ELECTRICAL INSULATION
FOR ROTATING MACHINES
ELECTRICAL INSULATION FOR ROTATING MACHINES
Design, Evaluation, Aging, Testing, and Repair

Second Edition

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CONTENTS

PREFACE

CHAPTER 1  ROTATING MACHINE INSULATION SYSTEMS

1.1 Types of Rotating Machines
  1.1.1 AC Motors 2
  1.1.2 Synchronous Generators 4
  1.1.3 Induction Generators 6
  1.1.4 Permanent Magnet (PM) Synchronous Motors and Generators 7
  1.1.5 Classification by Cooling 7
1.2 Winding Components 9
  1.2.1 Stator Winding 9
  1.2.2 Insulated Rotor Windings 10
  1.2.3 Squirrel Cage Induction Motor Rotor Windings 11
1.3 Types of Stator Winding Construction 11
  1.3.1 Random-Wound Stators 12
  1.3.2 Form-Wound Stators—Coil Type 12
  1.3.3 Form-Wound Stators—Roebel Bar Type 13
1.4 Form-Wound Stator Winding Insulation System Features 14
  1.4.1 Strand Insulation 14
  1.4.2 Turn Insulation 17
  1.4.3 Groundwall Insulation 19
  1.4.4 Groundwall Partial Discharge Suppression 21
  1.4.5 Groundwall Stress Relief Coatings for Conventional Stators 24
  1.4.6 Surface Stress Relief Coatings for Inverter-Fed Stators 27
  1.4.7 Conductor Shields 29
  1.4.8 Mechanical Support in the Slot 30
  1.4.9 Mechanical Support in the End winding 32
  1.4.10 Transposition Insulation 34
1.5 Random-Wound Stator Winding Insulation System Features 36
  1.5.1 Partial Discharge Suppression in Inverter-Fed Random Windings 37
1.6 Rotor Winding Insulation System Components 38
  1.6.1 Salient Pole Rotor 40
  1.6.2 Round Rotors 41
  1.6.3 Induction Machine Wound Rotors 43

References 45

CHAPTER 2  EVALUATING INSULATION MATERIALS AND SYSTEMS

2.1 Aging Stresses 49
  2.1.1 Thermal Stress 49
2.1 Electrical Stress 50
  2.1.2 Electrical Stress 50
  2.1.3 Ambient Stress (Factors) 52
  2.1.4 Mechanical Stress 53
  2.1.5 Radiation Stress 54
  2.1.6 Multiple Stresses 54
2.2 Principles of Accelerated Aging Tests 54
  2.2.1 Candidate and Reference Materials/Systems 55
  2.2.2 Statistical Variation 55
  2.2.3 Failure Indicators 61
2.3 Thermal Endurance Tests 62
  2.3.1 Basic Principles 62
  2.3.2 Thermal Identification and Classification 63
  2.3.3 Insulating Material Thermal Aging Test Standards 64
  2.3.4 Insulation System Thermal Aging Test Standards 64
  2.3.5 Future Trends 67
2.4 Electrical Endurance Tests 67
  2.4.1 Proprietary Tests for Form-Wound Coils 68
  2.4.2 Standardized AC Voltage Endurance Test Methods for Form-Wound Coils/Bars 69
  2.4.3 Voltage Endurance Tests for Inverter-Fed Windings 70
2.5 Thermal Cycling Tests 71
  2.5.1 IEEE Thermal Cycling Test 72
  2.5.2 IEC Thermal Cycling Test 73
2.6 Nuclear Environmental Qualification Tests 74
  2.6.1 Environmental Qualification (EQ) by Testing 75
  2.6.2 Environmental Qualification by Analysis 76
  2.6.3 Environmental Qualification by a Combination of Testing and Analysis 77
2.7 Multifactor Stress Testing 77
2.8 Material Property Tests 78
References 80

CHAPTER 3 HISTORICAL DEVELOPMENT OF INSULATION MATERIALS AND SYSTEMS 83

3.1 Natural Materials for Form-Wound Stator Coils 84
3.2 Early Synthetics for Form-Wound Stator Coils 86
3.3 Plastic Films and Non-Wovens 89
3.4 Liquid Synthetic Resins 90
  3.4.1 Polyesters 90
  3.4.2 Epoxides (Epoxy Resins) 92
3.5 Mica 95
  3.5.1 Mica Splittings 95
  3.5.2 Mica Paper 96
  3.5.3 Mica Backing Materials 98
3.6 Glass Fibers 99
3.7 Laminates 100
3.8 Evolution of Wire and Strand Insulations 101
3.9 Manufacture of Random-Wound Stator Coils 102
3.10 Manufacture of Form-Wound Coils and Bars 103
CONTENTS

3.10.1 Early Systems 103
3.10.2 Asphaltic Mica Systems 103
3.10.3 Individual Coil and Bar Thermoset Systems 104
3.10.4 Global VPI Systems 105
3.11 Wire Transposition Insulation 106
3.12 Methods of Taping Stator Groundwall Insulation 107
3.13 Insulating Liners, Separators, and Sleeving
   3.13.1 Random-Wound Stators 109
   3.13.2 Rotors 110
References 110

