Contents

Preface xi
About the authors xv

1 Condition monitoring and fault diagnosis of induction motors 1
1.1 Introduction 1
References 7

2 Theory of line-start and inverter-fed induction motors 11
2.1 Introduction 11
2.2 Induction motor structure 12
2.3 Line-start induction motor: linear and single harmonic model of a healthy motor 18
2.3.1 Flux equation 22
2.3.2 Electromagnetic torque equation 28
2.4 Inverter-fed induction motors 40
2.4.1 Constant voltage per frequency strategy (CV/F) 40
2.4.2 Space vector modulation 44
2.4.3 Analysis of motor behavior in open-loop CV/F mode 48
2.4.4 Reference frame theory of induction motors 53
2.4.5 Field-oriented control of induction motors 56
2.4.6 Direct torque control of induction motors 59
References 67

3 Induction motor faults: basics, developments and laboratory-scale implementation 71
3.1 Introduction 71
3.2 Broken bar/end-ring fault in induction motors 74
3.2.1 Time-domain behavior of induction motors with broken bar/end-ring faults 84
3.3 Eccentric/misaligned and bearing faults in induction motors 87
3.3.1 Misalignment inclined rotor 92
3.3.2 Theoretical analysis of eccentric induction motor 94
3.3.3 Bearing faults in induction motor 104
3.4 Short-circuit fault in induction motors 105
3.5 Laboratory-sale implementation of induction motor faults 118
3.5.1 Three-phase induction motor 119
3.5.2 Autotransformer 121

3.5.3 Drive 121
3.5.4 Motor load 125
3.5.5 Implementation of broken bar fault 130
3.5.6 Implementation of eccentricity fault 138
3.5.7 Implementation of interturn short-circuit fault 140
3.5.8 Signals and sensors 142
3.5.9 Data acquisition 153
3.5.10 Overall scheme of the conventional cabled diagnosis system implementation 158
3.5.11 Wireless condition monitoring setup 160
References 163

4 Magneto-motive force waves in healthy three-phase induction motors 169
4.1 Current sheet concept 169
4.2 Winding function concept 176
4.2.1 Concentrated full-pitch coil MMF 178
4.2.2 Distributed full-pitch phase winding 182
4.2.3 Pulsating MMF 184
4.2.4 Three-phase full-pitch (single-layer) winding 188
4.2.5 Three-phase shorted-pitch coil (double-layer) winding 191
4.3 Rotating MMF wave—analytical approach 197
4.4 Fractional slot winding 200
4.5 Wound rotor MMF space harmonics 202
4.6 Cage rotor MMF space harmonics 202
References 207

5 Multiple-coupled circuit model of induction motors 209
5.1 Model description 210
5.1.1 Electrical subsystem equations 210
5.1.2 Mechanical subsystem equations 211
5.1.3 Model parameters 212
5.2 Skewing of rotor bars 219
5.3 Linear rise of MMF across slot 221
5.4 Solution of mathematical model 226
5.4.1 Stator phase windings connection 228
5.5 Modeling inductions motors with broken rotor bar(s)/end-ring(s) 236
5.6 Modeling induction motors with air-gap eccentricity 239
5.6.1 Inductance calculation 239
5.6.2 Static eccentricity 240
5.6.3 Dynamic eccentricity 243
5.6.4 Numerical model results 247
5.7 Modeling induction motors with interturn short circuit in stator winding 249
5.7.1 Numerical model results 252
References 254

6 Finite element implementation of induction motors in healthy and faulty conditions 257
6.1 Introduction 257
6.2 Electromagnetic field equations 259
6.3 Magnetic vector potential, magnetic scalar potential, current vector potential 262
6.4 $\vec{T}$-Φ Formulation 264
6.5 $\vec{A}$–V Formulation 265
6.6 Coupled magneto-static and eddy current-field problem 266
6.7 Transient-with-motion formulation 268
6.8 Finite element method 271
6.8.1 Material modeling 272
6.8.2 Magnetic loss calculation 276
6.8.3 Mesh generation 278
6.8.4 Set-up system of equations 280
6.9 Induction motor examples 286
6.9.1 Healthy motor operation 290
6.9.2 Broken bar motor operation 297
6.9.3 Eccentric motor operation 300
6.9.4 Short-circuited motor operation 305
References 320

7 Signal-processing techniques utilized in fault diagnosis procedures 325
7.1 Introduction 325
7.2 Fourier transform 327
7.2.1 Recursive FFT algorithm in MATLAB 331
7.2.2 Iterative FFT algorithm in MATLAB 331
7.2.3 Example 331
7.3 Short-time Fourier transform 338
7.4 Multiresolution analysis 339
7.5 Wavelet transform 343
7.5.1 Resolution in time-frequency map 343
7.6 Inverse wavelet transform 346
7.7 Discrete of wavelet transform 346
7.8 Hilbert–Huang transform 353
References 366

8 Diagnosis of broken bars fault in induction motors 367
8.1 Introduction 367
8.2 Motor current signature analysis (MCSA) 369
8.3 Pendulous oscillation 374
8.4 Virtual current technique 375
8.5 Air gap flux density 376
8.6 Speed fluctuations 377
8.7 Gyration radius 379

8.8 Time-domain analysis of nonadjacent broken bars fault 381
8.9 Spectrum of motor current 385
8.10 Effect of closed loops on faulty motor signals 393
8.11 Analytical analysis of the effect of speed variation on sideband components 398
8.12 Motor power spectrum 401
8.13 Additional frequency-domain fault indices 404
8.14 Motor transient operation 405
8.15 Application of wavelet transform to the diagnosis of broken bars fault 407
8.16 Application of Hilbert–Huang transform to the diagnosis of broken bars fault 409
8.17 Loss characterization of induction motors with broken bars fault 416
8.18 Conclusion 419
References 420

9 Diagnosis of eccentricity fault in induction motors 431
9.1 Introduction 431
9.2 Effect of mixed eccentricity fault on time-domain variation of speed and torque signals 432
9.3 Normalized splitting severity factor 433
9.4 Ratio of area enclosed by stator current in two consecutive cycles to average area of two stator current cycles 435
9.5 High-frequency components of stator current 438
9.6 Low-frequency components of stator current 442
9.7 Joint analysis of low- and high-frequency patterns of stator current 448
9.8 Low-frequency components of voltage space vector and high-frequency components of current space vector 449
9.9 The ratio of sum of right (high) and left (low) sideband components to no-load current 451
9.10 Negative sequence current 457
9.11 Harmonic components of instantaneous power 464
9.12 Loss characterization of induction motors with eccentricity fault 467
References 467

10 Diagnosis of interturn short-circuit fault in induction motors 473
10.1 Motor current signature analysis 473
10.2 Healthy cage rotor induction motor 474
10.2.1 MMF space harmonics 474
10.2.2 Slot permeance harmonics 478
10.2.3 Saturation permeance harmonics 480
10.3 MCSA of an induction motor with interturn fault 486

10.4 A review of interturn short-circuit fault detection techniques for induction motors 497
10.5 MCSA of wound-rotor induction motor 502
References 505

Index **509**