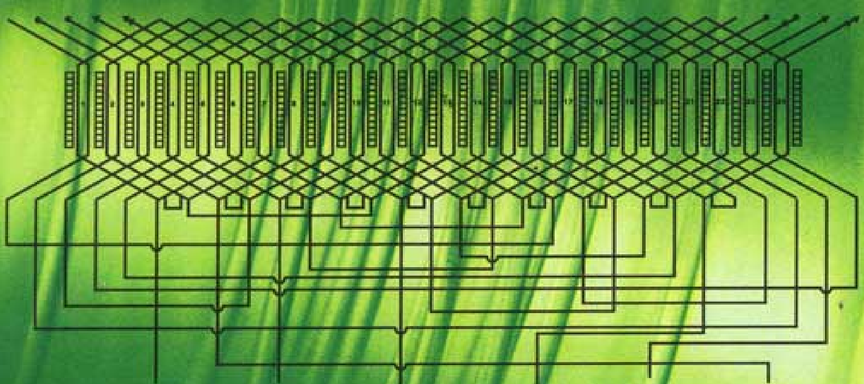
# Electrical Machinery

Dr. S.K. Sen



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# ELECTRICAL MACHINERY

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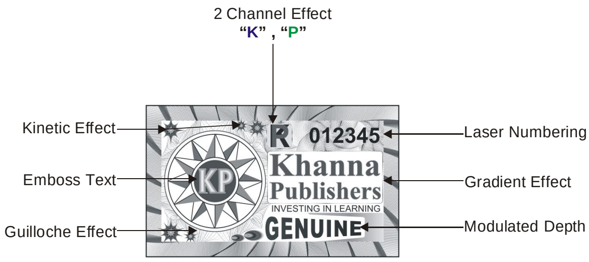


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# PREFACE TO THE FOURTH EDITION

Traditionally analysis of electrical apparatus-rotating and static has been based on piecemeal dealing of individual apparatus with emphasis on steady-state performance. Since machines ope ate as a component in a system, study of dynamic behaviour assumes considerable importance. This has lead to the development of a Generalised approach, and also a Unified approach to the analysis of electrical machines.

Generalised study, developed in terms of circuit equations on the basis of Park's two-axis equations or Doherty & Nickle's symmetrical component model is an excellent approach. Performance under a given condition is derived in the form of impedance and connection matrices. The approach is extremely user friendly probably because of its base on circuit conception which is a continuity of a student's earlier training. But it has a limitation of non-applicability to certain problems, such as, machines with more than one saliency.

Unified approach, on the other hand, is based on energy principles which is applicable to all kinds of electromagnetic devices. The machines is considered as part of a set of linked electrical, magnetic and mechnical systems and provides a physical basis for generalised approach.

In this edition I have tried to present the introductory to both the approaches, intending to build a synergy of both the approaches, keeping in mind the system, in vogue a decade back, in Indian Universities that steady-state analysis would be mainly covered in the undergraduate curriculum followed by transient and dynamic studies in the post-graduate level. However, during the last decade or so, there has been a sea change, specially in the Power Engineering curriculam, in view of more and more emphasis on digital electronics and computer, environmental studies, and financial & project managements, and consequent inclusion in Electrical Engineering curriculum. It must however be remembered that the school curriculum have also been updated during this period and that total student-hours in Universities have not increased. Side by side, when we are shifting from a 'technological society' to a 'knowledge society' it demands a renewed look into the curriculum, and mode of presentation in class room and it is a teacher's duty to inculcate innovative mind in the students. For that purpose, teachers in the undergraduate classes should highlight the assumptions involved in the machine analysis thoroughly and elaborately so that students are aware of the limitations. This will introduce questions in the young mind and wil pavy way for future development in machine analysis.

