

Handbook
of Rotating
Electric
Machinery

Donald V. Richardson

8465267

Handbook of Rotating Electric Machinery

Donald V. Richardson, MME, PE

Electrical Engineering Technology
Waterbury State Technical College

Consulting Engineer



Reston Publishing Company, Inc.
A Prentice-Hall Company
Reston, Virginia

RESTON

Library of Congress Cataloging in Publication Data

Richardson, Donald V

Handbook of rotating electric machinery.

Bibliography: p. 622

Includes index.

1. Electric machinery—Handbooks, manuals, etc.

I. Title.

TK2181.R47 621.31'042 79-26216

ISBN 0-8359-2759-8

© 1980 by Reston Publishing Company, Inc.

A Prentice-Hall Company

Reston, Virginia 22090

All rights reserved. No part of this book may be reproduced in any way, or by any means, without permission in writing from the publisher.

10 9 8 7 6 5 4 3 2

Printed in the United States of America



Handbook of Rotating Electric Machinery

Preface

The generation since World War II has seen some major changes of emphasis in the education of an electrical engineer on one hand and the requirement to work with actual apparatus on the other. The graduate of the traditional four-year engineering course, by virtue of the curriculum that was presented, has become able to analyze the result of transient conditions by the use of differential equations and the LaPlace transformation. This analysis required the treatment of motor transient conditions by using a transfer function or mathematical expression of the motor that approximately accounts for its inertia and its accelerating torque, but that does not address how or why the motor responds as it does.

The same engineers may never have actually worked “hands on” with a motor in a laboratory situation. The technician who actually works with the motor or generator usually has not had the training in transient analysis and has had to work with older texts that were limited to an algebraic treatment of motor and generator analysis. Another approach has been to apprentice under an experienced worker who knows the connection and operation of electrical machines, but who has never been trained in analysis.

Another condition is that of the applications engineer or the plant engineer who at the present time must work from manufacturers’ literature and various code requirements. Then there is the senior worker in the field, whose education dates from an era of the algebraic approach to steady-state conditions, which was then slightly spiced with the calculus whose added flavor has dissipated.

This handbook is specifically prepared to enable the practitioner in the field to recognize, understand, analyze, specify, connect, control, and satisfactorily apply the various existing types of electric motors and generators.

In the current and still worsening energy crisis, there is a new emphasis on the efficiency of all machine processes. For this reason, strong emphasis is placed upon the production and measurement of horsepower or its watt equivalent and the isolation of the accompanying losses. The intended result is that the reader who is

**PREFACE** xvii**Chapter 1****INTRODUCTION** 1

- 1-1 Change of Major Use to Alternating Current, 1
- 1-2 Early Use of Motors, 4
- 1-2 Electric Power Distribution to Homes, 7
- 1-4 Electric Motors Not Widely Understood, 9
- 1-5 Prerequisite Requirements, 9
- 1-6 Efficient Use of Energy, 9
- 1-7 System International Metric Units, 10
- 1-8 Future of Electric Machines, 12

Chapter 2**ELECTROMECHANICAL ENERGY CONVERSION** 14

- 2-1 Electricity in the Middle, 14
- 2-2 Scarcity of Useful Energy-Conversion Devices, 15
- 2-3 Faraday's Basic Discovery, 16
- 2-4 Related Fundamental Laws, 16
- 2-5 Faraday's Law of Induction, 17
- 2-6 Neumann's Formulation, 18
- 2-7 Fleming's Relationships, 24
- 2-8 Lenz's Law, 25
- 2-9 Direct-Current Generator and Motor Mechanical Construction, 25
- 2-10 Practical Generator Voltage Development, 31
- 2-11 Biot-Savart Force Relationship, 37
- 2-12 Left-Hand Rule of Motor Action, 40
- 2-13 Other Related Laws, 41
- 2-14 Unit Conversions, 43
- 2-15 Review of Voltage and Flux Relations, 46
 - 2-15-1 Individual Winding Turn Average Voltage, 46
 - 2-15-2 Individual Conductor Instantaneous Voltage, 46
 - 2-15-3 Coil Average Voltage, 47
 - 2-15-4 Practical Generator Total Voltage, 47

