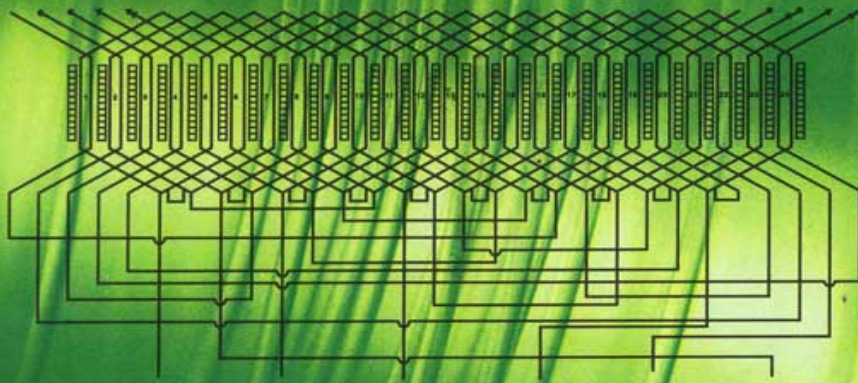


Electrical Machinery

Dr. S.K. Sen



Khanna Publishers

ELECTRICAL MACHINERY

Prof. S.K. Sen

*B.E. (Cal), Ph.D. (Lond), DIC, FIE, FNAE, FIC (Lond),
Ex-Professor & Head, Electrical Engg., B.E. College, Howrah,
Ex-vice-Chancellor, Jadavpur Univeristy, Kolkata,
Ex-Minister-in-charge, Power, Science Technology &
Non-conventional Energy Sources, Govt. of West Bengal.
Hony Advisor to C.M., Govt. of Sikkim,
Hony. Member, Sikkim State Planning Commission.*



KHANNA PUBLISHERS

Operational Office

B-35/9, G.T. Karnal Road, Industrial Area,
(Near Telephone Exchange), Delhi-110033
Phones : 011-27224179 • Mob. 09811541460
email : contactus@khannapublishers.in

Published by :

Romesh Chander Khanna & Vineet Khanna
for **KHANNA PUBLISHERS**
2-B, Nath Market, Nai Sarak
Delhi- 110 006 (India)

Website : www.khannapublishers.in

© 1979 and onward

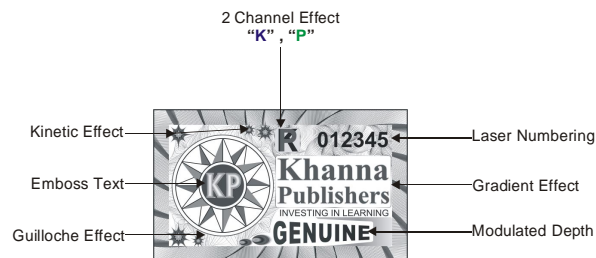
This book or part thereof cannot be translated or reproduced in any form without the written permission of the Authors and the Publishers. The right to translation, however, reserved with the author alone.

Copyright: Author and Publishers Jointly

Hologram & Description

To all readers of our books, from yourself if being defrauded by pirates to prevent, please make sure that there is an Hologram on the cover of our books with the below specifications. If you find any book without Hologram and Description, please mail us at contactus@khannapublishers.in

Thanking you



ISBN No. 978-81-7409-152-1

First Edition : 1977

Fourth Edition :

First Reprint : 2019

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 operate as a component in a system, study of dynamic behaviour assumes considerable importance. This has led 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 mechanical 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 curriculum, 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 will pave 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 derived 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. This has not only led to the obsolescence 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 of thanking 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 piecemeal fashion with no apparent 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 approach 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 of the 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, saturation, 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 of the 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 steady-state theory has been developed first in this book.