In view of above, I have endeavoured to streamline the subject through judicious merger of generalised and unified approaches. For example, the elements of inductance matrix in the generalised approach can be usefully dervied using the unified approach. I feel that since the students would be conversant with the matrix algebra by the time they reach second year in the University, a phased orientation towards application of matrix algebra to machine analysis should be made now. As such, in this edition, fundamentals of generalised matrix equations for the analysis of electrical machines is added.

During the last decade or so, 'advances in power electronic

switching devices and microprocessor-based controls have led to the availability of variable frequency electric supplies at continuously decreasing cost. Tills has not only lead to the obsolesence of A.C. Commutator machines, but opened up new interesting possibility in the use of suitable electric motors as an alternative to direct current machines. As such, in this edition a.c. commutator machines have been omitted.

Side by side, development of newer permanent materials have renewed interest in the development of permanent magnet synchronous motors and drives. This interest is economically viable in spite of the present high cost of permanent magnet materials since motors of very high efficiency can be designed leading to ultimate energy saving considering the life span of 12-15 years of these motors.

In view of above it was thought necessary to provide the students on the basics of power electronics control as well as permanent magnet motors.

I take this opportunity ofthanking Dr. D. Dasgupta of Bengal Engineering College (Deemed University) and Dr. Sujit. K. Biswas of Jadavpur University for help. Secretarial helps from my daughter Anasua Chakraborti and son-in-law Shyamal Chakraborti helped for faster modifications of the old edition.

— Prof. S.K. SEN

# PREFACE TO THE FIRST AND SECOND EDITIONS

Teachers connected with courses on Electrical Machinery are often found to debate: 'Which approach should be adopted in teaching and learning the courses in an undergraduate curriculum with special reference to the Indian condition-the Classical, the Generalised, or the Unified ?'

Of the three approaches, the classical or the traditional approach deals with machines in a priecemeal fashion with no a pparen t connection between the various types of electrical machines. The approach mainly concerns with the steady-state analysis of the machines.

The generalised theory presents a well-developed aproach based on the original contributions of G. Kron and R.H. Park. Performance equations are developed for a 'Primitive machine' under the transient condition, and individual machines are analysed with the help of these equations using suitable 'transformations'. Steady-state analysis follows as a special case of the transient condition.

The unified theory, on the other hand, presents the greatest degree of generality. An electrical machine is viewed as a transducer having a magnetic field which can store energy; and like the generalised theory copes with the transient as well as the steady-state conditions.

However, an important drawback ofthe generalised theory as well as the unified theory is the assumption of linearity. The classical approach has the advantage that it considers important practical non-linear effects such as commutation, slotting, satuation, voltage build-up in a self-excited machines etc. and directly links the analysis with the design of a machine.

It has been the endeavour of the author to correlate the unified and the classical approaches. The author has found that the appreciation of the unified theory is more profound when a student has a certain grasp ofthe physical phenomenon in an electromagnetic machines; otherwise it is. quite possible that he looks at a machine as a set of simultaneous equations. With this in view, that steadystate theory has been developed first in this book.

The author takes this opportunity of recording his greatful acknow ledgement to the advice and criticism of his friends, colleagues and students. Indeed, this book is an outcome of an effort in which so many have played useful part that individual mention will surely miss a name or two.

It is but natural that in spite of best of efforts, there are still a few mistakes in the book. The author will deem it a great favour if these are pointed out.

*B.E. College, Howrah-3.* 1975.
- Prof. S.K. SEN

## PREFACE TO THE THIRD EDITION

This book is a revised version of its fore-runner, *'Rotating Electrical Machinery',* . first published in 1975, and subsequently reprinted with a subsidy under the Indo-American Textbook programme operated by the N.B.T., India.

The necessity of changing the title ofthe book arose because of the inclusion of 'Transformers' in the main text, as advised by many of my collegues and students. This, and also suitable incorporation ofthe Unified theory necessitated revision of the first few chapters. Further, short questions have been added at the end of each chapter.