Chapter 3	ACTUAL MACHINE CONSTRUCTION, DC DYNAMOS	49
3-1	Mechanical Construction, 49	
3-1-1	Main Frame, 49	
3-1-2	Field Poles, 51	
3-1-3	Armature Structure, 53	
3-1-4	Armature Winding Coils, 53	
3-1-5	Commutator, 53	
3-1-6	Brushes, 54	
3-1-7	Armature Shaft Bearings, 55	
3-1-8	End Bell Structure, 55	
3-1-9	Brush Rigging, 55	
3-1-10	Field Coils, 55	
3-1-11	Commutating Fields, 56	
3-1-12	Compensating Windings, 56	
3-2	Armature Windings, 57	
3-2-1	Winding Types, 57	
3-2-2	Lap Windings, 58	
3-2-3	Wave Windings, 59	
3-2-4	Frog-Leg Windings and Equalizer Connections, 59	
3-2-5	Multielement and Multiplex Coils, 60	
3-3	Commutator and Related Elements, 62	
3-3-1	Brush Spacing, 62	
3-3-2	Brush Neutral Position, 62	
3-4	Armature Reaction, 63	
3-4-1	Correcting Armature Reaction Effect, 63	
3-5	Armature Reactance, 66	
3-5-1	Brush Short-Circuiting Effect, 67	
3-5-2	Opposing Effects of Design Features, 67	
3-5-3	Desired Improvements, 69	
3-6	Magnetic Circuit, 71	
3-6-1	Simplified Magnetic Circuit Analysis, 72	
3-6-2	Magnetic Circuit Design Observations, 76	
3-6-3	Generalized Procedure for Magnetic Circuit Analysis, 80	
Chapter 4	DIRECT-CURRENT GENERATOR CHARACTERISTICS	84
4-1	Separately Excited Generator, 85	
4-1-1	Generator Magnetization Curve, 87	
4-2	Basic Generator Types, 87	
4-3	Shunt Generator Buildup and Polarity, 88	
4-3-1	Field Excitation Line, 89	
4-3-2	Generator Build Down, 89	
4-3-3	Residual Magnetic Field and Field Flashing, 91	
4-3-4	Generator Polarity, 91	
4-4	Shunt Generator External Characteristics, 91	
4-4-1	Internal Voltage Loss in a Shunt Generator, 92	
4-4-2	Internal and Related External Characteristics, 94	
4-4-3	Generator Regulation, 96	

- 4-5 Series Generator, 97
 - 4-5-1 Series Generator Buildup and Polarity, 97
 - 4-5-2 Series Generator Characteristic and Adjustment, 97
 - 4-5-3 Series Generator Polarity and Build Down, 99
- 4-6 Series Generator External Characteristics, 99
 - 4-6-1 Series Generator Internal Voltage Loss, 100
- 4-7 Compound Generator Operation, 101
 - 4-7-1 Cumulative Compound Operation, 101
 - 4-7-2 Differential Compound Operation, 102
- 4-8 Compound Generator Characteristics, 104
- 4-9 Compound Generator Adjustments, 105
 - 4-9-1 Actual Compound Generator Performance, 107

Chapter 5 PARALLELING OF DIRECT-CURRENT GENERATORS 110

- 5-1 Modern Uses of Paralleling, 111
- 5-2 Parallel Direct-Current Generator Requirements, 111
- 5-3 Parallel Shunt Generators: Identical Units, 113
- 5-4 Parallel Shunt Generators: Different Units, 115
- 5-5 Parallel Cumulative Compound Generators: Identical Units, 116
 - 5-5-1 Equalizer Bus Connection, 117
- 5-6 Parallel Cumulative Compound Generators: Different Ratings, 119
 - 5-6-1 Transposed Equalizer Connections, 119
- 5-7 Parallel Cumulative Compound Generator Procedure, 121
 - 5-7-1 Paralleling Requirements, Cumulative Compound Generators, 121
 - 5-7-2 Paralleling Procedures, 121

