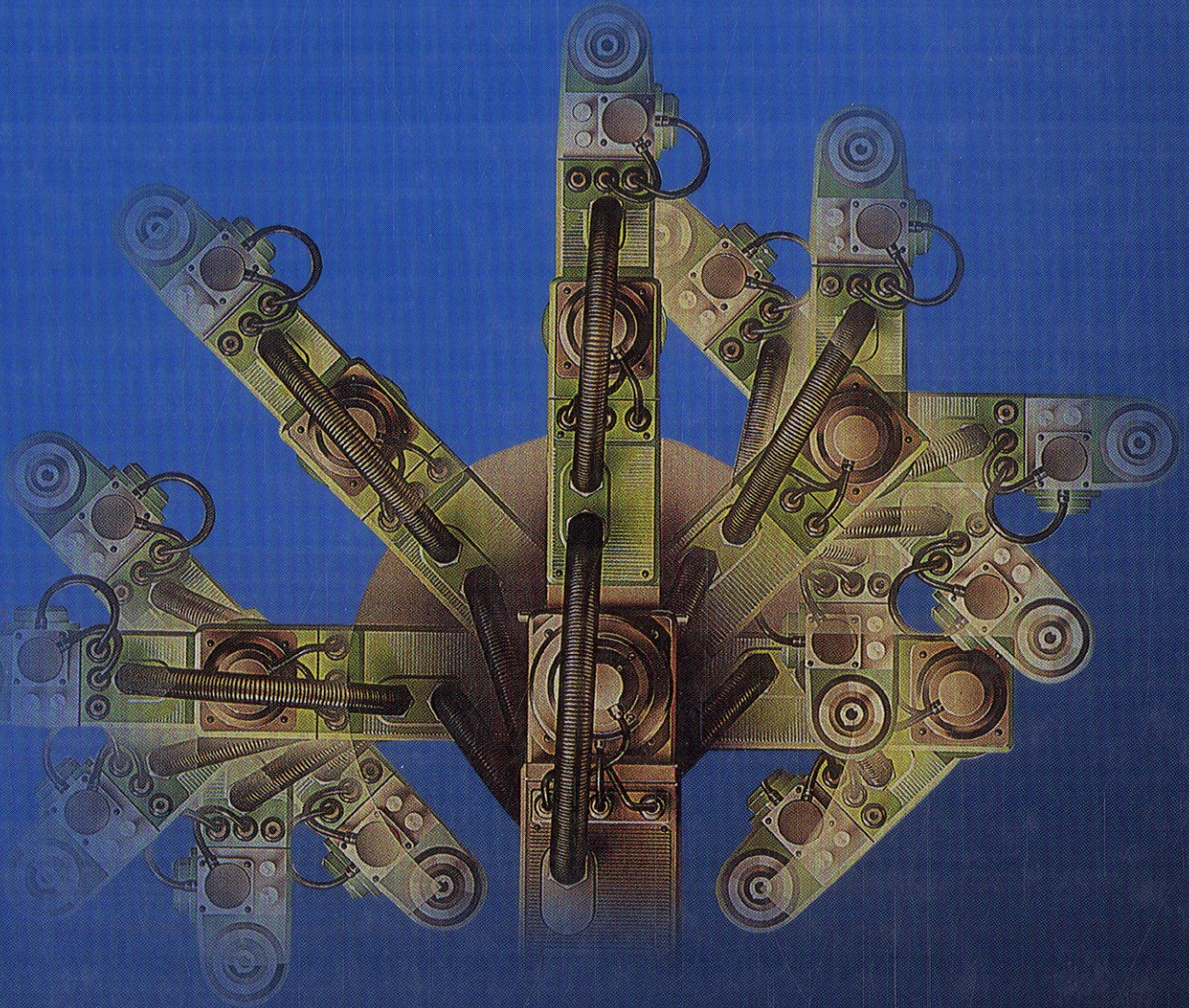


ELECTRIC MACHINES



MULUKUTLA S. SARMA
MUKESH K. PATHAK

Contents

Preface to This Edition xv

Preface xvii

PART 1 INTRODUCTION 1

1 A Review of Phasor Diagrams 3

1.1 Phasors 3

1.2 Analysis with Phasor Diagrams 9

Bibliography 14

Problems 14

2 Three-Phase Circuits 19

2.1 Three-Phase Source Voltages and Phase Sequence 19

Phase Sequence 22

2.2 Balanced Three-Phase Loads 24

Balanced Wye-Connected Load 24

Balanced Delta-Connected Load 27

Power in Balanced Three-Phase Circuits 29

2.3 Measurement of Power 31

Bibliography 37

Problems 37

3 The Magnetic Aspect 41

- 3.1 Review of Electromagnetic Field Theory 41**
- 3.2 Magnetic Field and Force of Electromagnetic Origin 43**
- 3.3 The Magnetomotive Force 45**
- 3.4 Magnetic Materials 46**
- 3.5 Magnetic Circuits 53**
- 3.6 AC Operation of Magnetic Circuits 66**
 - Iron Losses 67
- 3.7 Energy Storage 72**
- 3.8 Inductance and Equivalent Circuit of AC Excited Core 75**
 - Equivalent Circuit of AC Excited Magnetic Circuit 80
- 3.9 Permanent Magnets and their Applications 82**
 - Bibliography 89
 - Problems 89

