Electromagnetics for Electrical Machines

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Foreword

Electromagnetics for Electrical Machines explains the intricacies of its subject in a simple and systematic manner. I thoroughly enjoyed poring over it. It is one of the few books that covers a difficult subject through investigation and by using programmed concepts for learning. The authors have spent considerable time in formulating the structure of the book and its contents. I believe they have been successful in their attempt. There have been several books on electromagnetics, each having its own facets. However, this book is unique in that it attempts to teach the concept of EMFT and its application to the theory and design of electrical machines.

The contributions of the authors of this book in various research and scientific areas have been outstanding. They are academicians who have devoted themselves to the task of educating young minds and inculcating scientific temper in them.

I must heartily congratulate the authors for the magnificent job they have done.

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Preface

The contents of this book are based on the syllabi of MTech courses on electrical machines in some of the Indian universities and technical institutes. It is basically designed to serve for a one-semester course at the postgraduate level for electrical engineering students. Its contents are mainly confined to the linear theory of electromagnetics. Since this book lays more emphasis on concepts than on developing problem-solving skills, no numerical methods (viz. an iterative solution using relaxation techniques, finite difference methods, finite-element methods, the method of moment, etc.) are included. The first few introductory chapters of this book may also be used by students of physics, electronics and communication engineering, as well as those research scholars who are concerned with the problems involving electromagnetics.

The contents of this book are divided into the following nine chapters.

Chapter 1 is an introductory chapter that highlights the essence of field theory and its correlation with the electrical machines.

Chapter 2 includes a review of Maxwell's equations and scalar and vector potentials. It briefly describes the special cases leading to the Laplace, Poisson's, eddy current and wave equations.

Chapter 3 includes the uniqueness theorems, generalised Poynting theorem and a brief treatment of the Helmholtz theorem. It also deals with the approximation theorems developed to enhance the acceptability of approximate solutions of the field equations obtained under certain specified boundary conditions.

Chapter 4 is devoted to the solution of Laplace equation encountered in the design of electrical machines. It also introduces the Schwarz–Christoffel transformation and its applications and includes the determination of air-gap permeance.

Chapter 5 outlines the solutions for eddy current equations. The skin effects in circular conductors, eddy currents in solid and laminated iron cores are also discussed.

Chapter 6 is devoted to the analyses of electromagnetic fields in laminated-rotor induction machines. Field theory for anisotropic media and its application in laminated-rotor induction machines is briefly presented. The effects of skewed rotor slots in laminated-rotor induction machines are discussed.

Chapter 7 presents three-dimensional field analyses for three-phase solid rotor induction machines. It also describes the end effects in solid rotor induction machines. Field analysis for harmonic fields, in solid rotor induction machines due to tooth ripples, is also discussed.

Chapter 8 includes the examples relating to the slot leakage inductance of rotating electrical machines, transformer leakage inductance and theory of hysteresis machines. It presents the modelling of fields for a potentially new type of single-phase induction motor with composite poles. It also includes the electromagnetic transients in solid-conducting plates. An extension of this treatment may lead to the study of electromagnetic transients in electrical machines.

Chapter 9 briefly describes the common techniques employed in numerical analysis. It also classifies all the cases described in Chapters 4 through 8 in accordance with the equations involved therein. This chapter also indicates the methods through which these equations can be solved to yield the desired results.

In order to enhance the subject knowledge of the reader, this book includes some presentation/project problems at the end of each chapter. Some of the mathematical material, for example, evaluation of some lengthy integrals, is included in the appendices. One of these appendices includes a brief note on the Hilbert transform. One appendix is fully devoted to the current sheet simulation of a balanced three-phase armature winding carrying a balanced three-phase alternating current. Throughout this book, standard symbols are used without defining them. Any nonstandard symbol is defined at the point it is first introduced; the meaning continues as long as it is not redefined.

