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Electrical Machines and their Applications

4th Edition

John Hindmarsh

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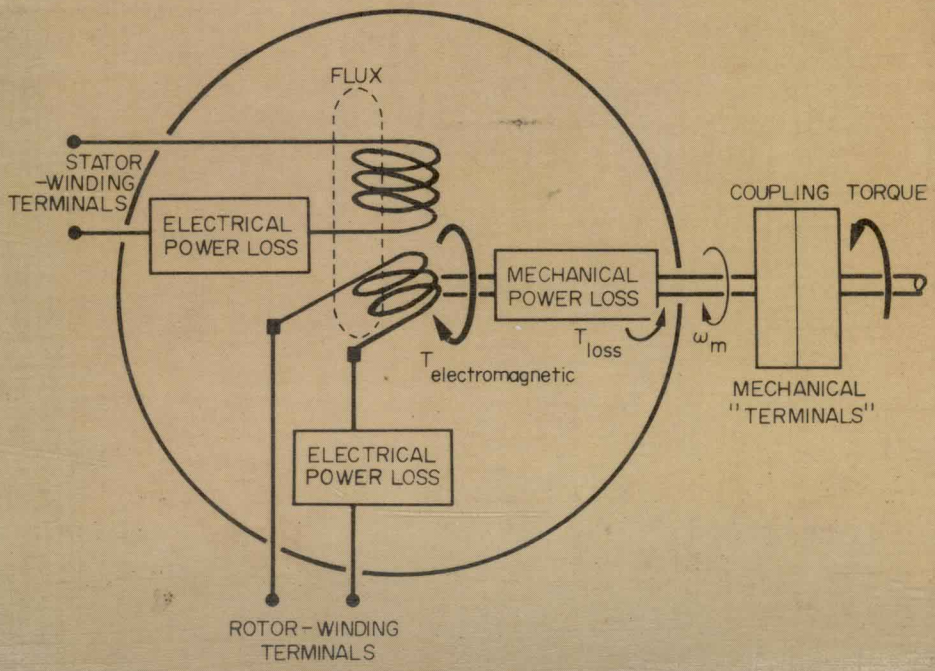

ELECTRICAL MACHINES AND THEIR APPLICATIONS

FOURTH EDITION

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DEDICATED TO
THE AUTHOR OF LIFE
WHO MADE IT POSSIBLE
AND TO MY LONG-SUFFERING FAMILY
WHO PATIENTLY ENDURED LONG PERIODS
OF DEPRIVATION AND NEGLECT DURING THE
PREPARATION AND REVISIONS OF THIS BOOK

PREFACE TO THE FOURTH EDITION

ALTHOUGH the various reprints since the third edition was first published have included some modifications, it has seemed appropriate in the present instance to undertake a more thorough revision, combing the text carefully, ensuring that all references conform to the latest national (BS) and international (IEC) recommendations and recording latest developments. The objective of the book remains, to provide understanding and instruction in the essential, unchanging principles governing electrical-machine performance. After substantial changes in the earlier editions, one might hope that the correct balance is being approached. But many minor textual alterations have been made in an attempt to clarify further any incomplete explanations and add material reflecting current thinking and practice. The old Appendix A dealt with alternative phasor-diagram conventions but these discussions have subsided somewhat and the conventions adopted since the second edition have become more generally accepted, as are the terms *time-phasor* and *space-phasor*, which designate the representation of sinusoidal time and space variations. This practice, which is now followed, avoids any possible confusion with true vector terminology, even though the methods of combination and presentation share some similarities. The new Appendix A covers a different topic. It deals more fully with permanent-magnet theory, recognising the growing importance of permanent-magnet machines, following the extensive developments of new materials.

