Contents

Preface xxv
Acknowledgements xxxix

PART A DRIVE TYPES AND CORE TECHNOLOGY 1

A1 Industrial motors 11
A1.1 Introduction and basic electromagnetic principles 11
A1.1.1 Magnetic circuits 11
A1.1.2 Electromechanical energy conversion 16
A1.1.2.1 The alignment of magnetic force/flux lines 16
A1.1.2.2 The interaction between a magnetic field and a current-carrying conductor 18
A1.2 D.C. motors 20
A1.2.1 General 20
A1.2.2 Operating principles 21
A1.2.3 Fundamental equations of steady-state performance 25
A1.2.3.1 The separately excited d.c. motor 25
A1.2.3.2 The series d.c. motor 29
A1.2.3.3 The shunt d.c. motor 30
A1.2.3.4 The compound d.c. motor 30
A1.2.4 Permanent magnet d.c. motor 31
A1.2.5 Construction of the d.c. motor 32
A1.2.5.1 D.C. motor frame 32
A1.2.5.2 D.C. motor armature 33
A1.2.5.3 Brush gear 34
A1.2.5.4 Degree of protection and mounting 34
A1.2.5.5 DCPM design 35
A1.3 A.C. induction motors 36
A1.3.1 General 36
A1.3.2 Operating principles 36
A1.3.2.1 Rotating magnetic field 37
A1.3.2.2 Torque production 38

A1.3.3 Fundamental equations of steady-state performance 43
A1.3.3.1 Direct on line (DOL) starting current and torque 43
A1.3.3.2 Starting current and torque when the motor is connected to a variable-frequency and/or variable-voltage supply 45
A1.3.4 Voltage–frequency relationship 45
A1.3.5 Slip-ring induction motor 48
A1.3.6 Speed-changing motors 50
A1.3.7 A.C. induction motor construction 50
A1.4 A.C. synchronous motors 52
A1.4.1 General 52
A1.4.2 Operating principles 53
A1.4.3 Fundamental equations of steady-state performance 54
A1.4.3.1 General 54
A1.4.3.2 Brushless PM servo motor 55
A1.4.4 Limits of operation 57
A1.4.5 Synchronous motor construction 58
A1.4.5.1 Permanent-magnet servo motors 58
A1.4.5.2 Permanent-magnet industrial motors 60
A1.4.5.3 Wound-rotor synchronous motors 61
A1.4.6 Starting of synchronous motors 61
A1.5 Reluctance motors 62
A1.6 A.C. commutator motors 63
A1.7 Motors for special applications 64
A1.7.1 Geared motors 64
A1.7.2 Brake motors 64
A1.7.3 Torque motors 64
A1.8 Motors for hazardous locations 65
A1.8.1 General 65
A1.8.2 CENELEC 65
A1.8.3 North American standards 69
A1.8.4 Testing authorities 69

A2 Drive converter circuit topologies 71
A2.1 Introduction 71
A2.2 A.C. to d.c. power conversion 72
A2.2.1 General 72
A2.2.2 Converters for connection to a single-phase supply 73
A2.2.2.1 Uncontrolled converters 73
A2.2.2.2 Controlled converters 74
A2.2.2.3 Sine-wave input converters 76
A2.2.2.4 Summary of characteristics 76

A2.2.3 Converters for connection to a three-phase supply 78
A2.2.3.1 Uncontrolled converters 78
A2.2.3.2 Controlled converters 78
A2.2.3.3 Summary of characteristics 79
A2.2.4 Converters for d.c. motor drive systems 82
A2.2.4.1 Single-converter drives 83
A2.2.4.2 Dual-converter drives 84
A2.2.4.3 Field control 85
A2.3 D.C. to d.c. power conversion 86
A2.3.1 General 86
A2.3.2 Step down d.c. to d.c. converters 87
A2.3.2.1 Single-quadrant d.c. to d.c. converter 87
A2.3.2.2 Two-quadrant d.c. to d.c. converter 88
A2.3.2.3 Four-quadrant d.c. to d.c. converter 89
A2.3.3 Step-up d.c. to d.c. converters 90
A2.4 A.C. to a.c. power converters with intermediate d.c. link 91
A2.4.1 General 91
A2.4.2 Voltage source inverters 91
A2.4.2.1 General characteristics 91
A2.4.2.2 Six-step/quasi-square-wave inverter 94
A2.4.2.3 Pulse-width modulated inverter 96
A2.4.2.4 Multi-level inverter 97
A2.4.3 Current source inverters 99
A2.4.3.1 General characteristics 99
A2.4.3.2 Converter-fed synchronous machine (LCI) 100
A2.4.3.3 Converter-fed induction motor drive 101
A2.4.3.4 Forced commutated induction motor drive 101
A2.4.3.5 Static Kramer drive 102
A2.5 Direct a.c. to a.c. power converters 103
A2.5.1 General 103
A2.5.2 Soft starter/voltage regulator 103
A2.5.3 Cycloconverter 104
A2.5.4 Matrix converter 106
A2.5.5 Static Scherbius drive 107