The author takes this opportunity of recording his grateful acknowledgement 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 of the book arose because of the inclusion of 'Transformers' in the main text, as advised by many of my colleagues and students. This, and also suitable incorporation of the 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

1.	Introductory	1—49
1.1	Effects of Magnetic Field	1
1.2	Types of Rotating Electrical Machines	7
1.3	Signs and Conventions	11
1.4	Basis of Analysis	13
1.4.1	Stored Magnetic Field Energy	17
1.4.2	Stored Mechanical Energy	17
1.5	Mechanism of Electro-Mechanical Energy Conversion	30
1.6	Torque Equation-Field-Energy Approach	33
1.6.1	Singly-Excited Machine	34
1.6.2	Doubly-Excited Machine	42
1.7	Per Unit System	4:3
1.7.1	Transformer	43
1.7.2	Rotating Machines	44
	Questions	45
2.	Magnetically Coupled Circuits and Transformers	50-146
2.1	Single Coil	50
2.1.1	Core Losses	54
2.2	Two Mutually Linked Coils	57
2.3	Transformer	70
2.3.1	Construction	71
2.3.2	Performance Analysis	72
2.3.3	Regulation	78
2.3.4	Losses and Efficiency	87
2.3.5	Determination of Parameters of the Equivalent Circuit	90
2.3.6	Three-phase Connections	95
2.3.7	Three-phase Transformers	104
2.3.8	Interconnection of Transformers	106
2.3.9	Voltage Variation by Tap-Changing	124
2.3.10	Special Types of Transformers	127
	Questions	142
	Objective Type	144

3. Field Excitation and Generated Voltage	147—178
3.1. Salient Poles with Direct Current Excitation	147
3.2. Non-salient Poles with Direct Current Excitation	148
3.3. Single Phase A.C. Excitation	149
3.4. Polyphase Excitation	150
3.5. Space-Phasor and Time-Phasor	154
3.6. Permanent Magnet Excitation	154
3.7. Voltage Generated in Electrical Machine	159
3.8. KMF, in a Short-pitched Coil	168
3.9. KMF, in a Distributed Winding	169
3.10. Saturation in Electrical Machines	171
Questions	175
Objective Type	170
4. Armature Excitation and Torque in Electrical Machine	179—208
4.1. Current Sheet.	179
4.2. M.M.F. and Flux-density Waveforms	180
4.3. M.M.F. Equations-D.C. Machine	183
4.4. M.M.F. Equation-A.C. Machine	184
4.5. Armature Reaction and Resultant Field-Form	186
4.6. Armature-Reaction in a Permanent Magnet Machine	189
4.7. Electromagnetic Torque in Electrical Machines	190
4.8. Inductance Equations	195
4.9. Production of Torque-Practical Machines	200
4.9.1 Three-Phase Induction Motor	201
4.9.2 Three-Phase Synchronous Motor	202
4.9.3 Three-Phase Synchronous Generator	204
Questions	205
Objective Type	206
5. Flux-m.m.f. Relationship and Phasor Diagram	209-243
5.1. Methods of Excitation	209
5.2. Flux and M.M.F. Relationships	209
5.3. Phasor Diagram : Non-Salient Pole Machine	213
5.4. Generator and Motor Action	219
5.5. Phasor Diagram of Salient-Pole Synchronous Machine-Two-Reaction Theory	221
5.6. Phasor Diagram-Important Modifications	224
5.7. Steady-State Equivalent Circuit	228
5.8. Determination of Synchronous Reactance	229

