

# Contents

Preface	xi	
<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	The need for variable speed drives	1
1.2	Fundamental principles	2
1.3	Torque-speed curves for variable speed drives	7
1.4	Types of variable speed drives	11
1.5	Mechanical variable speed drive methods	13
1.5.1	Belt and chain drives with adjustable diameter sheaves	13
1.5.2	Metalic friction drives	14
1.6	Hydraulic variable speed drive methods	14
1.6.1	Hydrodynamic types	15
1.6.2	Hydrostatic type	15
1.7	Electromagnetic or 'Eddy Current' coupling	16
1.8	Electrical variable speed drive methods	20
1.8.1	AC commutator motor – schrage motor	20
1.8.2	Ward-Leonard system	20
1.8.3	Electrical variable speed drives for DC motors (DC drives)	21
1.8.4	Electrical variable speed drives for AC motors (AC drives)	23
1.8.5	Slip control AC variable speed drives	28
1.8.7	Cycloconverters	34
1.8.8	Servo-drives	34
<b>2</b>	<b>3-phase AC induction motors</b>	<b>36</b>
2.1	Introduction	36
2.2	Basic construction	37
2.2.1	The stator	37
2.2.2	The rotor	38
2.2.3	The other parts	38
2.3	Principles of operation	39
2.4	The equivalent circuit	41
2.5	Electrical and mechanical performance	45
2.6	Motor acceleration	48
2.7	AC induction generator performance	50
2.8	Efficiency of electric motors	51
2.9	Rating of AC induction motors	52
2.10	Electric motor duty cycles	54
	S1: Continuous running duty	54
	S2: Short-time duty	55
	S3: Intermittent periodic duty not affected by the starting process	55

S4: Intermittent periodic duty affected by the starting process	56
S5: Intermittent periodic duty affected by the starting process and also by electric braking	57
S6: Continuous operation, periodic duty with intermittent load	58
S7: Uninterrupted periodic duty, affected by the starting process and also by electric braking	58
S8: Uninterrupted periodic duty with recurring speed and load changes	59
2.11 Cooling and ventilation of electric motors (IC)	60
2.12 Degree of protection of motor enclosures (IP)	62
2.13 Construction and mounting of AC induction motors	63
2.14 Anti-condensation heaters	65
2.15 Methods of starting AC induction motors	65
2.16 Motor selection	66
<hr/>	
<b>3 Power electronic converters</b>	<b>68</b>
<hr/>	
3.1 Introduction	68
3.2 Definitions	68
3.3 Power diodes	71
3.4 Power thyristors	73
3.5 Commutation	76
3.6 Power electronic rectifiers (AC/DC converters)	77
3.6.1 Line commutated diode rectifier bridge	81
3.6.2 The line commutated thyristor rectifier bridge	85
3.6.3 Practical limitations of line commutated converters	91
3.6.4 Applications for line commutated rectifiers	92
3.7 Gate commutated inverters (DC/AC converters)	94
3.7.1 Single-phase square wave inverter	95
3.7.2 Single-phase pulse width modulation (PWM) inverter	97
3.7.3 Three-phase inverter	101
3.8 Gate controlled power electronic devices	104
3.8.1 Gate turn-off thyristor (GTO)	104
3.8.2 Field controlled thyristors (FCT)	105
3.8.3 Power bipolar junction transistors (BJT)	105
3.8.4 Field effect transistor (FET)	108
3.8.5 Insulated gate bipolar transistor (IGBT)	109
3.8.6 Comparison of power ratings and switching speed of gate controlled power electronic devices	112
3.9 Other power converter circuit components	112
<hr/>	
<b>4 Electromagnetic compatibility (EMC)</b>	<b>114</b>
<hr/>	
4.1 Introduction	114
4.2 The sources of electromagnetic interference	116
4.3 Harmonics generated on the supply side of AC converters	118
4.3.1 Definitions	118
4.3.2 The analysis of the harmonic distortion	119

