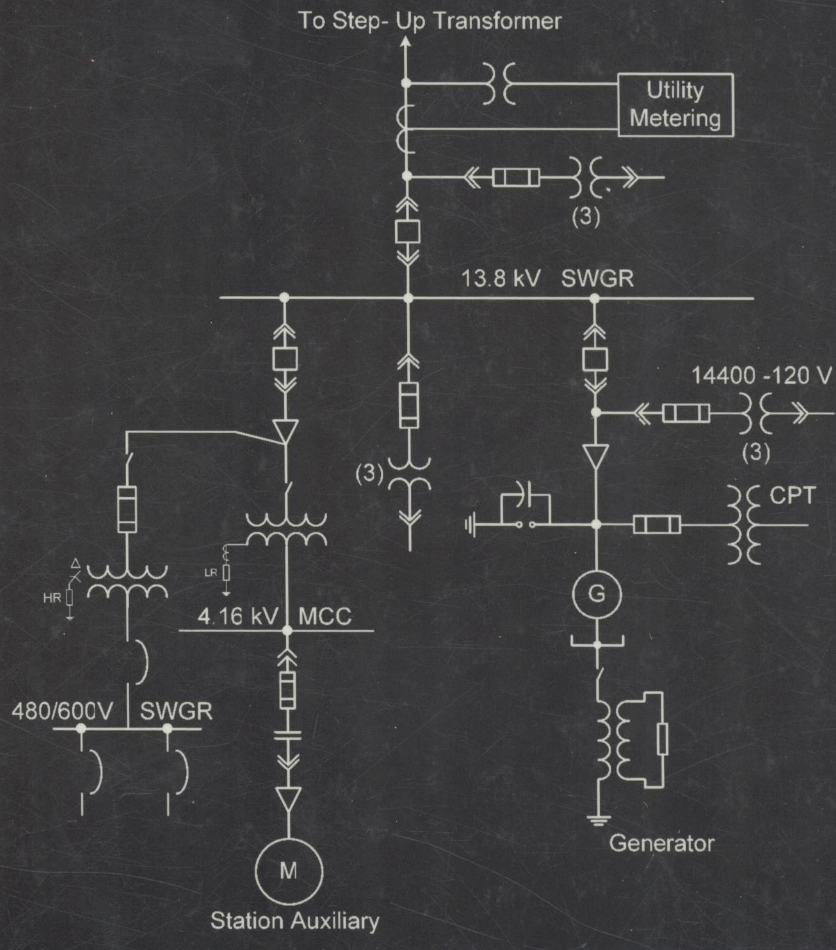
INDUSTRIAL POWER SYSTEMS



Shoaib Khan

CRC Press
Taylor & Francis Group

4|
45

INDUSTRIAL POWER SYSTEMS

Shoaib Khan

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-13: 978-0-8247-2443-6 (Hardcover)

Library of Congress Cataloging-in-Publication Data

Khan, Shoaib.
Industrial power systems / Shoaib Khan, Sheeba Khan, Ghariani Ahmed.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-8247-2443-6 (alk. paper)
1. Electric power systems. I. Khan, Sheeba. II. Ahmed, Ghariani. III. Title.

TK1005.K495 2007
621.319--dc22
2007032836

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

INDUSTRIAL POWER SYSTEMS

Dedication

My father dedicated the draft version of this book to my mother, his wife Shamim, whose love, patience and support inspired him to pursue knowledge and share it with others.

The publication of this book was my father's dream, as it will allow the knowledge he acquired over the years to be shared with others on a larger scale. I'm grateful for having had the opportunity to play a small role in making his dream come true. I would like to dedicate the final version to him.

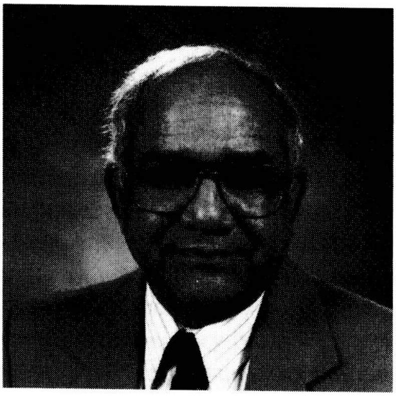
Sheeba Khan

Acknowledgments

This book was inspired by power systems courses developed and taught by my father for IEEE Continuing Education (Montreal) over several years. It was intended to respond to what he felt was a need in the field for an engineering/design guide for all working engineers, particularly younger ones who are not exposed to power systems during their undergraduate studies and who may not get guidance or training at their work place. It was an idea which was enthusiastically supported and encouraged by members of IEEE Continuing Education (Montreal), the not-for-profit engineering education organization my father collaborated with for over thirty years.