CHAPTER 4
STATOR WINDING INSULATION SYSTEMS IN CURRENT USE 111

4.1 Consolidation of Major Manufacturers 114
4.2 Description of Major Trademarked Form-Wound Stator Insulation Systems 115
   4.2.1 Westinghouse Electric Co.: Thermalastic\textsuperscript{TM} 115
   4.2.2 General Electric: Micapals I and II\textsuperscript{TM}, Epoxy Mica Mat\textsuperscript{TM}, Micapal HT\textsuperscript{TM}, and Hydromat\textsuperscript{TM} 116
   4.2.3 Alstom, GEC Alstom, and Alstom Power: Isotenax\textsuperscript{TM}, Resitherm\textsuperscript{TM}, Resiflex\textsuperscript{TM}, Resivac\textsuperscript{TM}, and Duritenax\textsuperscript{TM} 117
   4.2.4 Siemens AG, KWU: Micalastic\textsuperscript{TM} 118
   4.2.5 Brown Boveri, ASEA, ABB, and Alstom Power: Micadur\textsuperscript{TM}, Micadur Compact\textsuperscript{TM}, Micapac\textsuperscript{TM}, and Micarex\textsuperscript{TM} 119
   4.2.6 Toshiba Corporation: Tosrich\textsuperscript{TM} and Tostight\textsuperscript{TM} 120
   4.2.7 Mitsubishi Electric Corporation 121
   4.2.8 Hitachi, Ltd.: Hi-Resin\textsuperscript{TM}, Hi-Mold\textsuperscript{TM}, and Super Hi-Resin\textsuperscript{TM} 121
   4.2.9 Dongfang Electric Machinery 122
   4.2.10 Harbin Electric Corporation (HEC) 122
   4.2.11 Shanghai Electric Machinery 122
   4.2.12 Jinan Power Equipment: Resitherm\textsuperscript{TM}, Micadur\textsuperscript{TM}, and Micadur Compact\textsuperscript{TM} 123
   4.2.13 Summary of Present-Day Insulation Systems 123
4.3 Recent Developments for Form-Wound Insulation Systems 123
   4.3.1 Reducing Groundwall Thermal Impedance 124
   4.3.2 Increasing Electric Stress 125
   4.3.3 Environmental Issues 126
4.4 Random-Wound Stator Insulation Systems 127
   4.4.1 Magnet Wire Insulation 127
   4.4.2 Phase and Ground Insulation 127
   4.4.3 Varnish Treatment and Impregnation 128
References 129

CHAPTER 5
ROTOR WINDING INSULATION SYSTEMS 133

5.1 Rotor Slot and Turn Insulation 134
5.2 Collector Insulation 136
5.3 End Winding Insulation and Blocking 136
5.4 Retaining Ring Insulation 137
5.5 Direct-Cooled Rotor Insulation 138
5.6 Wound Rotors 139
8.1.3 Symptoms 175
8.1.4 Remedies 176

8.2 Thermal Cycling 176
  8.2.1 General Process 177
  8.2.2 Root Causes 180
  8.2.3 Symptoms 180
  8.2.4 Remedies 181

8.3 Inadequate Resin Impregnation or Dipping 181
  8.3.1 General Process 182
  8.3.2 Root Causes 183
  8.3.3 Symptoms 184
  8.3.4 Remedies 184

8.4 Loose Coils in the Slot 185
  8.4.1 General Process 185
  8.4.2 Root Causes 186
  8.4.3 Symptoms 189
  8.4.4 Remedies 190

8.5 Semiconductive Coating Failure 190
  8.5.1 General Process 190
  8.5.2 Root Causes 191
  8.5.3 Symptoms 192
  8.5.4 Remedies 193

8.6 Semiconductive/Grading Coating Overlap Failure 194
  8.6.1 General Process 194
  8.6.2 Root Causes 195
  8.6.3 Symptoms 196
  8.6.4 Remedies 196

8.7 High Intensity Slot Discharge 197
  8.7.1 General Process 198
  8.7.2 Root Causes 198
  8.7.3 Symptoms 199
  8.7.4 Repairs 199

8.8 Vibration Sparking (Spark Erosion) 199
  8.8.1 General Process 199
  8.8.2 Root Cause 201
  8.8.3 Symptoms 201
  8.8.4 Repair 202

8.9 Transient Voltage Surges 202
  8.9.1 General Process 203
  8.9.2 Root Causes 204
  8.9.3 Symptoms 204
  8.9.4 Remedies 206

8.10 Repetitive Voltage Surges Due to Drives 207
  8.10.1 General Process 207
  8.10.2 Root Cause 209
  8.10.3 Symptoms 209
  8.10.4 Remedies 210

8.11 Contamination (Electrical Tracking) 211
  8.11.1 General Process 211
  8.11.2 Root Causes 214
CHAPTER 9  ROUND ROTOR WINDING FAILURE MECHANISMS AND REPAIR  235

