THIRD EDITION

PERMANENT MAGNET MOTOR TECHNOLOGY

DESIGN AND APPLICATIONS

JACEK F. GIERAS

Hamilton Sundstrand Aerospace, Rockford, Illinois, U.S.A.
University of Technology and Life Sciences, Bydgoszcz, Poland

CRC Press
Taylor & Francis Group
Boca Raton London New York

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

Contents

Preface to the Third Edition XV

1 Introduction 1
1.1 Permanent magnet versus electromagnetic excitation 1
1.2 Permanent magnet motor drives 2
1.2.1 d.c. commutator motor drives 4
1.2.2 Synchronous motor drives 6
1.2.3 PM d.c. brushless motor drives 9
1.2.4 Stepping motor drives 9
1.3 Toward increasing the motor efficiency 10
1.4 Classification of permanent magnet electric motors 13
1.5 Trends in permanent magnet motors and drives industry 15
1.6 Applications of permanent magnet motors 18
1.7 Mechatronics 26
1.8 Fundamentals of mechanics of machines 27
1.8.1 Torque and power 27
1.8.2 Simple gear trains 28
1.8.3 Efficiency of a gear train 28
1.8.4 Equivalent moment of inertia 29
1.8.5 Rotor dynamics 29
1.8.6 Mechanical characteristics of machines 31
1.9 Torque balance equation 31
1.10 Evaluation of cost of a permanent magnet motor 31
Numerical examples 33

2 Permanent Magnet Materials and Circuits 45
2.1 Demagnetization curve and magnetic parameters 45
2.2 Early history of permanent magnets 51
2.3 Properties of permanent magnets 51
2.3.1 Alnico 52
2.3.2 Ferrites 53

2.3.3 Rare-earth permanent magnets 54
2.3.4 Corrosion and chemical reactivity 58
2.3.5 Market issues 59
2.4 Approximation of demagnetization curve and recoil line 60
2.5 Operating diagram 61
2.5.1 Construction of the operating diagram 61
2.5.2 Operating point for magnetization without armature 64
2.5.3 Operating point for magnetization with armature ... 67
2.5.4 Magnets with different demagnetization curves 68
2.6 Permeances for main and leakage fluxes 69
2.6.1 Permeance evaluation by flux plotting 69
2.6.2 Permeance evaluation by dividing the magnetic field into simple solids 69
2.6.3 Calculation of leakage permeances for prisms and cylinders located in an open space 77
2.7 Calculation of magnetic circuits with permanent magnets 77
2.8 Mallinson–Halbach array and Halbach cylinder 79
Numerical examples 80

3 Finite Element Analysis 89
3.1 Gradient, divergence and curl 89
3.2 Biot–Savart, Faraday's, and Gauss's laws 90
3.2.1 Biot–Savart law 91
3.2.2 Faraday's law 92
3.2.3 Gauss's law 92
3.3 Gauss's theorem 92
3.4 Stokes' theorem 93
3.5 Maxwell's equations 93
3.5.1 First Maxwell's equation 93
3.5.2 Second Maxwell's equation 94
3.5.3 Third Maxwell's equation 95
3.5.4 Fourth Maxwell's equation 95
3.6 Magnetic vector potential 95
3.7 Energy functionals 96
3.8 Finite element formulation 98
3.9 Boundary conditions 102
3.9.1 Dirichlet boundary conditions 102
3.9.2 Neumann boundary conditions 102
3.9.3 Interconnection boundary conditions 103
3.10 Mesh generation 103
3.11 Forces and torques in an electromagnetic field 104
3.11.1 Maxwell stress tensor 104
3.11.2 Co-energy method 105

3.11.3 Lorentz force theorem 106
3.12 Inductances 106
3.12.1 Definitions 106
3.12.2 Dynamic inductances 106
3.12.3 Steady-state inductance 107
3.12.4 Reactances of synchronous machines 108
3.12.5 Synchronous reactances 108
3.12.6 Armature reaction reactances 109
3.12.7 Leakage reactance 110
3.13 Interactive FEM programs 110
3.13.1 Pre-processor 111
3.13.2 Solver 111
3.13.3 Post-processor 112
Numerical examples 112