When he passed away unexpectedly, the book was incomplete. IEEE members approached me and asked that I continue where my father had left off. I was apprehensive about taking on such a project without an engineering background, but IEEE was insistent that it was needed, and offered to assist in its completion. I knew my father had been very committed to the project, and finally, upon reflection, I decided to take it on, despite my concerns. Fortunately, my father's former colleagues, as well as members of IEEE came to my aid whenever requested, and provided the guidance and assistance needed to complete my father's book. Michael Care, Gabor Furst, and Vijay Sood provided much-needed expertise and help in editing, and Maurice Huneault also assisted. Finally, this project might not have been completed if not for the dedication of Ahmed Ghariani, my father's former assistant and mentee, who worked tirelessly to compile materials, draw diagrams and provide constant assistance whenever needed. This book would not have been possible without the contributions and dedication of these dear friends and colleagues.

Sheeba Khan



SHOAIB A. KHAN

May 4, 1936 - February 10, 2005

Shoaib Khan was an electrical engineer who worked for over 40 years in power systems engineering, application, and protective relaying for power (hydro, thermal, nuclear), pulp and paper, mining and metals, and chemical plants in North America and overseas. Born in India, he received a bachelor of science degree in electrical engineering with major in electric power from Banares Hindu University in 1957. He worked with Kaiser Engineers and M.N. Dastur & Co in India until 1965, when he immigrated to Canada with his wife and young daughter. In Canada, he was responsible for the engineering, construction and operation of steel, aluminium and power plants. He soon became known as an expert in power systems and protection, and organized, developed and taught courses in those areas. He wrote numerous technical papers on power systems, application engineering and protection, some of which have been published in IAS/PES transactions and *Pulp & Paper Canada.*

Shoaib was a senior member of the Institute of Electrical and Electronic Engineers (IEEE), and was very active with the IEEE Education Committee (Montreal Section) for over thirty years. He received the IEEE Centennial and Third Millennium Medals for achievement in education, the Honoured Engineers Medal and the Meritorious Engineering Award from the IEEE Pulp and Paper Industry Committee in 2001. He was also an auxiliary professor with the Department of Electrical Engineering and a guest lecturer with the Department of Chemical Engineering at McGill University, Montreal, where he organized, developed, and taught courses in power systems and protection.

Shoaib will be remembered by all his colleagues and friends for his dedication to the advancement of applied engineering, and for his hard work and dedication to education in his field of endeavor. He was not only an outstanding engineer, but also a true friend to his colleagues and a committed educator and supporter of young engineers.

Contents

Acknowledgments.........xxv
Shoaib A. Khan.........xxvii

Chapter 1 Introduction.........1

Chapter 2 System Planning.........3

2.1 Introduction.........3
2.2 Basic Design Considerations.........3
2.2.1 Safety of Life.........3
2.2.2 Reliability of Utility Power Supply.........4
2.2.3 Reliability of Plant Distribution System.........4
2.2.4 Simplicity of Operation and Maintenance.........5
2.2.5 Voltage Regulation and Flicker.........5
2.2.6 Cost (Last Priority).........5
2.3 Plant Distribution Systems.........5
2.3.1 An Overview.........5
2.3.2 Plant Main Substation.........5
2.3.3 Primary Distribution System.........6
2.3.4 Secondary Distribution System.........7
2.3.5 In-Plant Generation.........7
2.3.6 Emergency Power Supply.........7
2.3.7 Power Supply for Monitoring and Control Systems.........8
2.3.8 DC Power Supply for Protection and Control.........9
2.4. Distribution Types.........9
2.4.1 Simple Radial.........9
2.4.2 Expanded Radial.........9
2.4.3 Primary Selective.........10
2.4.4 Secondary Selective.........10
2.4.5 Sparing Transformer.........10
2.5. Plant Power Demand and Load Estimate.........11
2.5.1 Estimate of Power Demand and Energy Cost.........11
2.5.1.1 Energy Consumption or Average Kilowatt Hours Required for One Unit of Production.........11
2.5.1.2 Typical Demand Factors for Utilization Equipment.........12
2.5.1.3 Estimate of Power Demand from Equipment List.........15
2.5.2 Factors Used for Load Estimate and Power Demand.........15
2.6 Voltage Considerations.........15
2.6.1 Voltages Used in North America.........15
2.6.2 Voltages Used in Europe.........16