9.1 Thermal Deterioration  235
  9.1.1 General Process  236
  9.1.2 Root Cause  236
  9.1.3 Symptoms  237
9.2 Thermal Cycling  237
  9.2.1 General Process  238
  9.2.2 Root Cause  238
  9.2.3 Symptoms  240
9.3 Abrasion Due to Imbalance or Turning Gear Operation (Copper Dusting)  241
  9.3.1 General Process  242
  9.3.2 Root Causes  243
  9.3.3 Symptoms  244
9.4 Pollution (Tracking)  244
  9.4.1 General Process  244
  9.4.2 Root Causes  245
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.4.3</td>
<td>Common Symptoms</td>
<td>245</td>
</tr>
<tr>
<td>9.5</td>
<td>Repetitive Voltage Surges</td>
<td>245</td>
</tr>
<tr>
<td>9.5.1</td>
<td>General Process</td>
<td>246</td>
</tr>
<tr>
<td>9.5.2</td>
<td>Root Causes</td>
<td>246</td>
</tr>
<tr>
<td>9.5.3</td>
<td>Common Symptoms</td>
<td>247</td>
</tr>
<tr>
<td>9.6</td>
<td>Centrifugal Force</td>
<td>247</td>
</tr>
<tr>
<td>9.6.1</td>
<td>General Process</td>
<td>247</td>
</tr>
<tr>
<td>9.6.2</td>
<td>Root Causes</td>
<td>247</td>
</tr>
<tr>
<td>9.6.3</td>
<td>Common Symptoms</td>
<td>248</td>
</tr>
<tr>
<td>9.7</td>
<td>Operating Without Field Current</td>
<td>249</td>
</tr>
<tr>
<td>9.7.1</td>
<td>Loss of Field During Operation</td>
<td>249</td>
</tr>
<tr>
<td>9.7.2</td>
<td>Inadvertent Closure of Generator Breaker</td>
<td>249</td>
</tr>
<tr>
<td>9.7.3</td>
<td>Root Causes</td>
<td>250</td>
</tr>
<tr>
<td>9.7.4</td>
<td>Common Symptoms</td>
<td>250</td>
</tr>
<tr>
<td>9.8</td>
<td>Remedies</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>252</td>
</tr>
</tbody>
</table>

CHAPTER 10  
*SALIENT POLE ROTOR WINDING FAILURE MECHANISMS AND REPAIR*  
253

10.1 Thermal Deterioration  
10.1.1 General Process  
10.1.2 Root Causes  
10.1.3 Common Symptoms  
253

10.2 Thermal Cycling  
10.2.1 General Process  
10.2.2 Root Causes  
10.2.3 Common Symptoms  
255

10.3 Pollution (Tracking and Moisture Absorption)  
10.3.1 General Process  
10.3.2 Root Causes  
10.3.3 Common Symptoms  
256

10.4 Abrasive Particles  
10.4.1 General Process  
10.4.2 Root Causes  
10.4.3 Common Symptom  
258

10.5 Centrifugal Force  
10.5.1 General Process  
10.5.2 Root Causes  
10.5.3 Common Symptoms  
259

10.6 Repetitive Voltage Surges  
10.6.1 General Process  
10.6.2 Root Causes  
10.6.3 Common Symptoms  
260

10.7 Salient Pole Repair  
261

References 263

CHAPTER 11  
*WOUND ROTOR WINDING FAILURE MECHANISMS AND REPAIR*  
265

11.1 Voltage Surges  
266
11.1 General Process 266
11.1.1 General Process 266
11.1.2 Root Causes 267
11.1.3 Common Symptoms 267
11.2 Unbalanced Stator Voltages 267
11.2.1 General Process 267
11.2.2 Root Causes 268
11.2.3 Common Symptoms 268
11.3 High Resistance Connections-Bar Lap and Wave Windings 268
11.3.1 General Process 268
11.3.2 Root Causes 268
11.3.3 Common Symptoms 268
11.4 End Winding Banding Failures 269
11.4.1 General Process 269
11.4.2 Root Causes 269
11.4.3 Common Symptoms 269
11.5 Slip Ring Insulation Shorting and Grounding 270
11.5.1 General Process 270
11.5.2 Root Causes 270
11.6 Wound Rotor Winding Repair 271
11.6.1 Failed Windings 271
11.6.2 Contaminated Windings and Slip Ring Insulation 271
11.6.3 Failed Connections in Bar-Type Windings 271
11.6.4 Damaged End Winding Banding 271
11.6.5 Failed or Contaminated Slip Ring Insulation 272
References 272

CHAPTER 12  SQUIRREL CAGE INDUCTION ROTOR WINDING FAILURE MECHANISMS AND REPAIR 273

12.1 Thermal 273
12.1.1 General Process 274
12.1.2 Root Causes 274
12.1.3 Common Symptoms 275
12.2 Cyclic Mechanical Stressing 275
12.2.1 General Process 276
12.2.2 Root Causes 277
12.2.3 Common Symptoms 278
12.3 Poor Design/Manufacture 278
12.3.1 General Process and Root Causes 279
12.3.2 Common Symptoms 281
12.4 Repairs 283
References 284