The authors thankfully acknowledge the help and encouragement received from Professor S. C. Jain, former vice-chancellor; Professor A. B. Datye, former director of engineering and technology; Ms. Nidhi Singh, assistant professor, Department of Mechanical Engineering; Mr. Manoj Kumar Bhardwaj, assistant professor, Department of Electrical Engineering, all from Mangalayatan University, Aligarh. The authors are indebted to Professor Satnam Prasad Mathur, former pro vice-chancellor, Mangalayatan University, who has meticulously gone through second and third chapters and provided many valuable suggestions. The authors are thankful to Ms. Shivani Sharma, lecturer and Mr. Ashok Kumar, both from the Electrical Engineering Department, Mangalayatan University, for drawing figures included in this book. Thanks are also due to Mr. Anuj Verma, Gaurav Kumar Sharma and other MTech students who helped us in one way or the other in the preparation of this book.

Saurabh Kumar Mukerji, Ahmad Shahid Khan and Yatendra Pal Singh

Authors

Saurabh Kumar Mukerji obtained his BSc (Engg) degree in electrical engineering from Aligarh Muslim University (AMU), Aligarh, in 1958, and MTech and PhD degrees in electrical engineering from IIT Bombay, in 1963 and 1968, respectively. He has more than 50 years of teaching experience. During this period, he served Madhav Engineering College, Gwalior (India), AMU, Aligarh (India), SRMS College of Engineering and Technology, Bareilly (India), Multimedia University (MMU), Melaka (Malaysia) and Alfatha University (Air Academy), Misurata (Libya), in various capacities, including as a professor. Having served for five years as senior professor and head of the Electrical Engineering Department at Mangalayatan University, Aligarh (India), he is presently teaching as guest professor in the same university. He has served as a professor and chairman, Department of Electrical Engineering, AMU, Aligarh (India). He has published more than 40 research papers in various national and international journals and conference proceedings. He taught electrical machines and electromagnetic fields to graduate and postgraduate classes for more than 20 years. He has also taught network theory, optimization techniques, electrical machine design, antenna and wave propagation, microwave engineering, electrical measurements and measuring instruments and so on. His main area of research includes electromagnetic field applications to electrical machines.

Professor Mukerji has been on the review board for the *Journal of the Institution of Engineers* (India), *Progress in Electromagnetic Research* (PIER) and *Journal of Electromagnetic Waves and Applications* (JEMWA) (MIT, USA) and the *Journal of Engineering Science and Technology* (JESTEC) (Malaysia). He has served as an executive editor with Thomson George Publishing House, Malaysia.

Ahmad Shahid Khan has more than 42 years of teaching, research and administrative experience. He obtained his BSc (Engg), MSc (Engg) and PhD degrees from Aligarh Muslim University (AMU), Aligarh (India), in 1968, 1971 and 1980, respectively. He served at AMU, Aligarh in various capacities, including as a professor and chairman, Department of Electronics Engineering; registrar, AMU, Aligarh; and as estate officer (gazetted). After retirement in December 2006 from AMU, Aligarh, he served as the director, International Institute of Management and Technology, Meerut; director, Vivekananda College of Technology and Management, Aligarh; and director, Jauhar College of Engineering and Technology, Rampur. He also served as a professor in Krishna Institute of Engineering and Technology, Ghaziabad, and Institute of Management Studies, Ghaziabad. All these engineering institutes are affiliated with UP Technical University, Lucknow (India). He is currently a visiting professor in Mewat Engineering College (Wakf) Palla, Nuh affiliated to Mehrishi Dayanand University Rohtak, Haryana (India).

Dr. Khan is a fellow of the Institution of Electronics and Telecommunication Engineers (India) and a life member of the Institution of Engineers (India), Indian Society for Technical Education and Systems Society of India. He has attended many international and national conferences and refresher/orientation courses in the emerging areas of electronics and telecommunication. His area of interest is mainly related to electromagnetics, antennas and wave propagation, microwaves and radar systems. He has published 23 papers mainly related to electromagnetics. He is a recipient of Pandit Madan Mohan Malviya Memorial Gold Medal for one of his research papers published in the *Journal of the Institution of Engineers*, India, in 1978.

Dr. Khan edited *A Guide to Laboratory Practice in Electronics and Communication Engineering* in 1998, which was republished in 2002 by the Department of Electronics Engineering. His name was added as a coauthor in the Indian-adopted third edition of *Antennas for All Applications* published by Tata McGraw-Hill, New Delhi, in 2006. The fourth edition of this book was published in April 2010 with a new title, *Antennas and Wave Propagation* published by Tata McGraw-Hill, New Delhi. Dr. Khan added six new chapters in this edition. Its 13th printing appeared in October 2014. His latest book, *Microwave Engineering: Concepts and Fundamentals*, was published by CRC Press in March 2014.

