



**GENERALIZED THEORY  
OF  
ELECTRICAL  
MACHINES**

**Dr. P.S. Bimbhra**



**KHANNA PUBLISHERS**

---

---

# **GENERALIZED THEORY OF ELECTRICAL MACHINES**

---

---

## ***OTHER BOOKS ON ELECTRICAL ENGINEERING***

1. Control Systems Analysis and Design by *K.K. Agarwal*
2. Control System Theory by *Dr. S.D. Gupta*
3. EHV-AC & HVDC Transmission Engineering & Practice by *S. Rao*
4. Electrical Motor Drives by *M.S. Berde*
5. Electric Power System – Analysis, Stability & Protection by *K.A. Gangadhar*
6. Electric Circuit Theory by *Arumugan & Prem Kumar*
7. Electrical Engineering Materials by *G.K. Mithal*
8. Electrical Machinery by *Dr. P.S. Bimbhra*
9. Electrical Machinery by *S.K. Sen*
10. Electrical Measurements & Measuring Instruments by *Dr. R. Prasad*
11. Electrical Power by *S.L. Uppal*
12. Electrical Substation Engineering & Practice by *S. Rao*
13. Electrical Wiring, Estimating and Costing by *S.L. Uppal*
14. Handbook of Electrical Engineering by *S.L. Bhatia*
15. High Voltage Engineering by *Dr. M.P. Chaurasia*
16. Laboratory Experiments in Electrical Power by *C.S. Indulkar*
17. Linear Control Systems by *B.S. Manke*
18. Power Electronics by *Dr. P.S. Bimbhra*
19. Power System Analysis and Stability by *S.S. Vadhera*
20. Power Transformers and Special Transformers by *S. Rao*
21. Switchgear and Protection by *Sunil. S. Rao*
22. Testing, Commissioning & Maintenance of Electrical Equipments by *S. Rao*
23. Textbook of Electrical Engineering Materials by *Kapoor*
24. Thyristor Engineering by *M.S. Berde*
25. Utilization of Electrical Power & Traction by *G.C. Garg*

---

---

# GENERALIZED THEORY OF ELECTRICAL MACHINES

---

---

**Dr. P. S. Bimbhra**

*Ph. D., M.E. (Hons.), F.I.E. (India), M.I.S.T.E. (U.K.)*  
Ex-Dean; Ex-Prof. and Head of Electrical & Electronics Engg. Dept.  
Thapar Institute of Engineering and Technology  
PATIALA-147004



**KHANNA PUBLISHERS**

**Operational Office**

4575/15, Onkar House, Ground Floor

Darya Ganj, New Delhi-110002

*Phones : 011-23 24 30 42, 23 24 30 43 & Mob. 9811541460*

**e-mail : khannapublishers@yahoo.in**

**Website : www.khannapublishers.in**

**Published by :**

Romesh Chander Khanna & Vineet Khanna  
for **KHANNA PUBLISHERS**  
2-B, Nath Market, Nai Sarak,  
Delhi-110006 (India)

Visit us at : [www.khannapublishers.in](http://www.khannapublishers.in)

**Copyright: Author and Publishers Jointly**

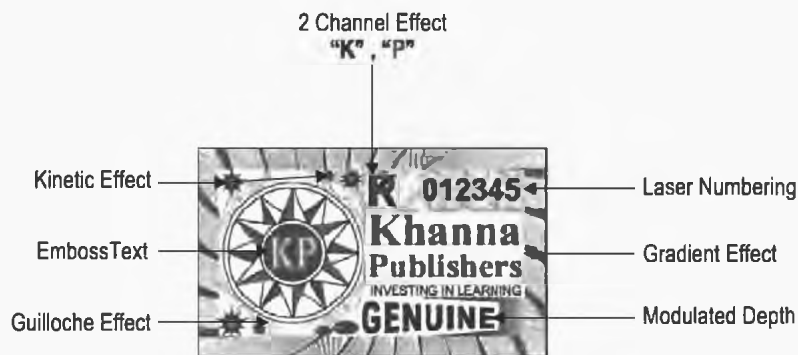
**© 1979 and onward.**

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

**Hologram & Description**

To all readers of our books, to prevent yourself from being frauded by pirated books. Please make sure that there is an Hologram on the cover of our books with the below specifications. If you find any book without the Hologram or Description, please mail us at [khannapublishers@yahoo.in](mailto:khannapublishers@yahoo.in).

