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To our families:
Susan Klempner,
Jackie, Livi, and Yigal Kerszenbaum
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It is not uncommon for a large utility to have units of disparate size, origin, and vintage in its fleet of generators. Among its dozens of generators, there might be some from the 1950s or 1960s and some with their original asphalt or thermoplastic windings. These, and later units, may be running with and without magnetic retaining rings. Some might have thermoelastic windings of all sorts, with or without asbestos; they might be hydrogen-cooled or air-cooled, have split-stator windings, be self-excited or different types of externally excited, steam-driven or combustion-driven, and the list goes on and on. Now, take that diversity and include units operating in 50 and 60 Hz grids, built by Western, Asian, and Eastern European manufacturers to different standards. This is what you may find in some of the new independent, deregulated power producers that, in addition to building new plants, have purchased entire fleets of older units in several countries around the globe.

The reasons why one may find so many “old” units still in operation are not difficult to discern. First of all, a typical generator is made with an intent to last no less than 30 years or so. Second, replacing an operating unit is very capital intensive and, thus, done only when a catastrophic failure has occurred or some other major failure of the machine that renders continuous operation not economically viable. Third, although expected to last 30 years, large turbogenerators are known to have their lives extended far beyond that, if well maintained and operated. Sometimes that also requires replacing a major component, such as the armature winding and/or a rotor winding (or the entire rotor!). Significant changes in design tend to occur every few years, for different components. For instance, a history of the insulation systems encountered in generators shows that every few years there is some big change resulting in increased ratings. These changes typically derive from the adoption of a new materials such as the change from magnetic to nonmagnetic material for retaining rings. Not all changes are always positive. Some new designs end up being reversed or revised after experience unmasks significant defects in them.

There are countless scraps of information about the operation, maintenance, and troubleshooting of large turbogenerators in many publications. All vendors at one stage or another have produced and published interesting literature about the operation of their generators. In particular, the technical information letters put out by some manufacturers (called different names by different vendors) offer a wealth of detailed
O&M topics. Institutions such as EPRI in the United States, CIGRE, IEC, ANSI, IEEE, and other national standards cover various aspects of the operation and maintenance of generators in general, but offer no specifics that may help troubleshoot a particular unit. It is difficult to obtain from those sources a condensed and operational set of insights useful to the solution of a given problem with a specific machine. It is no wonder then that with so many dissimilar units in operation and such a variegated experience, we are often forced to call the “experts,” who tend to be folks almost as old as the oldest units in operation. These are individuals who have crawled, inspected, tested, and maintained many diverse generators over the years. In doing so, they have retained knowledge about the different design, material, and manufacturing characteristics, typical problems, and most effective solutions. This type of expertise cannot be learned in a classroom.

Unfortunately, not every company retains an individual with the breadth and depth of expertise required for troubleshooting all its units. In fact, with the advent of deregulation, many small nonutility (third-party) power producers operate small fleets of generators without the benefit of in-house expertise. In lieu of that, they depend heavily on OEMs and independent consultants. Large utilities in many places have also seen their expertise dissipate, not to a small extent because of a refocus of management priorities. All these developments are occurring at the same time that these units are called to operate in a more onerous environment. Economic dispatch in a deregulated or semideregulated world results in an increased use of double-shifting and load-cycling.

Some effort has been made over the years to capture the experts’ knowledge and make it readily available to any operator. This effort took the shape of expert systems. However, adaptation of these computer programs to the many different types of generators and associated equipment in existence has proved to be the Achilles heel of this technology.

This book is designed to partially fill the gap by offering a comprehensive view of the many issues related to the operation, inspection, maintenance, and troubleshooting of large turbine generators. The contents of this second edition have been significantly enhanced and many new additional topics included. All of the information in the book is the result of many years of combined hands-on experience of the authors. It was written with the machine’s operator and inspector in mind, as well as providing a guide to uprating and life enhancement of large generators. Although not designed to provide a step-by-step guide for the troubleshooting of large generators, it serves as a valuable source of information that may prove to be useful during troubleshooting activities. The topics covered are also cross-referenced to other sources. Many such references are included to facilitate those readers interested in enlarging their knowledge of a specific issue under discussion. For the most part, theoretical equations have been left out, as there are several exceptionally good books on the theory of operation of synchronous machines. Those readers who so desire can readily access those books. Several references are cited. This book, however, is about the practical aspects that characterize the design, operation, and maintenance of large turbine-driven generators, and a significant number of practical calculations used commonly in maintenance and testing situations have been added.
Chapter 1 (“Principles of Synchronous Machines”) provides a basis of theory for electricity and electromagnetism upon which the machines covered in this book are based. As well, the fundamentals of synchronous machine construction and operation are also discussed. This is for the benefit of generator operators who have a mechanics background and are inclined to attain a modicum of proficiency in understanding the basic principles of operation of the generator. It also comes in handy for those professors who would like to adopt this book as a reference for a course on large rotating electrical machinery.

Chapters 2 and 3 (“Generator Design and Construction” and “Generator Auxiliary Systems”) contain a very detailed and informative description of all the components found in a typical generator and its associated auxiliary systems. Described therein are the functions that the components perform, as well as all relevant design and operational constraints. Some additional insight into design methods and calculations are also provided.

Chapter 4 (“Operation and Control”) introduces the layperson to the many operational variables that describe a generator. Most generator–grid interaction issues and their affect on the machine components and operation are covered in great detail.