The reaction of modern electrical machines to the continued proliferation of power-electronic circuits remains stoical, dignified and co-operative; not changing their basic electromechanical behaviour appreciably, except in terms of the more rapid and precise response such circuits have made possible. Taking a broad view, these developing systems are, for the most part, a convenient means of subjecting

machines to changes of voltage and/or frequency, inevitably involving somewhat distorted waveforms. The electromechanical result is an "averaged out" behaviour, attenuating the high supply-harmonic content but with the possibility of increased noise and vibration. New designs proceed, with the aim of producing integrated machine/electronic-systems for optimum performance. The general performance with the above features is covered in the text, but the interaction of machines and solid-state circuitry is relatively complex, and it receives greater consideration in the author's companion volume, *Worked Examples in Electrical Machines and Drives.*

J. H.

Sale, Cheshire 1984

PREFACE TO THE THIRD EDITION

THE changes to this edition are not so extensive as those made in the second edition. The purpose of the book is to establish a sound understanding of the basic principles of electrical machine operation. The method is first to delineate the common ground, before considering alternative possibilities for providing the electromagnetic reaction between the two elements, the one fixed and the other moving, normally. From this it emerges that there are four main types of machine, each with its own special characteristics in terms of performance, convenience and cost. One of the interesting consequences of the control and semiconductor revolutions has been the attempt to produce an economic, robust and flexibly controlled machine-drive system which combines the desirable features of all types. The main changes in the book are concerned with discussing more fully, the practice and influence of variable-frequency control which have made these attempts possible—especially in the further developments of "brushless" machines.

Although these developments are instructive, even fascinating, the bulk of the text must still be concerned with explaining how these desirable (and less desirable) characteristics arise in the first place, and further, how they can be applied to the appropriate engineering situations. It is not easy to decide how much engineering detail to include in a book of this kind; students' requirements differ. Much importance is given, not only to providing a physical understanding, but also to answering the practical questions which arise and exploring theoretical notions which present themselves in the study of electrical machines. But students must also learn to be selective and for example, the chapter on Windings, which is there for those who want it or need it, does not require study in depth for an adequate understanding of machine performance and equations. Some guidance on selecting a short course for study is given in the Preface for the second edition.

The diagram on the front cover of the book indicates in a schematic way, the external and internal viewpoints of an electrical machine. "Access" to the machine is gained via external "terminals", through which it is connected as a link between the electrical and mechanical systems, and transfer of power between the systems is regulated. Internally, the required reactions are developed electromagnetically and inevitably power losses are involved in the conversion process. These must be minimised. Since the majority of students will eventually be involved with electrical machines only as devices to be used when required, some emphasis is given to the terminal characteristics which show for which application they are suited. An additional Appendix has been included to present, concisely, the factors which govern the choice of machine for a particular drive and the drive requirements which may have to be met.

The text is updated generally, new developments are put in context and a few more illustrations, problems and references for further reading are added. Opportunity has been taken to scrutinise the text carefully so that any ambiguities and errors could be removed. The author is grateful both to those who have spoken or written to him to point these out, and to his colleagues and students at UMIST who patiently allow themselves to be used as sounding boards in trying out new explanations and attempts to elucidate obscure points.

The University of Manchester Institute of Science and Technology J. H.

PREFACE TO THE SECOND EDITION

SEVERAL changes have been made in this revised edition though the general pattern remains the same. More emphasis is given to considering the machine as an element in an electrical circuit and as a link between electrical and mechanical systems. In this way it is intended that the special terminal characteristics of a machine as an active circuit element will follow naturally from an extension of simple circuit theory. The phasor diagrams have been redrawn, so that together with the equivalent circuits they can be seen clearly as alternative methods of presenting and remembering the machine equations. Other conventions used in the drawing of phasor diagrams are reviewed briefly in Appendix A.

To emphasise further the common principles of machine operation, two new approaches are explained which derive the equivalent circuits from the basic equations of the transformer. The first method, given in Section 3.9, is closely related to the electrical circuit, electromagnetic and physical concepts. The alternative method,[1] explained in Appendix B, is based on feedback-control principles which are first outlined briefly and then used to consider the machine as a simple closed-loop system with e.m.f. and m.m.f. feedback. For the reader with some prior knowledge of electrical machines, or one who wishes to follow a short, concentrated course, either of these two approaches can be used as a starting point since the first three chapters are of a revisory nature. Subsequently, the remainder of such a short course could be based on the derivation and application of the machine equations given in Sections 4.2, 6.7, 7.3, 8.3 and 8.4, supplemented if necessary by the earlier sections of these chapters and the later sections of Chapter 5. This procedure might well be suitable for those who are not specialising in electrical machines and applications, but who are taking one of the many Electronic Engineering courses now available. For those who wish to go further and acquaint themselves with a more comprehensive analytical

approach, a new chapter has been added to introduce generalised theory. In Chapter 10, this powerful method, which requires a sound mathematical background for successful application, is explained in sufficient detail to relate it to the equivalent-circuit approach as adopted in the main text and to indicate its appropriate fields of application.