Chapter 6 THE DIRECT-CURRENT MOTOR 123

- 6-1 Meaning of Power, 124
 - 6-1-1 Force, 124
 - 6-1-2 Work, 125
 - 6-1-3 Power, 125
- 6-2 Relation of Torque and Power, 126
 - 6-2-1 Development of Torque, 128
- 6-3 Measurement of Torque, 130
 - 6-3-1 Prony Brake, 130
 - 6-3-2 Two-Scale Prony Brake, 132
 - 6-3-3 Dynamometer, 133
- 6-4 Back Electromotive Force in a Motor, 136
 - 6-4-1 Armature Power Developed, 137
 - 6-4-2 Equilibrium Motor Speed, 139
- 6-5 Shunt Motor, 140
 - 6-5-1 Shunt Motor Speed Characteristics, 140
 - 6-5-2 Shunt Motor Torque Characteristics, 140
 - 6-5-3 Speed Regulation, 142
 - 6-5-4 Standard Power Ratings, 142
 - 6-5-5 Permanent Magnet Field Motors, 144

- 6-6 Series Motor, 144
 - 6-6-1 Series Motor Speed Characteristics, 145
 - 6-6-2 Series Motor Torque Characteristics, 145
 - 6-6-3 Series Versus Shunt Motor Usage, 151
- 6-7 Compound Motor, 151
 - 6-7-1 Compound Motor Speed Characteristics, 152
 - 6-7-2 Compound Motor Torque Characteristics, 153
- 6-8 Comparison of Direct-Current Motor Characteristics, 154
- 6-9 Direct-Current Motor Starting Problems, 155
 - 6-9-1 Dc Starting Switch, 156
- 6-10 Direct-Current Motor Reversing, 160
 - 6-10-1 Direct-Current Motor Reversing Circuit Connections, 161
- 6-11 Force, Torque, and Speed Unit Conversions, 161
- 6-12 Review of Force, Torque, and Power Relations, 164
 - 6-12-1 Force on a Conductor in a Magnetic Field, 164
 - 6-12-2 Torque in a Generator or Motor, 165
 - 6-12-3 Review of Basis of Rotating Mechanical Power, 166

Chapter 7 EFFICIENCY OF DIRECT-CURRENT MACHINERY 167

- 7-1 Basic Efficiency Relationships, 169
 - 7-1-1 Convenient Data Sources, 170
- 7-2 Types of Losses in Direct-Current Machines, 170
 - 7-2-1 Rotational Losses, 171
 - 7-2-2 Winding Resistance Losses, 172
 - 7-2-3 Shunt Field Loss, 173
- 7-3 Relationships Between Losses, 174
- 7-4 Isolation and Determination of Losses, 181
 - 7-4-1 Self-Powered Rotational Loss Tests, 181
 - 7-4-2 Separately Powered Rotational Loss, 184
 - 7-4-3 Mechanical Brush Drag, 184
 - 7-4-4 Hysteresis and Eddy Current Losses, 186
 - 7-4-5 Winding Resistances, 187
 - 7-4-6 Resistance from Wire Characteristics, 187
 - 7-4-7 Temperature Effect on Resistance, 196
- 7-5 Armature Circuit Resistance, 200
 - 7-5-1 Ohmmeter or Ohm's Law Method, 200
 - 7-5-2 Voltmeter-Ammeter Methods, 201
 - 7-5-3 Resistance Calculation, 201
 - 7-5-4 Forgue's Method, 202
- 7-6 Calibrating a Direct-Current Motor or Generator, 205
- 7-7 Direct-Current Motor Efficiency Using Calibrated Generator, 213

