

---

# Contents

## **1 Introduction**

|  |    |
|--|----|
| 1.1 General View .....                     | 1  |
| 1.2 The Electromagnetic Drive System ..... | 2  |
| 1.3 Drive Units .....                      | 3  |
| 1.3.1 Motors .....                         | 3  |
| 1.3.2 Electronic Circuits .....            | 8  |
| References .....                           | 11 |

## **2 Motors for Continuous Rotation**

|  |     |
|--|-----|
| 2.1 Motors with Commutator .....                                 | 13  |
| 2.1.1 Electrically Excited DC Motors .....                       | 13  |
| 2.1.2 Permanent Magnet DC Motors .....                           | 14  |
| 2.1.3 Commutator Series Motor (Universal Motor) .....            | 33  |
| 2.1.4 Contact System and Commutation .....                       | 51  |
| 2.1.5 Noise Behaviour .....                                      | 65  |
| 2.1.6 Radio Interference Suppression .....                       | 65  |
| 2.2 Brushless Permanent Magnet Motors .....                      | 66  |
| 2.2.1 Introduction .....   | 66  |
| 2.2.2 Design Features .....                                      | 72  |
| 2.2.3 Dynamic Model of the Brushless AC Motor .....              | 92  |
| 2.2.4 Electronic Suppression of Torque Ripples .....             | 99  |
| 2.2.5 Motor Characteristics .....                                | 104 |
| 2.2.6 Sensor Technology .....                                    | 105 |
| 2.2.7 Special Designs of Brushless Permanent Magnet Motors ..... | 111 |
| 2.3 Switched Reluctance Motor .....                              | 116 |
| 2.3.1 Magnetic Circuitry .....                                   | 116 |
| 2.3.2 Operation .....  | 117 |
| 2.3.3 Commutation .....  | 118 |
| 2.3.4 Control Strategies and Motor Performance .....             | 121 |
| 2.3.5 Sensorless Modes of Operation .....                        | 123 |
| 2.3.6 Characteristics .....                                      | 124 |

2.4 Rotating-Field Motors ..... 125  
 2.4.1 Asynchronous Motors ..... 125  
 2.4.2 Synchronous Motors ..... 144  
 References ..... 155

**3 Electromagnetic Stepping Drives**

3.1 Overview ..... 161  
 3.2 Classification of Stepping Motors ..... 164  
 3.2.1 Claw-Poled Stepping Motor ..... 164  
 3.2.2 Disk Rotor Stepping Motor ..... 166  
 3.2.3 Reluctance Stepping Motor ..... 167  
 3.2.4 Hybrid Stepping Motor ..... 168  
 3.3 Control of Stepping Motors ..... 170  
 3.4 Operating Behaviour of Stepping Motors ..... 179  
 3.4.1 Step Angle ..... 179  
 3.4.2 Torque ..... 181  
 3.4.3 Positioning Accuracy ..... 182  
 3.4.4 Step *vs* Time Characteristic ..... 183  
 3.4.5 Operating Characteristics ..... 185  
 3.4.6 Resonance Frequencies ..... 188  
 3.4.7 Micro Stepping ..... 188  
 3.4.8 Assigning Reference Position ..... 190  
 3.5 Motion Sequences ..... 191  
 3.5.1 Classified Motion Sequences ..... 191  
 3.5.2 Closer Examination of Dynamic Operation ..... 194  
 References ..... 203