2.6.3 Voltage and Frequency Used in Other Countries 16
2.6.4 Voltage Drop and Flicker 17
2.6.4.1 Steady-State Voltage Drop 17
2.6.4.2 Voltage Flicker 20
2.6.4.3 Voltage Drop Due to Motor Starting 24
2.6.4.4 Voltage Drop/Rise Due to Switching 24
2.6.5 Voltage Sag and Threshold Voltage 24
References 25
Bibliography 26

Chapter 3 Power System Studies 27

3.1 Introduction and Overview 27
3.2 Useful Formulae 27
3.3 Load Flow 28
3.3.1 Overview 28
3.3.2 Load-Flow Runs 29
3.4 Short Circuits 29
3.4.1 Contribution from Different Sources 29
3.4.2 Steps Required for a Short-Circuit Study 31
3.4.3 Medium- and High-Voltage Circuit Breakers 31
3.4.3.1 Contact Parting or Interrupting Duty 32
3.4.3.2 Close-and-Latch Duty 33
3.4.4 Interrupting Duty of Low-Voltage Circuit Breakers (<1000 V) 35
3.4.4.1 Metal-Enclosed Circuit Breakers [S6, S7] 35
3.4.4.2 Molded-Case Circuit Breakers 36
3.4.5 Interrupting Duty of Medium- and High-Voltage Fuses [S5] 36
3.4.6 For Time-Delayed Relaying Devices 36
3.4.7 Rotating Machine Impedance Multipliers [S9] 36
3.4.8 Short-Circuit Current Multiplying Factors for Higher X/R Ratio 37
3.4.9 X/R Ratio of System Component 38
3.4.10 System and Equipment Data 39
3.4.11 Example: Short-Circuit Calculation for Equipment Rating 45
3.4.11.1 Hand Calculations 45
3.4.11.2 Computer Solution 52
3.5 Protective Device Coordination 53
3.5.1 Introduction 53
3.5.2 Data Required for a Study 54
3.5.3 Time Interval for Coordination of Overcurrent Elements 54
3.5.3.1 Between Relays Controlling Circuit Breakers 54
3.5.3.2 Between Upstream and Downstream Fuses 55
3.5.3.3 Upstream Fuse and Downstream Circuit Breaker 55
3.5.3.4 Static Trip Units of Low-Voltage Circuit Breakers 55
3.5.4 Computer Programs for Overcurrent Coordination 55
3.6 Arc-Flash Hazard Calculations 55
3.6.1 Introduction 55

3.6.2 Steps Required for the Analysis 57
3.7 Harmonic Analysis 57
3.7.1 Introduction 57
3.7.2 Methods and Techniques 57
3.7.3 Necessary Steps for the Study 58
3.8 Power System Stability 59
3.8.1 An Overview 59
3.8.2 Transient Behavior of Synchronous Generators and Motors 59
3.8.3 Stability Study for an Ammonia Plant 60
3.9 Other Common Studies and Calculations 62
3.9.1 Switching Transients 62
3.9.2 Cable Ampacity Calculations 63
3.9.3 DC Power Supply 63
3.9.4 Motor Starting 63
3.9.5 Ground Grid 64
References 64
Bibliography 64