Thanking you



**ISBN No. : 978-81-7409-225-0**

*First Edition* : 1981

*Sixth Edition* : 2017

*To*

**My Wife**

*For her Continuous Encouragement*



# Preface

It has been a matter of great controversy about whether the electrical machines theory be taught by generalized approach or by conventional approach. Some people argue that generalized approach provides little understanding of a real machine and they emphasize their line of reasoning by quoting some jokes. The author feels that first physical concepts of electrical machines be taught to the students along with an extensive laboratory course. Then the generalized theory of electrical machines can be taught with advantage, in conjunction with a set of appropriate laboratory experiments. An untoward behaviour of the machine should be explored by the students themselves and in case they fail, the instructor incharge should help them. For example, if the direction of motor rotation turns out to be wrong in any experiment, then students should be made to think so as to correct the direction of rotation. This type of laboratory course work would definitely obviate absurd answers from the students and would go a long way in imparting a real physical understanding of the various types of electrical machines.

In the earlier stages, the machine worked in isolation and its steady-state analysis was sufficient to be known. Now the electrical machine forms an integral part of a large system comprising of other components as well. In feedback control systems, a motor operates mainly under transient and dynamic conditions. In view of these facts, the transient and dynamic analysis of electrical machines and systems have gained importance and therefore the students must be taught the art of reducing a practical problem to an accurate mathematical model. The generalized theory of electrical machines, emphasizing the basic similarities of all the machines, now forms the basis of mathematical-machine modelling. The magnetic field view-point leads to steady-state analysis, whereas the generalized approach leads only to steady-state, transient and dynamic analysis. The ability of a teacher to correlate the two independent treatments in the class leads to a better understanding of the subject.

The coupled circuit theory of synchronous machines makes use of the Park's transformation. First of all, the voltage equation  $v = ri + p\psi$  is written for each phase and then the flux linkages  $\psi$  are expressed in terms of self and mutual inductances. These voltage and flux-linkage equations are then transformed to  $d$ - $q$  variables by using Park's transformations. This process of transformation from phase variables to  $d$ - $q$  variables is so

tedious and cumbersome that students lose sight of what is going on in the machine. In this regard, G. Kron wrote as follows: “The author has seen hundreds of student engineers in company courses start the study of Park’s equations with zest, then after several weeks of relentless manipulations of the  $\cos (\theta - 120)$  and  $\sin (\theta - 240)$  terms, give up in disgust. By the time they thought they understood the dc machine type equations, the students were all ready and willing to become executives and vice-presidents rather than synchronous machine experts.” With generalized approach, the synchronous machine equations in  $d-q$  variables can be obtained by a simple graphical method of writing the machine equations, from merely observing the primitive machine. It may be concluded from above that generalized approach for polyphase synchronous and induction machines is simpler than the coupled-circuit approach.

It is sometimes argued that generalized approach can’t take saturation into consideration. Actually, this approach is more useful for studying the transient and dynamic behaviour of electrical machines and of interconnected electrical machine systems. This does not mean that this approach fails to do the steady-state analysis. In order to highlight the various factors effecting the transient performance and to study the dynamic system problems, it is relatively of much less importance to take magnetic saturation into consideration. Saturation can, however, be taken into account but with the use of computers.

The physical understanding of single-phase induction motors and asymmetrical operation of 3-phase induction motors can be better appreciated by counter-rotating field theory associated with symmetrical component concepts. It is because of this reason that single-phase induction motor is dealt with in detail by double revolving field theory, in addition to the generalized concepts. The physical approach is presented in this book where the generalized approach becomes too involved for the undergraduate students.