CHAPTER 13  CORE LAMINATION INSULATION FAILURE AND REPAIR 285

13.1 Thermal Deterioration 285
13.1.1 General Process 286
13.1.2 Root Causes 286
13.1.3 Common Symptoms 289
13.2 Electrical Degradation 290
15.5 Poor Connection Hot Spot (High Current-Infrared Camera) 334
  15.5.1 Purpose and Theory 334
  15.5.2 Test Method 335
  15.5.3 Interpretation 335
15.6 AC Hipot 335
  15.6.1 Purpose and Theory 336
  15.6.2 Test Method 337
  15.6.3 Interpretation 338
15.7 Capacitance 339
  15.7.1 Purpose and Theory 339
  15.7.2 Test Method 340
  15.7.3 Interpretation 341
15.8 Stator Capacitance Tip-Up 342
  15.8.1 Purpose and Theory 342
  15.8.2 Test Method 342
  15.8.3 Interpretation 343
15.9 Capacitive Impedance Test for Motor Stators 344
15.10 Dissipation (or Power) Factor 344
  15.10.1 Purpose and Theory 345
  15.10.2 Test Method 345
  15.10.3 Interpretation 347
15.11 Power (Dissipation) Factor Tip-Up 348
  15.11.1 Purpose and Theory 348
  15.11.2 Test Method 349
  15.11.3 Interpretation 350
15.12 Off-Line Partial Discharge for Conventional Windings 350
  15.12.1 Purpose and Theory 351
  15.12.2 Test Method 352
  15.12.3 Interpretation 354
15.13 Off-Line Partial Discharge for Inverter-Fed Windings 357
  15.13.1 Purpose and Theory 357
  15.13.2 Test Method and Interpretation 358
15.14 Stator Blackout and Ultraviolet Imaging 359
  15.14.1 Purpose and Theory 359
  15.14.2 Test Method 360
  15.14.3 Interpretation 360
15.15 Stator Partial Discharge Probe 361
  15.15.1 Purpose and Theory 361
  15.15.2 Test Method 362
  15.15.3 Interpretation 362
15.16 Stator Surge Voltage 363
  15.16.1 Purpose and Theory 363
  15.16.2 Test Method 365
  15.16.3 Interpretation 366
15.17 Inductive Impedance 367
15.18 Semiconductive Coating Contact Resistance 368
  15.18.1 Purpose and Theory 368
  15.18.2 Test Method 369
  15.18.3 Interpretation 369
15.19 Conductor Coolant Tube Resistance 369
15.19.1 Purpose and Test Method 369
15.20 Stator Wedge Tap 370
  15.20.1 Purpose and Theory 370
  15.20.2 Test Method 370
  15.20.3 Interpretation 372
15.21 Slot Side Clearance 373
  15.21.1 Purpose and Theory 373
  15.21.2 Test Method 373
  15.21.3 Interpretation 373
15.22 Stator Slot Radial Clearance 374
  15.22.1 Purpose and Theory 374
  15.22.2 Test Method 374
  15.22.3 Interpretation 374
15.23 Stator End Winding Bump 375
  15.23.1 Purpose and Theory 375
  15.23.2 Test Method 375
  15.23.3 Interpretation 376
15.24 Stator Pressure and Vacuum Decay 377
  15.24.1 Purpose and Theory 377
  15.24.2 Test Methods and Interpretation 377
15.25 Rotor Pole Drop (Voltage Drop) 378
  15.25.1 Purpose and Theory 379
  15.25.2 Test Method—Salient Pole Rotor 379
  15.25.3 Test Method—Round Rotor 380
  15.25.4 Interpretation 380
15.26 Rotor RSO and Surge 380
  15.26.1 Purpose and Theory 380
  15.26.2 Test Method 381
  15.26.3 Interpretation 382
15.27 Rotor Growler 382
  15.27.1 Purpose and Theory 383
  15.27.2 Test Method 383
  15.27.3 Interpretation 383
15.28 Rotor Fluorescent Dye Penetrant 383
  15.28.1 Purpose and Theory 383
  15.28.2 Test Method and Interpretation 384
15.29 Rotor Rated Flux 384
  15.29.1 Purpose and Theory 384
  15.29.2 Test Method 384
  15.29.3 Interpretation 384
15.30 Rotor Single-Phase Rotation 385
  15.30.1 Purpose and Theory 385
  15.30.2 Test Method 385
  15.30.3 Interpretation 385
References 385

CHAPTER 16 IN-SERVICE MONITORING OF STATOR AND ROTOR WINDINGS 389

16.1 Thermal Monitoring 390
  16.1.1 Stator Winding Point Sensors 390
CONTENTS

16.1 Rotor Winding Sensors 392
  16.1.2 Monitoring Principles 392
  16.1.3 Data Acquisition and Interpretation 393
  16.1.4 Thermography 394
16.2 Condition Monitors and Tagging Compounds 395
  16.2.1 Monitoring Principles 395
  16.2.2 Interpretation 397
16.3 Ozone 398
  16.3.1 Monitoring Principles 398
  16.3.2 Interpretation 399
16.4 Online Partial Discharge Monitor 400
  16.4.1 Monitoring Principles 400
  16.4.2 Interpretation 408
16.5 Online Capacitance and Dissipation Factor 415
  16.5.1 Monitoring Principle 415
  16.5.2 Data Acquisition and Interpretation 416
16.6 Endwinding Vibration Monitor 417
  16.6.1 Monitoring Principles 417
  16.6.2 Data Acquisition and Interpretation 418
16.7 Synchronous Rotor Flux Monitor 420
  16.7.1 Monitoring Principles 421
  16.7.2 Data Acquisition and Interpretation 425
16.8 Current Signature Analysis 427
  16.8.1 Monitoring Principles 427
  16.8.2 Data Acquisition 429
  16.8.3 Interpretation 430
16.9 Bearing Vibration Monitor 432
  16.9.1 Vibration Sensors 432
  16.9.2 Induction Motor Monitoring 433
  16.9.3 Synchronous Machine Monitoring 434
16.10 Stator Winding Water Leak Monitoring 435