Chapter 4 System Neutral Grounding 67

4.1 Introduction and Overview 67
4.2 Ungrounded System 68
4.2.1 Normal Operation 68
4.2.2 Ground Fault on Phase "a" 68
4.2.3 Derivation of Equivalent Circuit 69
4.2.4 Overvoltage Due to Ground Fault through an Impedance 69
4.2.5 Conclusion and Recommendation 70
4.3 High-Resistance Grounded System 71
4.3.1 Normal Operation 71
4.3.2 Ground Fault on Phase "a" 71
4.3.3 Example of a High-Resistance Grounding Calculation 72
4.3.4 HR Grounding for Delta-Connected Systems (System Neutral not Available) 74
4.3.5 HR Grounding for Low-Voltage (480 and 600 V) Systems 75
4.3.6 Measurement of System Charging Current 75
4.3.7 Conclusions 75
4.3.8 Recommendations 76
4.4 Low-Resistance (LR) Grounded System 76
4.4.1 LR Grounding for Wye-Connected System 76
4.4.2 LR Grounding for Delta-Connected System 77
4.4.3 Conclusions 77
4.4.4 Recommendations 78
4.5 Solidly Grounded Neutral System 79
4.5.1 Solidly Grounded Neutral 79
4.5.2 Power System Considerations 79
4.5.3 Conclusions 79

4.5.4 Recommendations ... 80
4.6 Generator Neutral Grounding ... 80
4.6.1 Solidly Grounded Neutral ... 80
4.6.2 High-Resistance Grounding ... 81
4.6.2.1 Resistor Directly Connected to Generator Neutral ... 81
4.6.2.2 Distribution Transformer-Resistor Combination ... 82
4.6.2.3 Example: Sizing of Generator Neutral Grounding Equipment ... 82
4.6.3 Low-Resistance Grounding ... 84
4.6.4 Generator HR Grounded and System LR Grounded ... 85
4.6.5 Hybrid High-Resistance Grounding ... 85
4.6.6 Low-Reactance Grounding ... 85
4.6.7 Resonant Grounding ... 85
4.7 Grounding of Mine Power System ... 86
4.7.1 An Overview ... 86
4.7.2 Safety Considerations in HV Substation ... 86
4.7.3 Factors Involved in Shock Hazard ... 86
4.7.4 Neutral Grounding Resistor ... 87
4.7.5 Ground-Fault Relaying and Ground-Conductor Monitoring ... 88
4.7.6 Low-Voltage (600 V and 480 V) Systems ... 88
4.8 Neutral Grounding Equipment ... 89
4.8.1 HR Grounding for Wye-Connected MV Systems ... 89
4.8.2 HR Grounding for Wye-Connected LV Systems ... 89
4.8.3 LR Grounding for Wye-Connected MV Systems ... 90
4.8.4 HR Grounding for Wye-Connected Generator Neutral ... 90
4.8.5 Grounding Transformer ... 90
4.8.6 Zig-Zag Grounding Transformer ... 91
4.8.7 Wye-Delta Grounding Transformer ... 92
4.9 System Capacitance Data ... 93
4.9.1 Surge Capacitors for Rotating Machines ... 93
4.9.2 Overhead Transmission/Distribution Lines ... 93
4.9.3 Power Cable ... 94
4.9.4 Power Transformers ... 95
4.9.5 Outdoor Apparatus Bushings ... 95
4.9.6 Isolated Phase, Segregated, and Nonsegregated Bus ... 95
4.9.7 Synchronous Motors with Class B Insulation System ... 95
4.9.8 Air-Cooled Generators ... 96
4.9.9 Induction Motors ... 96
References ... 97
Bibliography ... 97