The full text covers the needs of those whose training requires a deep understanding of all aspects of machine behaviour, as in studies of power systems, control systems, machine design and general industrial applications. The text reviews the latest developments, including the new modes of operation made available by the use of combined semiconductor/machine circuits and the first practical application of superconducting techniques to electrical machines. The work on electromechanical transients has been extended to show some simple practical examples involving the solution of linear and non-linear differential equations. Finally, more information relevant to the electrical machines laboratory course is included, to complete the comprehensive treatment of the subject which is the object of the book.

Much of the new material and modifications to the presentation have resulted from the author's discussions with his colleagues. To Dr. N. N. Hancock in particular, for his co-operation during the preparation of Chapter 10, and to Dr. B. J. Chalmers, the author records his acknowledgements and appreciation.

J. H.

Sale, Cheshire

PREFACE TO THE FIRST EDITION

THE subject of Electrical Machinery, which once formed the core of the Electrical Engineering syllabus, must now constitute a more modest portion of the course so that more time may be devoted to covering the vast range of developments in other fields. The situation is not without advantages. It has stimulated thought on means of rationalising the theory to emphasise the unity underlying the behaviour of the numerous different types of machine. For those with a flair for mathematics, generalised treatments have been and are being developed which are very satisfying in their results. By considering the electrical machine as a combination of inductively coupled coils, the interconnection of which determines the characteristic machine behaviour, an all-embracing theory has been approached. This has been made possible by the work of Gabriel Kron who first developed and applied the techniques of Tensor Analysis to electrical circuits and machines. One book on this basis has already been published in this series.[2]

However, the problem still remains of conveying in a manner more concise than previously, the essential details concerning the physical nature of machines. Further, there are many practical problems which will have to be faced by the electrical student in the laboratory, by the applications engineer and by the machines specialist for which the physical approach is more suitable.

In this volume an attempt has been made to survey practically the whole field of Electrical Machinery, without recourse to advanced mathematics but with the intention of supporting any mathematical generalised treatment. The method adopted is to give most space to a careful explanation of four main electromagnetic devices in their basic form, viz. the two-coil transformer, the d.c. machine, the induction machine and the synchronous machine. A sound knowledge of these four will permit the ready understanding of all other machines, which for the most part are modifications of one or other type. Although

there are distinguishing features between the main kinds of machine there are many similarities too; these are brought out wherever possible, and the treatment of each machine follows similar lines where this is practicable. The theory is extended to introduce other modes of operation in a manner adequate for general understanding but without detailed explanation in all cases. The text is supported by nearly fifty comprehensive worked examples which cover most of the theoretical points raised.

The first chapter is a brief review of the common principles underlying machine operation and the application of these principles to produce the different machine types. A minimal knowledge of electrical machinery is assumed. However, Chapters 2 and 3 revise the appropriate magnetic and circuit theory so that to some extent the book is self-contained. These two chapters can be skipped by the student who feels secure enough on their subject matter, but they will be referred to frequently either implicitly or explicitly in the later chapters. Towards the end of Chapter 3, a concentrated review of more advanced work is given which necessitates the use of simple differential equations. For example, transient behaviour is discussed and a few elementary problems are considered in the later text. The ideas which form the basis of generalised treatments are also explained briefly in order that reference may be made in Chapter 9 to certain possible uses of the Generalised Laboratory Machine.

Since machine windings are the means by which theory is translated into practice, it has been considered necessary to devote one short chapter to them. In themselves they form a unifying link between different machines. Although the treatment has been simplified, it is adequate for straightforward winding problems, and the material is useful support for the remaining chapters.

Following the bulk of the text which is devoted to the main machine types, the final chapter serves to consider the general relationships obtaining when both commutator and slip rings are provided on the armature. Practical applications of these principles to various commutator machines are described, together with a discussion of the recently available generalised laboratory machines.

Although work for the final year of Electrical Engineering Degree courses is introduced, the main intention of the book is to meet the requirements of all courses dealing with Electrical Machinery up to this stage, where students take up a few specialised studies. However, the Machines portions of the Electrical Power and Machines syllabus for the External B.Sc.(Eng.) degree of London University and for Higher National Certificate and equivalent courses are all covered.