4 Transformers 99

- 4.1 Constructional Features of Transformers 100**
- 4.2 Transformer Theory 106**
 - Ideal Transformer 106
 - Ideal Transformer on No Load 106
 - Ideal Transformer on Load 108
 - Real Transformer on No Load 113
 - Real Transformer on Load 117
 - Per-Unit Values 127
- 4.3 Transformer Tests 132**
 - Open-Circuit Test 132
 - Short-Circuit Test 134
 - Sumpner's Test 139
- 4.4 Transformer Performance 140**
 - Regulation 144
- 4.5 Three-Phase Transformers 148**
 - Three-Phase Transformer Connections 149
 - Per-Unit System and Phase Shift 157
- 4.6 Autotransformers 162**
- 4.7 Multiwinding Transformers 166**
- 4.8 Some Other Transformer Topics 170**
 - Instrument Transformers 170
 - Variable-Frequency Transformers 171
 - Pulse Transformers 172
 - Saturable Reactors 175

Excitation Phenomenon and Inrush Current	175
Parallel Operation of Transformers	180
Load Sharing	181
Three-phase to Two-phase Conversion	184
Superconducting Transformer Windings	186
Bibliography	187
Problems	187

5 Principles of Electromechanical Energy Conversion 199

5.1	Forces and Torques in Magnetic Field Systems	202
5.2	Singly Excited and Multiply Excited Magnetic Field Systems	211
	Multiply Excited Magnetic-Field Systems	219
5.3	Elementary Concepts of Rotating Machines	227
5.4	Basic Aspects of Electromechanical Energy Converters	237
	Losses and Efficiency	237
	Ventilation and Cooling	238
	Machine Ratings	240
	Magnetic Saturation	241
	Leakage and Harmonic Fluxes	242
	General Nature of Machine-Application Problems	243
	Bibliography	244
	Problems	244

6 Machine Windings 253

6.1	Basic Winding Arrangements in Rotating Machines	253
6.2	DC Field Windings	257
6.3	DC Armature Windings	259
	Lap Windings	260
	Wave Windings	262
	Choice between Lap and Wave Windings	263
6.4	AC Armature Windings	264
6.5	Winding Factors	267
	Distribution Factor	267
	Pitch Factor	270
6.6	EMF Produced by an Armature Winding	273
6.7	MMF Produced by Windings	278
	Cylindrical Machine with a Single Coil	279
	Distributed Winding	280

Partially Distributed Winding	282
Concentrated Coils on Salient Poles	285
Distributed Winding on the Rotor with Saliency on Stator	286
Bibliography	288
Problems	289

PART 2 STEADY-STATE THEORY AND PERFORMANCE 293

7 Induction Machines 295

7.1	Constructional Features of Polyphase Induction Machines	296
7.2	Stator and the Rotating Magnetic Field	300
7.3	Torque Production	302
7.4	Slip	303
7.5	Equivalent Circuit of a Polyphase Induction Machine	304
	The Rotor Equivalent Circuit	306
	The Complete Per-Phase Equivalent Circuit	307
	Phasor Diagram	310
7.6	Equivalent Circuit from Test Data	312
	No-Load Test	312
	Blocked-Rotor Test	313
7.7	Three-Phase Induction Machine Performance	318
7.8	Torque-Slip Characteristic	323
7.9	Circle Diagram	330
	Derivation of Circle Diagram	330
	Construction of Circle Diagram	332
	Maximum Torque and Power	333
7.10	Speed Control of Polyphase Induction Motors	336
7.11	Starting Methods for Polyphase Induction Motors	342
7.12	Induction Generator	346
7.13	Cogging and Crawling	347
7.14	Single-Phase Induction Motors	348
	Revolving Field Theory and Equivalent Circuit	349
7.15	No-load and Blocked-rotor Test	355
7.16	Starting Methods for Single-Phase Induction Motors	357
	Phase Splitting and Rotating Field	357
	Types of Single-phase Induction Motors	358
7.17	Applications for Induction Motors	362
	Bibliography	366
	Problems	366