5.9	Calculation of x_d and x_q	235
5.10	Short-Circuit Ratio.	236
5.11	Saturated Synchronous-Reactance.	237
	Questions.	240
	Objective Type	241
<hr/>		
6.	Steady-State Characteristics	244—284
<hr/>		
6.1.	Load Characteritics	244
6.2.	Effect of Variation of Field Excitation	245
6.3.	Regulation of an Alternator	249
6.4.	Separation of Armature Reaction and Leakage Reactance Effects	252
6.5.	Steady-State Power Flow	254
6.6.	Electrical Load Diagram	264
6.7.	Current Locus for Constant Excitation	266
6.8.	Loss of Excitation	271
	Questions	278
	Objective Type	279
<hr/>		
7.	Operation and Control	285-342
<hr/>		
7.1	Interconnected Synchronous Generators	285
7.1.1	Synchronising	287
7.1.2	Resynchronising	289
7.1.3	Self-Synchronising	289
7.1.4	Load Sharing	290
7.1.5	Synchronising Torque	295
7.2	Operating Chart for Large Generators	299
7.3	Starting Phenomenon of Synchronous Motor	304
7.3.1	George's Phenomenon	307
7.4	Synchronous Induction Motor	309
7.4.1	Salient-Pole Synchronous-Induction Motor	311
7.5	Solid-State Control of Synchronous Machines	314
7.5.1	Excitation Control	314
7.5.2	Speed Control of Synchronous Motor	317
7.6	Divided Winding Rotor Synchronous Machine	323
7.7	Permanent Magnet Synchronous Motor	326
7.7.1	General Features	328
7.7.2	Trapezoidal PMAC Motor	330
7.7.3	Sinusoidal PMAC Motor	332
7.7.4	Comaprison with 3-phase Cage-rotor Motor	337
	Questions	318
	Objective Type	339

8. Theory of Polyphase Asynchronous Machines 343—377

8.1	Flux and M.M.F. Relationships	344
8.2	Phasor Diagram	345
8.3	Motor and Generator Action	349
8.4	Equivalent Circuit	352
8.5	Performance Calculation	354
8.6	Determination of Equivalent Circuit Parameters	355
8.7	Torque Characteristic	357
8.8	Reactive Power	361
8.9	Squirrel-Cage Rotor	362
8.10	Current Locus	364
8.11	Improvement of Starting Torque of Cage-Rotor Motor	369
	Questions	373
	Objective Type	375

9. Starting, Braking and Speed-Control of Induction Motor 378—433

9.1	Starting Methods	378
9.2	Electrical Braking of Induction Motor	388
9.3	Speed-Control of Three-Phase Induction Motor	396
9.3.1	Frequency Variation	397
9.3.2	Variation of Number of Poles	401
9.3.3	Variation of Supply Voltage	411
9.3.4	Variation of Motor Parameters	411
9.3.5	Control of Rotor Slip-Power	415
9.4	Power-Factor Control of Three-Phase Induction Motor	424
	Questions	429
	Objective Type	431

10. Induction Machine for Special Purpose 434—444

10.1	Eddy-Current Slip Coupling	434
10.2	The Linear Motor.	436
	Questions	443
	Objective Type	443

11. Single-phase Asynchronous Motor 445—478

11.1	Starting Torque	445
11.2	Classification	448
11.3	Performance Analysis	450
11.4	Nature of Resultant Field	464

11.5 Equation for the Starting Torque	466
11.6 Condition for Maximum Starting Torque.	468
Questions	474
Objective Type	474
12. Commutator Action	479—486
12.1 Slip-Ring and Commutator	476
12.2 Action of Commutator as Frequency Changer	481
12.3 Thyristor-Commutator	483
Questions	486
13. Direct Current Machines	487—558
13.1 Basic Parts	487
13.2 Methods of Excitation	487
13.3 Armature Reaction	489
13.4 Compensating Winding	493
13.5 Commutation	494
13.6 Interpoles	501
13.7 Characteristics	503
13.8 Interconnected D.C. Generators	530
13.9 Starting Methods	533
13.10 Speed Control of D.C. Motor	541
13.11 Braking of D.C. Motor	547
Questions	552
Objective Type	555
14. Transients and Dynamics	559—647
14.1 General Torque Equation	559
14.2 Per-Unit Representation-Inertia Constant	560
14.3 Dynamic Equation-D.C. Machines	561
14.4 Transfer Function and Block-Diagram	577
14.5 Electrical Transients in Synchronous Machine	588
14.5.1 The Prototype Model	588
14.5.2 Representation of Damper Winding	589
14.5.3 Qualitative Study	591
14.5.4 Expressions for Reactances & Time-Constants	599
14.5.5 Generalised Equations for Synchronous Machine	606
14.6 Electrical Transients in Induction Machine	620
14.7 Dynamics of Synchronous Machine	624