Yatendra Pal Singh has more than 7 years of teaching experience. He obtained his graduate and postgraduate degrees in physics from Aligarh Muslim University (AMU), Aligarh, in 1999 and 2001, respectively. He obtained his PhD degree in the area of solar physics from AMU, Aligarh, in 2008. He is currently working as an assistant professor in the Department of Applied Physics, Institute of Engineering and Technology, Mangalayatan University, Aligarh, India. He has taught applied physics, electromagnetic field theory, mechanics, waves and oscillations to graduate students and quantum field theory, mathematical physics to postgraduate students for more than 5 years. He has so far published 15 papers in peer-reviewed journals, including *Journal of Geophysical Research* (JGR), *Astronomy & Astrophysics* (A&A), *Solar Physics* and in Elsevier journals such as *Journal of Atmospheric and Solar Terrestrial Physics* and *Planetary and Space Science* and 10 papers in proceedings of international conferences. Dr. Singh is a reviewer of research papers for the *Progress in Electromagnetic Research* (PIER), MIT, USA, and *Astrophysics and Space Science*, Europe. His major areas of interest include solar physics, heliospheric magnetic fields and magnetosphere.

1

Introduction

1.1 Introduction

Electromagnetic field theory has innumerable practical applications. The terms resistance, inductance, capacitance, conductance, potential, power, energy, force and torque emanate from the field concepts. The involvement of its concepts is imminent in all electrical and electronic devices and systems and the literature about most of these is available in abundance. The area of electrical machines is also deeply related to the electromagnetic field theory but has not yet been addressed to the level of satisfaction. One of the likely reasons for this neglect is that the field theory is presumed to be very conceptual with the general notion that it cannot be easily grasped without deep insight. It is further presumed that the field theory leads to complicated mathematical expressions, which create a sort of repulsive effect in the mind of the reader. In fact these myths are more psychological than real. The involvement of such mathematical expressions is quite common in other fields of science and engineering. Besides, the easy availability of design software based on numerical techniques has provided an excuse to those who want to avoid field concepts, mathematical complexities, and significant inaccuracies.

1.2 Field Approach

As of today, most of electrical machines are designed by employing software based on numerical techniques. Some of such readily available programs rely on over simplification of the problems, whereas some others are overly dependent on the data curves or empirical relations. These programs are neither generic nor optimal in nature. Besides, in implementing these techniques, computers normally execute voluminous calculations and even then, the ultimate outcome remains approximate. This scenario, therefore, calls for more accurate approaches. In this book, this task has been taken as a challenge. In essence, the basic aim of this book is to systematically correlate electrical machines to the field theory.

1.3 Domain of Machines

At this stage, it is pertinent to mention that the domain of electrical machines in itself is quite wide. As far their types are concerned, these contain devices with stationary and rotating (or moving) parts. Except transformers, which belong to the first category, all other machines fall to the second. The transformer in itself may have different types of cores and windings. The rotating (or linear) electrical machines may include direct current machines, induction machines, synchronous machines, eddy current machines, hysteresis machines, actuators and so forth. Many of these can further be classified as generators and motors. Besides, their rotors, stators, windings and modes of connections may also vary in shapes and sizes. These machines pose problems of electrical and thermal insulation. The shapes, sizes and types of slots also differ greatly. In particular, induction machines use semi-closed or fully closed slots. These machines contain rims and shafts and their presence is bound to influence the distribution of fields. There are problems of the induced eddies in the conductor cross sections, magnetic cores and other such artefacts. There are problems of teeth saturation, end effects and the nonlinearity of the core materials. All these aspects and factors play pivotal roles in electrical machines. Thus, accounting of all the above factors and aspects in one go is a horrendous task. It calls for tremendous effort and energy not usually seen in books of this scope.

At first sight the situation appears to be quite discouraging if not hopeless. As a way out, this book deals only with the general aspects of the involvement of field theory, in some of the commonly used machines. In order to provide for its extension to other machines, an effort has been made to develop the theory in a generalised way. Thus this book discusses only the simplified models of machines in regard to field theory and leaves the complicated cases to others to tread in. In general, this book deals with two-dimensional fields, but in some cases the variations in third dimension are also accounted for.