Chapter 8 DIRECT-CURRENT MOTOR CONTROL AND OPERATION 217

- 8-1 Motor Load Characteristic List, 217
 - 8-1-1 Power Supply, 217

- 8-1-2 Starting Requirement Considerations, 217
- 8-1-3 Stopping Requirement Considerations, 218
- 8-1-4 Reversing Requirement Considerations, 218
- 8-1-5 Normal Running Requirement Considerations, 219
- 8-1-6 Speed Control Requirement Considerations, 219
- 8-1-7 Safety and Environmental Requirement Considerations, 219
- 8-2 Components and Related Diagram Symbols, 220
 - 8-2-1 Primary Control Devices, 221
 - 8-2-2 Pilot Control Devices, 229
- 8-3 Manual Direct-Current Motor Starters, 235
 - 8-3-1 Two-Point Starter, 235
 - 8-3-2 Three-Point Starter, 235
 - 8-3-3 Four-Point Starter, 235
 - 8-3-4 Drum Rotary Switch Starter, 238
- 8-4 Automatic Direct-Current Motor Starters, 241
 - 8-4-1 Definite Time Acceleration dc Starters, 242
 - 8-4-2 Current Limit Acceleration Starters, 246
- 8-5 Reversing Control of Direct-Current Motors, 249
 - 8-5-1 Manual Reverse Control, 249
 - 8-5-2 Pushbutton Control with Reverse, 250
- 8-6 Plugging Reverse Control, 254
 - 8-6-1 Typical Plugging Reverse Controller, 255
- 8-7 Retardation and Stopping, 258
 - 8-7-1 Dynamic Braking, 259
 - 8-7-2 Regenerative Braking, 260
 - 8-7-3 Electric Brakes, 261
- 8-8 Jogging, 262
- 8-9 Direct-Current Motor Speed Control, 264
 - 8-9-1 Basic Causes and Limits of Speed, 265
 - 8-9-2 Specific Speed Relationships, 266
 - 8-9-3 Mechanisms Used in Speed Control, 270
- 8-10 The Changing Basis of Direct-Current Motor Control, 271

Chapter 9 DIRECT-CURRENT MOTOR AND GENERATOR SELECTION 274

- 9-1 Shaft Power, 274
- 9-2 Characteristics of Driven Load, 275
- 9-3 Speed Rating, 275
- 9-4 Frame Size, 276
- 9-5 Speed Classification, 284
- 9-6 Effect of Duty Cycle, 284
- 9-7 Ambient Temperature Effects, 286
- 9-8 Allowable Temperature Rise, 287
- 9-9 Voltage and Current Ratings, 289
- 9-10 Machine Enclosure Types, 289
- 9-11 Maintenance and Accessibility, 292
- 9-12 International Standardization Developments, 292