References 435

CHAPTER 17  CORE TESTING  439

17.1 Knife 439
  17.1.1 Purpose and Theory 439
  17.1.2 Test Method 440
  17.1.3 Interpretation 440
17.2 Rated Flux 441
  17.2.1 Purpose and Theory 441
  17.2.2 Test Method 443
  17.2.3 Interpretation 449
17.3 Core Loss 450
  17.3.1 Purpose and Theory 450
  17.3.2 Test Method 450
  17.3.3 Interpretation 450
17.4 Low Core Flux (El-CID) 451
  17.4.1 Purpose and Theory 452
  17.4.2 Test Method 453
## CHAPTER 18  NEW MACHINE WINDING AND REWIND SPECIFICATIONS  463

18.1 Objective of Stator and Rotor Winding Specifications  464
18.2 Trade-Offs Between Detailed and General Specifications  464
18.3 General Items for Specifications  465
18.4 Technical Requirements for New Stator Windings  467
18.5 Technical Requirements for Insulated Rotor Windings  475
  18.5.1 New Round Rotor Windings  475
  18.5.2 Refurbishment and Replacement of Existing Round Rotor Windings  478
  18.5.3 New Salient Pole Windings  481
  18.5.4 Refurbishment and Repair of Existing Salient Pole Windings  484

References  486

## CHAPTER 19  ACCEPTANCE AND SITE TESTING OF NEW WINDINGS  487

19.1 Stator Winding Insulation System Prequalification Tests  487
  19.1.1 Dissipation Factor Tip-Up  488
  19.1.2 Partial Discharge Test for Conventional Windings  488
  19.1.3 Partial Discharge Test for Inverter Fed Windings  489
  19.1.4 Impulse (Surge)  490
  19.1.5 Voltage Endurance for Conventional Windings  490
  19.1.6 Voltage Endurance for Form-Wound Inverter Fed Windings  492
  19.1.7 Thermal Cycling  492
  19.1.8 Thermal Classification  493

19.2 Stator Winding Insulation System Factory and On-Site Tests  494
  19.2.1 Insulation Resistance and Polarization Index  494
  19.2.2 Phase Resistance and/or Thermal Imaging  495
  19.2.3 AC and DC Hipot  495
  19.2.4 Impulse (Surge)  497
  19.2.5 Strand-to-Strand  498
  19.2.6 Power Factor Tip-Up  498
  19.2.7 Partial Discharge  498
  19.2.8 Semiconductive Coating Test  499
  19.2.9 Wedge Tap  499
  19.2.10 Endwinding Bump  500

19.3 Factory and On-Site Tests for Rotor Windings  501
  19.3.1 Tests Applicable to All Insulated Windings  501
  19.3.2 Round Rotor Synchronous Machine Windings  502
  19.3.3 Salient Pole Synchronous Machine Windings  503
  19.3.4 Wound Induction Rotor Windings  504
  19.3.5 Squirrel Cage Rotor Windings  504

19.4 Core Insulation Factory and On-Site Tests  505
  19.4.1 Core Tightness  505
  19.4.2 Rated Flux  505
  19.4.3 Low Flux (El-CID)  506

References  506
20.1 Maintenance and Inspection Options 509
   20.1.1 Breakdown or Corrective Maintenance 510
   20.1.2 Time-Based or Preventative Maintenance 510
   20.1.3 Condition-Based or Predictive Maintenance 512
   20.1.4 Inspections 513

20.2 Maintenance Strategies for Various Machine Types and Applications 515
   20.2.1 Turbogenerators 516
   20.2.2 Salient Pole Generators and Motors 519
   20.2.3 Squirrel Cage and Wound-Rotor Induction Motors 521
   Reference 525

APPENDIX A INSULATION MATERIAL TABLES 527

APPENDIX B INSULATION SYSTEM TABLES 553

INDEX 629
This edition was updated by two of us, Greg Stone and Ian Culbert. Given the developments in rotating machine insulation in the past decade, readers will see expanded information on the effect of drives on insulation, the addition of a number of relatively new failure mechanisms, and new diagnostic tests. Many more photos of deteriorated insulation systems have been added in this edition. Many more references have been added, and recent changes in IEEE and IEC standards have been incorporated. We have also added descriptions of the insulation systems used by Chinese and Indian machine manufacturers. The information on Chinese systems came from Mr. Yamin Bai of North China EPRI. Mr. Bai and his colleagues were also responsible for the Chinese version of the first edition of this book. New appendices were added, which give detailed information on the insulation systems used by many manufacturers, as well as insulation material properties. These tables first appeared in a US Electric Power Research Institute (EPRI) document that is long out of print. However, given the number of machines still using these systems and materials, we thought it will be useful to include the information here.

We again would like to thank our spouses, Judy and Anne, and also our employer, Iris Power L.P. We are also grateful to Ms. Resi Zarb for help in organizing and editing the second edition. Finally, we thank the readers of the first edition who took time to point out errors and omissions in the first edition.

Greg Stone and Ian Culbert
Since electrical motors and generators were invented, a vast range of electrical machine types have been created. In many cases, different companies called the same type of machine or the same component by completely different names. Therefore, to avoid confusion, before a detailed description of motor and generator insulation systems can be given, it is prudent to identify and describe the types of electrical machines that are discussed in this book. The main components in a machine, as well as the winding subcomponents, are identified and their purposes described.