14.8 Dynamics of Induction Machine	639
Questions	643
Objective Type	645
<hr/>	
15. Electrical Machines in Control Systems	648-699
<hr/>	
15.1 Direct-Current Machines	
15.2 Alternating-Current Machines	
Questions	
Objective Type	
<hr/>	
APPENDICES	700—735
<hr/>	
I. Permanent Magnet Materials	700
II. Armature Winding	702
III. Motor Stability	722
IV. Static Inverter and Cycloconverter	725
V. Two-phase Symmetrical Component Analysis	729
<hr/>	
Problems	736
Answers to Problems	773
<hr/>	
Index	780

LIST OF SYMBOLS

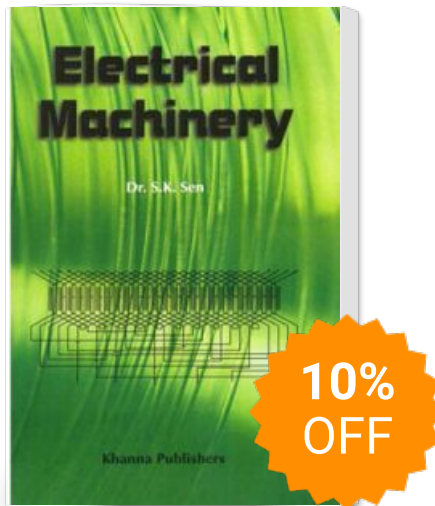
<i>a</i>	number of parallel paths
<i>ac</i>	specific electric loading (Amp-cond/metre)
<i>B</i>	magnetic flux-density (Tesla)
<i>b</i>	instantaneous flux-density
<i>C</i>	a constant
<i>D</i>	differential operator (d/dt)
<i>E</i>	voltage (volt)
<i>e</i>	instantaneous voltage (volt)
<i>F</i>	force (Newton)
<i>f</i>	frequency (Hz)
<i>g</i>	gap-length (metre)
<i>H</i>	inertia constant (sec) <i>H</i> coercivity (A.t/metre)
<i>h</i>	order of harmonics
<i>I</i>	current (amp)
<i>L</i>	instantaneous current (amp)
<i>J</i>	angular current density (amp/radian) <i>J</i> , moment of inertia (kg - metre ²)
<i>J</i>	instantaneous angular current-density (amp/radian)
<i>J</i>	rotation operator through + 90
<i>K</i>	a constant
<i>K_p</i>	coil-span factor
<i>k</i>	an integer
<i>k</i>	saturation factor
<i>kl</i>	breadth factor
<i>L</i>	inductance (Henry)
<i>l</i>	axial length (metre)
<i>l</i>	leakage inductance (Henry)
<i>M</i>	magneto-motive force (A-t/pole)
<i>n</i>	instantaneous m.m.f (A-t/pole)
<i>N</i>	number of turns
<i>n</i>	speed of rotation (rev. per sec.)
<i>P</i>	power (watt)
<i>P</i>	permenance
<i>p</i>	number of poles
<i>p</i>	differential operator (d/dt)
<i>Q</i>	reactive power (var)
<i>R</i>	magnetic reluctance (A-t/Wb)
<i>r</i>	rotor radius (metre)
<i>r</i>	resistance (ohm)
<i>S</i>	number of armature slots

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

Subscripts

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

Electrical Machinery



Publisher : KHANNA PUBLISHERS

ISBN : 9788174091521

Author : S. K. Sen

Type the URL : <https://www.kopykitab.com/product/40226>



Get this eBook