Chapter 5 (“Monitoring and Diagnostics”) and Chapter 6 (“Generator Protection”) serve to introduce all aspects related to the on-line and off-line monitoring and protection of a large turbogenerator. Although not intended to serve as a guideline for designing and setting up the protection systems of a generator, they provide a wealth of background information and pointers to additional literature.

Chapters 7 (“Inspection Practices and Methodology”), leads off the second part of the book with a look at preparing for a hands-on inspection of large generators. The chapter discusses the issues of concern for both safety of personnel and the equipment as well as the types of tools and approaches used in inspecting large generators. This chapter also contains a collection of most inspection forms typically used for inspecting turbogenerators. These forms are very useful and can be readily adapted to any machine and plant.

Chapter 8 (“Stator Inspection”), Chapter 9 (“Rotor Inspection”), and Chapter 10 (“Auxiliaries Inspection”) constitute the core of this book. They describe all components presented in Chapters 2 and 3, but within the context of their behavior under real operational constraints, modes of failure, and typical troubleshooting activities. These chapters provide detailed information on what to look for, and how to recognize problems in the machine during inspection. Chapters 8 and 9 also contain some basic formulas and procedures for some of the various activities that occur during inspection, maintenance, and testing of large generators.

Chapter 11 (“Generator Maintenance Testing”) contains a comprehensive summary of the many techniques used to test the many components and systems comprising a generator. The purpose of the descriptions is not to serve as a guide to performing the tests—there are well-established guides and standards for that—rather, they are intended to illustrate the palette of possible tests to choose from. Provided as well is a succinct explanation of the character of each test and explanations of how they are carried out.

Chapter 12 (“Maintenance Philosophies”) is included to provide some perspective to the reader on the many choices and approaches that can be taken in generator and
auxiliary systems maintenance. Often, there are difficult decisions on how far to take maintenance. In some cases, only basic maintenance may be required, and on other occasions it may be appropriate to carry out extensive rehabilitation of existing equipment or even replacement of components. This chapter discusses some of the issues that need to be considered when deciding on what, how much, and where to do it. Along with the regular maintenance aspects, other important issues like uprating and long-term storage are also addressed.

We hope that this book will be not only useful to the operator in the power plant but also to the design engineer and the systems operations engineer. We have provided a wealth of information obtained in the field about the behavior of such machines, including typical problems and conditions of operation. The book should also be useful to the student of electrical rotating machines as a complementary reference to the books on machine theory.

Although we have tried our best to cover each topic as comprehensively as possible, the book should not be seen as a guide to troubleshooting. In each case in which a real problem is approached, a whole number of very specific issues only relevant to that very unique machine come into play. These can never be anticipated or known and thus described in a book. Thus, we recommend the use of this book as a general reference source, but that the reader should always obtain adequate on-the-spot expertise when approaching a particular problem.

We remain intent on updating the contents of this book from time to time, from our own experience as well as from that of others. Therefore, we would welcome from the readers their comments, which they can submit to the publisher, for incorporation in future editions.

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The contents of this book are impossible to learn in a class. They are the result of personal experience accumulated over years of working with large turbine-driven generators. Most of all, they are the result of the invaluable long-term contribution of coworkers and associates. Each author was motivated by an important individual at an early stage of his career, and by many outstanding individuals in the profession over subsequent years. Attempting to mention all these people would lead to the unintended omission of some.

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G.K.
I.K.
THEORY, CONSTRUCTION, AND OPERATION
The synchronous electrical generator (also called alternator) belongs to the family of electric rotating machines. Other members of the family are the direct-current (dc) motor or generator, the induction motor or generator, and a number of derivatives of all these three. What is common to all the members of this family is that the basic physical process involved in their operation is the conversion of electromagnetic energy to mechanical energy, and vice versa. Therefore, to comprehend the physical principles governing the operation of electric rotating machines, one has to understand some rudiments of electrical and mechanical engineering.

Chapter 1 is written for those who are involved in operating, maintaining, and trouble-shooting electrical generators, and who want to acquire a better understanding of the principles governing the machines’ design and operation, but who do not have an electrical engineering background. The chapter starts by introducing the rudiments of electricity and magnetism, quickly building up to a description of the basic laws of physics governing the operation of the synchronous electric machine, which is the type of machine to which all turbogenerators belong.

1.1 INTRODUCTION TO BASIC NOTIONS ON ELECTRIC POWER

1.1.1 Magnetism and Electromagnetism

Certain materials found in nature exhibit a tendency to attract or repel each other. These materials, called magnets, are also called ferromagnetic because they include the element iron as one of their constituent elements.
Magnets always have two poles: one called north, the other called south. Two north poles always repel each other, as do two south poles. However, north and south poles always attract each other. A magnetic field is defined as a physical field established between two poles. Its intensity and direction determine the forces of attraction or repulsion existing between the two magnets.

Figures 1.1 and 1.2 are typical representations of two interacting magnetic poles and the magnetic field established between them.

Magnets are found in nature in all sorts of shapes and chemical constitution. Magnets used in industry are artificially made. Magnets that sustain their magnetism for long periods of time are denominated “permanent magnets.” The magnetic field produced by the north and the south pole of a permanent magnet is directional from north to south (see Fig. 1.3). These are widely used in several types of electric rotating ma-

**Fig. 1.1** Schematic representation of two magnetic poles of opposite polarity, with the magnetic field between them shown as “lines of force.”

**Fig. 1.2** Schematic representation of two north poles and the magnetic field between them. South poles will create similar field patterns, but the lines of force will point toward the poles.