Chapter 10	ALTERNATING-CURRENT DYNAMOS 295
10-1	Physical Construction of Alternating-Current Machines, 295
10-1-1	Fixed Armature or Stator, 296
10-1-2	Rotating Field Structure, 297
10-2	Alternator Windings, 298
10-2-1	Chording of Windings, 298
10-2-2	Coil Group Connections, 300
10-2-3	Winding Distribution, 301
10-3	Synchronous Alternator, 301
10-4	Summary of Important Relationships, 306
Chapter 11	THE SYNCHRONOUS ALTERNATOR 308
11-1	Voltage Relations, 308
11-1-1	Basic Voltage Generation Formula, 308
11-2	Winding Pitch, 310
11-3	Winding Distribution, 310
11-4	Complete Pole-Phase Group Voltage Relations, 314
11-5	Summary of Alternator Voltage Relationships, 315
Chapter 12	SYNCHRONOUS ALTERNATOR REGULATION 317
12-1	Representative Alternator Performance, 318
12-2	Alternator Percentage Regulation, 320
12-3	Unity Power Factor Regulation, 322
12-4	Lagging Power Factor Regulation, 324
12-5	Leading Power Factor Loads, 324
12-6	Load Power Factor Relations Summarized, 325
12-7	Winding Resistance, 326
12-8	Synchronous Impedance, 327
12-9	Actual Voltage Regulation, Small Alternator, 332
12-10	Summary of Alternator Regulation Relationships, 334
Chapter 13	PARALLELING OF SYNCHRONOUS ALTERNATORS 335
13-1	Parallel Voltage Requirements, 337
13-1-1	Matching Voltages and Transformers, 337
13-1-2	Oposing Versus Same Voltages, 337
13-2	Phase Sequence Considerations, 338
13-2-1	Out-of-Phase Sequence Problem Magnitude, 338
13-2-2	Incorrect Phase Sequence Forces, 339
13-3	In-Phase Requirement for Paralleling, 340
13-4	Identical Frequency Requirement, 341
13-4-1	Allowable Frequency Differences, 341
13-5	Prime-Mover Torque Speed Relation, 342
13-5-1	Unmatching Torque Speed Relations, 343
13-6	Alternator Synchronizing Procedures, 343
13-6-1	Voltage Matching, 343
13-6-2	Phase Sequence Matching, 344
13-6-3	Dark Lamp Phase Sequence Indication, 344
13-6-4	Bright Lamp Phase Sequence Indication, 344

- 13-6-5 Two Bright, One Dark Phase Sequence Indication, 344
- 13-6-6 Alternative Phase Sequence Indication Methods, 344
- 13-7 In-Phase Determination, 346
 - 13-7-1 Dark Lamp In-Phase Indication, 346
 - 13-7-2 Bright Lamp In-Phase Indication, 346
 - 13-7-3 Two Bright, One Dark In-Phase Indication, 347
- 13-8 Frequency Synchronization, 348
- 13-9 Synchroscope Synchronization, 348

Chapter 14 IDEAL AND PRACTICAL TRANSFORMERS 350

- 14-1 Ideal Transformer, 353
 - 14-1-1 Transformation Ratio Relations, 356
 - 14-1-2 General Transformer Equation, 360
- 14-2 Practical Transformer Conditions, 364
- 14-3 Ideal and Practical Transformer Relations, 368

Chapter 15 TRANSFORMER EQUIVALENT CIRCUITS 371

- 15-1 Reflected Impedance, 371
- 15-2 Simplified Equivalent Circuits, 373
- 15-3 Secondary Voltage Phasor Relations, 376
 - 15-3-1 Unity Power Factor Voltage Relations, 378
 - 15-3-2 Lagging Power Factor Voltage Relations, 378
 - 15-3-3 Leading Power Factor Voltage Relations, 378
- 15-4 Transformer Voltage Regulation by Phasor Relations, 379
- 15-5 Transformer Voltage Regulation by Short-Circuit Test, 382
- 15-6 Open-Circuit Test for Magnetic Losses, 385
- 15-7 Transformer Efficiency, 387
- 15-8 Transformer Equivalent Circuit Relationships, 391

Chapter 16 SPECIFIC TRANSFORMER TYPES 394

- 16-1 Transformers With Multiple Windings, 394
 - 16-1-1 Coil Identification Tests, 395
 - 16-1-2 Polarity and Voltage Tests, 396
- 16-2 Autotransformer, 398
 - 16-2-1 Autotransformer Power Division, 401
- 16-3 Instrument Transformers, 403
 - 16-3-1 Potential Transformers, 403
 - 16-3-2 Current Transformers, 404
- 16-4 Summary of Autotransformer Relationships, 405

Chapter 17 TRANSFORMER CONNECTIONS 407

- 17-1 Parallel Transformer Connections, 407
 - 17-1-1 Unmatching Parallel Transformers, 408
 - 17-1-2 Matching Parallel Transformers, 408
- 17-2 Three-Phase Transformer Circuits, 410
 - 17-2-1 Three-Phase Y-Y Connections, 411
 - 17-2-2 Three-Phase Δ - Δ Connections, 413
 - 17-2-3 Three-Phase Y- Δ Connections, 413
 - 17-2-4 Three-Phase Δ -Y Connections, 413

