

# INDUSTRIAL ELECTRONICS

Applications for Programmable Controllers, Instrumentation &  
Process Control, and Electrical Machines & Motor Controls

SECOND EDITION



Suranaree University of Technology



31051000609007

Thomas E. Kissell

|        |                                                                                                  |    |
|--------|--------------------------------------------------------------------------------------------------|----|
| 1      | SOLID-STATE DEVICES USED IN INDUSTRIAL LOGIC CIRCUITS                                            | 1  |
| 1.1    | OVERVIEW OF LOGIC USED IN INDUSTRIAL LOGIC CIRCUITS                                              | 2  |
| 1.2    | RELAY LOGIC                                                                                      | 3  |
| 1.2.1  | Terms for Relays                                                                                 | 4  |
| 1.2.2  | Types of Relays                                                                                  | 5  |
| 1.2.3  | Voltage Ratings for Coils and Contacts                                                           | 5  |
| 1.2.4  | Troubleshooting Relay Coils and Contacts                                                         | 6  |
| 1.3    | TYPICAL LOGIC CIRCUITS                                                                           | 6  |
| 1.3.1  | Identifying Inputs and Logic in the Circuit                                                      | 7  |
| 1.3.2  | Relay Ladder Logic                                                                               | 7  |
| 1.4    | RELAY LOGIC USED TO CONTROL A PNEUMATIC CYLINDER                                                 | 8  |
| 1.5    | USING RELAY LOGIC TO DETERMINE ROBOT PROGRAM FOR INSERTING STUDS INTO TAILLIGHTS FOR AUTOMOBILES | 10 |
| 1.5.1  | Understanding the Relay Logic                                                                    | 11 |
| 1.6    | SOLID-STATE DEVICES USED FOR LOGIC                                                               | 12 |
| 1.6.1  | Transistor Equivalent to AND and OR Circuits                                                     | 13 |
| 1.7    | SOLID-STATE LOGIC BLOCKS                                                                         | 14 |
| 1.7.1  | Early Examples of Logic Gates                                                                    | 15 |
| 1.7.2  | Programmable Logic Arrays                                                                        | 16 |
| 1.7.3  | Programmable Array Logic (PAL)                                                                   | 18 |
| 1.7.4  | Programmable Logic Controllers                                                                   | 18 |
| 1.8    | SOLID-STATE LOGIC EQUIVALENT TO THE COUGAR TAILLIGHT ASSEMBLY CIRCUIT                            | 18 |
| 1.8.1  | Operation of the Solid-State Logic Circuit                                                       | 19 |
| 1.9    | CONNECTING INPUTS TO SOLID-STATE LOGIC DEVICES                                                   | 20 |
| 1.10   | OUTPUTS FOR LOGIC CIRCUITS                                                                       | 22 |
| 1.11   | SOLID-STATE RELAYS                                                                               | 23 |
| 1.11.1 | Features of SSRs                                                                                 | 24 |
| 1.12   | A COMPARISON OF SOLID-STATE LOGIC AND RELAY LOGIC                                                | 25 |
| 1.12.1 | Strengths and Weaknesses of Solid-State Logic Devices                                            | 25 |
| 1.12.2 | Strengths and Weaknesses of Relays                                                               | 27 |
| 1.13   | SOLID-STATE AND RELAY LOGIC CIRCUITS TO CONTROL PART BINS FOR ROBOTIC AUTOMATIC WORK CELLS       | 27 |
| 1.13.1 | Operation of the Relay Logic for Parts Bin Level Control                                         | 30 |

## 2 ADVANCED SOLID-STATE LOGIC: FLIP-FLOPS, SHIFT REGISTERS, COUNTERS, AND TIMERS 35

### 2.1 OVERVIEW OF THE NEED FOR ADVANCED LOGIC 36

### 2.2 LATCHES 37

#### 2.2.1 RS Latch 38      2.2.2 Edge-Triggered Flip-Flops 38

#### 2.2.3 The Edge-Triggered RS Flip-Flop 39      2.2.4 The Edge-Triggered JK

#### Flip-Flop 39      2.2.5 The Edge-Triggered D Flip-Flop 40      2.2.6 Using

#### Flip-Flops to Cycle Two Air Compressors 40      2.2.7 Using Flip-Flops to Control an Industrial Surface Grinder 41      2.2.8 Using Flip-Flops for Safety Circuits 42