A3 Power semiconductor devices 109
A3.1 General 109
A3.2 Diode 114
A3.2.1 PN diode 114
A3.2.2 PIN diode 116
A3.2.3 Transient processes (reverse and forward recovery) 118
A3.2.3.1 Reverse recovery 118
A3.2.3.2 Forward recovery 120
A3.2.4 Diode types 121

A3.3 Thyristor (SCR) 122
A3.3.1 Device description 122
A3.3.2 Transient processes 124
A3.3.2.1 Turn-on 125
A3.3.2.2 Turn-off 126
A3.3.3 Thyristor gating requirements 127
A3.3.4 Thyristor types 127
A3.4 Triac 130
A3.5 Gate turn-off thyristor (GTO) 130
A3.5.1 Device description 130
A3.5.2 Switching characteristics and gate drive 132
A3.5.2.1 Turn-on 133
A3.5.2.2 Turn-off 134
A3.5.3 Voltage and current ratings 135
A3.6 Integrated gate commutated thyristor (IGCT) 135
A3.6.1 Device description 135
A3.6.2 Switching behaviour and gate drive 136
A3.6.3 Voltage and current ratings 137
A3.7 MOSFET 137
A3.7.1 Device description 137
A3.7.2 Principal features and applications 137
A3.7.3 D.C. characteristics 139
A3.7.4 Switching performance 140
A3.7.5 Transient characteristics 141
A3.7.5.1 Switching waveforms 141
A3.7.5.2 Turn-on 142
A3.7.5.3 Turn-off 143
A3.7.6 Safe operating area (SOA) 143
A3.7.6.1 Forward-bias safe operating area (FBSOA) 143
A3.7.6.2 Reverse-bias safe operating area (RBSOA) 144
A3.7.7 Parasitic diode 144
A3.7.8 MOSFET gate drive requirements 145
A3.7.8.1 Speed limitations 146
A3.7.8.2 Driving paralleled MOSFETs 147
A3.7.9 Voltage and current ratings 147
A3.8 Insulated gate bipolar transistor (IGBT) 147
A3.8.1 Device description 147
A3.8.2 Principal features and applications 148
A3.8.3 D.C. characteristics 149
A3.8.4 Punch-through versus non-punch-through structures (PT and NPT) 150
A3.8.5 Switching performance 151
A3.8.6 Transient characteristics 151
A3.8.6.1 Switching waveforms 152
A3.8.6.2 Turn-on 152
A3.8.6.3 Turn-off 154

A3.8.7 Safe operating area (SOA) 155
A3.8.7.1 Forward-bias safe operating area (FBSOA) 155
A3.8.7.2 Reverse-bias safe operating area (RBSOA) 156
A3.8.8 Parasitic thyristor 157
A3.8.9 IGBT gate drive requirements 157
A3.8.9.1 IGBT switching speed limitations 157
A3.8.9.2 Series and parallel operation 158
A3.8.9.3 IGBT short-circuit performance 159
A3.8.10 Voltage and current ratings 159
A3.9 Bipolar junction transistor (BJT) 159
A3.10 Other power devices and materials 160
A3.10.1 MOS controlled thyristor (MCT) 160
A3.10.2 MOS turn-off thyristor 161
A3.10.3 Junction field-effect transistors (JFETs) 162
A3.11 Materials 162
A3.12 Power device packaging 163
A3.12.1 General 163
A3.12.2 Pressure contact packages 165
A3.12.2.1 Construction 165
A3.12.2.2 Features 166
A3.12.3 Large wire-bonded packages for power modules 166
A3.12.3.1 Construction 166
A3.12.3.2 Package types 167
A3.12.3.3 Features 168
A3.12.4 Small wire-bonded packages for discrete devices 168
A3.12.4.1 Construction 169
A3.12.4.2 Package types 169
A3.12.4.3 Features 169