1.4 Review of Field Theory[1–5]

The book begins with the review of field theory as the effective operation of rotating electrical machines, transformers, inductors and other devices rely on proper magnetic field arrangement. In micro-electro-mechanical systems (MEMS) wherein the size reduces to the order of nanometres, both magnetic and electric fields are used for motion control. The electric motors, generators and actuators are referred to as energy conversion devices. This conversion between electrical and mechanical energy takes place in the coupling fields. Thus even a cursory look at any electrical machine reveals that the field phenomenon is deeply involved in its analysis and operation. It, therefore, appears to be proper to first understand the various aspects of the electromagnetic field and then to understand its role in the functioning of electrical machines.

The study of the electromagnetic field revolves around some basic laws. These include Coulomb's, Gauss's, Biot–Savart's, Ampere's, Faraday's laws and so on. These laws lead to certain quantities referred to as field quantities, which include electric field intensity ($\boldsymbol{E}$), electric flux density ($\boldsymbol{D}$), magnetic field intensity ($\boldsymbol{H}$) and magnetic flux density ($\boldsymbol{B}$). The integrated effect of these gives rise to the concept of current (I), surface current density (K), (volumetric) current density ($\boldsymbol{J}$), scalar electric potential ($\boldsymbol{V}$), scalar magnetic potential ($\mathcal{V}$), vector magnetic potential ($\boldsymbol{A}$), force (F), torque (T), power (P), energy ($\hat{E}$) and so on. Some of these quantities are interrelated by a set of relations called Maxwell's equations, whereas some others are obtained by manipulating this set. Maxwell's equations can be expressed either in integral or in differential (or point) form. These equations may take different forms for time-variant and time-invariant conditions, in static and moving media, and in accordance with the presence or absence of charge and current densities. These laws and relations are deeply related to the operation of rotating electrical machines. In the transient performance for many of these machines the concept of the retarded potentials, continuity equation and relaxation time is also deep rooted. Thus these laws, relations and concepts need to be reviewed for ready reference.

1.5 Field Theorems[6–8]

The four magical Maxwell's equations form the basis of design and analysis of rotating electrical machines. The manipulation of Maxwell's equations along with other field relations ultimately leads to another set of four equations known as Laplace's, Poisson's, wave and diffusion (or eddy current) equations. All of these are involved in the analysis of electrical machines in one way or the other. In some cases, the Laplace's and Poisson's equations have the lion's share, whereas in others the eddy current equation plays a pivotal role. In some situations, the wave equations too play a role and lead to the concept of retarded potentials.

1.5.1 Uniqueness Theorem

The solutions of these equations deserve careful scrutiny vis-à-vis their correctness and accuracy. The uniqueness theorem provides a mean through which the solutions obtained can be scrutinised. It is, therefore, necessary to explore the utility of this theorem in relation to Laplace and Poisson's equations, vector magnetic potentials and Maxwell's equations.

1.5.2 Poynting Theorem

Beside the uniqueness theorem, the Helmholtz theorem and the generalized Poynting theorem play a significant role in the analysis of electrical machines. The Helmholtz theorem assumes significance as and where the fields are of vector nature, whereas the Poynting theorem takes cognizance of electromechanical energy transfer.

1.5.3 Approximation Theorem

Since in most of the cases the solutions of field equations satisfy boundary conditions only approximately, for such cases, the approximation theorems are developed to review the acceptability of the solution.

1.6 Problem of Slotting[9–12]

In most electrical machines the rotor and/or stator are slotted, which affects the overall performance of the machine. These effects can be noticed while the analysis is carried out for the magnetic flux density distribution in the air gap, the magneto-motive-force (mmf) resulting due to the field current, the torque exerted on the rotor and the induced electro-motive-force (emf). The intensity of these effects depends on the types, shapes, sizes, relative displacements of slots and the relative dimensions of teeth and air gap. While designing an electrical machine, due consideration needs to be given to the effect of slotting to predict its exact behaviour. In most of such problems, the slots are considered to be source free. In cases wherein the sources are present, these sources are presumed to be located deep inside the slots. Thus, the problem reduces to the solution of the Laplace equation. The fields involved in such problems can be referred to as Laplacian fields. In view of the significance of such problems, due emphasis is to be given to the Laplacian fields. Such problems can be solved by using the Schwarz–Christoffel transformation method or separation of variables method. These methods lead to the determination of air gap permeance.