**4 Drives with Limited Motion**

4.1 Electromagnets ..... 205  
 4.1.1 Electromagnets as Drive Sections ..... 205  
 4.1.2 Direct Current Magnets ..... 207  
 4.1.3 Alternating Current Magnets ..... 227  
 4.1.4 Polarized Electromagnets ..... 236  
 4.1.5 Project Planning of Electromagnets and Magnetic Drives ..... 240  
 4.1.6 Design of Magnetic Drives ..... 241  
 4.2 Electrodynamic Linear and Multi-Coordinate Drives ..... 250  
 4.2.1 Working Principle and Basic Structure ..... 251  
 4.2.2 Configurations of Electrodynamic Linear Motors ..... 255  
 4.2.3 Types of Construction of Integrated Electrodynamic  
 Multi-Coordinate Drives With Single-Mass Armatures  
 for  $xy$ -,  $x\phi$ -,  $xy\phi$ - and  $xy\phi z$ -Travel ..... 269  
 4.2.4 Behaviour of Electrodynamic Linear and Multi-Coordinate  
 Motors ..... 285  
 4.2.5 Control of Electrodynamic Linear  
 and Multi-Coordinate Motors ..... 288

4.2.6 Commercially Offered Systems . . . . . 298

4.3 Linear and Planar Hybrid Stepping Motors . . . . . 298

4.3.1 Linear Hybrid Stepping Motors . . . . . 298

4.3.2 Multi-Coordinate Hybrid Stepping Motors . . . . . 303

4.3.3 Dynamic Properties of Linear Hybrid Stepping Motors . . . . . 306

4.3.4 Principle of Microstepping . . . . . 309

4.3.5 Linear Hybrid Stepping Motors  
as Non-Linear Magnetic Drives . . . . . 310

References . . . . . 311

**5 Piezoelectric Drives**

5.1 Physical Effect . . . . . 317

5.2 Piezoelectric Components . . . . . 318

5.2.1 Piezoelectric Materials . . . . . 318

5.2.2 Piezoelectric Elements . . . . . 320

5.3 Piezoelectric Actuators . . . . . 322

5.3.1 Stack Translator (Stacked Design) . . . . . 322

5.3.2 Laminar Translators . . . . . 326

5.3.3 Bending Elements . . . . . 326

5.3.4 Tube Elements . . . . . 327

5.3.5 Displacement Amplification . . . . . 328

5.4 Piezoelectric Motors . . . . . 329

5.4.1 Inchworm and Walking Motors . . . . . 330

5.4.2 Ultrasonic Motors . . . . . 332

5.5 Driving Electronics . . . . . 338

5.5.1 Power Amplifier . . . . . 338

5.5.2 Inverse Control . . . . . 340

5.6 Implementation Examples . . . . . 341

5.6.1 Positioning System with Piezo Drives . . . . . 342

5.6.2 Clamping Elements for Inchworm Motors . . . . . 343

References . . . . . 345

**6 Open-Loop and Closed-Loop Control  
of Electric Fractional-Horsepower Motors**

6.1 Introduction . . . . . 347

6.2 Circuit Components and Pulse-Width Modulation . . . . . 348

6.2.1 Circuits for Indirect Coupling and Voltage Level Adapting . . . . . 348

6.2.2 Control Elements for DC and Rotating-Field Motors . . . . . 352

6.2.3 Control Elements for Stepper Motors . . . . . 358

6.2.4 Modulation Methods for Three-Phase Motors . . . . . 359

6.2.5 Control Elements . . . . . 364

6.3 Open-Loop Control of Rotational Speed . . . . . 367

6.3.1 Control Elements and Power Sections for Universal Motors . . . . . 367

6.3.2 Open-Loop Rotational Speed Control of DC Motors . . . . . 368

|                                      |  |     |
|--------------------------------------|--|-----|
| 6.3.3                                | Open-Loop Rotational Speed Control<br>of Asynchronous Motors   | 371 |
| 6.3.4                                | Open-Loop Control of Motors with Synchronous Speed   | 373 |
| 6.3.5                                | Positioning and Rotational Speed Open-Loop Control<br>of Stepper Motors  | 376 |
| 6.4                                  | Positioning and Rotational Speed<br>Closed-Loop Control  | 376 |
| 6.4.1                                | Closed-Loop Control of Universal Motors  | 376 |
| 6.4.2                                | Closed-Loop Control of DC Motors   | 377 |
| 6.4.3                                | Closed-Loop Control of Asynchronous Motors   | 380 |
| 6.4.4                                | Closed-Loop Control of Electronically Commutated Motors  | 390 |