- 17-2-5 Three-Phase Open Delta or V-V, 418
- 17-2-6 Three-Phase Scott Tee or T-T, 420
- 17-2-7 Three-Phase to Two-Phase Scott Tee, 422
- 17-3 Three-Phase Transformer Paralleling, 424
- 17-4 Multiple-Phase Transformation, 424
- 17-5 Transformer Connection Relationships, 424
- 17-6 Three-Phase Transformer Circuit Summary, 426

Chapter 18 THE POLYPHASE INDUCTION MOTOR 427

- 18-1 Induction Motor Action, 427
 - 18-1-1 Rotating Magnetic Field from Polyphase Fixed Stator Coils, 428
 - 18-1-2 Induction Motor Rotor Torque Development, 432
- 18-2 Induction Motor Performance Parameters, 434
 - 18-2-1 No-Load Test or Rotational-Loss Test, 435
 - 18-2-2 Blocked Rotor Test, 435
 - 18-2-3 Stator Resistance Test, 438
 - 18-2-4 Induction Motor Load Test, 438
 - 18-2-5 Motor Parameters Summarized, 438
- 18-3 Induction Motor Performance, 439
 - 18-3-1 Rotor Current and Power, 439
 - 18-3-2 Induction Motor Torque, 444
 - 18-3-3 Maximum Torque Developed, 445
 - 18-3-4 Starting Torque Relations, 449
- 18-4 Polyphase Induction Motor Relationships, 451

Chapter 19 POLYPHASE INDUCTION MOTOR CHARACTERISTICS 454

- 19-1 Motor Classes of the National Electrical Manufacturers Association, 454
 - 19-1-1 NEMA Class Motor Characteristics, 456
- 19-2 Wound-Rotor Motor Characteristics, 457
- 19-3 Induction Motor Speed Control, 460
 - 19-3-1 Motor Speed Change by Frequency Change, 461
 - 19-3-2 Motor Speed Change by Pole Change, 462
 - 19-3-3 Motor Speed Change by Voltage Change, 463
 - 19-3-4 Motor Speed Change by Rotor Resistance, 463
- 19-4 Induction Motor Efficiency, 463
 - 19-4-1 Efficiency from No-Load and Blocked-Rotor Tests, 464
 - 19-4-2 Efficiency from the AIEE Load Slip Method, 466
 - 19-4-3 Efficiency Test Comparison, 468
- 19-5 Polyphase Induction Motor Performance Relationships, 468

Chapter 20 THE SYNCHRONOUS MOTOR 470

- 20-1 Similarity to Synchronous Alternators, 471
 - 20-1-1 Synchronous Motor Action, 471
- 20-2 Synchronous Motor Starting, 472
- 20-3 Synchronous Motor Power Factor Control, 474

- 20-4 Synchronous Motor V Curve, 476
- 20-5 Synchronous Motor Power Factor Correction, 477
- 20-6 Synchronous Capacitor, 481
- 20-7 Synchronous Dynamo Efficiency, 481
- 20-8 Synchronous Motor Characteristic Curves, 485
- 20-9 Synchronous Motor In-Service Adjustments, 486