Although this book concentrates on machines rated at 1 kW or more, much of the information on insulation system design, failure, and testing can be applied to smaller machines, linear motors, servomotors, etc. However, these latter machine types will not be discussed explicitly.

1.1 TYPES OF ROTATING MACHINES

Electrical machines rated at about 1 HP or 1 kW and above are classified into two broad categories: (i) motors, which convert electrical energy into mechanical energy (usually rotating torque) and (ii) generators (also called alternators), which convert mechanical energy into electrical energy. In addition, there is another machine called a synchronous condenser that is a specialized generator/motor generating reactive power. Consult any general book on electrical machines for a more extensive description of machines and how they work [1,2]. An excellent book that focuses on all aspects of turbogenerators has been written by Klemmner and Kerszenbaum [3].

Motors or generators can be either AC or DC, that is, they can use/produce alternating current or direct current. In a motor, the DC machine has the advantage that its output rotational speed can be easily changed. Thus, DC motors and generators were widely used in industry in the past. However, with variable-speed motors now easily made by combining an AC motor with an electronic “inverter-fed drive” (IFD), DC motors in the hundreds of kilowatt range and above are becoming less common.

Machines are also classified according to the type of cooling used. They can be directly or indirectly cooled, using air, hydrogen, and/or water as a cooling medium.
This book concentrates on AC induction and synchronous motors, as well as synchronous and induction generators. Other types of machines exist; however, these motors and generators constitute the vast majority of electrical machines rated more than 1 kW presently used around the world.

1.1.1 AC Motors

Nearly all AC motors have a single-phase (for motors less than about 1 kW) or three-phase stator winding through which the input current flows. For AC motors, the stator is also called the armature. AC motors are usually classified according to the type of rotor winding. The rotor winding is also known as a field winding in synchronous machines. A discussion of each type of AC motor follows.

Squirrel Cage Induction (SCI) Motor The SCI motor (Figure 1.1) is by far the most common type of motor made, with millions manufactured each year. The rotor produces a magnetic field by transformer-like AC induction from the stator (armature) winding. The squirrel cage induction motor (Figure 1.1) can range in size from a fraction of a horsepower (<1 kW) to many tens of thousands of horsepower (>60 MW). The predominance of the SCI motor is attributed to the simplicity and ruggedness of the rotor. SCI rotors normally do not use any electrical insulation. In an SCI motor, the speed of the rotor is usually 1% or so slower than the “synchronous” speed of the rotating magnetic field in the air gap created by the stator winding. Thus, the rotor speed “slips” behind the speed of the air gap magnetic flux [1, 2]. The SCI motor is used for almost every conceivable application, including fluid pumping, fans, conveyor systems, grinding, mixing, gas compression, and power tool operation.

Wound Rotor Induction Motor The rotor is wound with insulated wire and the leads are brought off the rotor via slip rings. In operation, a current is induced into the rotor from the stator, just as for an SCI motor. However, in the wound rotor machine, it is possible to limit the current in the rotor winding by means of an external resistance or slip-energy recovery system. This permits some control of the rotor speed. Wound rotor induction motors are relatively rare because of the extra maintenance required for the slip rings. IFDs with SCI motors now tend to be preferred for variable-speed applications as they are often a more reliable, cheaper alternative.

Synchronous Motor This motor has a direct current flowing through the rotor (field) winding. The current creates a DC magnetic field, which interacts with the rotating magnetic field from the stator, causing the rotor to spin. The speed of the rotor is exactly related to the frequency of the AC current supplied to the stator winding (50 or 60 Hz). There is no “slip.” The speed of the rotor depends on the number of rotor pole pairs (a pole pair contains one north pole and one south pole) times the AC frequency. There are two main ways of obtaining a DC current in the rotor. The oldest method, is to feed current onto the rotor by means of two slip rings (one positive, one negative). Alternatively, the “brushless exciter” method, by most manufacturers, uses a DC winding mounted on the stator to induce a current in an auxiliary three-phase
winding mounted on the rotor to generate AC current, which is rectified (by “rotating” diodes) to DC. Synchronous motors require a small “pony” motor to run the rotor up to near synchronous speed. Alternatively, an SCI type of winding on the rotor can be used to drive the motor up to speed, before DC current is permitted to flow in the main rotor winding. This winding is referred to as an *amortisseur* or *damper winding*. Because of the more complicated rotor and additional components, synchronous motors tend to be restricted to very large motors today (>10 MW) or very slow speed motors. The advantage of a synchronous motor is that it usually requires less “inrush” current on startup in comparison to an SCI motor, and the speed is more constant. In addition, the operating energy costs are lower as, by adjusting the rotor DC current, one can improve the power factor of the motor, reducing the need for reactive power and the associated AC supply current. Refer to Section 1.1.2 for further subdivision of the types of synchronous motor rotors. Two-pole synchronous motors use round rotors, as described in Section 1.1.2.
1.1.2 Synchronous Generators

Although induction generators do exist (Section 1.1.3), particularly in wind turbine generators, they are relatively rare compared to synchronous generators. Virtually all generators used by electrical utilities are of the synchronous type. In synchronous generators, DC current flows through the rotor (field) winding, which creates a magnetic field from the rotor. At the same time, the rotor is spun by a steam turbine (using fossil or nuclear fuel), gas turbine, diesel engine, or hydroelectric turbine. The spinning DC field from the rotor induces current to flow in the stator (armature) winding. As for motors, the following types of synchronous generators are determined by the design of the rotor, which is primarily a function of the speed of the driving turbine.