4 Permanent Magnet d.c. Commutator Motors 119
4.1 Construction 119
4.1.1 Slotted-rotor PM d.c. motors 123
4.1.2 Slotless-rotor PM motors 123
4.1.3 Moving-coil cylindrical motors 124
4.1.4 Disk motors 129
4.2 Fundamental equations 129
4.2.1 Terminal voltage 129
4.2.2 Armature winding EMF 130
4.2.3 Electromagnetic (developed) torque 131
4.2.4 Electromagnetic power 131
4.2.5 Rotor and commutator linear speed 131
4.2.6 Input and output power 132
4.2.7 Losses 132
4.2.8 Pole pitch 134
4.2.9 Air gap magnetic flux density 134
4.2.10 Armature line current density 134
4.2.11 Armature winding current density 134
4.2.12 Armature winding resistance 135
4.2.13 Armature winding inductance 135
4.2.14 Mechanical time constant 136
4.3 Sizing procedure 136
4.4 Armature reaction 139
4.5 Commutation 144
4.6 Starting 147
4.7 Speed control 148
4.7.1 Armature terminal-voltage speed control 149
4.7.2 Armature rheostat speed control 150
4.7.3 Shunt-field control 150
4.7.4 Chopper variable-voltage speed control 150

4.8 Servo motors 151
4.9 Magnetic circuit 152
4.9.1 MMF per pole 153
4.9.2 Air gap permeance 154
4.9.3 Leakage permeances 154
4.10 Applications 157
4.10.1 Toys 157
4.10.2 Car starters 157
4.10.3 Underwater vehicles 158
4.10.4 Linear actuators 160
4.10.5 Wheelchairs 161
4.10.6 Mars robotic vehicles 163
Numerical examples 164

5 Permanent Magnet Synchronous Motors 171
5.1 Construction 171
5.2 Fundamental relationships 173
5.2.1 Speed 173
5.2.2 Air gap magnetic flux density 173
5.2.3 Voltage induced (EMF) 174
5.2.4 Armature line current density and current density 175
5.2.5 Electromagnetic power 175
5.2.6 Synchronous reactance 176
5.2.7 Subtransient synchronous reactance 176
5.2.8 Transient synchronous reactance 176
5.2.9 Electromagnetic (developed) torque 177
5.2.10 Form factor of the excitation field 178
5.2.11 Form factors of the armature reaction 178
5.2.12 Reaction factor 179
5.2.13 Equivalent field MMF 179
5.2.14 Armature reaction reactance 180
5.3 Phasor diagram 180
5.4 Characteristics 185
5.5 Starting 187
5.5.1 Asynchronous starting 187
5.5.2 Starting by means of an auxiliary motor 189
5.5.3 Frequency-change starting 189
5.6 Reactances 189
5.6.1 Analytical approach 190
5.6.2 FEM 194
5.6.3 Experimental method 194
5.7 Rotor configurations 195
5.7.1 Merrill's rotor 195
5.7.2 Interior-type PM motors 196
5.7.3 Surface PM motors 196

5.7.4 Inset-type PM rotor 196
5.7.5 Buried PM motors 196
5.8 Comparison between synchronous and induction motors 198
5.9 Sizing procedure and main dimensions 200
5.10 Performance calculation 202
5.11 Dynamic model of a PM motor 203
5.12 Noise and vibration of electromagnetic origin 205
5.12.1 Radial forces 205
5.12.2 Deformation of the stator core 209
5.12.3 Natural frequencies of the stator 211
5.13 Applications 211
5.13.1 Open loop control 211
5.13.2 High-performance closed-loop control 212
5.13.3 High-performance adaptive fuzzy control 213
Numerical examples 214

