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The Electric Generators Handbook

VARIABLE SPEED GENERATORS

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Preface

Electric energy is a key ingredient in a community at the civilization level. 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 the electric generator to produce electric energy. Water potential and kinetic energy and wind energy are also converted to mechanical energy in a prime mover (turbine) that, in turn, drives an electric generator. All primary energy resources are limited, and they have thermal and chemical (pollutant) effects on the environment.

So far, most electric energy is produced in rather constant-speed-regulated synchronous generators that deliver constant alternating current (AC) voltage and frequency energy into regional and national electric power systems that then transport it and distribute it to various consumers. In an effort to reduce environment effects, electric energy markets were recently made more open, and more flexible distributed electric power systems emerged. The introduction of distributed power systems is leading to increased diversity and the spread of a wider range of power/unit electric energy suppliers. Stability and quick and efficient delivery and control of electric power in such distributed systems require some degree of power electronics control to allow for lower speed for lower power in the electric generators in order to better tap the primary fuel energy potential and increase efficiency and stability. This is how variable-speed electric generators recently came into play, up to the 400 (300) megavolt ampere (MVA)/ unit size, as pump-storage wound-rotor induction generators/motors, which have been at work since 1996 in Japan and since 2004 in Germany.

The present handbook takes an in-depth approach to both constant and variable-speed generator systems that operate in stand-alone and at power grid capacities. From topologies, through steady-state modeling and performance characteristics to transient modeling, control, design, and testing, the most representative standard and recently proposed electric generator systems are treated in dedicated chapters.

This handbook 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 assimilation of the art of electric generators by senior undergraduate students, graduate students, faculty, and, especially, by industrial engineers, who investigate, design, control, test, and exploit the latter for higher-energy conversion ratios and better control. This handbook represents a single-author unitary view of the multifaceted world of electric generators, with standard and recent art included. The handbook consists of two volumes: *Synchronous Generators* and *Variable Speed Generators*.

An outline of *Synchronous Generators* follows:

- Chapter 1 introduces energy resources and the main electric energy conversion solutions and presents their merits and demerits in terms of efficiency and environmental touches.
- Chapter 2 displays a broad classification and the principles of various electric generator topologies, with their power ratings and main applications. Constant-speed synchronous generators (SGs) and variable-speed wound rotor induction generators (WRIGs), cage rotor induction generators (CRIGs), claw pole rotor, induction, permanent magnet (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 and are dedicated topics in one or more subsequent chapters in the book.

- Chapter 3 covers 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.
- Chapter 4 through Chapter 8 deal with synchronous generator (SG) steady state, transients, control, design, and testing, with plenty of numerical examples and sample results presented so as to comprehensively cover these subjects.

Variable Speed Generators is dedicated to electric machine and power system people and industries as follows:

- Chapter 1 through Chapter 3 deal with the topic of wound rotor induction generators (WRIGs), with information about a bidirectional rotor connected AC–AC partial rating pulse-width modulator (PWM) converter for variable speed operation in stand-alone and power grid modes. Steady-state (Chapter 1) transients and vector and direct power control (Chapter 2) and design and testing (Chapter 3) are treated in detail again, with plenty of application cases and digital simulation and test results to facilitate the in-depth assessment of WRIG systems now built from 1 to 400 MVA per unit.
- Chapter 4 and Chapter 5 address the topic of cage rotor induction generators (CRIGs) in self-excited mode in power grid and stand-alone applications, with small speed regulation by the prime mover (Chapter 4) or with a full rating PWM converter connected to the stator and wide variable speed (Chapter 5) with ±100% active and reactive power control and constant (or controlled) output frequency and voltage, again at the power grid and in stand-alone operation. Chapter 1 through Chapter 5 are targeted to wind, hydro, and, in general, to distributed renewable power system people and industries.
- Chapter 6 through Chapter 9 deal with the most representative electric generator systems recently proposed for integrated starter alternators (ISAs) on automobiles and aircraft, all at variable speed, with full power ratings electronics control. The standard (and recently improved) claw pole rotor alternator (Chapter 6), the induction (Chapter 7), and the PM-assisted synchronous (Chapter 8) and switched reluctance (Chapter 9) ISAs are investigated thoroughly. Again, numerous applications and results are presented, from topologies, steady state, and transient performance to modeling to control design and testing for the very challenging speed range constant power requirements (up to 12 to 1) typical of ISAs. ISAs already reached the markets on a few mass-produced (since 2004) hybrid electric vehicles (HEVs) that feature notably higher gas mileage and emit less pollution for in-town driving. This part of the handbook (Chapter 6 through Chapter 9) is addressed to automotive and aircraft people and industries.
- Chapter 10 deals extensively with radial and axial airgap, surface and interior PM rotor permanent magnet synchronous generators that work at variable speed and make use of full-rating power electronics control. This chapter includes basic topologies, thorough field and circuit modeling, losses, performance characteristics, dynamic models, bidirectional AC–AC PWM power electronics control at the 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 through numerical examples and transient performance illustrations. This chapter is directed to wind and hydraulic energy conversion, generator-set (stand-alone) interested people with power per unit up to 3 to 5 MW (from 10 rpm to 15 krpm) and, respectively, 150 kW at 80 krpm (or more).