Chapter 5 Power Transformers and Reactors ... 99

5.1 General ... 99
5.1.1 Basic Construction ... 99
5.1.2 Normal (Usual) Service Conditions ... 99

5.1.3 Unusual Service Conditions 100
5.1.3.1 Altitude Correction Factors 100
5.1.3.2 Unusual Cooling Air and Water Temperature 101
5.1.4 Transformer Categories and Short-Circuit Withstand 102
5.1.5 Short-Circuit Impedance or Impedance Voltage (Z_T) 103
5.1.6 Vector Group, Angular Displacement, and Terminal Markings 103
5.1.7 Taps or Tap Changer 105
5.1.7.1 Off-Circuit Taps 106
5.1.7.2 Load Tap Changer 106
5.1.8 Parallel Operation 106
5.2 Oil-Filled (Immersed) Transformers 107
5.2.1 Classification of Mineral-Oil-Immersed Transformers 107
5.2.2 Voltage, Power Rating, and Temperature Rise 107
5.2.3 Impedance 108
5.2.4 Cooling Designation 108
5.2.5 Oil or Liquid Preservation System 110
5.2.5.1 Sealed-Tank System 110
5.2.5.2 Gas-Oil Seal System 110
5.2.5.3 Conservator Design 111
5.2.5.4 Conservator Diaphragm 112
5.2.6 Winding Insulation Levels 112
5.2.7 Tap Changers 113
5.2.7.1 Tap Changer Design 113
5.2.7.2 Basic Construction Features 113
5.2.7.3 Controls and Indication 113
5.2.8 Transformer Bushings 114
5.2.9 Bushing Current Transformers 114
5.2.10 Accessories 115
5.2.11 Cooling Equipment 116
5.2.12 Nameplate Information 117
5.2.13 Core Grounding 117
5.2.14 Transformer Gas Analysis: Dissolved Gases in Transformers 117
5.3 Nonflammable Liquid-Filled Transformers 118
5.3.1 Overview 118
5.3.2 Askeral-Immersed Transformers 118
5.3.3 Silicone-Immersed Transformers 119
5.3.4 Other Available Transformer Types 119
5.4 Dry-Type Transformers 119
5.4.1 Type and Rating 119
5.4.2 Insulation Class and Temperature Rise 120
5.4.3 Primary System Fault Level for Short-Circuit Withstand 120
5.4.4 Insulation Level 121
5.4.5 Impedance 121
5.4.6 Tap Changer or Taps 121
5.4.7 Accessories 122
5.4.8 Surge Arresters for Dry-Type Transformers 122

5.5 Transformers for Nonlinear Loads 122
5.5.1 Standard Design 122
5.5.2 Transformer Losses 122
5.5.3 K-Rated Transformers 123
5.6 Generator Step-Up and Other Special Transformers 124
5.7 Installation of Oil-Filled Transformers and Reactors 126
5.7.1 General 126
5.7.2 Indoor (Inside Buildings) 126
5.7.3 Outdoor Installation 127
5.8 Reactors 127
5.9 Inspection and Testing 128
5.9.1 Factory Routine and Type Tests 128
5.9.2 Test of Transformer 130
5.9.3 Routine Power Transformer Inspection 131
5.9.4 Internal Inspection of Transformer 132
References 132
Bibliography 133

Chapter 6 Instrument Transformers 135

6.1 Introduction and Overview 135
6.2 Current Transformers 135
6.2.1 Bushing Type 135
6.2.1.1 Bar Type 135
6.2.1.2 Window Type 135
6.2.1.3 Wound Type 136
6.2.1.4 Post Type 136
6.2.1.5 Auxiliary CT 136
6.2.1.6 Linear Couplers (Air-Core Mutual Reactors) 136
6.2.1.7 Optical or Digital CT 136
6.2.2 Equivalent Circuit 137
6.2.3 Excitation Characteristics 138
6.2.4 Accuracy Class and Burden 139
6.2.5 Current Transformers Saturation 141
6.2.5.1 Saturation with Symmetrical Fault Current (No DC Component) 141
6.2.5.2 Saturation with Asymmetrical Fault Current (with DC Component) 141
6.2.5.3 Example 141
6.2.5.4 Recommendations 142
6.2.5.5 Saturation Factor and Time to Saturate 143
6.2.6 Remnant Flux 144
6.2.7 Accuracy Voltage of Bushing Current Transformers 144
6.2.8 Accuracy Voltage of Current Transformers Used in Switchgear 144
6.2.9 Current Transformers in Series 145
6.2.10 Polarity of CT: Polarity Marking 145

6.2.11 Auxiliary Current Transformers ... 146
6.2.12 Metering Current Transformers ... 146
6.3 Voltage Transformers ... 146
6.3.1 Inductive Voltage Transformer ... 146
6.3.2 Capacitor Voltage Transformers ... 147
6.3.3 Standard Accuracy Class and Burden ... 148
6.3.4 Ratings and Characteristics ... 148
6.3.5 Protection of Voltage Transformers ... 149
6.3.6 Ferro-Resonance in Voltage Transformer ... 150
6.4 Grounding of Secondary ... 150
6.5 European Standards ... 151
6.5.1 Current Transformers ... 152
6.5.1.1 Protection-Class Current Transformers ... 152
6.5.1.2 Example ... 152
6.5.1.3 Measuring or Metering Current Transformers ... 152
6.5.2 Voltage Transformers ... 152
6.5.2.1 Standard Accuracy Class ... 152
6.5.2.2 Voltage Factor ... 153
References ... 153
Bibliography ... 154