8 Synchronous Machines 373

- 8.1 Constructional Features of Synchronous Machines 373**
- 8.2 Elementary Synchronous Machines 376**
- 8.3 Equivalent Circuit of a Synchronous Machine 385**
- 8.4 Voltage Regulation 388**
 - Calculation of Voltage Regulation 390
 - Calculation of Armature Leakage Reactance and Armature Reaction MMF 392
 - The EMF Method 394
 - Open-Circuit and Short-Circuit Characteristics 395
 - The MMF Method 399
- 8.5 Power-Angle and Other Performance Characteristics 403**
- 8.6 Effects of Saliency: Two-Reactance Theory of Salient-Pole Synchronous Machines 417**
- 8.7 Determining Reactances by Test Data 421**
- 8.8 Parallel Operation of Interconnected Synchronous Generators 423**
- 8.9 Steady-State Stability 427**
- 8.10 Excitation Systems 429**
- 8.11 Hunting and Damper Winding 432**
- 8.12 Applications for Synchronous Motors 433**
 - Bibliography 434
 - Problems 435

9 Direct-Current Machines 441

- 9.1 Constructional Features of DC Machines 442**
- 9.2 Elementary DC Machine 445**
 - EMF Equation 447
 - Torque Equation 448
- 9.3 Methods of Excitation of DC Machines 449**
- 9.4 Equivalent Circuit of a DC Machine 450**
 - Back EMF and Speed Equations 452
- 9.5 Commutator Action 454**
- 9.6 Armature Reaction 455**
- 9.7 Interpoles and Compensating Windings 457**
- 9.8 Magnetization Characteristic of a DC Machine 461**
- 9.9 Characteristics of a Separately Excited DC Generator 463**
- 9.10 Self Excitation 465**
- 9.11 Characteristic of a DC Shunt Generator 467**
- 9.12 Characteristic of a DC Series Generator 469**

9.13	Characteristics of a DC Compound Generator	470
	Cumulatively Compounded DC Generator	470
	Differentially Compounded DC Generator	472
9.14	DC Motor Characteristics	474
9.15	Control of DC Motors	481
9.16	DC Motor Starting	483
9.17	Testing and Efficiency	486
9.18	Applications for DC Machines	491
	Bibliography	491
	Problems	492

PART 3 TRANSIENTS AND DYNAMICS 499

10 Transients and Dynamics of AC Machines 501

10.1	Mathematical Description of a Three-Phase Synchronous Machine	501
	Inductances	502
	Flux-Linkage Relations	505
	Armature Voltage Equations	507
	Power Output	508
	Electromagnetic Torque	509
	L_{ad} -Base Per-Unit Representation	509
10.2	Synchronous-Machine Transient Reactances and Time Constants	512
	Negative Sequence Reactance X_2	514
	Synchronous-Machine Resistances	515
	Synchronous-Machine Time Constants	515
10.3	Synchronous-Machine Transient Parameters from Sudden Three-Phase Short-Circuit Test Data	518
10.4	Synchronous-Machine Dynamics	523
	The Swing Equation	526
	Equal-Area Criterion for Transient Stability	527
	Factors Affecting Transient Stability	531
10.5	Mathematical Description of a Three-Phase Induction Machine	532
10.6	Induction-Machine Electrical Transients	537
	Decay of the Short-Circuit Current	538
	Transient Equivalent Circuit	539
10.7	Induction-Machine Dynamics	541
	Bibliography	543
	Problems	544

11 Direct-Current Machine Dynamics 551

11.1 Dynamic Models 551

11.2 Dynamic Analysis 553

Separately Excited DC Generator 556

Separately Excited DC Motor 558

Effect of Saturation 562

Dynamic Analysis with Time-Domain Techniques 563

11.3 Metadynes and Amplidynes 565

Metadyne as a Generalized Machine 567

Bibliography 568

Problems 568

12 Power Semiconductor-Controlled Drives 577

12.1 Introduction to Power Electronic Drives 577

Power Semiconductor Devices 580

Control Characteristics of Power Semiconductor Switching Devices 587

Power Electronic Circuits 589

12.2 Solid-State Control of DC Motors 596

Rectifier Control of DC Motors 596

Chopper Control of DC Motors 605

12.3 Solid-State Control of Induction Motors 609

AC Voltage Controllers 609

Frequency-Controlled Induction-Motor Drives 610

Slip-Power Controlled Wound-Rotor Induction-Motor Drives 616

12.4 Solid-State Control of Synchronous Motors 622

Brushless (and Commutatorless) DC and AC Motors 624

Current-Source Inverter and Load Commutation 625

12.5 Applications for the Electronic Control of Motors 630

Bibliography 632

Problems 632

Appendix A Units, Constants, and Conversion Factors for the SI System 639

A.1 Physical Quantities 640

A.2 Prefixes 641

A.3 Physical Constants 641

A.4 Conversion Factors 642

Appendix B Special Machines 643

- B.1 Reluctance Motors 643**
- B.2 Hysteresis Motors 644**
- B.3 Permanent-Magnet Machines 644**
- B.4 Stepping Motors 646**
- B.5 Inductor Alternators 649**
- B.6 AC Commutator Motors 651**
- B.7 Servo Components 653**
- B.8 Linear Induction Motors 656**
- B.9 Linear Synchronous Motors 658**
- B.10 Cryogenerators 660**

Answers 663

Index 693