In the present edition, some material of the book has been reworded and rewritten so as to make the presentation easily comprehensible. More illustrative examples mainly from IAS, IES and GATE and other Competitive Examinations have been added and problem material with answers, at the end of each chapter, has been considerably enlarged.

With recent advances in power electronics and microelectronics, new electric machine types like brushless dc motors, variable reluctance motors etc. are found in modern electric drive systems. Keeping these advances into consideration, also devoted to the discussion of brushless dc, variable reluctance and stepping motors, is included in the book. An appendix, containing objective-type questions pertaining to the topics covered in this book, is given in the end.

A great deal of time has gone into the updating of the fourth edition, and I must acknowledge the patience exhibited by my wife and children, though at a great inconvenience to them.

The author would welcome the advice and suggestions leading to the improvement of the book.

**Dr. P. S. BIMBHRA**

# Contents

<b>1. ELEMENTS OF GENERALIZED THEORY</b>		<b>1-25</b>
1.1	Essentials of Rotating Electrical Machines	... 1
1.2	Conventions	... 2
1.3	The Basic Two-pole Machine	... 4
1.3.1	Commutator Machines	... 4
1.3.2	D.C. Compound Machine	... 5
1.3.3	D.C. Shunt Machine with Interpoles	... 5
1.3.4	Amplidyne	... 5
1.3.5	Single Phase A.C. Series Machine	... 6
1.3.6	Repulsion Motor	... 6
1.3.7	(a) Synchronous Machine without Dampers	... 7
1.3.7	(b) Synchronous Machine with Dampers	... 7
1.3.8	Three-Phase Induction Machines	... 8
1.4	The Per Unit System	... 8
1.5	Transformer with a Movable Secondary	... 11
1.6	Transformer and Speed Voltages in the Armature	... 11
1.7	Kron's Primitive Machine	... 13
1.7.1	Leakage Flux in Machines with more than two Windings	... 15
1.7.2	Voltage Equations	... 16
1.8	Analysis of Electrical Machines	... 21
1.8.1	Concept of Phasors	... 21
1.8.2	Operational Method	... 24
	<i>Problems</i>	... 25
<b>2. LINEAR TRANSFORMATIONS IN MACHINES</b>		<b>26-51</b>
2.1	Invariance of Power	... 27
2.2	Transformation from a Displaced Brush-Axis	... 28
2.3	Transformations in Electrical Machines	... 29
2.3.1	Three-phase to Two-phase Transformation (a, b, c to $\alpha$ , $\beta$ , o)	... 29
2.3.2	Two-phase to Two-axis Transformation ( $\alpha$ - $\beta$ to d-q)	... 32
2.3.3	Three-phase to Two-axis Transformation (a, b, c to d, q, o)	... 34

<i>Chapter</i>	<i>Pages</i>
2.4 Power Invariance	... 36
2.5 Physical Concepts of Park's Transformations	... 38
2.5.1 Three-phase Synchronous Machines	... 39
2.5.2 Three-phase Induction machines	... 42
2.6 Transformed Impedance Matrix	... 43
2.7 How to Apply Generalized Theory	... 46
2.8 Electrical Torque	... 47
2.9 Restrictions of the Generalized Theory of Machines	... 48
<i>Problems</i>	... 49
<hr/>	
<b>3. D.C. MACHINES</b>	<b>52-124</b>
3.1 Separately Excited D.C. Generators	... 53
3.1.1 Sudden Short-Circuit for a Separately Excited D.C. Generator	... 59
3.2 Separately-Excited D.C. Motors	... 61
3.2.1 Sudden Application of Inertia Load	... 67
3.3 Interconnection of Machines	... 69
3.3.1 Ward-Leonard System of Speed Control	... 69
3.4 D.C. Series Motor	... 74
3.5 D.C. Shunt Machines	... 75
3.5.1 Motor Operation	... 75
3.6 D.C. Compound Machine	... 81
3.6.1 Cumulatively Compounded (Long Shunt) D.C. Motor	... 83
3.7 Linearization Techniques for Small Perturbations	... 85
3.8 Cross Field Machines	... 88
3.8.1 Amplidyne	... 89
3.9 Parallel Operation of D.C. Generators	... 95
3.9.1 Parallel Operation of Shunt Generators	... 96
3.9.2 Parallel Operation of Compound Generators	... 99
3.10 Electric Braking of D.C. Motors	... 107
3.10.1 Regenerative Braking	... 107
3.10.2 Counter-current Braking (or Plugging)	... 108
3.10.3 Dynamic Braking	... 111
3.11 Some Worked Examples	... 116
<i>Problems</i>	... 120
<hr/>	
<b>4. POLYPHASE SYNCHRONOUS MACHINES</b>	<b>125-301</b>
4.1 Basic Synchronous-machine Parameters	... 125
4.1.1 Synchronous-machine Resistances	... 126
4.1.2 Synchronous-machine Inductances	... 127
4.2 General Machine Equations	... 132
4.3 Three-phase Synchronous Machine (With no Amortisseurs)	... 137