A4 Torque, speed and position control 171
A4.1 General principles 171
A4.1.1 The ideal control system 171
A4.1.2 Open-loop control 171
A4.1.3 Closed-loop control 172
A4.1.4 Criteria for assessing performance 173
A4.2 Controllers in a drive 175
A4.2.1 General 175
A4.2.2 Torque control 176
A4.2.3 Flux control 179
A4.2.4 Speed control 179
A4.2.4.1 Basic speed control 179
A4.2.4.2 Setting speed controller gains 183
A4.2.4.3 Speed control with torque feed-forward 185
A4.2.5 Position control 186
A4.2.5.1 Basic position control 186
A4.2.5.2 Position control with speed feed-forward 190

A4.3 D.C. motor drives 192
A4.3.1 General 192
A4.3.2 Torque control 192
A4.3.3 Flux control 194
A4.4 A.C. motor drives 195
A4.4.1 Torque and flux control 195
A4.4.1.1 Introduction 195
A4.4.1.2 D.C. motor torque and flux control 196
A4.4.1.3 Permanent magnet motor torque and flux control 197
A4.4.1.4 Induction motor torque and flux control 203
A4.4.1.5 Open-loop induction motor drive 205
A4.4.2 Direct torque control 206
A4.4.3 Performance summary 208
A4.4.3.1 Permanent-magnet motor drives 209
A4.4.3.2 Induction motor drives with closed-loop current control 210
A4.4.3.3 Open-loop induction motor drives 210

A5 Position and speed feedback 211
A5.1 General 211
A5.1.1 Feedback quantity required 211
A5.1.2 Absolute position feedback range 212
A5.1.3 Position resolution 212
A5.1.4 Position accuracy 214
A5.1.5 Speed resolution 214
A5.1.6 Speed accuracy 214
A5.1.7 Environment 215
A5.1.8 Maximum speed 215
A5.1.9 Electrical noise immunity 215
A5.1.10 Distance between the feedback device and the drive 216
A5.1.11 Additional features 216
A5.2 Speed feedback sensors 216
A5.2.1 D.C. tacho-generator 216
A5.3 Position feedback sensors 218
A5.3.1 Resolver 218
A5.3.2 Incremental encoder 221
A5.3.3 Incremental encoder with commutation signals 223
A5.3.4 Incremental encoder with commutation signals only 224
A5.3.5 SINCOS encoder 224
A5.3.6 Absolute SINCOS encoder 226
A5.3.7 Absolute encoders 227
A5.3.8 SINCOS encoders with serial communications 228
A5.3.8.1 EnDat 228
A5.3.8.2 Hiperface 229

A5.3.8.3 SSI 229
A5.3.8.4 Summary 230
A5.3.9 Serial communications encoders 230
A5.3.9.1 BiSS 230
A5.3.9.2 EnDat 230
A5.3.10 Wireless encoders 231

A6 Motion control 233
A6.1 General 233
A6.1.1 Position, speed, acceleration and jerk 234
A6.1.1.1 Speed 234
A6.1.1.2 Acceleration 234
A6.1.1.3 Jerk 235
A6.1.2 Possible configurations 236
A6.2 Time-based profile 239
A6.3 CAM profile 243
A6.4 Electronic gearbox 248
A6.5 Practical systems 249
A6.5.1 Control Techniques' Advanced Position Controller 249
A6.5.2 Control Techniques' Indexer 250

A7 Voltage source inverter: four-quadrant operation 253
A7.1 General 253
A7.2 Controlled deceleration 254
A7.2.1 Performance and applications 255
A7.2.1.1 Advantages 256
A7.2.1.2 Disadvantages 256
A7.3 Braking resistor 256
A7.3.1 Performance and applications 257
A7.3.1.1 Advantages 257
A7.3.1.2 Disadvantages 257
A7.4 Active rectifier 257
A7.4.1 Performance and applications 259
A7.4.1.1 Advantages 259
A7.4.1.2 Disadvantages 260

A8 Switched reluctance and stepper motor drives 261
A8.1 General 261
A8.2 Switched reluctance motors and controllers 261
A8.2.1 Basic principle of the switched reluctance motor 261
A8.2.1.1 Operation as a motor 264
A8.2.1.2 Operation as a brake or generator 265
A8.2.1.3 Summary so far 265
A8.2.1.4 Relationship between torque polarity and motoring and generating 267