- Chapter 11 investigates, with numerous design case studies, two high-torque-density PM SGs (transverse flux [TFG]) and flux reversal [FRG]), introduced in the last two decades to take advantage of multipole stator coils that do not overlap. They are characterized by lower copper losses per Newton meter, (Nm) and kilogram per Nm and should be applied to very low-speed (down to 10 rpm or so) wind or hydraulic turbine direct drives or to medium-speed automotive starter-alternators or wind and hydraulic turbine transmission drives.
- Chapter 12 investigates linear reciprocating and linear progressive motion alternators. Linear reciprocating PMSGs (driven by Stirling free piston engines) were introduced (up to 350 W) and used recently for NASA mission generators with 50,000 h or more fail-proof operation; they are also pursued aggressively as electric generators for series (full electric propulsion) vehicles for powers up to 50 kW or more; finally, they are being proposed for combined electric (1 kW or more) and thermal energy production in residencies, with gas as the only prime energy provider.

The author wishes to thank the following:

- The illustrious people who have done research, wrote papers, books, and patents, and built and tested electric generators and their controls over the past decades for providing the author with "the air beneath his wings"
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- The highly professional, friendly, and patient editors at Taylor & Francis

Ion Boldea
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About the Author

Professor Ion Boldea, Institute of Electrical and Electronics Engineers (IEEE) member since 1977, and Fellow from 1996, worked and published extensively, since 1970, papers (over 120, many within IEEE) and monographs (13) in the United States and the United Kingdom, in the broad field of rotary and linear electric machines modeling, design, power electronics advanced (vector and direct torque [power]) control, design, and testing in various applications, including variable-speed wind and hydraulic generator systems, automotive integrated starter-alternators, magnetically levitated vehicles (MAGLEV), and linear reciprocating motion permanent magnet (PM) generators. To stress his experience in writing technology books of wide impact, we mention his three latest publications (with S.A. Nasar): *Induction Machine Handbook*, 950 pp., CRC Press, 2001; *Linear Motion Electromagnetic Devices*, 270 pp., Taylor & Francis, 2001; and *Electric Drives*, 430 pp., CD-Interactive, CRC Press, 1998.

He has been a member of IEEE–IAS Industrial Drives and Electric Machines Committees since 1990; associate editor of the international journal *Electric Power Components and Systems*, Taylor & Francis, since 1985; co-chairman of the biannual IEEE–IAS technically sponsored International Conference in Electrical Engineering, OPTIM, 1996, 1998, 2000, 2002, 2004, and upcoming in 2006; founding director (since 2001) of the Internet-only *International Journal of Electrical Engineering* (www.jee.ro). Professor Boldea won three IEEE–IAS paper awards (1996–1998) and delivered intensive courses, keynote addresses, invited papers, lectures, and technical consultancy in industry and academia in the United States, Europe, and Asia, and acted as Visiting Scholar in the United States and the United Kingdom for a total of 5 years. His university research power electronics and motion control (PEMC) group has had steady cooperation with universities in the United States, Europe, and Asia.

Professor Boldea is a full member of the European Academy of Sciences and Arts at Salzburg and of the Romanian Academy of Technical Sciences.

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