1.7 Eddy Current Phenomena[13,14]

The flow of eddy currents is another important aspect of field phenomena, which is deeply involved in some of the rotating electrical machines. The genesis of this phenomenon relates to the presence of a time-varying magnetic flux in a conducting medium, which generates an electromotive force. This force lies in the plane perpendicular to the direction of flux change. This electromotive force causes flow of current in the material, which is referred to as eddy current. These currents depend on the geometry of the medium, the rate of alternation of the flux and the electric and magnetic properties of the materials involved. The flow of these currents is always in such a direction so as to oppose the change in the flux that produces them. The net effect of such a flow is to prevent immediate penetration into the interior of the matter. As a result, for continuously varying applied field the magnetising force in the interior of the material never exceeds a small fraction of the magnetising force at the surface. When these eddy currents react with the inducing field, they create a mechanical torque. Such a phenomenon is noticed in case of a polyphase induction machine with a solid rotor acting either as a motor or as a break. The flow of eddy currents also produces loss of power, generating heat in a material. Such a loss is referred to as eddy current loss. Induction heating is an example of using this power.

The study of eddy current phenomena gains ground particularly when one studies the distribution of field and current in a conducting medium, which is subjected to a time-varying field. Such a situation arises in electrical machines and devices wherein magnetic cores are used. In the design of electromechanical clutches, eddy current brakes, electromagnetic couplings, solid iron rotor-induction machines and self-starting synchronous motors, the penetration of alternating flux into the solid iron needs proper estimation and thus requires a thorough understanding of eddy current phenomena. Such a study must encompass magnetic cores of different shapes and types, induction machines with solid rotors, large plates subjected to ac single-phase and polyphase excitations.

1.8 Polyphase Induction Machines[15–20]

The polyphase induction machines can be classified into two broad groups. These can be referred to as the laminated-rotor-induction machines and the unlaminated rotor-induction machines. The squirrel cage induction machines and slip-ring-type induction machines belong to the first category, while solid rotor-induction machines and drag cup-type induction machines belong to the second group. Some of their salient aspects are briefly described in the following sections.

1.8.1 Laminated Iron Cores

Laminated iron cores are used for cage-rotor and wound-rotor-induction machines. The slotted region of the rotor is isotropic but inhomogeneous. This region can be roughly represented as an equivalent anisotropic homogeneous region extending radially from the rotor air gap surface to the base of the rotor slots. In a linear treatment, a finite constant value for the saturated rotor teeth permeability may be chosen. The rotor core beyond the slotted region is rather magnetically unsaturated and the permeability for this region, being large, can be taken as infinite.

In view of the above description, the analyses of electromagnetic fields in laminated-rotor-induction machines need thorough consideration. Field theory for anisotropic media and its application to laminated-rotor-induction machines also invites due attention. Besides, the effects of skewed rotor slots in laminated-rotor-induction machines need to be properly addressed in terms of the field theory.

In a highly simplified treatment for the eddy current loss in laminated cores, the inhomogeneous laminated core region is often simulated by an anisotropic homogeneous region. The slotted region of laminated-rotor-induction machines can likewise be represented by an equivalent anisotropic homogeneous region. An exhaustive treatment for the electromagnetic field theory of squirrel cage induction machines was published by Mishkin, as early as 1954, wherein he simulated the heterogeneous isotropic slotted regions by homogeneous anisotropic regions.

1.8.2 Unlaminated Iron Cores

As noted above, the solid-rotor-induction machines fall into the second group of polyphase induction machines. In view of its importance, the proper field analyses for harmonic fields in solid-rotor-induction machines due to tooth ripples become more than a necessity. The study of end effects in the solid-rotor-induction machines requiring three-dimensional field analyses for three phase solid-rotor-induction machines also deserves due consideration.

1.8.3 Simulation of Armature Winding

For the field analyses of rotating electrical machines, the three-phase armature winding is often simulated by a suitable surface current sheet. Due attention is, therefore, required for simulating a balanced three-phase armature winding carrying a balanced three-phase alternating current.