### 2.3 COUNTERS 43

#### 2.3.1 Asynchronous and Synchronous Counters 43      2.3.2 Binary-Coded

#### Decimal Counters 45      2.3.4 Up/Down Counters 46

### 2.4 SHIFT REGISTERS 46

#### 2.4.1 Operation of a Shift Register 47      2.4.2 Using Edge-Triggered JK

#### Flip-Flops to Make a Shift Register 48      2.4.3 Using Shift Registers to

#### Provide Time Delay 48      2.4.4 Word-Shift Registers 50

### 2.5 FIRST-IN, FIRST-OUT (FIFO) SHIFT REGISTERS 51

#### 2.5.1 The Johnson Counter 53      2.5.2 The Ring Counter 54

#### 2.5.3 The Gray Code Counter 54

### 2.6 TIMERS 56

#### 2.6.1 One-Shot Timers 56      2.6.2 The 555 Timer 57

### 2.7 INDUSTRIAL TIMERS 58

#### 2.7.1 On-Delay Timers 58      2.7.2 Off-Delay Timers 59      2.7.3 Normally

#### Open and Normally Closed Time-Delay Contacts 60      2.7.4 Pneumatic

#### Timer Operators 62      2.7.5 Motor-Driven Timers 63      2.7.6 Solid-State

#### Time-Delay Devices 66      2.7.7 Programmable Timers 67

## 3 PROGRAMMABLE CONTROLLERS 71

### 3.1 OVERVIEW OF PROGRAMMABLE CONTROLLERS 72

#### 3.1.1 The Generic Programmable Logic Controller 73      3.1.2 Basic Parts of

#### a Simple Programmable Controller 75      3.1.3 The Programming Panel 75

### 3.2 AN EXAMPLE PROGRAMMABLE CONTROLLER APPLICATION 76

#### 3.2.1 Operation of a Conveyor Sorting System 77

### 3.3 SCANNING A PLC PROGRAM WHEN IT IS IN THE RUN MODE 79

#### 3.3.1 Image Registers 79      3.3.2 The Run Mode and the Program Mode 81

#### 3.3.3 On-Line and Off-Line Programming 81

### 3.4 EQUATING THE PLC WITH TRADITIONAL SOLID-STATE LOGIC 82

### 3.5 FEATURES OF THE PROGRAMMABLE CONTROLLER 82

#### 3.5.1 Classifications of Programmable Controllers 84

### 3.6 OPERATION OF PROGRAMMABLE CONTROLLERS 84

#### 3.6.1 Immediate I/O Updates 84      3.6.2 The Need for High-Speed Inputs and Outputs 85

**3.7 ADDRESSES FOR INPUTS AND OUTPUTS FOR THE MICROLOGIX 1000 86**

**3.8 EXAMPLE INPUT AND OUTPUT INSTRUCTIONS FOR THE MICROLOGIX 1000 87**

**3.8.1 Mnemonics: Abbreviations for Instructions 89**

**3.9 USING THE MICROLOGIX 1000 TO CONTROL THE BATCH-MIXING AND HEAT-TREATING PROCESS: MAKING CARBON BRUSHES 89**

**3.10 INPUTS AND OUTPUTS FOR THE CARBON BRUSH PROCESS SYSTEM 89**

**3.11 OPERATION OF THE HEAT-TREATING PART OF THE SYSTEM 90**

**3.11.1 Using Latch and Unlatch Coils 92**

**3.12 USING TIMERS TO STAGE ELECTRIC HEAT 93**

**3.12.1 TON and RTO Timers 93      3.12.2 Using the TON as an Automatic Resetting Timer for Lubrication 94**

**3.13 COUNTER OPERATION IN A PLC 95**

**3.13.1 Using an Up/Down Counter to Count Good and Bad Parts 96**

**3.13.2 Using Counters in the Carbon Brush Application 96**

**3.13.3 Using a Resetting Counter Application 96**

**3.14 TIMING AND COUNTING LARGE VALUE 97**

**3.15 SEQUENCES USED TO CONTROL THE BATCH MIXING FOR THE CARBON BRUSH APPLICATION 99**

**3.15.1 Sequencer Application for the Carbon Brush-Mixing System 100**

**3.15.2 Programming the Sequencer into the MicroLogix 1000 101**

**3.15.3 Selecting a Mask for the Sequencer 101      3.15.4 Setting the Time for Each Step of the Sequencer 102**

**3.16 OTHER SEQUENCER FUNCTIONS 103**

**3.17 CIRCUITS FOR INPUT AND OUTPUT MODULES 103**

**3.17.1 Electronic Circuit for a 110 AC Output Module 103**

**3.17.2 Electronic Circuit for the Relay Output Module 105**

**3.18 WIRING INPUT SWITCHES AND OUTPUT DEVICES TO THE PLC 105**

**3.19 ANALOG INPUT MODULES 106**

**3.20 MASTER CONTROL RESET AND ZONE CONTROL LAST STATE 108**

**3.21 USING A HAND-HELD PROGRAMMER 108**

**3.21.1 Force and Unforce Functions 111      3.21.2 Entering Programs with a Hand-Held Calculator 111**

**3.21.3 Programming Basic Circuits in the PLC 111      3.21.4 Wiring a Start-Stop Circuit to Input and Output Terminals on the PLC 113**

**3.21.5 Typical Problems a Technician Will Encounter with PLCs 115**

**3.21.6 Troubleshooting the PLC 115**

**3.22 ADVANCED INSTRUCTIONS FOUND IN LARGER PLCs 116**

**3.23 ADDRESSING OTHER ALLEN BRADLEY PLCs 117**

**3.23.1 Allen Bradley PLC2 Addressing System 120      3.23.2 Allen Bradley SLC 500 and PLC5 Addressing System 120**

**3.23.3 Allen Bradley SLC 500 and PLC5 Hardware 122**

**3.24 DOCUMENTING A PLC PROGRAM WITH SOFTWARE 124**

## 4 SOLID-STATE DEVICES USED TO CONTROL POWER: SCRs, TRIACS, AND POWER TRANSISTORS 129

### 4.1 OVERVIEW OF SCRs, TRIACS, AND TRANSISTORS IN INDUSTRIAL APPLICATIONS 130

### 4.2 SILICON-CONTROLLED RECTIFIERS (SCRs) 131

- 4.2.1 Anode, Cathode, and Gate 132
- 4.2.2 Two-Transistor Model of an SCR 132
- 4.2.3 Static Characteristic Curve and Waveforms for the SCR 133
- 4.2.4 Waveforms of the SCR and the Load 134
- 4.2.5 Methods of Turning On an SCR 134
- 4.2.6 Turning On an SCR by Gate Triggering 136
- 4.2.7 Characteristics of the SCR Gate Signal 136
- 4.2.8 Basic Gate Circuit 138
- 4.2.9 Using Unijunction Transistors and Diacs to Trigger SCRs 139
- 4.2.10 Methods of Commutating SCRs 140
- 4.2.11 SCR Turn-Off Time and Reverse Recovery Time 141
- 4.2.12 Example Applications Using SCRs 142
- 4.2.13 Complementary SCRs, Silicon-Controlled Switches, Gate Turn-Off Devices, and Other Thyristors 144

### 4.3 TRIACS 146

- 4.3.1 Operation of a Triac 148
- 4.3.2 Characteristics of Triacs 149
- 4.3.3 Switching On a Triac 149
- 4.3.4 Circuit Commutation for a Triac 151

### 4.4 POWER TRANSISTORS 152

- 4.4.1 Power Transistor Applications 153
- 4.4.2 Darlington Transistors 155
- 4.4.3 The Need for Darlington Transistors 156

### 4.5 INSULATED-GATE BIPOLAR TRANSISTORS 157

### 4.6 HIGH-VOLTAGE BIPOLAR TRANSISTORS 157

### 4.7 JUNCTION FIELD-EFFECT TRANSISTORS (J-FETs) 159

### 4.8 COMPARISON OF POWER SEMICONDUCTORS 159

## 5 SOLID-STATE DEVICES USED FOR FIRING CIRCUITS 164

### • 5.1 OVERVIEW OF FIRING CIRCUITS 165

### • 5.2 UNIJUNCTION TRANSISTOR (UJT) 166

- 5.2.1 Theory of Operation of a UJT 166
- 5.2.2 Firing Characteristics of a UJT 167
- 5.2.3 Voltage and Current Characteristics When a UJT Fires 168
- 5.2.4 Relaxation Oscillator 169
- 5.2.5 Voltage and Current in the Relaxation Oscillator 169
- 5.2.6 Synchronizing a UJT Pulse with AC Line Voltage 172
- 5.2.7 Isolating the UJT Firing Circuit from the SCR Load Circuit 174