<i>Chapter</i>	<i>Pages</i>
4.4	Balanced Steady-State Analysis ... 138
4.4.1	Phasor Equations and Phasor Diagrams ... 139
4.5	Steady-state Power-angle Characteristics ... 146
4.5.1	Reactive Power ... 149
4.6	Short-circuit Ratio ... 154
4.7	Transient Analysis ... 157
4.8	Transient Torque ... 172
4.9	Sudden Reactive Loading and Unloading ... 173
4.9.1	Sudden Reactive Loading ... 173
4.9.2	Sudden Reactive Unloading ... 176
4.10	Transient Analysis—A Qualitative Approach ... 179
4.11	Reactances and Time-Constants from Equivalent Circuits ... 181
4.11.1	Direct-axis Reactances from Equivalent-Circuits ... 181
4.11.2	Direct-axis Time Constants from Equivalent-Circuits ... 183
4.11.3	Quadrature-axis Reactances and Time Constants ... 184
4.12	Concepts of Synchronous Machine Reactances ... 186
4.12.1	Positive Sequence Reactances ... 187
4.12.2	Negative-sequence Reactance, $X_2$ ... 191
4.12.3	Zero-sequence Reactance, $x_0$ ... 192
4.13	Measurement of Reactances ... 193
4.14	Reactances and Time-constants from Short-circuit Oscillogram ... 196
4.15	Transient Power-angle Characteristics ... 200
4.16	Phasor Diagrams under Transient and Subtransient Conditions ... 204
4.16.1	Synchronous-machine Representation in a Power System Network ... 207
4.17	Synchronous-machine Dynamics (or Electro-mechanical Transients) ... 210
4.17.1	Electromechanical Equation ... 210
4.17.2	Cyclic Variations of Shaft Torque (or Forced Oscillations) ... 220
4.18	Large Angular Oscillations ... 224
4.19	Synchronizing ... 229
4.19.1	Synchronizing by Dark-lamp Method ... 230
4.19.2	Synchronizing by a Synchroscope ... 232
4.20	Parallel Operation of Two Alternators ... 236
4.20.1	Effect of Changing Mechanical Torque ... 237
4.20.2	Effect of Changing Excitation ... 240
4.21	Synchronous Machine on an Infinite Bus ... 251
4.21.1	Effect of Varying the Excitation ... 251
4.21.2	Effect of Varying the Driving Torque ... 253
4.22	DWR Synchronous Generator ... 266
4.22.1	Constructional Features ... 267
4.22.2	Flux and m.m.f. Phasors in dwr Alternators ... 268
4.22.3	Balanced Steady-state Analysis ... 271
4.23	Inductor Alternators ... 274
4.23.1	Homopolar Inductor Alternator ... 275
4.23.2	Hetropolar Inductor Alternator ... 276

<i>Chapter</i>	<i>Pages</i>
4.24 Electric Braking of Synchronous Motors	... 277
4.25 Speed Control of Synchronous Motors	... 282
4.25.1 Speed Control Below Rated Speed	... 282
4.25.2 Speed Control above Rated Speed	... 283
5.26 Permanent Magnet Synchronous Machines	... 286
<i>Problems</i>	... 289