A8.2.2 Control of the machine in practice 267
A8.2.2.1 Low-speed operation 267
A8.2.2.2 What happens as speed is increased? 267
A8.2.2.3 Medium-speed operation 268
A8.2.2.4 How is performance maintained as speed increases? 269
A8.2.2.5 High-speed operation 269
A8.2.2.6 Summary of typical/practical control 270
A8.2.2.7 Control of speed and position 271
A8.2.3 Polyphase switched reluctance machines 272
A8.2.4 Losses in the switched reluctance motor 273
A8.2.5 Excitation frequency 274
A8.2.6 Power electronics for the switched reluctance motor 275
A8.2.6.1 Power supply and 'front end' bridge 275
A8.2.6.2 Power switching stage 275
A8.2.6.3 Single-switch-per-phase circuits 275
A8.2.6.4 Multiple-phase operation 277
A8.2.6.5 Single-switch circuit using bifilar winding 278
A8.2.6.6 Two-switch asymmetrical bridge 278
A8.2.7 Advantages of the switched reluctance system 279
A8.2.7.1 Rotor construction 279
A8.2.7.2 Stator construction 280
A8.2.7.3 Electronics and system-level benefits 280
A8.2.8 Disadvantages of the switched reluctance system 282
A8.2.8.1 Torque ripple 282
A8.2.8.2 Acoustic noise 283
A8.3 Stepper motor drives 284
A8.3.1 Stepping motor principles 284
A8.3.1.1 The permanent-magnet motor 284
A8.3.1.2 The VR motor 285
A8.3.1.3 The hybrid motor 286
A8.3.2 Stepping motor drive circuits and logic modes 287
A8.3.2.1 General 287
A8.3.2.3 Unipolar switching 288
A8.3.2.3 Bipolar switching 290
A8.3.2.4 High-speed stepping: L/R drives 290
A8.3.2.5 Chopper drives 292
A8.3.2.6 Bilevel drives 292
A8.3.3 Application notes 293
A8.3.3.1 Effect of inertia 293
A8.3.3.2 Resonance 293
A8.3.3.3 Stepper/encoders 294

PART B THE DRIVE IN ITS ENVIRONMENT 297

B1 The a.c. supply 299
B1.1 General 299
B1.2 Supply harmonics and other low-frequency disturbances 299
B1.2.1 Overview 299
B1.2.2 Regulations 300
B1.2.2.1 Regulations for installations 301
B1.2.2.2 Regulations and standards for equipment 301
B1.2.3 Harmonic generation within variable-speed drives 302
B1.2.3.1 A.C. drives 302
B1.2.3.2 D.C. drives 304
B1.2.4 The effects of harmonics 306
B1.2.5 Calculation of harmonics 307
B1.2.5.1 Individual drives: d.c. 307
B1.2.5.2 Individual drives: a.c. 308
B1.2.5.3 Systems 308
B1.2.5.4 Isolated generators 310
B1.2.6 Remedial techniques 310
B1.2.6.1 Connect the equipment to a point with a high fault level (low impedance) 311
B1.2.6.2 Use three-phase drives where possible 311
B1.2.6.3 Use additional inductance 311
B1.2.6.4 Use a lower value of d.c. smoothing capacitance 315
B1.2.6.5 Use a higher pulse number (12 pulse or higher) 316
B1.2.6.6 Use a drive with an active input converter 318
B1.2.6.7 Use a harmonic filter 318
B1.2.7 Typical harmonic current levels for a.c. drive arrangements 319
B1.2.8 Additional notes on the application of harmonic standards 319
B1.2.8.1 The effect of load 319
B1.2.8.2 Choice of reference current: application of IEEE Std 519-1992 321
B1.2.9 Interharmonics and emissions up to 9 kHz 321
B1.2.10 Voltage notching 322
B1.2.11 Voltage dips and flicker 323
B1.3 Power factor 324
B1.4 Supply imperfections 326
B1.4.1 General 326

B1.4.2 Frequency variation 326
B1.4.3 Voltage variation 326
B1.4.4 Temporary and transient over-voltages between live conductors and earth 327
B1.4.5 Voltage unbalance 327
B1.4.6 Harmonic voltage 329
B1.4.7 Supply voltage dips and short interruptions 329
B1.4.8 Interharmonics and mains signalling 330
B1.4.9 Voltage notching 331
B1.4.10 EMC standards 333