### • 5.3 PROGRAMMABLE UNIJUNCTION TRANSISTORS 175

- 5.3.1 Operation of a Programmable Unijunction Transistor 176

### • 5.4 USING A DIAC TO PROVIDE A PULSE FOR THYRISTORS 177

- 5.4.1 Theory of Operation of a Diac 178

### • 5.5 OTHER SOLID-STATE DEVICES USED AS TRIGGERS 179

- 5.5.1 Small SCRs and Complementary UJTs 179
- 5.5.2 Silicon-Controlled Switch (SCS) 180
- 5.5.3 Silicon Unilateral Switch (SUS) 180
- 5.5.4 Silicon Bilateral Switch (SBS) 180
- 5.5.5 SIDAC 182
- 5.5.6 Silicon Asymmetrical Switch (SAS) 183
- 5.5.7 Asymmetrical Silicon

## \* 5.6 LIGHT-ACTIVATED SOLID-STATE DEVICES 184

## 6 PHOTOELECTRONICS, LASERS, AND FIBER OPTICS 190

## 6.1 ANALYSIS OF LIGHT 191

## 6.2 PHOTODIODES 193

6.2.1 Photovoltaic Cells 194      6.2.2 Theory of Operation of Photovoltaic Cells 194      6.2.3 Applications for Photoelectric Controls 194

## 6.3 PHOTOCONDUCTIVE CELLS 195

6.3.1 Cadmium Selenide Cell 197      6.3.2 Modulated Light Source (MLS) 197

## 6.4 INDUSTRIAL PHOTOELECTRIC DEVICES 198

6.4.1 Through-Beam Photoelectric Devices 198      6.4.2 Retroreflective Scan Photoelectric Devices 200      6.4.3 Diffuse Scan Photoelectric Switches 203      6.4.4 Electronic Circuits for Photoelectric Switches 203      6.4.5 Output Signals for Photoelectric Controls 204

## 6.5 OPTOELECTRONIC DEVICES 205

6.5.1 Phototransistors, Light-Activated SCRs, and Phototriacs 206      6.5.2 Light-Emitting Diodes (LEDs) 207

## 6.6 OPTOISOLATORS AND OPTOINTERRUPTERS 208

6.6.1 Applications for Optocouplers 209      6.6.2 Theory of Operation of the Optoisolated Circuits 209      6.6.3 Optoisolation Relays (Solid-State Relays) 210      6.6.4 Optocouplers Used in Input and Output Module Circuits 212      6.6.5 Specialty Types of Optocouplers 214      6.6.6 Adding Bias to the Phototransistor of the Optocoupler 216      6.6.7 Using an Optocoupler to Convert a 4–20-mA Signal to a Variable-Voltage Signal 217      6.6.8 Photo IC Interrupter 218

## 6.7 OPTODEVICES USED FOR DISPLAYS 218

6.7.1 Liquid Crystal Displays (LCD) and Plasma Display Screens 219

## 6.8 LASERS 221

6.8.1 Theory of Laser Operation 221      6.8.2 Types of Lasers 221      6.8.3 Diode Lasers 221      6.8.4 Industrial Laser Applications 222

## 6.9 FIBER OPTICS 223

6.9.1 Fiber Optic Transmitter and Receiver 223      6.9.2 Types of Fiberoptic Cables 225

## 6.10 BAR-CODE EQUIPMENT 225

6.10.1 Bar-Code Scanner and Decoder 227      6.10.2 Types of Scanners 228      6.10.3 Typical Bar-Code Applications in Industry 228

## 7 INDUSTRIAL POWER SUPPLIES, INVERTERS, AND CONVERTERS 234

## 7.1 OVERVIEW 235

## 7.2 INDUSTRIAL RECTIFIER CIRCUITS: AC-TO-DC CONVERSION 236

|                                                                 |     |                                                                    |     |                                                  |     |
|-----------------------------------------------------------------|-----|--------------------------------------------------------------------|-----|--------------------------------------------------|-----|
| 7.2.1 Single-Phase Rectifiers                                   | 236 | 7.2.2 Two-Diode Full-Wave Single-Phase Rectifiers                  | 238 | 7.2.3 Four-Diode Full-Wave Bridge Rectifiers     | 239 |
| 7.2.4 Three-Phase Full-Wave Rectifiers                          | 241 | 7.2.5 Other Types of Three-Phase Rectifiers                        | 242 | 7.2.6 Six-Phase Full-Wave Bridge Circuits        | 244 |
| 7.2.7 A Comparison of the Different Types of Rectifier Circuits | 245 | 7.2.8 Using Capacitors and Inductors as Filters for Power Supplies | 246 | 7.2.9 Using a Zener Diode for Voltage Regulation | 247 |
| 7.2.10 Surge Protection for Rectifier Circuits                  | 248 | 7.2.11 Crowbar Protection Against Overvoltage                      | 249 |                                                  |     |
| 7.3 APPLICATIONS FOR INDUSTRIAL POWER SUPPLIES                  | 250 |                                                                    |     |                                                  |     |
| 7.3.1 Power Supply for a Variable-Frequency Motor Drive         | 251 | 7.3.2 Welding Power Supply                                         | 251 | 7.3.3 Uninterruptible Power Supplies             | 253 |
| 7.4 INVERTERS: CHANGING DC VOLTAGE TO AC VOLTAGE                | 254 |                                                                    |     |                                                  |     |
| 7.4.1 Single-Phase Inverters                                    | 255 | 7.4.2 Using Transistors for a Six-Step Inverter                    | 255 | 7.4.3 Three-Phase Inverters                      | 257 |
| 7.4.4 Variable-Voltage Inverters (VVI)                          | 258 | 7.4.5 Pulse-Width Modulation Inverters                             | 258 | 7.4.6 Current-Source Input (CSI) Inverters       | 260 |
| 7.4.7 Cycloconverters                                           | 260 | 7.4.8 Applications for Inverters                                   | 260 |                                                  |     |
| 7.5 DC-TO-DC CONTROL (CONVERTERS AND CHOPPERS)                  | 261 |                                                                    |     |                                                  |     |
| 7.5.1 Overview of DC-to-DC Voltage Conversion                   | 261 | 7.5.2 Linear Power Supplies                                        | 261 | 7.5.3 Switching Power Supplies                   | 262 |
| 7.5.4 The Buck Converter                                        | 263 | 7.5.5 The Boost Regulator                                          | 264 | 7.5.6 The Buck-Roost Regulator                   | 265 |
| 7.5.7 The Forward Converter                                     | 265 | 7.5.8 The Push-Pull Converter                                      | 266 | 7.5.9 The Half-Bridge Converter                  | 267 |
| 7.5.10 The Full-Bridge Converter                                | 267 |                                                                    |     |                                                  |     |
| 7.6 WHAT YOU MAY FIND WHEN YOU WORK ON A POWER SUPPLY           | 268 |                                                                    |     |                                                  |     |

