SYNCHRONOUS MACHINES

(Their Theory, Stability, and Excitation Systems)

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Dedicated to:

my wife, Savitri Devi, without whose patience, understanding and encouragement this book would not have been written.

PREFACE

During the thirties and forties most universities in the United States used to offer good electric-machinery courses and power-engineering programs well-suited to the needs of those times. In fact, some of the present courses in the general field of electric power are remnants from those days. Also, a large percentage of today's electric-machine designers and power-system engineers are of pre-World War II vintage. As most of these engineers are retiring through natural attrition, the manufacturers of electric power apparatus and so also the electric utility industry have been facing somewhat of a manpower shortage. The whole field of energy is in the midst of a crisis with a new set of technological problems due to ever-increasing power density, limited fuel resources, complex and costly environmental considerations, competition from outside countries, and the controversial nuclear revolution.

In 1978 only a very few universities in the United States have well-established and modern programs in electric power apparatus and systems. Most universities offer neither well-balanced undergraduate/graduate courses nor graduate research opportunities in the field. At a time when several new textbooks are annually published in relatively new areas such as computer sciences, control theory, solid-state electronics, etc., a professor offering courses in electric power apparatus must be content with textbooks which were published ten to twenty-five years ago; this is particularly true at the graduate level.

The electric utility industry in the United States is the largest industry not only in the country but also in the world from the viewpoint of a total plant and equipment investment of about 100 billion dollars, and an annual production figure of about 2 trillion kilowatthours, accounting for more than one-third of the total production of electric energy in the world. More nuclear plant capacity than the rest of the world combined is under development and construction in the United States. With the advent of this development and the general energy crisis, there has been renewed interest on the part of the universities in developing modern energy engineering programs and establishing distinguished power professorships supported by the manufacturing and utility industries. The urgent need for updating the power programs and production of highly competent engineers capable of working on the frontiers of fast-developing, competitive technology has been recognized.

The synchronous machine may be cited as the single most important basic component of an electric energy system. For economic reasons, the size of a single generator unit is of the order of 500 to 1000 MW. Conversion of energy from mechanical to electrical form and vice-versa remains a major aspect of our current engineering practice. All the benefits of gigantic computational robots and sophisticated automatic controls would shrink to insignificance if energy-conversion equipment did not operate satisfactorily in order to assure uninterrupted power supply within set limits of voltage and frequency. It is therefore very important for all electric power engineers to have a sound knowledge of energy conversion principles.

A synchronous machine constitutes a multitude of windings characterized by time-varying self-inductances and mutual inductances. Also, saturation and magnetic nonlinearity tend to complicate matters considerably.

Physical behavior may often become obscure in the light of mathematical analysis unless one is very careful.

The main objective of this book is to present a unified development of the fundamental coupled-circuit theory of the transient performance of synchronous machines. Steady-state theory is deduced as a special case. Transient performance under balanced and unbalanced short-circuit conditions, as well as short-circuit torques have been analyzed. Various aspects of saturation and flux distribution in synchronous machines are also discussed. Formulation for computer-aided analysis from an electromagnetic field point of view is put forth. Relevant stability studies and excitation systems are also presented to make it a complete and comprehensive text on the subject. In addition, the philosophy of modeling, generator protection as well as trends in future development are briefly discussed. Emphasis is on a more or less rigorous mathematical development which is sound enough from a practical engineering point of view and on presenting a fundamental physical understanding of the machine so that the reader will be equipped with the concepts required to extend the theory as he or she needs it. It is, after all, the fundamental concepts that underlie creative engineering and become the most valuable and permanent part of a student's background.

The material that has been scattered in a few books and hundreds of technical papers has been brought together under one cover to make it available for students in a comprehensive manner. Recent topics such as flux distribution by the latest numerical methods, subsynchronous resonance and modeling techniques have been included in a textbook for the first time. The material of this text is the result of a gradual development to meet the needs of the author's classes taught at universities in the United States and India over the past fifteen years. In developing this text extensive use has been made of technical papers, most of which were published in the IEEE Transactions by R. H. Park, R. E. Doherty, C. A. Nickle, C. F. Wagner, L. A. Kilgore, S. B. Crary, C. Concordia, S. H. Wright, R. D. Evans, E. W. Kimbark, W. A. Lewis, A. W. Rankin, G. Kron, E. Clarke, E. A. Erdélyi, and many others. Without the developments made by these outstanding engineers and several IEEE committees, this textbook could not have been written. Profound influence of the earlier books written by C. Concordia, W. A. Lewis, E. W. Kimbark, A. E. Fitzgerald and some others, as well as the notes developed by H. B. Palmer, C. C. Young and N. Simons is gratefully acknowledged. The theory presented in this book is the culmination of the work of many engineers over a period of about fifty years. Acknowledgement of sources can therefore be made only through the bibliography.