Round Rotor Generators Also known as cylindrical rotor machines, round rotors (Figure 1.2) are most common in high speed machines, that is, machines in which the rotor revolves at about 1000 rpm or more. Where the electrical system operates at 60 Hz, the rotor speed is usually either 1800 or 3600 rpm. The relatively smooth surface of the rotor reduces “windage” losses, that is, the energy lost to moving the air (or other gas) around in the air gap between the rotor and the stator—the fan effect. This loss can be substantial at high speeds in the presence of protuberances from the rotor surface, but these losses can be substantially reduced in large generators with pressurized hydrogen cooling. The smooth cylindrical shape also lends itself to a more robust structure under the high centrifugal forces that occur in high speed machines. Round rotor generators, sometimes called “turbogenerators,” are usually driven by steam turbines or gas turbines (jet engines). Turbogenerators using round rotors have been made up to 2000 MVA (1000 MW is a typical load for a city of 500,000 people in an industrialized country). Such a machine may be 10 m in length and about 5 m in diameter, with a rotor on the order of 1.5 m in diameter. Such large turbogenerators almost always have a horizontally mounted rotor and are hydrogen-cooled (see Section 1.1.5).

Salient Pole Generators Salient pole generator rotors (Figure 1.3) usually have individual magnetic field pole windings that are mounted on solid or laminated magnetic steel poles that either are an integral part of or are mounted on the rotor shaft.

Figure 1.2 Photograph of a round rotor. The retaining rings are at each end of the rotor body.
In slower speed generators, the pole/winding assemblies are mounted on a rim that is fastened to the rotor shaft by a “spider”—a set of spokes. As the magnetic field poles protrude from the rim with spaces between the poles, the salient pole rotor creates considerable air turbulence in the air gap between the rotor and the stator as the rotor rotates, resulting in a relatively high windage loss. However, as this type of rotor is much less expensive to manufacture than a round rotor type, ratings can reach 50 MVA with rotational speeds up to 1800 rpm. Salient pole machines typically are used with hydraulic (hydro) turbines, which have a relatively low rpm (the higher is the penstock, i.e., the larger is the fall of the water, the faster will be the speed) and with steam or gas turbines where a speed reducing gearbox is used to match the turbine and generator speeds. To generate 50- or 60-Hz current in the stator, a large number of field poles are needed (recall that the generated AC frequency is the number of pole pairs times the rotor speed in revolutions per second). Fifty pole pairs are not uncommon on a hydrogenerator, compared to one or two pole pairs on a turbo-generator. Such a large number of pole pairs require a large rotor diameter in order to mount all the poles. Hydrogenerators are now being made up to about 1000 MVA in China. The rotor in a large hydrogenerator is almost always vertically mounted, and may be more than 15 m in diameter, but there are some horizontal applications for use with bulb hydraulic turbines for low head high flow application with ratings up to about 10 MVA.

**Pump/Storage Motor Generator**  This is a special type of salient pole machine. It is used to pump water into an upper reservoir during times of low electricity demand. Then, at times of high demand for electricity, the water is allowed to flow from the upper reservoir to the lower reservoir, where the machine operates in reverse as a generator. The reversal of the machine from the pump to generate mode is commonly accomplished by changing the connections on the machine’s stator winding to reverse rotor direction. In a few cases, the pitch of the hydraulic turbine blades is changed. In the pump motor mode, the rotor can come up to speed using an SCI-type winding on the rotor (referred to as an amortisseur or damper winding), resulting in a large inrush current, or using a “pony” motor. If the former is used, the machine is often
energized by an IFD that gradually increases the rotor speed by slowly increasing the AC frequency to the stator. As the speed is typically less than a few hundred rpm, the rotor is usually of the salient pole type. However, high speed pump storage generators may have a round rotor construction [4]. Pump storage units have been made up to 500 MVA.

### 1.1.3 Induction Generators

The induction generator differs from the synchronous generator in that the excitation is derived from the magnetizing current in the stator winding. Therefore, this type of generator must be connected to an existing power source to determine its operating voltage and frequency and to provide it with magnetizing volt-amperes. As this is an induction machine, it has to be driven at a super-synchronous speed to achieve a generating mode. This type of generator comes in two forms that can have the same type of stator winding, but which differ in rotor winding construction. One of these has a squirrel-cage rotor and the other has a three-phase wound rotor connected to slip rings for control of rotor currents and therefore performance. The squirrel cage type is used in some small hydrogenerator and wind turbine generator applications with ratings up to a few MVA. The wound rotor type has, until recently, been used extensively in wind turbine generator applications. When used with wind turbines, the wound rotor induction generator is configured with rectifier/inverters both in the rotor circuit and at the stator winding terminals as indicated in Figure 1.4. In this configuration, commonly known as the doubly fed rotor concept (for use in doubly fed induction generators or DFIGs), the output converter rectifies the generator output power and inverts it to match the connected power system voltage and frequency. The converter in the rotor circuit recovers the slip energy from the rotor to feed it back into the power supply and controls the rotor current. This slip recovery significantly improves the efficiency of the generator. Such generators are connected to the low speed wind turbine via a speed-increasing gearbox and have ratings up to around 3 MVA. The DFIG has also been used in large variable-speed pump storage generators.