## 8 OPERATIONAL AMPLIFIERS 272

|                                                         |     |
|---------------------------------------------------------|-----|
| 8.1 OVERVIEW OF OPERATIONAL AMPLIFIERS                  | 273 |
| 8.1.1 What Op Amps Do                                   | 274 |
| 8.2 BASIC OP AMP CIRCUIT                                | 274 |
| 8.2.1 The Op Amp Power Supply                           | 275 |
| 8.2.2 The Ideal Amplifier                               | 276 |
| 8.3 THE COMPARATOR                                      | 276 |
| 8.4 THE VOLTAGE FOLLOWER                                | 278 |
| 8.5 THE INVERTING LINEAR AMPLIFIER                      | 279 |
| 8.5.1 Operation of the Inverting Amplifier              | 280 |
| 8.6 THE NONINVERTING OP AMP                             | 280 |
| 8.7 VOLTAGE-TO-CURRENT CONVERTERS                       | 282 |
| 8.7.1 Applications for the Voltage-to-Current Converter | 283 |
| 8.8 CURRENT-TO-VOLTAGE AMPLIFIERS                       | 283 |
| 8.9 SUMMING AMPLIFIERS                                  | 284 |
| 8.10 OP AMPS USED AS INTEGRATORS                        | 285 |
| 8.11 OP AMPS USED AS DIFFERENTIATORS                    | 286 |
| 8.12 THE OP AMP WINDOW DETECTOR                         | 288 |
| 8.12.1 Operation of the Window Detector (Comparator)    | 289 |

## 8.13 ADDING ZERO AND SPAN TO AN OP AMP CIRCUIT 289

### 8.13.1 Setting Zero and Span 290

## 8.14 THE DIFFERENTIAL AMPLIFIER 290

## 8.15 INSTRUMENTATION AMPLIFIERS 291

9

# OPEN-LOOP AND CLOSED-LOOP FEEDBACK SYSTEMS 296

## 9.1 OVERVIEW OF OPEN-LOOP AND CLOSED-LOOP SYSTEMS 297

## 9.2 PARTS OF A TYPICAL CONTROL SYSTEM 298

### 9.2.1 An Electric Heating Application 298

## 9.3 A TYPICAL OPEN-LOOP SYSTEM 299

- 9.3.1 Manual Mode and Auto Mode 300      9.3.2 An Example of a Sump Pump Control 301      9.3.3 On-Off Control 301      9.3.4 Adding Differential Gap (Dead Band) to the Sump Pump Application 302      9.3.5 Automating the Sump Pump Application 304

## 9.4 SINGLE-POINT PROCESS CONTROLLER 304

### 9.4.1 Operating a Controller in Manual and Auto Modes 305

## 9.5 BUMPLESS TRANSFER 305

## 9.6 VALVE POSITIONING SYSTEM TO CONTROL WATER LEVEL IN A TANK 306

## 9.7 HOW FAST CONTROLLERS WILL CHANGE THE OUTPUT 307

## 9.8 UNDERSTANDING GAIN, RESET, AND RATE 308

- 9.8.1 Using Gain for Control 309      9.8.2 Problems with Using Only Gain for Control 310      9.8.3 Using a Gain-Only Controller 311

## 9.9 ADDING OFFSET (BIAS) 312

### 9.9.1 Problems with Adding Bias Manually 312

## 9.10 EXAMPLE OF AN INDUSTRIAL SYSTEM THAT USES GAIN AND RESET 313

- 9.10.1 Adding Integral (Reset) to the Formula to Change Bias Automatically 313      9.10.2 Using Values for Integral Action 314      9.10.3 Reset Action 316

## 9.11 ADDING DERIVATIVE (RATE) TO THE FORMULA 316

- 9.11.1 Rate Action 317      9.11.2 Other Effects of Derivatives 317

## 9.12 PROPORTIONAL AND DERIVATIVE CONTROL (PD) 318

## 9.13 PROPORTIONAL BAND 318

## 9.14 RATIO CONTROL FOR ON-OFF HEATING CONTACTOR 320

## 9.15 TYPES OF SYSTEM RESPONSE 321

## 9.16 TUNING THE CONTROLLER 322

- 9.16.1 Determining Gain, Reset, and Rate (PID) in Manual Mode 322      9.16.2 Determining PID Values from Process Gain, Dead Time, and Time Constant 325      9.16.3 Determining PID Values for a Slower Responding System 325      9.16.4 Determining PID Values in Automatic (Closed-Loop) Mode 326

## 9.17 ADJUSTING GAIN, RESET, AND RATE AFTER A SYSTEM HAS BEEN RUNNING 327

## 9.18 PROCESS ALARMS AND DEVIATION ALARMS 328

- 9.18.1 Inner and Outer Alarm Bands 329
- 9.18.2 Statistical Process Control (SPC) 329

## 9.19 ADVANCED CLOSED-LOOP SYSTEMS 330

- 9.19.1 Cascaded Loops 330
- 9.19.2 Operation of the Cascade Controller 331

## 9.20 EXAMPLE SERVO APPLICATIONS 331

- 9.20.1 A Simple Analog Servo Positioning System 332
- 9.20.2 Closed-Loop Velocity and Positioning Control of a Servomotor 332

# 10 INPUT DEVICES: SENSORS, TRANSDUCERS, AND TRANSMITTERS FOR MEASUREMENT 338

## 10.1 OVERVIEW OF SENSORS, TRANSDUCERS, AND TRANSMITTERS 340

- 10.1.1 Signal Types 341
- 10.1.2 Analog and Digital Signals 341
- 10.1.3 Basic Sensor Circuits 342
- 10.1.4 Transmitters 343
- 10.1.5 Recorders 346
- 10.1.6 Alarm Systems 347
- 10.1.7 Applications for Explosion-Proof Sensors 347
- 10.1.8 Overview 348