B2 Interaction between drives and motors 335
B2.1 General 335
B2.2 Drive converter effects upon d.c. machines 335
B2.3 Drive converter effects upon a.c. machines 336
B2.3.1 Introduction 336
B2.3.2 Machine rating: thermal effects 336
B2.3.3 Machine insulation 337
B2.3.3.1 Current source inverters 337
B2.3.3.2 Voltage source inverters 337
B2.3.4 Bearing currents 349
B2.3.4.1 Root causes of bearing currents 349
B2.3.4.2 Good practices to reduce the risk of bearing currents 351
B2.3.5 Overspeed 352
B2.4 Motors for hazardous (potentially flammable or explosive) locations 353

B3 Physical environment 355
B3.1 Introduction 355
B3.2 Enclosure degree of protection 355
B3.2.1 General 355
B3.2.2 Motor 356
B3.2.2.1 General 356
B3.2.2.2 US practice 356
B3.2.3 Drive 356
B3.3 Mounting arrangements 360
B3.3.1 Motor 360
B3.3.1.1 General 360
B3.3.1.2 IEC 60034-7 standard enclosures 360
B3.3.1.3 NEMA standard enclosures 360
B3.3.2 Drive 360
B3.3.3 Integrated motor drive 363
B3.4 Terminal markings and direction of rotation 363
B3.4.1 Motor 363
B3.4.1.1 General 363

B3.4.1.2 IEC 60034-8/EN 60034-8 364
B3.4.1.3 NEMA 366
B3.4.2 Drive 371
B3.5 Ambient temperature 371
B3.5.1 Motor 371
B3.5.2 Drive 372
B3.5.2.1 Maximum operating temperature 372
B3.5.2.2 Minimum operating temperature 372
B3.6 Humidity and condensation 373
B3.6.1 Motor 373
B3.6.2 Drive 373
B3.7 Noise 373
B3.7.1 Motor 373
B3.7.2 Drive 376
B3.7.3 Motor noise when fed from a drive converter 376
B3.8 Vibration 378
B3.8.1 Motor 378
B3.8.2 Drive 380
B3.9 Altitude 380
B3.10 Corrosive gases 380
B3.10.1 Motors 380
B3.10.2 Drives 381

B4 Thermal management 383
B4.1 Introduction 383
B4.2 Motor cooling 383
B4.2.1 General 383
B4.2.2 D.C. motors 385
B4.2.2.1 Air filters 386
B4.2.3 A.C. industrial motors 386
B4.2.4 High-performance/servo motors 386
B4.2.4.1 Intermittent/peak torque limit 388
B4.2.4.2 Forced-air (fan) cooling 388
B4.3 Drive cooling: the thermal design of enclosures 389
B4.3.1 General 389
B4.3.2 Calculating the size of a sealed enclosure 389
B4.3.3 Calculating the air-flow in a ventilated enclosure 391
B4.3.4 Through-panel mounting of drives 392

B5 Drive system power management: common d.c. bus topologies 393
B5.1 Introduction 393
B5.2 Power circuit topology variations 396
B5.2.1 General 396
B5.2.2 Simple bulk uncontrolled external rectifier 396
B5.2.3 A.C. input and d.c. bus paralleled 397
B5.2.4 One host drive supplying d.c. bus to slave drives 398

B5.2.5 A bulk four-quadrant controlled rectifier feeding the d.c. bus 399
B5.2.6 Active bulk rectifier 400
B5.3 Fusing policy 402
B5.4 Practical systems 402
B5.4.1 Introduction 402
B5.4.2 Variations in standard drive topology 403
B5.4.3 Inrush/charging current 404
B5.4.4 Continuous current 404
B5.4.5 Implementation: essential knowledge 406
B5.4.5.1 A.C. and d.c. terminals connected: drives of the same current rating only 406
B5.4.5.2 A.C. and d.c. terminals connected: drives of different current ratings 407
B5.4.5.3 One host drive supplying d.c. bus to slave drives 407
B5.4.5.4 Simple bulk uncontrolled external rectifier 408
B5.4.6 Practical examples 408
B5.4.6.1 Winder/unwinder sharing energy via the d.c. bus 408
B5.4.6.2 Four identical drives with a single dynamic braking circuit 409
B5.4.7 Note on EMC filters for common d.c. bus systems 409