Chapter 21 THE SINGLE-PHASE INDUCTION MOTOR 488

- 21-1 Single-Phase Induction-Motor Starting, 489
 - 21-1-1 No Torque at Standstill with Single Phase, 491
 - 21-1-2 Double Revolving Field Theory, 491
 - 21-1-3 Rotor Cross Field Theory, 492
- 21-2 Resistance Split-Phase Starting, 494
 - 21-2-1 Starting-Switch Problems, 496
 - 21-2-2 Reversing Resistance Split-Phase Motors, 498
- 21-3 Capacitor-Start Induction Motors, 498
 - 21-3-1 Capacitor Requirements, 499
 - 21-3-2 Starting-Switch Problems, 500
- 21-4 Capacitor-Start Capacitor-Run Motors, 501
 - 21-4-1 Autotransformer and Capacitor Circuits, 503
- 21-5 Permanent-Split Capacitor Motor, 503
- 21-6 Single-Phase Induction Motor Load Characteristics, 506
 - 21-6-1 Resistance Split-Phase Motors, 506
 - 21-6-2 Capacitor-Start Motors, 508
 - 21-6-3 Capacitor-Start Capacitor-Run Motors, 509
- 21-7 Single-Phase Induction-Motor Efficiency, 509
 - 21-7-1 No-Load or Rotational-Loss Tests, 509
 - 21-7-2 Blocked-Rotor Test, 510
 - 21-7-3 Stator Resistance Test, 510
 - 21-7-4 Efficiency from the AIEE Method, 510
 - 21-7-5 Efficiency Test Comparison, 510

Chapter 22 SHADED-POLE, SYNCHRONOUS, UNIVERSAL, AND OTHER SINGLE-PHASE AC MOTORS 513

- 22-1 Shaded-Pole Induction Motors, 514
 - 22-1-1 Shaded-Pole Motor Reversing, 517
- 22-2 Reluctance-Start Induction Motors, 518
- 22-3 Single-Phase Synchronous Motors, 520
 - 22-3-1 Reluctance Motors, 520
 - 22-3-2 Hysteresis Motors, 522
 - 22-3-3 Subsynchronous Motors, 523
- 22-4 Polyphase Synchronous Induction Motors, 523
- 22-5 Induction-Type Motor Efficiencies, 524
 - 22-5-1 Nonsynchronous Motors, 524
- 22-6 Universal Motor, 527
 - 22-6-1 Universal Motor Characteristics, 528
 - 22-6-2 Universal Motor Efficiency, 529
- 22-7 Single-Phase Motor Application, 529

- 22-8 Small Motor Performance Relation Nomograms, 532
 - 22-8-1 English Unit Nomogram, 532
 - 22-8-2 System International Unit Nomogram, 533

Chapter 23 ALTERNATING-CURRENT MOTOR CONTROL AND OPERATION 535

- 23-1 Alternating-Current Motor Load Characteristic List, 535
 - 23-1-1 Power Supply, 535
 - 23-1-2 Starting Requirement Considerations, 536
 - 23-1-3 Stopping Requirement Considerations, 536
 - 23-1-4 Reversing Requirement Considerations, 536
 - 23-1-5 Normal Running Requirement Considerations, 536
 - 23-1-6 Speed Control Requirement Considerations, 536
 - 23-1-7 Safety and Environmental Requirement Considerations, 536
- 23-2 Components and Related Design Symbols, 536
 - 23-2-1 Line Voltage Transformers, 536
 - 23-2-2 Pilot Control Circuit Transformers, 536
- 23-3 Nonreversing Full-Voltage Motor Starter, 537
- 23-4 Reversing Full-Voltage Motor Starters, 540
 - 23-4-1 Drum Rotary Switch Controls, 540
 - 23-4-2 Three-Phase Integral Horsepower Controls, 540
- 23-5 Reduced-Voltage Three-Phase Motor Controls, 543
 - 23-5-1 Specific Starting Circuits, 544
 - 23-5-2 Other Reduced-Current Starting Circuits, 546
 - 23-5-3 Wound-Rotor Induction-Motor Starting, 546
- 23-6 Reversing Reduced-Current Controls, 548
- 23-7 Plugging Reverse of Alternating-Current Motors, 548
- 23-8 Retarding and Stopping Alternating-Current Motors, 549
- 23-9 Alternating-Current Motor Jogging Controls, 550
- 23-10 Alternating-Current Motor Speed Control, 550
 - 23-10-1 Consequent Pole Speed Controls, 551
 - 23-10-2 Two-Winding Speed Controls, 551
 - 23-10-3 Two Speed with Reverse Controls, 551
- 23-11 The Changing Basis of Alternating-Current Motor Control, 556