## 10.2 TEMPERATURE SENSORS 349

- 10.2.1 Temperature Conversions 349
- 10.2.2 Thermocouples 350
- 10.2.3 Types of Thermocouples 353
- 10.2.4 Resistance Temperature Detector (RTD) 359
- 10.2.5 Thermistors 363
- 10.2.6 Integrated Circuit (IC) Solid-State Temperature Sensors 366
- 10.2.7 Infrared Thermometry and Optical Pyrometers 368
- 10.2.8 Nonelectrical Temperature Sensors 371
- 10.2.9 Comparison of Temperature Sensors 371

## 10.3 PRESSURE SENSORS 373

- 10.3.1 Parameters of Pressure 373
- 10.3.2 Vacuum: Pressure Readings Below Atmospheric Pressure 374
- 10.3.3 The Bourdon Tube as a Pressure Sensor 376
- 10.3.4 Diaphragm Pressure Sensor 377
- 10.3.5 Differential Pressure Sensor 377
- 10.3.6 Bellows Pressure Sensor 378
- 10.3.7 The Strain Gauge 378
- 10.3.8 Load Cells 383
- 10.3.9 Pressure Transducers and Transmitters 386
- 10.3.10 Industrial Scales and Weighing Systems 387
- 10.3.11 Piezoelectric Pressure Sensors 389
- 10.3.12 Capacitance Pressure Sensors 389
- 10.3.13 Variable Reluctance/Inductance Pressure Sensors 390
- 10.3.14 Differential Pressure Sensors ( $\Delta P$  Sensors) 390
- 10.3.15 Ultralow-Pressure Sensors 390
- 10.3.16 Multiple Uses for Pressure Sensors 391

## 10.4 FLOW SENSORS 391

- 10.4.1 Flow Technology 392
- 10.4.2 Calculating Flow from a Pressure-Drop Measurement 394
- 10.4.3 Types of Flow Meters That Utilize a Pressure Drop 395
- 10.4.4 Velocity Flow Meters 398
- 10.4.5 Positive Displacement Flow Meters 401
- 10.4.6 Mass Flow Meters 402
- 10.4.7 Nonelectrical Flow Meters 403
- 10.4.8 Applications of Flow Meters 404

## 10.5 DENSITY AND VISCOSITY SENSORS 405

- 10.5.1 Liquid Density Sensors 406
- 10.5.2 Viscosity Sensors 408

## 10.6 LEVEL SENSORS 408

10.6.1 Point-Contact Level Sensors 409  
Sensors 415

10.6.2 Continuous Level

## 10.7 POSITION SENSORS 423

10.7.1 Linear Potentiometer 424 10.7.2 Rotary Potentiometer 425

10.7.3 Linear Variable Differential Transformers (LVDTs) 426

10.7.4 Magnetostrictive-Type Position Sensor 428 10.7.5 Proximity  
Switches 431 10.7.6 Hall-Effect Sensors 433 10.7.7 Linear and

Rotary Encoders 435

## 10.8 MOTION SENSORS 442

10.8.1 Accelerometers 442 10.8.2 Tachometers 444

10.9 PH SENSORS 445

## 10.10 HUMIDITY SENSORS 446

## 10.11 GAS DETECTORS 446

# 11 OUTPUT DEVICES: AMPLIFIERS, VALVES, RELAYS, VARIABLE-FREQUENCY DRIVES, STEPPER MOTORS, AND SERVOMOTOR DRIVES 455

## 11.1 OVERVIEW OF OUTPUT DEVICES 457

## 11.2 SOLENOID VALVES 457

11.2.1 Typical Voltages and Wattages for Solenoid Valves 459

11.2.2 Types of Solenoids 461 11.2.3 Applications for Solenoids 462

11.2.4 Three-Position Solenoid Valves 463 11.2.5 Diagrams of Solenoids  
as Outputs 463

## 11.3 PROPORTIONAL VALVES 465

11.3.1 Types of Control from a Proportional Control Valve 466

11.3.2 Proportional Valve Amplifiers 468 11.3.3 Constant-Voltage

Proportional Valves 470 11.3.4 Troubleshooting Proportional Amplifiers  
and Valves 471

## 11.4 PNEUMATIC-ASSISTED CONTROL VALVES 472

11.4.1 Simplified Pneumatic-Assisted Valve 473 11.4.2 Parts of a

Pneumatic-Assisted Control Valve 474 11.4.3 Butterfly Pneumatic-

Assisted Control Valves 476 11.4.4 Current-to-Pressure ( $I/P$ )  
Converters 476

## 11.5 MOTOR-DRIVEN VALVES 479

11.5.1 Using a Proportional Amplifier with a Motor-Driven Valve 480

## 11.6 RELAYS, CONTACTORS, AND MOTOR STARTERS 481

11.6.1 Types of Relays 481 11.6.2 Methods of Operation for Relays 481

11.6.3 Sets of NO and NC Contacts 481 11.6.4 Changing NO Contacts to  
NC Contacts in the Field 481 11.6.5 Pull-In and Hold-In Current 482

11.6.6 Types of Relays 484 11.6.7 Contactors 484 11.6.8 Basic Parts  
of a Contactor 487 11.6.9 Ratings for Coils 487 11.6.10 Motor

Starters 489 11.6.11 Operation of the Overloads 492 11.6.12 Sizing

Motor Starters 494 11.6.13 Sizing Heater Elements for Motor

Starters 495 11.6.14 Solid-State Motor Starters 497

- 11.7 VARIABLE-FREQUENCY DRIVES 498
  - 11.7.1 Block Diagram of a Variable-Frequency Drive 499
  - 11.7.2 A Typical Drive Installation 500
  - 11.7.3 External Control Switches and Contacts for the Drive 501
  - 11.7.4 External Outputs for the Drive 503
  - 11.7.5 Solid-State Circuits for Variable-Frequency Drives 503
  - 11.7.6 Pulse-Width Modulation Waveforms for Variable-Frequency Drives 505
  - 11.7.7 Insulated Gate Bipolar Transistor Drives 506
  - 11.7.8 Variable-Frequency Drive Parameters 506
  - 11.7.9 Typical Applications for Variable-Frequency Drives 509
  - 11.7.10 Operating the Variable-Frequency Drive 512
  - 11.7.11 Scalar Drives and Vector Drives 512
  - 11.7.12 Variable-Voltage Input Drives 513
  - 11.7.13 Current-Source Input Drives 514
- 11.8 DC DRIVES 514
  - 11.8.1 Modern Programmable DC Drives 517
- 11.9 STEPPER MOTORS 518
  - 11.9.1 Types of Stepper Motors 519
  - 11.9.2 Stepper Motor Theory of Operation 519
  - 11.9.3 Switching Sequence for Full- and Half-Step Motors 522
  - 11.9.4 Microstep Mode 524
  - 11.9.5 Stepper Motor Amplifier Circuits 524
  - 11.9.6 Stepper Motor Applications 527
  - 11.9.7 Selecting the Proper Size Stepper Motor 527
- 11.10 LINEAR STEPPER MOTORS 530
  - 11.10.1 Operation of the Linear Stepper Motor 531
  - 11.10.2 Linear Motor Applications 531
- 11.11 SERVOMOTORS 533
  - 11.11.1 Simple Servo Amplifiers 535
  - 11.11.2 Amplifiers for DC Servomotors 538
  - 11.11.3 AC Servo Amplifiers 539
  - 11.11.4 Digital Servo Drives 540
  - 11.11.5 Servomotors 541
  - 11.11.6 Servomotor Controllers 543
  - 11.11.7 PWM Servo Amplifier 546
  - 11.11.8 Applications for Servo Amplifiers and Motors 546
  - 11.11.9 Selecting a Servomotor for an Application 551