B6 Electromagnetic compatibility (EMC) 411
B6.1 Introduction 411
B6.1.1 General 411
B6.1.2 Principles of EMC 411
B6.1.3 EMC regulations 412
B6.2 Regulations and standards 412
B6.2.1 Regulations and their application to drive modules 412
B6.2.2 Standards 413
B6.3 EMC behaviour of variable-speed drives 414
B6.3.1 Immunity 414
B6.3.2 Low-frequency emission 414
B6.3.3 High-frequency emission 415
B6.4 Installation rules 416
B6.4.1 EMC risk assessment 416
B6.4.2 Basic rules 417
B6.4.2.1 Cable segregation 417
B6.4.2.2 Control of return paths, minimising loop areas 417
B6.4.2.3 Earthing 417
B6.4.3 Simple precautions and ‘fixes’ 420
B6.4.4 Full precautions 420

B6.5 Theoretical background 422
B6.5.1 Emission modes 422
B6.5.2 Principles of input filters 424
B6.5.3 Screened motor cables 425
B6.5.4 Ferrite ring suppressors 425
B6.5.5 Filter earth leakage current 426
B6.5.6 Filter magnetic saturation 426
B6.6 Additional guidance on cable screening for sensitive circuits 426
B6.6.1 Cable screening action 426
B6.6.2 Cable screen connections 428
B6.6.3 Recommended cable arrangements 431

B7 Protection 433
B7.1 Protection of the drive system and power supply infrastructure 433
B7.1.1 General 433
B7.1.2 Fuse types 433
B7.1.3 Application of fuses to drive systems 434
B7.1.4 Earth faults 435
B7.1.5 IT supplies 435
B7.1.6 Voltage transients 436
B7.2 Motor thermal protection 438
B7.2.1 General 438
B7.2.2 Protection of line-connected motor 438
B7.2.3 Protection of inverter-driven motor 439
B7.2.4 Multiple motors 440
B7.2.5 Servo motors 440

B8 Mechanical vibration, critical speed and torsional dynamics 441
B8.1 General 441
B8.2 Causes of shaft vibrations independent of variable-speed drives 443
B8.2.1 Sub-synchronous vibrations 443
B8.2.2 Synchronous vibrations 443
B8.2.3 Super-synchronous vibrations 444
B8.2.4 Critical speeds 444
B8.3 Applications where torque ripple excites a resonance in the mechanical system 444
B8.4 High-performance closed-loop applications 446
B8.4.1 Limits to dynamic performance 446
B8.4.2 System control loop instability 446
B8.5 Measures for reducing vibration 446

B9 Installation and maintenance of standard motors and drives 449
B9.1 Motors 449
B9.1.1 General 449

B9.1.2 Storage 449
B9.1.3 Installation 450
B9.1.4 Maintenance guide 451
B9.1.5 Brush gear maintenance 452
B9.2 Electronic equipment 454
B9.2.1 General 454
B9.2.2 Location of equipment 454
B9.2.3 Ventilation systems and filters 455
B9.2.4 Condensation and humidity 455
B9.2.5 Fuses 455

PART C PRACTICAL APPLICATIONS 457

C1 Application and drive characteristics 461
C1.1 General 461
C1.2 Typical load characteristics and ratings 461
C1.3 Drive characteristics 472
C1.3.1 General 472

C2 Duty cycles 477
C2.1 Introduction 477
C2.2 Continuous duty: S1 477
C2.3 Short-time duty: S2 478
C2.4 Intermittent duty: S3 479
C2.5 Intermittent duty with starting: S4 480
C2.6 Intermittent duty with starting and electric braking: S5 481
C2.7 Continuous operation periodic duty: S6 481
C2.8 Continuous operation periodic duty with electric braking: S7 482
C2.9 Continuous operation periodic duty with related load speed changes: S8 482
C2.10 Duty with non-periodic load and speed variations: S9 482
C2.11 Duty with discrete constant loads: S10 483

C3 Interfaces, communications and PC tools 485
C3.1 Introduction 485
C3.2 Overview of interface types 485
C3.3 Analogue signal circuits 486
C3.3.1 General 486
C3.3.2 Hardware implementations and wiring advice 487
C3.3.2.1 General guidance on connecting analogue signal circuits 487
C3.3.2.2 Single-ended circuits 490
C3.3.2.3 Differential circuits 491
C3.3.2.4 The case for 4–20 mA and other current loop circuits 496