6 d.c. Brushless Motors 227
6.1 Fundamental equations 227
6.1.1 Terminal voltage 227
6.1.2 Instantaneous current 228
6.1.3 EMF 228
6.1.4 Inverter a.c. output voltage 229
6.1.5 d.c. bus voltage of a controlled rectifier 229
6.1.6 Electromagnetic torque 230
6.1.7 Electromagnetic torque of a synchronous motor 230
6.1.8 Electromagnetic torque of a PM brushless d.c. motor 230
6.1.9 Linear and rotational speed of brushless motors 230
6.1.10 Concentrated-coil armature winding 231
6.2 Commutation of PM brushless motors 231
6.2.1 Unipolar-driven PM brushless motor 231
6.2.2 Bipolar-driven PM brushless motor, two phases on 233
6.2.3 Bipolar-driven PM brushless motor, three phases on 235
6.3 EMF and torque of PM brushless motors 235
6.3.1 Synchronous motor 235
6.3.2 PM d.c. brushless motors 239
6.4 Torque–speed characteristics 242
6.5 Winding losses 243
6.6 Torque ripple 244
6.6.1 Sources of torque pulsations 246
6.6.2 Numerical methods of instantaneous torque calculation 246
6.6.3 Analytical methods of instantaneous torque calculation 246

6.6.4 Minimization of torque ripple 257
6.7 Rotor position sensing of d.c. brushless motors 260
6.7.1 Hall sensors 260
6.7.2 Encoders 262
6.7.3 Resolvers 265
6.8 Sensorless motors 265
6.9 Motion control of PM brushless motors 267
6.9.1 Converter-fed motors 267
6.9.2 Servo amplifiers 269
6.9.3 Microcontrollers 269
6.9.4 DSP control 272
6.10 Universal brushless motor electromechanical drives 273
6.11 Smart motors 278
6.12 Applications 280
6.12.1 Electric and hybrid electric vehicles 280
6.12.2 Variable-speed cooling fans 283
6.12.3 Computer hard disk drives 284
6.12.4 CD players 285
6.12.5 Factory automation 290
6.12.6 X–Y tables 291
6.12.7 Space mission tools 292
Numerical examples 292

7 Axial Flux Motors 305
7.1 Force and torque 305
7.2 Performance 307
7.3 Double-sided motor with internal PM disk rotor 307
7.3.1 Stator core 308
7.3.2 Main dimensions 310
7.4 Double-sided motor with one stator 311
7.5 Single-sided motors 316
7.6 Ironless double-sided motors 316
7.7 Multidisk motors 319
7.8 Applications 322
7.8.1 Electric vehicles 322
7.8.2 Gearless elevator propulsion system 326
7.8.3 Propulsion of unmanned submarines 326
7.8.4 Counterrotating rotor ship propulsion system 326
Numerical examples 327

8 High Power Density Brushless Motors 341
8.1 Design considerations 341
8.2 Requirements 343
8.3 Multiphase motors 344
8.4 Fault-tolerant PM brushless machines 346

8.5 Surface PM versus salient-pole rotor 347
8.6 Electromagnetic effects 348
8.6.1 Armature reaction 348
8.6.2 Damper 349
8.6.3 Winding losses in large motors 351
8.6.4 Minimization of losses 353
8.7 Cooling 353
8.8 Construction of motors with cylindrical rotors 355
8.8.1 Motor with reduced armature reaction 355
8.8.2 Motors with modular stators 356
8.8.3 Study of large PM motors with different rotor configurations 360
8.9 Construction of motors with disk rotors 364
8.10 Transverse flux motors 364
8.10.1 Principle of operation 364
8.10.2 EMF and electromagnetic torque 367
8.10.3 Armature winding resistance 369
8.10.4 Armature reaction and leakage reactance 369
8.10.5 Magnetic circuit 371
8.10.6 Advantages and disadvantages 372
8.11 Applications 373
8.11.1 Ship propulsion 373
8.11.2 Submarine propulsion 376
8.11.3 Hybrid electric transit bus 378
8.11.4 Light rail system 380
Numerical examples 383

9 High Speed Motors 403
9.1 Why high speed motors? 403
9.2 Mechanical requirements 404
9.3 Construction of high speed PM brushless motors 406
9.4 Design of high speed PM brushless motors 411
9.5 Ultra high speed motors 413
9.6 Applications 415
9.6.1 High speed aerospace drives 415
9.6.2 High speed spindle drives 417
9.6.3 Flywheel energy storage 419
9.6.4 Dental handpieces 422
9.6.5 Sheep shearing handpieces 425
Numerical examples 427

