applications are presented. Constant-speed-synchronous generators (SGs) and variable-speed wound-rotor induction generators (WRIGs); cage rotor induction generators (CRIGs); claw pole rotors; induction; PM-assisted synchronous, switched reluctance generators (SRGs) for vehicular and other

applications; PM synchronous generators (PMSGs); transverse flux (TF); and flux reversal (FR) PMSGs, and, finally, linear motion PM alternators are all included.

Chapter 3 treats the main prime movers for electric generators from topologies to basic performance equations and practical dynamic models and transfer functions.

Steam, gas, hydraulic, and wind turbines and internal combustion (standard, Stirling, and diesel) engines are dealt with. Their transfer functions are used in subsequent chapters for speed control in corroboration with electric generator power flow control.

Chapters 4 through 8 deal with SGs steady state, transients, control, design, and testing with plenty of numerical examples and sample results that cover the subject comprehensively.

This part of the book is dedicated to electric machines and power systems professionals and industries.

Chapters 9 through 11 deal with WRIGs that have a bidirectional rotor connected AC–AC partial rating PWM converter for variable-speed operation in stand-alone and power grid modes. Steady-state transients (Chapter 9), vector and direct power control (Chapter 10), and design and testing (Chapter 11) are treated in detail with plenty of applications and digital simulation and test results to facilitate in-depth assessment of WRIG systems currently built from 1 MVA to 400 MVA per unit.

Chapters 12 and 13 discuss cage rotor induction generators (CRIG) in self-excited modes used as power grid and stand-alone applications with small speed regulation by a prime mover (Chapter 12) or with full-rating PWM converters connected to a stator and wide-variable speed (Chapter 13) with $\pm 100\%$ active and reactive power control and constant (or controlled) output frequency and voltage in both power grid and stand-alone operations.

Chapters 9 through 13 are targeted to wind, hydro, and, in general, to distributed renewable power system professionals and industries.

Chapters 14 through 17 deal with representative electric generator systems proposed recently for integrated starter alternators (ISAs) on automobiles and aircraft, all operating at variable speed with full power ratings electronics control. Standard (and recently improved) claw pole rotor alternators (Chapter 14), induction (Chapter 15), PM-assisted synchronous (Chapter 16), and switched reluctance (Chapter 17) ISAs are discussed thoroughly. Again, with numerous applications and results, from topologies, steady state, and transients performance, from modeling to control design and testing for the very challenging speed range constant power requirements (up to 12 to 1) typical to ISA. ISAs have reached the markets, used on a mass-produced (since 2004) hybrid electric vehicles (HEVs) for notably higher mileage and less pollution, especially for urban transport.

This part of the book (Chapters 14 through 17) is targeted at automotive and aircraft professionals and industries.

Chapter 18 deals extensively with radial and axial air gaps, surfaces, and interior PM rotor permanent magnet synchronous generators that work at variable speed and make use of full power rating electronics control. This chapter includes basic topologies, thorough field and circuit modeling, losses, performance characteristics, dynamic models, and bidirectional AC–AC PWM power electronics control in power grid and in stand-alone applications with constant DC output voltage at variable speed. Design and testing issues are included, and case studies are treated using numerical examples and transient performance illustrations.

This chapter is directed at professionals interested in wind and hydraulic energy conversion, generator set (stand-alone) with power/unit up to 3–5 MW (from 10 rpm to 15 krpm) and 150 kW at 80 krpm (or more).

Chapter 19 investigates with numerous case study designs two high-torque density PM synchronous generators (transverse flux [TFG] and flux reversal [FRG]), introduced in the last two decades that take advantage of non-overlapping multipole stator coils. They are characterized by lower copper losses/N m and kg/N m and find applications in very-low-speed (down to 10 rpm or so) wind and hydraulic turbine direct and transmission drives, and medium-speed automotive starter-alternators.

Chapter 20 investigates linear reciprocating and linear progressive motion alternators. Linear reciprocating PMSGs (driven by Stirling free-piston engines) have been introduced (up to 350 W) and are

currently used for NASA's deep-mission generators that require fail-proof operation for 50,000 h. Linear reciprocating PMSGs are also pursued aggressively as electric generators for series (full electric propulsion) vehicles for power up to 50 kW or more; finally, they are being proposed for combined electric (1 kW or more) and thermal energy production in residences with gas as the only prime energy provider.

The author thanks the following:

- Illustrious people that have done research, wrote papers, books, patents, and built and tested electric generators and their control over the last decades for providing the author with "the air beneath his wings"
- The author's very able PhD students for electronic editing of the book
- The highly professional, friendly, and patient editors of CRC Press

Professor Ion Boldea

IEEE Life Fellow

University Politehnica Timisoara

Timisoara, Romania

Author

Ion Boldea:

- MS (1967), PhD (1973) in electrical engineering; IEEE member (1977), fellow (1996), and life fellow (2007)
- Visiting scholar in the United States (15 visits, 5 years in all, over 37 years), the United Kingdom, Denmark, South Korea
- Over 40 years of work and extensive publications (most in IEEE trans. and conferences and with IET (former IEE), London, in linear and rotary electric motor/generator modeling, design, their power electronics robust control, and MAGLEVs; 20 national and 5 international patents
- Eighteen books in the field, published in the United States and the United Kingdom
- Technical consultant for important companies in the United States, Europe, South Korea, and Brazil for 30 years
- Repeated intensive courses for graduate students and industries in the United States, Europe, South Korea, and Brazil
- Four IEEE paper prize awards
- Cofounding associate (now consulting) editor from 1977 for *EPCS Journal*
- Founding (2000) and current chief editor of the Internet-only international *Electronic Engineering Journal* : www.jee.ro
- General chair in 10 biannual consecutive events of the International Conference OPTIM (now IEEE-tech-sponsored, ISI and on IEEEExplore)
- Member of the European Academy of Arts and Sciences located in Salzburg, Austria
- Member of the Romanian Academy of Technical Sciences (since 1997)
- Correspondent member of Romania Academy (2011)
- IEEE-IAS Distinguished Lecturer (2008–2009) with continued presence ever since
- IEEE “Nikola Tesla” Award 2015

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