![Figure 1.4 Wound rotor induction generator doubly fed configuration](5)
1.1.4 Permanent Magnet (PM) Synchronous Motors and Generators

There has been significant recent development on permanent magnet (PM) machines [6]. The major efforts in this regard were to employ PM materials such as neodymium iron boron (NdFeB) for the rotor field poles that produce much higher flux densities than conventional permanent magnet rotors. Standard induction motors are not particularly well suited for low speed operation, as their efficiency drops with the reduction in speed. They also may be unable to deliver sufficient smooth torque at low speeds. The use of a gearbox is the traditional mechanical solution for this challenge. However, the gearbox is a complicated piece of machinery that takes up space, reduces efficiency, and needs both maintenance and significant quantities of oil. Elimination of the gearbox via the use of these new PM motor/drive configurations saves space and installation costs, energy, and maintenance, and provides more flexibility in production line and facility design. The PM AC motor also delivers high torque at low speed—a benefit traditionally associated with DC motors—and, in doing so, also eliminates the necessity of a DC motor and the associated brush replacement and maintenance. There are many applications for this type of motor in conjunction with inverters, which include electric car, steel rolling mill, and paper machine drives. In addition, larger versions are used in other industrial and marine applications that require precise speed and torque control.

The PM synchronous generator has basically the same advantages and construction as the motor. It is now being widely used in wind turbine generator applications because its construction is much simpler and efficiency much better than a wound rotor induction motor.

1.1.5 Classification by Cooling

Another important means of classifying machines is by the type of cooling medium they use: water, air, and/or hydrogen gas. One of the main heat sources in electrical machines is the DC or AC current flowing through the stator and rotor windings. These are usually called $I^2R$ losses, as the heat generated is proportional to the current squared times the resistance of the conductors (almost always copper in stator windings, but sometimes aluminum in SCI rotors). There are other sources of heat: magnetic core losses, windage losses, and eddy current losses. All these losses cause the temperature of the windings to rise. Unless this heat is removed, the winding insulation deteriorates because of the high temperature and the machine fails because of a short circuit. References 7 and 8 are general rotating machine standards that discuss the types of cooling in use.

**Indirect Air Cooling** Motors and modern generators rated less than about 100 MVA are almost always cooled by air flowing over the rotor and stator. This is called *indirect cooling* as the winding conductors are not directly in contact with the cooling air because of the presence of electrical insulation on the windings. The air itself may be continuously drawn in from the environment, that is, not recirculated. Such machines are termed open-ventilated machines, although there may be some
effort to prevent particulates (sand, coal dust, pollution, etc.) and/or moisture from entering the machine using filtering and indirect paths for drawing in the air. These open-ventilated machines are referred to as weather-protected (WP) machines.

A second means of obtaining cool air is to totally enclose the machine and recirculate air via a heat exchanger. This is often needed for motors and generators that are exposed to the elements. The recirculated air is most often cooled by an air-to-water heat exchanger in large machines, or cooled by the outside air via radiating metal fins in small motors or a tube-type cooler in large ones. Either a separate blower motor or a fan mounted on the motor shaft circulates the air.

Although old, small generators may be open-ventilated, the vast majority of hydrogenerators have recirculated air flowing through the machine with the air often cooled by air-to-water heat exchangers. For turbogenerators rated up to a few hundred megawatts, recirculated air is now the most common form of cooling [9,10].

**Indirect Hydrogen Cooling** Almost all large turbogenerators use recirculated hydrogen as the cooling gas. This is because the smaller and lighter hydrogen molecule results in a lower windage loss, and hydrogen has better heat transfer than air. It is then cost effective to use hydrogen in spite of the extra expense involved, because of the small percentage gain in efficiency. The dividing line for when to use hydrogen cooling is constantly changing. There is now a definite trend to reserve hydrogen cooling for machines rated more than 300 MVA, whereas in the past, hydrogen cooling was sometimes used on steam and gas turbine generators as small as 50 MVA [9,10].

**Directly Cooled Windings** Generators are referred to as being indirectly or conventionally cooled if the windings are cooled by flowing air or hydrogen over the surface of the windings and through the core, where the heat created within the conductors must first pass through the insulation. Large generator stator and rotor windings are frequently “directly” cooled. In directly cooled windings, water or hydrogen is passed internally through the conductors or through the ducts immediately adjacent to the conductors. Direct water-cooled stator windings pass very pure water through hollow copper conductor strands, or through stainless steel tubes immediately adjacent to the copper conductors. As the cooling medium is directly in contact with the conductors, this very efficiently removes the heat developed by $I^2R$ losses. With indirectly cooled machines, the heat from the $I^2R$ losses must first be transmitted through the electrical insulation covering the conductors, which forms a significant thermal barrier. Although not quite as effective in removing heat, in direct hydrogen-cooled windings, the hydrogen is allowed to flow within hollow copper tubes or stainless steel tubes, just as in the water-cooled design. In both cases, special provisions must be taken to ensure that the direct water or hydrogen cooling does not introduce electrical insulation problems (see Sections 1.4.3 and 8.16). Recently, some Chinese manufacturers have been experimenting with direct cooling of hydrogenerator stators using a Freon type of liquid [11]. The advantage of using this type of coolant instead of water is that if leaks develop, the resulting gas is an excellent insulator, unlike water. Water leaks are an important failure mechanism in direct water-cooled windings (see Section 8.16).