## 12 AC AND DC MOTORS AND GENERATORS, TRANSFORMERS, AND THREE-PHASE ELECTRICITY 558

- 12.1 INTRODUCTION 559
- 12.2 MAGNETIC THEORY 560
- 12.3 DC MOTOR THEORY 561
- 12.4 DC MOTOR COMPONENTS 564
  - 12.4.1 Armature 565
  - 12.4.2 Motor Frame 566
  - 12.4.3 End Plates 568
  - 12.4.4 Brushes and Brush Rigging 568
- 12.5 DC MOTOR OPERATION 569
- 12.6 TYPES OF DC MOTORS 570
  - 12.6.1 DC Series Motors 570
  - 12.6.2 Series Motor Operation 571
  - 12.6.3 Producing Back EMF 571
  - 12.6.4 Reversing the Rotation of a Motor 572
  - 12.6.5 Installing and Troubleshooting a Series Motor 574
  - 12.6.6 DC Series Motor Used as a Universal Motor 575

## **12.7 DC SHUNT MOTORS 575**

- 12.7.1 Shunt Motor Operation 576
- 12.7.2 Controlling the Speed of the Motor 576
- 12.7.3 Torque Characteristics 577
- 12.7.4 Reversing the Rotation of the Motor 578
- 12.7.5 Installing a Shunt Motor 578
- 12.7.6 Troubleshooting the Shunt Motor 579

## **12.8 DC COMPOUND MOTORS 581**

- 12.8.1 Cumulative Compound Motors 581
- 12.8.2 Differential Compound Motors 582
- 12.8.3 Compound Interpole Motors 582
- 12.8.4 Reversing the Rotation of the DC Compound Motor 582
- 12.8.5 Controlling the Speed of the Motor 583

## **12.9 AC MOTORS 584**

## **12.10 CHARACTERISTICS OF THREE-PHASE VOLTAGE 585**

## **12.11 THREE-PHASE MOTOR COMPONENTS 586**

- 12.11.1 Stator 586
- 12.11.2 Rotor 588
- 12.11.3 Motor End Plates 589

## **12.12 OPERATION OF AN AC INDUCTION MOTOR 589**

- 12.12.1 Induced Current in the Rotor 590

## **12.13 CONNECTING MOTORS FOR TORQUE SPEED AND HORSEPOWER CONDITIONS 591**

- 12.13.1 Wye-Connected Motors 592
- 12.13.2 Delta-Connected Motors 592

## **12.14 REVERSING THE ROTATION OF A THREE-PHASE INDUCTION MOTOR 593**

## **12.15 CONNECTING MOTORS FOR A CHANGE OF VOLTAGE 594**

## **12.16 CONNECTING THREE-PHASE MOTORS FOR A CHANGE OF SPEED 597**

- 12.16.1 Interpreting the Wiring Diagrams and Tables 597

## **12.17 MOTOR DATA PLATES 599**

- 12.17.1 Identification Number (ID) 599
- 12.17.2 Frame Type 599
- 12.17.3 Motor Type 600
- 12.17.4 Phase 600
- 12.17.5 Horsepower Rating (hp) 600
- 12.17.6 rpm (Speed) 600
- 12.17.7 Volts 601
- 12.17.8 Amps 601
- 12.17.9 Frequency 601
- 12.17.10 Service Factor (SF) 601
- 12.17.11 Duty Cycle 601
- 12.17.12 Insulation Class 602
- 12.17.13 Ambient Temperature Rise 602
- 12.17.14 NEMA Design 602
- 12.17.15 NEMA Code Letters 603

## **12.18 THREE-PHASE SYNCHRONOUS MOTORS 603**

## **12.19 AC SINGLE-PHASE MOTORS 605**

## **12.20 SINGLE-PHASE MOTOR COMPONENTS 605**

- 12.20.1 Stator 605
- 12.20.2 Terminal Identification 607
- 12.20.3 Rotor and End Plates 608
- 12.20.4 Centrifugal Switch for the Start Winding 609
- 12.20.5 Thermal Overload Protector 610