C3.3.2.5 The use of capacitors for connecting cable screens 496
C3.3.3 Typical specifications for analogue inputs and outputs 497
C3.4 Digital signal circuits 499
C3.4.1 Positive and negative logic 499
C3.4.2 Digital input 500
C3.4.3 Digital output 501
C3.4.4 Relay contacts 501
C3.5 Digital serial communications 501
C3.5.1 Introduction 501
C3.5.2 Serial network basics 502
C3.5.2.1 Physical layer 503
C3.5.2.2 Data link layer 506
C3.5.2.3 Application layer 508
C3.5.2.4 Device profile 508
C3.5.3 RS-232/RS-485 Modbus: A simple Fieldbus system 508
C3.6 Fieldbus systems 510
C3.6.1 Introduction to Fieldbus 510
C3.6.2 Centralised versus distributed control networks 512
C3.6.2.1 Centralised network 512
C3.6.2.2 Distributed network 513
C3.6.2.3 Hybrid networks 514
C3.6.3 Open and proprietary Fieldbus systems 516
C3.6.3.1 Open networks 516
C3.6.3.2 Proprietary networks 516
C3.6.4 OPC technology 517
C3.6.5 Industrial Fieldbus systems (non Ethernet) 517
C3.6.5.1 Profibus DP 517
C3.6.5.2 DeviceNet 518
C3.6.5.3 CANopen 519
C3.6.5.4 Interbus 520
C3.6.5.5 LonWorks 520
C3.6.5.6 BACnet 521
C3.6.5.7 SERCOS II 522
C3.6.6 Ethernet-based Fieldbuses 523
C3.6.6.1 General 523
C3.6.6.2 Modbus TCP/IP 523
C3.6.6.3 EtherNet IP 524
C3.6.6.4 PROFINET 525
C3.6.6.5 EtherCAT 525
C3.6.6.6 Powerlink 526
C3.6.7 Company-specific Fieldbuses 526
C3.6.7.1 CTNet 526
C3.6.7.2 CTSync 527
C3.6.8 Gateways 528

C3.7 PC tools 528
C3.7.1 Engineering design tools 529
C3.7.2 Drive commissioning and setup tools 529
C3.7.3 Application configuration and setup tools 530
C3.7.4 System configuration and setup tools 530
C3.7.5 Monitoring tools 531

C4 Typical drive functions 533
C4.1 Introduction 533
C4.2 Speed or frequency reference/demand 533
C4.3 Ramps 534
C4.4 Frequency slaving 535
C4.5 Speed control 535
C4.6 Torque and current control 535
C4.6.1 Open loop with scalar V/f control 535
C4.6.2 Closed-loop and high-performance open loop 536
C4.7 Automatic tuning 536
C4.8 Second parameter sets 537
C4.9 Sequencer and clock 537
C4.10 Analogue and digital inputs and outputs 537
C4.11 Programmable logic 537
C4.12 Status and trips 538
C4.13 Intelligent drive programming: user-defined functionality 539
C4.14 Functional safety 543
C4.14.1 Principles 543
C4.14.2 Technical standards 544
C4.14.3 Possible safety functions for drives 546
C4.14.3.1 Safe torque off (STO) 546
C4.14.3.2 Advanced drive-specific functions 547
C4.14.3.3 Other machinery safety functions 548
C4.14.3.4 Safety bus interfaces 549
C4.14.3.5 Integration into a machine 549
C4.15 Summary 549

C5 Common techniques 551
C5.1 General 551
C5.2 Speed control with particular reference to linear motion 552
C5.2.1 Linear to rotary speed reference conversion 555
C5.3 Torque feed-forward 555
C5.4 Virtual master and sectional control 556
C5.5 Registration 562
C5.6 Load torque sharing 567
C5.6.1 General 567
C5.6.2 Open-loop systems 568
C5.6.3 Paired d.c. motors 570
C5.6.4 Paired a.c. motors 572

C5.6.4.1 Parallel motors 572
C5.6.4.2 Frequency slaving 573
C5.6.4.3 Current slaving 573
C5.6.5 Torque slaving systems 574
C5.6.6 Speed-controlled helper with fixed torque 575
C5.6.7 Speed-controlled helper with shared torque 576
C5.6.8 Full closed-loop systems 577
C5.7 Tension control 578
C5.8 Sectional control 579
C5.9 Winding 580
C5.9.1 General 580
C5.9.2 Drum winders 581
C5.9.3 Centre-driven winders 582
C5.10 High-frequency inverters 589
C5.10.1 General 589
C5.10.2 Frequency control of a.c. induction motors 590
C5.10.3 Purpose-designed high frequency motors 592
C5.10.4 High-frequency inverters 593
C5.10.5 High-frequency applications 594
C5.11 Special d.c. loads 594
C5.11.1 Traction motor field control 595
C5.11.2 Battery charging 595
C5.11.3 Electrolytic processes 596
C5.11.4 Electric heating and temperature control 596