Chapter 7 Switchgear, Circuit Breakers, and Motor Control Center ... 155

7.1 Low Voltage ... 155
7.1.1 Short Circuit ... 155
7.1.2 Important Features to Be Specified ... 155
7.2 Medium Voltage ... 156
7.3 Load-Interrupter Switchgear ... 157
7.4 Power Fuse ... 166
7.4.1 Advantages ... 166
7.4.2 Disadvantages ... 166
7.4.3 Fuse Size for Motor Branch Circuit ... 167
7.4.4 Application of Fuse Let-Through Charts ... 167
7.5 Medium- and High-Voltage Circuit Breaker ... 167
7.5.1 Overview of Medium- and High-Voltage Circuit-Breaker Standards ... 168
7.5.2 Basic Performance Requirements: Medium- and High-Voltage Circuit-Breaker Standards ... 169
7.5.3 Circuit-Breaker Types ... 170
7.5.3.1 Air-Magnetic Air Quenching ... 170
7.5.3.2 Oil Circuit Breakers ... 170
7.5.3.3 Air-Blast Breakers ... 171
7.5.3.4 SF_6 Gas Circuit Breakers ... 171
7.5.3.5 Vacuum Circuit Breakers ... 172
7.5.4 Circuit-Breaker Short-Circuit Rating and E/X Method ... 173
7.6 SF_6 Gas-Insulated Switchgear ... 174

7.6.1 Main Features ... 175
7.6.2 Design Concepts ... 175
7.6.3 Specifications ... 176
7.7 Low- and Medium-Voltage Motor Control Centers ... 177
7.7.1 Low-Voltage Motor Control Center ... 177
7.7.2 Medium-Voltage Motor Control Center ... 178
7.7.3 Short-Circuit Capacity ... 178
7.7.4 Coordinated Protection in Medium-Voltage Fused Starters ... 179
7.7.5 Main and Vertical Bus Bars ... 179
7.7.6 Minimum Size ... 179
7.7.7 IEC-Rated Contactors ... 179
References ... 180

Chapter 8 Station Battery ... 181

8.1 Introduction ... 181
8.2 System Types ... 181
8.3 DC Distribution Systems ... 182
8.4 Types of Battery ... 185
8.5 Battery Chargers ... 188
8.6 Application Criteria ... 189
8.6.1 Application Voltage Levels ... 189
8.6.2 Rating ... 190
8.6.3 Load Classification ... 190
8.7 Battery Sizing ... 191
8.7.1 System Voltage ... 191
8.7.2 Correction Factor ... 193
8.7.3 Duty Cycle ... 193
References ... 193
Bibliography ... 194

Chapter 9 Application and Protection of Medium-Voltage Motors ... 195

9.1 Introduction and Overview ... 195
9.2 Load Characteristics ... 195
9.2.1 Load Categories ... 195
9.2.1.1 Constant-Torque Drives ... 195
9.2.1.2 Torque as a Function of Speed Drives ... 196
9.2.2 Steady-State Power ... 196
9.2.3 Average Starting Torque and Acceleration ... 197
9.2.3.1 Acceleration Torque ... 197
9.2.3.2 Inertia ... 198
9.2.3.3 Friction ... 198
9.2.3.4 Frequency of Starting ... 198
9.2.3.5 Induction-Motor Equipment Network ... 199
9.3 Squirrel-Cage Induction Motors ... 199