10 Brushless Motors of Special Construction 437
10.1 Single-phase motors 437
10.1.1 Single-phase two-pole motors 437
10.1.2 Single-phase multi-pole motors 440
10.1.3 Single-phase cost-effective PM brushless motors 442
10.2 Actuators for automotive applications 444
10.3 Integrated starter-generator 446
10.4 Large diameter motors 448
10.5 Three-axis torque motor 449
10.6 Slotless motors 450
10.7 Tip driven fan motors 452
Numerical examples 452

11 Stepping Motors 457
11.1 Features of stepping motors 457
11.2 Fundamental equations 458
11.2.1 Step 458
11.2.2 Steady-state torque 458
11.2.3 Maximum synchronizing torque 459
11.2.4 Frequency of the rotor oscillations 459
11.3 PM stepping motors 459
11.4 Reluctance stepping motors 461
11.5 Hybrid stepping motors 463
11.5.1 Full stepping 464
11.5.2 Half stepping 465
11.5.3 Microstepping 466
11.5.4 Practical hybrid motor 467
11.5.5 Bipolar and unipolar motors 469
11.6 Motion control of stepping motors 470
11.7 PM stepping motors with rotor position transducers 471
11.8 Single-phase stepping motors 472
11.9 Voltage equations and electromagnetic torque 473
11.10 Characteristics 475
11.10.1 Torque–angle characteristics 475
11.10.2 Torque–current characteristics 475
11.10.3 Torque–frequency characteristics 476
11.11 Applications 477
Numerical examples 480

12 Micromotors 485
12.1 What is a micromotor? 485
12.2 Permanent magnet brushless micromotors 486
12.2.1 Cylindrical micromotors 486
12.2.2 Fabrication of magnetic micromotors with planar coils 491
12.2.3 Disk-type micromotors 492

12.3 Applications 495
12.3.1 Motorized catheters 495
12.3.2 Capsule endoscopy 496
Numerical examples 498

13 Optimization 505
13.1 Mathematical formulation of optimization problem 506
13.2 Nonlinear programming methods 507
13.2.1 Direct search methods 507
13.2.2 Stochastic methods 508
13.2.3 Gradient methods 509
13.2.4 Constrained optimization techniques 509
13.3 Population-based incremental learning 510
13.4 Response surface methodology 512
13.4.1 Response surface designs 512
13.4.2 Estimation of errors in response surface fitting 513
13.5 Modern approach to optimization of PM motors 513
13.5.1 PM d.c. commutator motors 514
13.5.2 PM synchronous motors 516
Numerical examples 517

14 Maintenance 523
14.1 Basic requirements for electric motors 523
14.2 Reliability 524
14.3 Failures of electric motors 528
14.4 Calculation of reliability of small PM brushless motors 531
14.5 Vibration and noise 533
14.5.1 Generation and radiation of sound 534
14.5.2 Mechanical model 537
14.5.3 Electromagnetic vibration and noise 537
14.5.4 Mechanical vibration and noise 538
14.5.5 Aerodynamic noise 539
14.5.6 d.c. commutator motors 539
14.5.7 PM synchronous motors 540
14.5.8 Reduction of noise 540
14.6 Condition monitoring 541
14.7 Protection 543
14.8 Electromagnetic and radio frequency interference 547
14.8.1 Brush motors 548
14.8.2 Electronically commutated brushless motors 550
14.9 Lubrication 552
14.9.1 Bearings 552
14.9.2 Lubrication of rolling bearings 553
14.9.3 Lubrication of porous metal bearings 554
Numerical examples 556

Appendix A Leakage Inductance of a.c. Stator Windings 559
A.1 Stator winding factor 559
A.2 Slot leakage permeance 560
A.3 End winding connection leakage permeance 562
A.4 Differential leakage permeance 563
A.5 Tooth-top leakage permeance 563
A.6 Leakage reactance per phase 564

Appendix B Losses in a.c. Motors 565
B.1 Armature winding losses 565
B.2 Armature core losses 567
B.3 Rotor core losses 568
B.4 Core loss FEM model 568
B.5 Losses in conductive retaining sleeves 569
B.6 Losses in permanent magnets of brushless motors 570
B.7 Rotational losses 571
B.8 Windage losses in high speed motors 572
B.9 Losses due to higher time harmonics 574

Symbols and Abbreviations 577

References 585

Index 601