C6 Industrial application examples 599
C6.1 Introduction 599
C6.2 Centrifugal pumps 599
C6.2.1 Single-pump systems 599
C6.2.2 Multiple pump systems (duty-assist control) 605
C6.2.2.1 Note on parallel operation of pumps 605
C6.3 Centrifugal fans and compressors 606
C6.4 Heating, ventilation, air conditioning and refrigeration (HVAC/R) 607
C6.4.1 Introduction 607
C6.4.2 Commercial buildings 608
C6.4.2.1 Building automation systems 608
C6.4.2.2 HVAC applications 609
C6.4.3 Retail facilities 614
C6.4.3.1 Refrigeration applications 615
C6.4.4 Original equipment manufacturers 616
C6.5 Cranes and hoists 616
C6.5.1 General 616
C6.5.2 Overhead cranes 617
C6.5.3 Port cranes 617
C6.5.3.1 Ship-to-shore container cranes: grab ship unloaders 617

C6.5.3.2 Rubber-tyred gantry cranes 618
C6.5.3.3 Rail-mounted gantry cranes 618
C6.5.4 Automated warehousing 620
C6.5.5 Notes on crane control characteristics 620
C6.5.5.1 Hoisting control 620
C6.5.5.2 Slewing control 620
C6.5.6 Retrofit applications 621
C6.6 Elevators and lifts 622
C6.6.1 Lift system description 622
C6.6.2 Speed profile generation 625
C6.6.3 Load weighing devices 626
C6.6.4 Block diagram of lift electrical system 627
C6.7 Metals and metal forming 627
C6.7.1 Introduction 627
C6.7.2 Steel 627
C6.7.2.1 Main mill drives 628
C6.7.2.2 Auxiliary drives 629
C6.7.2.3 Strip rolling mills 630
C6.7.2.4 Continuous casting 633
C6.7.3 Wire and cable manufacture 635
C6.7.3.1 Wire drawing machine 635
C6.7.3.2 Twin carriage armourer 637
C6.8 Paper making 638
C6.8.1 General 638
C6.8.2 Sectional drives 639
C6.8.3 Loads and load sharing 640
C6.8.4 Control and instrumentation 642
C6.8.5 Winder drives 644
C6.8.6 Brake generator power and energy 645
C6.8.7 Unwind brake generator control 647
C6.8.8 Coating machines 648
C6.9 Plastics extrusion 649
C6.9.1 General 649
C6.9.2 Basic extruder components 652
C6.9.3 Overall extruder performance 653
C6.9.4 Energy considerations 654
C6.9.5 Motors and controls 656
C6.10 Stage scenery: film and theatre 657
C6.10.1 The Control Techniques orchestra 657

PART D APPENDICES 661

D1 Symbols and formulae 663
D1.1 SI units and symbols 663
D1.1.1 SI base units 663
D1.1.2 Derived units 664

D1.2 Electrical formulae 665
D1.2.1 Electrical quantities 665
D1.2.2 A.C. three-phase (assuming balanced symmetrical waveform) 666
D1.2.3 A.C. single-phase 666
D1.2.4 Three-phase induction motors 667
D1.2.5 Loads (phase values) 667
D1.2.6 Impedance 667
D1.2.7 A.C. vector and impedance diagrams 667
D1.2.8 Emf energy transfer 669
D1.2.9 Mean and rms values, waveform 670
D1.2.9.1 Principles 670
D1.2.9.2 Mean d.c. value 671
D1.2.9.3 rms value 672
D1.2.9.4 Form factor 674
D1.3 Mechanical formulae 674
D1.3.1 Laws of motion 674
D1.3.1.1 Linear motion 676
D1.3.1.2 Rotational or angular motion 677
D1.3.1.3 Relationship between linear and angular motion 678
D1.3.1.4 The effect of gearing 679
D1.3.1.5 Linear to rotary speed reference conversion 680
D1.3.1.6 Friction and losses 681
D1.3.1.7 Fluid flow 682
D1.4 Worked examples of typical mechanical loads 684
D1.4.1 Conveyor 684
D1.4.2 Inclined conveyor 689
D1.4.3 Hoist 689
D1.4.4 Screw-feed loads 693

D2 Conversion tables 695
D2.1 Mechanical conversion tables 695
D2.2 General conversion tables 700
D2.3 Power/torque/speed nomogram 706

D3 World industrial electricity supplies (<1 kV) 707

Bibliography 715

Index 717