## 5 POLYPHASE INDUCTION MACHINES

302-458

5.1 Transformations	... 302
5.2 Electrical Performance Equations	... 303
5.2.1 Steady-state Analysis	... 305
5.3 Analysis of the Equivalent Circuit	... 311
5.4 Torque-slip Characteristics	... 313
5.4.1 Power-slip Characteristics	... 317
5.5 Effect of Voltage and Frequency Variations on the Induction Motor Performance	... 323
5.5.1 Variable Voltage, Constant Frequency	... 323
5.5.2 Constant Voltage, Variable Frequency	... 325
5.5.3 Variable Voltage, Variable Frequency	... 326
5.5.4 Constant Current, Constant Frequency	... 330
5.6 High-torque Cage Motors	... 333
5.6.1 Deep-Bar Rotor	... 333
5.6.2 Double-cage Rotor	... 334
5.6.3 Steady State Analysis	... 337
5.7 Induction Machine Dynamics	... 344
5.7.1 Induction-Machine Dynamics During Starting and Braking	... 345
5.7.2 Accelerating Time	... 350
5.8 Speed Control of Induction Motors	... 353
5.9 Slip-power-recovery Schemes for Induction Motor Speed Control	... 387
5.9.1 Constant-torque Drive	... 387
5.9.2 Constant-power Drive	... 389
5.10 Frequency Converters (or Changers)	... 392
5.10.1 Commutator-Frequency Converter	... 392
5.10.2 Synchronous-Synchronous Frequency Converter	... 394
5.10.3 Induction-Frequency Converter	... 394
5.10.4 Synchronous-induction Frequency Converter	... 396
5.11 Static Slip-power Speed Control	... 402
5.11.1 Static Kramer Drive	... 402
5.11.2 Static Scherbius Drive	... 403
5.11.2.1 DC Link Static Scherbius Drive	... 403
5.11.2.2 Cycloconverter Static Scherbius Drive	... 404
5.12 Electrical Braking of Induction Motors	... 405
5.13 Operation on Unbalanced Supply Voltage	... 413

<i>Chapter</i>	<i>Pages</i>
5.14 Slot Harmonics	... 416
5.14.1 Skewed Slots	... 418
5.14.2 Winding Factor	... 419
5.15 Effect of Space Harmonics on 3-phase Induction-motor Performance	... 421
5.15.1 Harmonic Induction (or Asynchronous) Torques	... 422
5.15.2 Harmonic Synchronous Torques	... 424
5.15.3 Vibration Torques and Noise	... 426
5.15.4 Reduction of Harmonic Torques and Vibrations	... 427
5.15.5 Crawling due to Unsymmetrical Rotor Circuits	... 427
5.16 Linear Electric Motors	... 431
5.16.1 LIM and Its Principle of Operation	... 431
5.16.2 Linear Synchronous Motors (LSM)	... 434
5.16.3 Linear Levitated Machines (LLM)	... 434
5.16.4 Applications	... 434
5.17 Non-sinusoidal Supply Voltage	... 436
5.17.1 Pulsating Harmonic Torques	... 439
5.17.2 Losses	... 440
5.18 Doubly-Fed Induction Machines	... 440
5.18.1 Doubly-Fed Induction Motor	... 440
5.18.1.1 Power Flow in DFI Motor	... 441
5.18.1.2 Power Flow in DFI Generator	... 442
5.19 Conversion of DFI Machine from Motoring Mode to Generating Mode	... 444
<i>Problems</i>	... 447