The author is grateful to his colleagues in the Department of Electrical Engineering for the assistance received in various ways when preparing the text. He is particularly indebted to Dr. N. N. Hancock, F.I.E.E., who gave generously of his time to discuss and clarify many aspects of machine theory. Much helpful advice was received from Professor P. Hammond, M.A., F.I.E.E., the consulting editor, and Mr. G. E. Middleton, M.A., F.I.E.E., read through the manuscript and made many useful suggestions. Various firms have taken considerable trouble to find suitable photographs and these are acknowledged where they appear in the book. Figure 2.7 was copied from a flux plot kindly loaned by Mr. F. J. Pepworth, M.I.E.E., who had spent many hours in its preparation.

J. H.

Manchester College of Science
and Technology

LIST OF SYMBOLS

THE following list comprises those symbols which are used fairly frequently throughout the text. Other symbols which are confined to certain sections of the book and those which are in general use are not included, e.g. the circuit symbols like R for resistance and the use of A, B and C for 3-phase quantities. Some symbols are used for more than one quantity as indicated in the list. With few exceptions, the symbols conform to those recommended by the British Standards Institution BS 1991.

Instantaneous values are given small letters, e.g. e, i, for e.m.f. and current respectively.

R.M.S. and steady d.c. values are given capital letters, e.g. E, I.

Maximum values are written thus: $\hat{E}$, $\hat{I}$.

Bold face type is used for phasor and vector quantities, e.g. **E, I.**

In general, the symbol E (e) is used for induced e.m.f.s due to mutual flux and the symbol V (v) is used for terminal voltages.

a Number of pairs of parallel circuits in machine winding.

At Ampere turns—equivalent to amperes enclosed.

B Flux density, in teslas (webers/metre^2).

C Number of coils or commutator bars.

d Symbol for direct-axis quantities.

d Armature diameter, in metres.

e Base of natural logarithms.

E_f Induced e.m.f. due to field m.m.f. F_f.

f Frequency, in hertz (Hz) (cycles per second).

F Magnetomotive force (m.m.f.) in ampere turns. Peak m.m.f. per pole per phase.

F'_a Effective d.c. armature-winding magnetising m.m.f. per pole.

F_a Peak armature-winding m.m.f. per pole.

F_f Peak field-winding m.m.f. per pole.

(Note that the suffices a and f are also used with the symbols for currents, fluxes and resistances of armature and field respectively.)

F_r Peak resultant m.m.f. per pole.
$I_{f.l.}$ Full-load current.
I_0 Current in magnetising branch.
I_p Power component of I_0.
I_m Reactive or magnetising component of I_0.
J Polar moment of inertia (rotational inertia), in kg m^2.
k Coefficient of coupling. A constant.
k_{pn} Coil-pitch factor for the nth harmonic.
k_{dn} Distribution factor for the nth harmonic.
k_f Generated volts per field ampere or per unit of m.m.f.
k_{fs} Saturated value of k_f.
k_ϕ Flux factor; generated volts per radian/sec or torque per ampere.
l Conductor length. Magnetic path length.
l or l_1, l_2, etc., leakage inductance.
L General inductance symbol; e.g. L_{11} = self-inductance of coil 1; L_{12}, L_{13}, etc., for mutual inductances.
m Number of phases.
M Alternative mutual-inductance symbol for two coils.
n Rev/sec. n_s Rev/sec synchronous $= f/p$.
N Number of turns. Rev/min. N_s Rev/min synchronous $= 60f/p$.
p Operator d/dt.
p Number of pole pairs.
p.u. Suffix for per-unit quantities.
P Power per phase.
P_g (or P) Air-gap power per phase.
q Slots per pole per phase.
q Symbol for quadrature-axis quantities.
Q Slots per pole.
R_m Magnetising resistance, representing iron losses.
s Fractional slip $= (n_s - n)/n_s$.
S Per-unit relative motion n/n_s $(= 1-s)$. Number of slots.
$T_{coupling}$ Torque acting at mechanical shaft coupling.
T_e Torque developed electromagnetically, in newton metres.
T_{loss} Sum of all mechanical, internal loss-torques.
T_m Torque arising mechanically $= T_e$ in steady state.