## **12.21 CHANGING VOLTAGE AND SPEEDS OF SINGLE-PHASE MOTORS 610**

## **12.22 INCREASING THE STARTING TORQUE OF A SINGLE-PHASE MOTOR 611**

## **12.23 SPLIT-PHASE MOTORS 611**

- 12.23.1 Counter EMF 612
- 12.23.2 Applications for Split-Phase Motors 613

|         |                                                                       |     |
|---------|-----------------------------------------------------------------------|-----|
| 12.24   | CAPACITOR START, INDUCTION RUN MOTORS                                 | 613 |
| 12.24.1 | Electrical Diagram for a CSIR Motor                                   | 613 |
| 12.24.2 | Connecting the CSIR Motor for Dual-Voltage or Dual-Speed Applications | 614 |
| 12.24.3 | Connecting the CSIR Motor for a Change of Rotation                    | 614 |
| 12.24.4 | Applications for CSIR Motors                                          | 615 |
| 12.24.5 | Current Relay Operation                                               | 616 |
| 12.25   | CAPACITOR START, CAPACITOR RUN MOTORS                                 | 617 |
| 12.25.1 | Using a Potential Relay to Start a CSCR Motor                         | 618 |
| 12.26   | PERMANENT SPLIT-CAPACITOR MOTORS                                      | 619 |
| 12.26.1 | Connecting a PSC Motor for a Change of Speed                          | 620 |
| 12.26.2 | Changing Voltage or Direction of Rotation                             | 620 |
| 12.27   | SHADED-POLE MOTORS                                                    | 621 |
| 12.28   | REPULSION START MOTORS                                                | 622 |
| 12.29   | TROUBLESHOOTING THREE-PHASE AND SINGLE-PHASE MOTORS                   | 622 |
| 12.29.1 | Motor Will Not Turn When Power Is Applied                             | 622 |
| 12.29.2 | Motor Hums But Will Not Turn When Power Is Applied                    | 623 |
| 12.30   | DC GENERATORS                                                         | 623 |
| 12.30.1 | Basic Parts and Basic Operation of a DC Shunt Generator               | 623 |
| 12.30.2 | Separately Excited Shunt Generator                                    | 625 |
| 12.30.3 | Self-Excited Shunt Generator                                          | 626 |
| 12.30.4 | Compound Generator                                                    | 627 |
| 12.30.5 | Series Generator                                                      | 627 |
| 12.30.6 | Controlling the Amount of Voltage and Its Polarity in a DC Generator  | 627 |
| 12.30.7 | Troubleshooting a DC Generator                                        | 629 |
| 12.31   | AC ALTERNATORS                                                        | 630 |
| 12.31.1 | Theory of Operation of the Alternator                                 | 630 |
| 12.31.2 | AC Voltage in the Strator                                             | 631 |
| 12.31.3 | Producing Three-Phase Voltage                                         | 632 |
| 12.31.4 | Using an Alternator to Produce DC Voltage                             | 632 |
| 12.31.5 | Troubleshooting an Alternator                                         | 633 |
| 12.32   | OVERVIEW OF TRANSFORMERS                                              | 634 |
| 12.33   | OPERATION OF A TRANSFORMER AND BASIC MAGNETIC THEORY                  | 635 |
| 12.34   | CONNECTING A TRANSFORMER TO A DISCONNECT FOR TESTING                  | 637 |
| 12.35   | TRANSFORMER RATED FOR 230 VOLTS AND 208 VOLTS                         | 638 |
| 12.36   | TRANSFORMER VOLTAGE, CURRENT, AND TURNS RATIOS                        | 638 |
| 12.37   | STEP-UP AND STEP-DOWN TRANSFORMERS                                    | 640 |
| 12.38   | VA RATINGS FOR TRANSFORMERS                                           | 640 |
| 12.39   | THE 120-VOLT AC TRANSFORMER                                           | 641 |
| 12.40   | WIRING THE CONTROL TRANSFORMER FOR 480 VOLTS AC PRIMARY VOLTS         | 642 |
| 12.41   | WIRING THE CONTROL TRANSFORMER FOR 240 VOLTS AC PRIMARY VOLTS         | 643 |
| 12.42   | TROUBLESHOOTING A TRANSFORMER                                         | 644 |
| 12.43   | NATURE OF THREE-PHASE VOLTAGE                                         | 644 |
| 12.44   | WHY THREE-PHASE VOLTAGE IS GENERATED                                  | 645 |

- 12.45 THREE-PHASE TRANSFORMERS 645
- 12.46 THE WYE-CONNECTED THREE-PHASE TRANSFORMER 647
- 12.47 THE DELTA-CONNECTED THREE-PHASE TRANSFORMER 647
- 12.48 DELTA- AND WYE-CONNECTED TRANSFORMERS WITH A NEUTRAL TERMINAL 648 -
- 12.49 THE HIGH LEG DELTA SYSTEM 650
- 12.50 THREE-PHASE VOLTAGE ON SITE 651
- 12.51 INSTALLING WIRING IN A THREE-PHASE DISCONNECT 652
- 12.52 TESTING FOR A BAD FUSE IN A DISCONNECT 653
- 12.53 SINGLE-PHASE VOLTAGE FROM A THREE-PHASE SUPPLY 654
- 12.54 BUS DUCT AND BUS DISCONNECT BOXES 654
- 12.55 WIRING A DUPLEX RECEPTACLE AS A UTILITY OUTLET 655

## **13 CASE STUDIES OF FOUR INDUSTRIAL APPLICATIONS 661**

### **APPLICATION 1: NO CAN/NO FILL SENSING FOR BEVERAGE FILLERS 663**

- 13.1.1 Overview of the System 663
- 13.1.2 Typical Operation 663
- 13.1.3 Using a Shift Register to Control Signal Timing 665
- 13.1.4 Electrical Diagram of Sensors and Valves Connected to the Controller 667
- 13.1.5 Troubleshooting the System 667

### **APPLICATION 2: ALUMINUM ROLLING MILL 670**

- 13.2.1 Overview of the System 670
- 13.2.2 Controls for the Cold-Roll Mill 672
- 13.2.3 Typical Operation of the Mill 672
- 13.2.4 Butt-Weld Section 673
- 13.2.5 Accumulator Section 673
- 13.2.6 The Three-Stand Tandem Mill 672
- 13.2.7 Speed Control for the Rollers 674
- 13.2.8 Mainframe Computers, PLCs, and Motor Drives 675

### **APPLICATION 3: MICROPROCESSOR-CONTROLLED PLASTIC RESIN DRYER 677**

- 13.3.1 Overview of the System 677
- 13.3.2 Basic Parts of the System 678
- 13.3.3 Control Parameters for the Dryer 678
- 13.3.4 Normal Operation of the Dryer 679
- 13.3.5 Control Loops for the Dryer 680
- 13.3.6 Wiring Diagram for the Dryer 681

### **APPLICATION 4: FINISHING AND BALANCING BRAKE ROTORS 683**

- 13.4.1 Overview 683
- 13.4.2 Electronics Used 683
- 13.4.3 Sensors for Balancing 683

## **14 ROBOTS AND OTHER MOTION CONTROL SYSTEMS 688**

### **14.1 OVERVIEW OF ROBOTS 689**

### **14.2 TYPES OF ROBOTS 690**

- 14.2.1 Cylindrical Robots 692
- 14.2.2 Rectilinear Robots 693
- 14.2.3 Spherical Robots 695
- 14.2.4 Jointed Spherical (Articulated Arm) Robots 696