On many occasions, I have expressed my belief that the study of the principles of electrical machines should be based on flux-m.m.f, relationship rather than the matrix method, so that physical concepts are well understood. It is gratifying that such belief has support of eminent teachers, such as, Prof. M.G. Say: ..... the machine performance can be grasped more readily through the application of the flux-current interaction than by the manipulation of matrix equations; the latter give meaningful quantitative results only if the physical concepts are understood".

I thank my colleagues, friends, and students in the Universities, and in the industries, in India and abroad, for their kind help and criticisms, which have been of enormous value to me. I take this opportunity of inviting my readers for such critical comments and suggestions.

*B.E. College, Howrah 711103.*
- Prof. S.K. SEN

# CONTENTS

# LIST OF SYMBOLS

| | |
|---|---|
| $a$ | number of parallel paths |
| $ac$ | specific electric loading (Amp-cond/metre) |
| $B$ | magnetic flux-density (Tesla) |
| $b$ | instantaneous flux-density |
| $C$ | a constant |
| $D$ | differential operator *(d/dt)* |
| $E$ | voltage (volt) |
| $e$ | instantaneous voltage (volt) |
| $F$ | force (Newton) |
| $f$ | *frequency (Hz)* |
| $g$ | gap-length (metre) |
| $H$ | inertia constant (sec) $H$ coercivity (A.t/metre) |
| $h$ | order of harmonics |
| $I$ | current (amp) |
| $L$ | instantaneous current (amp) |
| $J$ | angular current density (amp/radian) $J$, moment of inertia (kg - metre+) |
| $J$ | instantaneous angular current-density (amp/radian) |
| J | rotation operator through + 90 |
| $K$ | a constant |
| $K_p$ | coil-span factor |
| $k$ | an integer |
| $k$ | saturation factor |
| $kl$ | breadth factor |
| $L$ | inductance (Henry) |
| $l$ | axial length (metre) |
| $l$ | leakage inductance (Henry) |
| $M$ | magneto-motive force (A-t/pole) |
| $n$ | instantaneous m.m.f (A-t/pole) |
| $N$ | number of turns |
| $n$ | speed of rotation (rev. per sec.) |
| $P$ | power (watt) |
| $P$ | permenance |
| $p$ | number of poles |
| $p$ | differential operator *(d/dt)* |
| Q | reactive power (var) |
| $R$ | magnetic reluctance (A-*t*/Wb) |
| r | rotor radius (metre) |
| $r$ | resistance (ohm) |
| $S$ | number of armature slots |

| | |
|---|---|
| *is* | number of slots per phase |
| *s* | slip |
| *T* | torque (Newton-metre) |
| *t* | time (sec) |
| *v* | velocity (metre/sec) |
| *W* | energy (Joule) |
| *W* | stored mechanical energy (J) |
| *W(* | stored magnetic energy (J) |
| *X,Y* | rectangular co-ordinates |
| y | admittance (mho) |
| *y* | pole-pitch (metre) |
| *Y* | pole arc (metre) |
| Z | impedance (ohm) |
| Z | total number of conductors |

**Subscripts**

| | |
|---|---|
| *A* | armature including brushes |
| *a* | armature winding |
| *a* | primary winding |
| *af* | between armature and field |
| *ag* | airgrap |
| *ar* | between armature and resultant |
| *b* | secondary winding |
| *b* | backward field |
| c | core-loss component |
| c | control winding |
| c | stabilising winding |
| *cu* | $i^2r$-*Ioss* component |
| *d* | direct-axis |
| e | electrical |
| e | electromagnetic |
| e | external |
| cz | electrical input |
| *eq* | equivalent |
| *t* | field |
| *f* | forward field |
| *II* | full load |
| *fr* | between field and resultant |
| *g* | gap |
| *i* | input |
| *ind* | induction motor |
| *kd* | direct-axis damper |
| *kq* | quardrature-axis damper |
| *I* | leakage |
| *Ie* | loss, electrical |