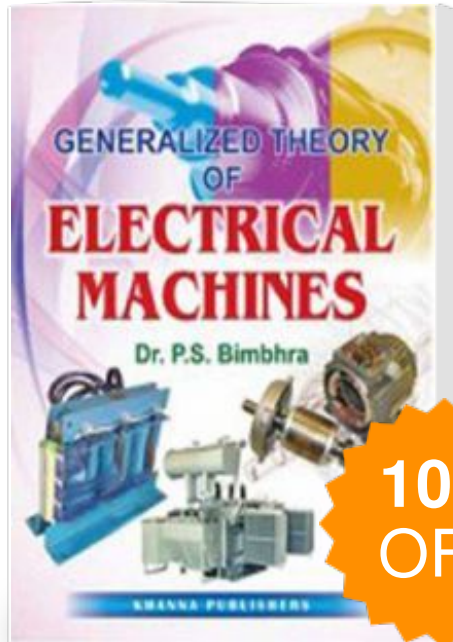
## 6. SINGLE PHASE MOTORS

459–520

6.1 Single-Phase Induction Motors	... 459
6.2 Revolving Field Theory of Single-phase Induction Motors	... 460
6.3 Equivalent Circuit for a Single-Phase Induction Motor	... 465
6.3.1 Measurement of Equivalent-Circuit Parameters	... 473
6.3.2 Approximate Equivalent Circuit	... 476
6.3.3 Comparison between Single-phase and Polyphase Induction Motors	... 478
6.4 Cross-field Theory of Single-phase Induction Motors	... 479
6.5 Starting Methods of Single-Phase Induction Motors	... 484
6.5.1 Split-phase Starting	... 484
6.5.2 Shaded-pole-Starting	... 488
6.5.3 Repulsion-motor-starting	... 489
6.5.4 Reluctance-starting	... 490
6.6 Maximum Starting Torque Conditions in Single Phase Induction Motors	... 491
6.6.1 Resistor Split-Phase Motors	... 491
6.6.2 Capacitor Split-Phase Motors	... 492
6.7 Single-Phase Synchronous Motors	... 497
6.7.1 Single-Phase Reluctance Motors	... 497

<i>Chapter</i>	<i>Pages</i>
6.7.2 Sub-synchronous Motors	... 498
6.7.3 Hysteresis Motors	... 499
6.8 Two-phase Servomotors	... 501
6.9 AC Tachometers	... 512
<i>Problems</i>	... 515
<b>7. A.C. COMMUTATOR MACHINES</b>	<b>521-564</b>
7.1 E.m.fs. Induced in Commutator Windings	... 521
7.1.1 E.m.fs. Produced by Pulsating Field	... 521
7.1.2 E.m.fs. Produced by Rotating Field	... 526
7.2 Torque	... 531
7.3 Single-phase Series Motors	... 532
7.3.1 Compensated A.C. Series Motors	... 536
7.3.2 Radio Interference	... 539
7.3.3 Generalized Theory	... 543
7.4 Schrage Motor	... 549
7.4.1 Generalized Theory	... 557
7.5 Summary	... 561
<i>Problems</i>	... 561
<b>8. TRANSFORMERS</b>	<b>565-724</b>
8.1 Three-phase Transformers	... 565
8.2 Three-phase Transformer Connections and Phasor Groups	... 568
8.2.1 Phasor Groups	... 570
8.2.2 Effect of Polarity Markings and Phase Sequence	... 574
8.3 Parallel Operation of Three-phase Transformers	... 577
8.4 Excitation Phenomena in Transformers	... 582
8.4.1 Harmonics in Single-phase Transformers	... 586
8.4.2 Harmonics in Three-phase Transformers	... 590
8.4.3 Disadvantages of Harmonics in Transformers	... 597
8.4.4 Suppression of Harmonics	... 598
8.4.5 Tertiary or Stabilizing Windings	... 599
8.5 Unbalanced Operation of Three-phase Transformers	... 604
8.5.1 Single-phase Load on Three-phase Transformers	... 605
8.5.2 Single-phase Line to Neutral Load on Three-phase Transformers	... 607
8.5.3 Single-phasing in 3-phase Transformers	... 611
8.5.4 Effect of Using Tertiary Winding	... 612
8.6 Open-delta or V-connection	... 620
8.6.1 Power Delivered to Purely Resistive Load	... 622
8.6.2 Power Delivered to Inductive Load	... 624

# Generalized Theory Of Electrical Machines



10%  
OFF

Publisher : KHANNA  
PUBLISHERS

ISBN : 9788174092250

Author : Dr. P. S. Bimbhra

Type the URL : <http://www.kopykitab.com/product/22289>



Get this eBook