- 14.3 TYPES OF ROBOT CONTROL 698
  - 14.3.1 Point-to-Point Robot Control 698
  - 14.3.2 Continuous-Path Control 699
  - 14.3.3 XYZ Control 700
  - 14.3.4 Positive-Stop Control 701
- 14.4 TYPES OF ROBOT PROGRAMS 702
  - 14.4.1 Point-to-Point and XYZ Programs 703
  - 14.4.2 Continuous-Path Programs 703
  - 14.4.3 Positive-Stop Programs and PLC Programs 704
  - 14.4.4 BASIC Programs and C Programs 704
- 14.5 COMPUTER NUMERICAL CONTROL (CNC) MACHINES 705
- 14.6 BASIC PARTS OF A ROBOT SYSTEM 706
  - 14.6.1 Power Supply 707
  - 14.6.2 Controllers and Teach Pendants 710
  - 14.6.3 Axis-Control Module 713
  - 14.6.4 Amplifiers, Motors, and Feedback Sensors 714
  - 14.6.5 Positional Feedback Loop and Velocity Feedback Loop 717
- 14.7 OTHER TYPES OF ROBOT ACTUATORS 718
  - 14.7.1 Hydraulic Actuators 718
  - 14.7.2 Pneumatic Actuators 718
  - 14.7.3 Comparison of Robot Actuator 719
- 14.8 INPUT AND OUTPUT SIGNALS FOR ROBOTS 720
- 14.9 INPUT CIRCUITS FOR ROBOT SIGNALS 722
- 14.10 OUTPUT CIRCUITS FOR ROBOT SIGNALS 724
- 14.11 INPUT AND OUTPUT MODULES 725
- 14.12 ROBOTS USED IN TYPICAL WORK CELLS AND MANUFACTURING CELLS 726
  - 14.12.1 Automotive Welding Line 727
  - 14.12.2 Loading and Unloading Bonding Machines 728
  - 14.12.3 Robotic Painting Cells 729

## 15 MOTOR-CONTROL DEVICES AND CIRCUITS 734

- 15.1 INTRODUCTION 735
- 15.2 PILOT DEVICES 736
  - 15.2.1 Limit Switches and Other Pilot Switches 737
  - 15.2.2 Symbols for Limit Switches and Other Motor-Control Devices 738
  - 15.2.3 Electrical Symbols for Other Pilot Devices 739
- 15.3 CONTROL CIRCUITS AND LOAD CIRCUITS 741
  - 15.3.1 Two-Wire Control Circuits 742
  - 15.3.2 The Three-Wire Control Circuit 744
  - 15.3.3 A Three-Wire Start/Stop Circuit with Multiple Start/Stop Push Buttons 745
  - 15.3.4 Three-Wire Control Circuit with Indicator Lamp 746
  - 15.3.5 Reverse Motor Starters 747
  - 15.3.6 Reversing Motors with a Drum Switch 749
  - 15.3.7 Jogging Control Circuits 751
  - 15.3.8 Sequence Controls for Motor Starters 753
- 15.4 OTHER TYPES OF PILOT DEVICES 754
  - 15.4.1 Timers 757
- 15.5 FUSES AND CIRCUIT BREAKERS 757
  - 15.5.1 Slow Overcurrents 757
  - 15.5.2 Protecting Against Slow Overcurrent 758
  - 15.5.3 Short-Circuit Currents 758
  - 15.5.4 Single-Element Fuses 760
  - 15.5.5 Dual-Element Fuses 761
  - 15.5.6 Interruption Capacity 762
  - 15.5.7 Types of Fuses 762

15.6 ENCLOSURES 762

15.7 CONDUCTORS 767

15.8 OVERVIEW OF LOCKOUT, TAG-OUT SAFETY 769

- 15.8.1 A Typical Lockout, Tag-out Policy 770
- 15.8.2 Determining the Lockout, Tag-out Policy and Procedure 770
- 15.8.3 Identifying the Sources of Kinetic Energy and Potential Energy 770
- 15.8.4 Designing Safety into the Machine 771
- 15.8.5 OSHA Inspections 772
- 15.8.6 What Is Lockout? 772
- 15.8.7 What Is Tag-out? 773
- 15.8.8 Designing a Lockout, Tag-out Procedure 774
- 15.8.9 Removing the Lockout, Tag-out Devices and Returning Power to the Machine 774
- 15.8.10 Review of Lockout, Tag-out Procedures 775

## 6 DATA COMMUNICATIONS FOR INDUSTRIAL ELECTRONICS 781

16.1 OVERVIEW OF DATA COMMUNICATIONS USED IN INDUSTRY 782

16.2 NETWORK ARCHITECTURES 784

- 16.2.1 The Physical Layer 785
- 16.2.2 The Data Link Layer 785
- 16.2.3 The Network Layer 786
- 16.2.4 The Transport Layer 786
- 16.2.5 The Session Layer 787
- 16.2.6 The Presentation Layer 787
- 16.2.7 The Application Layer 788
- 16.2.8 Review of the ISO Model 788

16.3 DATA FORMATS 789

- 16.3.1 The ASCII Code 789
- 16.3.2 The EBCDIC Code 789

16.4 PROTOCOLS AND STANDARDS 790

- 16.4.1 Ethernet and IEEE 802 Standards 791
- 16.4.2 MAP Protocol 792
- 16.4.3 The Technical Office Protocol (TOP) 792
- 16.4.4 Transmission Control Protocol and Internet Protocol (TCP/IP) 793
- 16.4.5 Systems Network Architecture (SNA) 793
- 16.4.6 Manufacturing Message Specification (MMS) 793
- 16.4.7 European Standards: The Fieldbus 793
- 16.4.8 PROFIBUS 794
- 16.4.9 Device Net 795
- 16.4.10 Comparing Standards and Protocols 795

16.5 PARTS AND MEDIA OF THE PHYSICAL LAYER 796

- 16.5.1 Transmission Media 796
- 16.5.2 Physical Cable Connections: The RS232 Interface 798
- 16.5.3 The Nine-Pin Connector for the RS232 Interface 801
- 16.5.4 The RS422 Interface 802
- 16.5.5 Other Common Connectors Used in Industrial Data Communications 802
- 16.5.6 De Facto Standards for DB25 Connectors for Modern Personal Computers 802

16.6 TYPICAL NETWORK TOPOLOGIES 804

- 16.6.1 Types of Network Topologies 804

16.7 TYPICAL FACTORY AUTOMATION NETWORKS 805

- 16.7.1 Strengths of the Ethernet 807

16.8 THE BROADBAND NETWORK 807

16.9 TROUBLESHOOTING NETWORKS 807

- 16.9.1 Test Equipment 808

APPENDIX A SHOP SAFETY AND SHOP PRACTICES 813

APPENDIX B TECHNICAL DATA 824

ACRONYMS 849

GLOSSARY 851

INDEX 861