This textbook may be used by machine designers and practicing power system engineers who are directly concerned with the prediction of machine performance under different conditions of operation. In the environment of a classroom in an educational institution, this text may be adopted for a two-semester sequence course at graduate level. The first half of it may also be offered as a senior undergraduate elective. The reader would be most comfortable if he or she had a usual undergraduate first course in rotating electric machinery. The reader is expected to have taken the usual undergraduate introductory circuit courses and to have been exposed to linear differential equations, Laplace transforms, and matrices.

The motivation for developing and publishing this text at this time, besides the urgent need for such a book on the subject, may best be described in terms of the following objectives:

1. A textbook that is student-oriented, comprehensive and up-to-date on the subject with consistent notation and necessary detailed explanation.
2. A text that can easily be adapted to the classroom environment, and that can also be used for independent study by a practicing engineer.
3. A text based on the material that is actually taught over the past fifteen years at different universities including Northeastern University and that incorporates student feedback.
4. A text containing the problems which have all actually been assigned to students at one time or another, and which have been solved in detail.
5. A textbook that would be within the reach of almost all the readers interested in the subject within the Unites States as well as other countries of the world, in spite of the rising cost of paper, printing, and publishing.

Assistance and encouragement were received from many sources during the preparation of the manuscript. The harmonious climate in our department provided the proper academic setting, due in great measure to the energetic, diplomatic, and intelligent leadership of our power-system engineering program director, Dr. James M. Feldman, and our department chairman, Dr. Harold R. Raemer. Finally, several typists and illustrators have worked on the manuscript in various stages and I would like to thank them as a group. I would also like to take this opportunity to thank

my wife and children for their confidence and constant encouragement.

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Boston, Massachusetts

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by

Mulukutla S. Sarma

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CHAPTER I

GENERAL CONSIDERATIONS

1.1 Physical Description of a Synchronous Machine

A synchronous machine is a rotating apparatus, which is usually a part of a power system. It essentially consists of two elements: a set of armature coils and a field structure in relative motion. For constructional convenience and economic reasons, the armature winding is normally located in the stator, and the rotor contains the field winding. When the field is supplied with the direct current and is rotated by a prime mover, alternating voltages are induced in the armature coils. A three-phase machine will be considered in this text because it is most commonly used in practice and because most electric power is generated as three-phase power.

The number of poles of a synchronous machine is determined by the mechanical speed and the electric frequency at which the machine is intended to operate. The synchronous speed of a synchronous machine is that speed at which the machine normally runs under balanced, steady-state conditions, and is given by

$$n = \frac{120f}{p} \qquad (1.1.1)$$

where n is the speed in rev/min, f is the frequency in hertz, and p is the number of poles.

Hydraulic turbines operate at relatively low speeds and therefore a relatively large number of poles is required to produce the desired frequency, which is 60Hz for most power systems in the United States. A salient-pole construction is characteristic of hydroelectric-generator rotors, as it is better suited mechanically to the situation. On the other hand, steam and gas turbines operate best at relatively high speeds. These turbine-generator rotors are commonly of 2- or 4-pole cylindrical-rotor construction, and are made from a single steel forging or from several forgings. Typical salient-pole and cylindrical rotors are shown in Figures 1.1.1 and 1.1.2.

The disposition of the armature coils and the magnetic-flux paths for two- and four-pole machines are sketched in Figures 1.1.3 and 1.1.4. Since the angle included in one pole pair is 360 electrical degrees, the angle θ in electrical units is then related to the mechanical angle θ_m through the number of poles P as follows:

$$\theta = \frac{P}{2}\,\theta_m \tag{1.1.2}$$

There must be as many complete sets of armature coils as the number of pairs of poles, symmetrically distributed around the stator, and each set consists of three coils that are 120 electrical degrees apart. A typical stator of a synchronous machine with its armature conductors is shown in Figure 1.1.5. The steady-state voltages produced under balanced load conditions are always 120° apart in phase regardless of the speed of rotation of the field. The three-phase windings are either star- or delta-connected. For most of the modern high-voltage machines, they are invariably connected in star from the viewpoint of insulation requirements and availability of the neutral.

The magnetic flux produced by the field winding under