Chapter 24 ALTERNATING-CURRENT MOTOR SELECTION 557

- 24-1 Shaft Power, 558
- 24-2 Characteristics of the Driven Load, 558
- 24-3 Speed Rating, 558
- 24-4 Frame Size, 559
- 24-5 Speed Classification, 561
- 24-6 Effect of Duty Cycle, 563
- 24-7 Ambient Temperature Effects, 564
- 24-8 Allowable Temperature Rise, 564
- 24-9 Voltage and Current Ratings, 564
 - 24-9-1 Alternating Current Voltage-Level Ratings, 564
 - 24-9-2 Alternating Current Frequency, 566

- 24-9-3 Alternating Current Motor Current Levels, 566
- 24-9-4 Motor Protective Devices, 571
- 24-9-5 Motor Power Factor, 572
- 24-10 Machine Enclosure Types, 575
- 24-11 Maintenance and Accessibility, 575
- 24-12 Efficiency, 575
- 24-13 Radio and Television Interference, 575
- 24-14 International Standardization Developments, 576
 - 24-14-1 Supply Voltage and Frequency, 576
 - 24-14-2 Physical Frame Size, 576
 - 24-14-3 Shaft Sizes, 577

Chapter 25**SPECIAL USES OF SYNCHRONOUS AND INDUCTION MACHINES 579**

- 25-1 Frequency Converter Set, 579
- 25-2 Induction Frequency Converter, 579
- 25-3 Induction Phase Converter, Single- to Three-Phase, 580
- 25-4 Induction Phase Converter, Single- to Two- to Three-Phase, 585
- 25-5 Induction Regulator, 585
- 25-6 Linear Motion Devices, 586

Appendix A**UNIT CONVERSIONS 588****Appendix B****LIST OF SYMBOLS 591****Appendix C****GREEK SYMBOLS 596****Appendix D****CONSTANTS AND COEFFICIENTS USED IN TEXT 598****Appendix E****INDUCTION MOTOR LOCKED ROTOR INDICATING CODE LETTERS 600****Appendix F****REVIEW OF MULTIPHASE WATTMETER CONNECTIONS 601****Appendix G****CURVE FITTING AND DATA IMPROVEMENT 607****BIBLIOGRAPHY 622****INDEX 624**

Introduction

Some major electrical developments that took place nearly a century ago started a chain of interlocking developments that have permanently changed our lives. Thomas Alva Edison experimentally developed a useful electric light. He immediately foresaw that widespread and effective use of his light would require a practical source and distribution of large amounts of electric power. His development work on steam-engine-driven direct-current (dc) generators enabled the commercial expansion of electric lighting. Figure 1-1 shows a very early dc generator.

Overlapping the early use of electric lighting was the development by Sprague and others of practical dc motors and motor speed controls. This enabled the building of what would now be called urban electric railroad systems. These early trolley cars enabled mass commuting to work and business toward the end of the last century. An early trolley car using dc motors is shown in Fig. 1-2.

1-1 CHANGE OF MAJOR USE TO ALTERNATING CURRENT

The widespread distribution of direct-current electric power has virtually disappeared. The single-unit street-surface electric rail car, as distinguished from the multiple-unit subway car, is about gone. Alternating-current electric distribution became nearly universal by the second half of the twentieth century.

The advantage of alternating current over direct current in power distribution is based on the ease of changing the ac voltage level. High-voltage power lines carry their energy with a correspondingly lower current. From the very basic Ohm's law, the voltage drop in a resistance is related to the current and the resistance. Since the resistance of a power line, or any conductor, is related to its cross-sectional area, a larger-sized wire will have less resistance. On the other hand, a long-distance line will cost a prohibitive amount if it is made of a large cross section. A modern high-voltage ac distribution line is shown in Fig. 1-3.