| 6.5                                  | Information on the Practice-Oriented Adjustment<br>of Controllers and Simulation of Rotating Speed<br>Closed-Loop Control Circuits | 395 |
| 6.6                                  | Structure of Drive Electronics<br>for Three-Phase Alternating Current Motors<br>Using Circuits with Large-Scale Integration        | 398 |
| 6.7                                  | Sensorless Determination and Closed-Loop Control<br>of Rotational Speed, Rotor Position and Internal Torque                        | 401 |
|                                      | References   | 414 |
| <b>7 Magnetic Bearing Technology</b> |  |     |
| 7.1                                  | Introduction   | 417 |
| 7.2                                  | Passive Magnetic Bearings  | 419 |
| 7.2.1                                | Permanent Magnet Bearings  | 420 |
| 7.3                                  | Active Magnetic Bearing Systems  | 426 |
| 7.3.1                                | Electromagnetic Bearings   | 427 |
| 7.3.2                                | Bearingless Motors   | 434 |
|                                      | References   | 445 |
| <b>8 Mechanical Transfer Units</b>   |  |     |
| 8.1                                  | Gearings   | 450 |
| 8.1.1                                | Kinds of Gearings  | 450 |
| 8.1.2                                | Gear Trains  | 452 |
| 8.1.3                                | Flexible Drives  | 472 |
| 8.1.4                                | Screw Mechanisms   | 477 |
| 8.1.5                                | Coupling Drives  | 477 |
| 8.1.6                                | Cam Mechanisms   | 480 |
| 8.1.7                                | Stepping Gears   | 481 |
| 8.2                                  | Couplings  | 482 |
| 8.2.1                                | Firm Couplings   | 484 |
| 8.2.2                                | Self-aligning Couplings  | 485 |
| 8.2.3                                | Clutches   | 487 |
| 8.3                                  | Axles and Shafts   | 492 |
| 8.3.1                                | Calculation of Conceptual Design   | 492 |

|  |     |
|--|-----|
| 8.3.2 Recalculation .....  | 493 |
| 8.4 Bearings .....   | 495 |
| 8.4.1 Sliding Bearings .....   | 496 |
| 8.4.2 Rolling Bearings .....   | 502 |
| References .....   | 505 |
| Standards and Directions .....   | 506 |
| <b>9 Project Design of Drive Systems</b>                                     |     |
| 9.1 Requirements and Specifications .....                                    | 509 |
| 9.2 Approach to Drive Functions .....  | 511 |
| 9.3 Classification of Common Drive Functions .....                           | 511 |
| 9.3.1 Classification According to Motion .....                               | 511 |
| 9.3.2 Classification According to Operating Mode .....                       | 514 |
| 9.4 Aspects of Motor Selection .....   | 517 |
| 9.5 Comparison of Position-Controlled DC Drives<br>and Stepping Drives ..... | 519 |
| 9.6 Conversion of Mechanical Drive Parameters .....                          | 524 |
| 9.7 Samples of Drive Functions .....   | 526 |
| 9.7.1 Direct Drive of a Disk Storage Device .....                            | 526 |
| 9.7.2 Drive of a Dosing Piston Pump .....                                    | 532 |
| 9.7.3 Drive of a Drilling Machine<br>for Printed Circuit Boards (PCBs) ..... | 539 |
| 9.7.4 Drive of a Light Pointer .....   | 546 |
| 9.7.5 Drive of a Flexible-Tube Pump or Peristaltic Pump .....                | 551 |
| 9.7.6 Bowden Wire Drive of a Recording Device .....                          | 556 |
| 9.7.7 Drum Drive .....   | 566 |
| Standards and Directions .....   | 576 |
| Important Symbols .....  | 579 |
| <b>Index</b> .....   | 585 |