9.3.1 Torque Characteristics 199
9.3.2 NEMA Design Letters 200
9.3.3 NEMA Code Letter 201
9.3.4 Inertia 201
9.3.5 Service Factor 202
9.3.6 Insulation Systems and Temperature Rise 203
9.3.7 Surge-Withstand Capability 203
9.3.8 Power Supply Voltage and Frequency 203
9.3.9 Starting or Locked-Rotor Power Factor 204
9.3.10 Enclosures 204
9.3.11 Motors for Classified (Hazardous) Areas 205
9.3.12 Bearing and Shaft Currents 206
9.3.12.1 Sleeve Bearings 206
9.3.12.2 Antifriction Bearing 207
9.3.12.3 Thrust Bearing 207
9.3.12.4 Bearing Protection Against Failures 207
9.3.12.5 Supply Voltage Unbalance 207
9.3.12.6 Shaft Current 207
9.3.13 Accessories 208
9.3.14 Motor Terminal Box 208
9.4 Wound Rotor (Slip Ring) Induction Motors 209
9.5 Synchronous Motors 211
9.5.1 An Overview 211
9.5.2 Power Supply Voltage and Frequency 211
9.5.3 Insulation System and Temperature Rise 212
9.5.4 Torque Characteristics 212
9.5.5 Inertia (Wk^2) 213
9.5.6 Excitation System 213
9.5.7 Rotor Protection and Monitoring 214
9.5.8 System Power Factor Improvement 214
9.5.9 Torque Pulsations during Acceleration 215
9.5.10 Current Pulsations 216
9.5.11 Application 217
9.6 Electric Motors for Variable Frequency Drives 217
9.7 Voltage Drop and Acceleration Time 218
9.7.1 Guidelines 218
9.7.2 Voltage Drop Using Hand Calculations 220
9.7.2.1 Short-Circuit Method 220
9.7.2.2 Per-Unit Method 220
9.7.2.3 Motor Representation 221
9.7.2.4 Voltage Drop Caused by Running Load 221
9.7.2.5 Commonly Used Formulae and Equations 221
9.7.2.6 Example Voltage Drop Due to Motor Starting 222
9.7.3 Voltage Dip When a Sudden Load Is Applied to a Small Generator 224
9.7.4 Voltage Drop and Acceleration Time Using Computer Software ... 225

9.7.5 Estimate of Acceleration Time Using Hand Calculations ... 226
9.7.6 Estimate of Deceleration Time ... 227
9.7.7 Simplified Method for Estimating the Acceleration Time of Centrifugal Drives (Fans, Blowers) ... 227
9.8 Motor Controllers and Starting Methods ... 228
9.8.1 Fused Starter ... 228
9.8.2 Switchgear-Type Controllers ... 230
9.8.3 Starting Methods ... 230
9.8.3.1 Direct-on Line Start ... 230
9.8.3.2 Reactor Start ... 230
9.8.3.3 Autotransformer Start ... 230
9.8.3.4 Capacitor Start ... 232
9.8.3.5 Reactor-Capacitor Start ... 232
9.8.3.6 Captive Transformer Start ... 233
9.8.3.7 Variable-Voltage Start ... 233
9.8.3.8 Variable-Frequency Start ... 233
9.8.3.9 Part Winding Start ... 234
References ... 234
Bibliography ... 234

Chapter 10 Power and Control Cables ... 237

10.1 Introduction and Overview ... 237
10.2 Cable Selection Criteria ... 237
10.2.1 Load Current Criteria ... 238
10.2.2 Voltage-Drop Limitations ... 238
10.2.3 Fault-Current Criteria ... 239
10.2.4 Insulation Levels and System Grounding ... 239
10.3 Cable Shielding ... 239
10.3.1 Inner Shield ... 239
10.3.2 Outer Shield ... 240
10.3.3 Outer or Overall Shield Size ... 240
10.3.4 Shield and Outer Sheath Grounding ... 241
10.3.5 Recommended Practice for Industrial Cable System ... 241
10.4 Additional Application Considerations ... 243
10.4.1 Short-Circuit Conductor Heating ... 243
10.4.2 Application of Power Cables for Variable-Frequency Drives ... 244
10.4.2.1 Feeder Cable to the Drive Cubicle ... 244
10.4.2.2 Feeder from the Drive Cubicle to the Motor ... 245
10.5 Cable Insulation ... 246
10.5.1 Standards ... 246
10.5.2 Insulation Characteristics ... 247
10.5.3 Insulation Levels ... 247
10.5.4 Insulation Reliability ... 248
10.6 Testing ... 249