4.3.3	Effects of harmonics on other equipment	121
4.3.4	Acceptable levels of distortion in the mains supply system	126
4.3.5	Methods of reducing harmonic voltages in the power supply	127
4.4	Power factor and displacement factor	129
4.5	Voltages and current on the motor side of PWM inverters	131
4.5.1	Effect of the high PWM switching frequency on long motor cables	131
4.5.2	Selection of PWM switching frequency	132
4.5.3	High rates of rise of voltage (dv/dt) at inverter output	133
4.5.4	Protection of motors against high PWM switching frequency	135
4.5.5	Compliance with EMC standards	137
4.5.6	EMI (or RFI) filters for PWM inverters	138
4.5.7	Concluding comments about high PWM switching frequency	138
<b>5</b>	<b>Protection of AC converters and motors</b>	<b>140</b>
5.1	Introduction	140
5.2	AC frequency converter protection circuits	140
5.2.1	AC and DC under-voltage protection	141
5.2.2	AC and DC bus over-voltage protection	142
5.2.3	Output over-current protection	144
5.2.4	Output earthfault protection	146
5.2.5	Heat-sink over-temperature protection	147
5.2.6	Motor thermaloverload protection	147
5.2.7	Overall protection and diagnostics	148
5.3	Operator information and fault diagnostics	148
5.4	Electric motor protection	150
5.5	Thermal overload protection – current sensors	152
5.6	Thermal overload protection – direct temperature sensing	153
<b>6</b>	<b>Control systems for AC variable speed drives</b>	<b>156</b>
6.1	The overall control system	156
6.2	Power supply to the control system	157
6.3	The DC bus charging control system	159
6.4	The PWM rectifier for AC converters	161
6.5	Variable speed drive control loops	163
6.5.1	Open-loop control	163
6.5.2	Closed-loop control	163
6.5.3	Cascaded closed-loop control	165
6.6	Vector control for AC drives	167
6.6.1	Basic fixed V/f drives	170
6.6.2	V/f sensorless flux-vector drives (open loop vector)	171
6.6.3	Closed-loop field oriented vector drives	172
6.7	Current feedback in AC variable speed drives	174
6.7.1	Methods of measuring current in variable speed drives	174
6.7.2	Current feedback in general purpose VVVF drives	175

6.7.3	Current feedback in high performance vector drives	176
6.7.4	DC bus current feedback	176
6.8	Speed feedback from the motor	176
<b>7</b>	<b>Selection of AC converters</b>	<b>178</b>
7.1	Introduction	178
7.2	The basic selection procedure	179
7.3	The loadability of converter fed squirrel cage motors	180
7.4	Operation in the constant power region	183
7.5	The nature of the machine load	184
7.5.1	The load torque	184
7.5.2	Variable torque machine loads	187
7.5.3	Constant torque machine loads	187
7.5.4	The speed range	188
7.5.5	The inertia of the machine load	191
7.6	The requirements for starting	194
7.7	The requirements for stopping	196
7.7.1	DC injection braking	197
7.7.2	Motor over-flux braking	198
7.7.3	Dynamic braking	198
7.7.4	Regenerative braking	201
7.8	Control of speed, torque and accuracy	203
7.9	Selecting the correct size of motor and converter	203
7.10	Summary of the selection procedures	205
	STEP 1. Specify the initial data for the drive application	205
	STEP 2. Selecting the number of poles of the motor	205
	STEP 3. Selecting the motor power rating	206
	STEP 4. Select a suitable frequency converter	206
	STEP 5. Final checks	207
	STEP 6. An example of a selection calculation	207
<b>8</b>	<b>Installation and commissioning</b>	<b>209</b>
8.1	General installation and environmental requirements	209
8.1.1	General safety recommendations	209
8.1.2	Hazardous areas	210
8.1.3	Environmental conditions for installation	210
8.1.4	De-rating for high temperature	210
8.1.5	De-rating for high altitude	211
8.2	Power supply connections and earthing requirements	211
8.2.1	Power supply cables	212
8.2.2	Cables between converter and motor	213
8.2.3	Control cables	213
8.2.4	Earthing requirements	214
8.2.5	Common cabling errors	214

8.3	Start/stop control of AC drives	214
8.4	Installing AC converters into metal enclosures	216
8.4.1	Calculating the dimensions of the enclosure	217
8.4.2	Ventilation of enclosures	219
8.4.3	Alternative mounting arrangements	221
8.5	Control wiring for variable speed drives	222
8.5.1	Hard-wired connections to PLC control systems	223
8.5.2	Serial communications with PLC control systems	224
8.5.3	Interface converters	225
8.5.4	Local area networks	226
8.6	Commissioning variable speed drives	227
8.6.1	The purpose of commissioning	227
8.6.2	Selecting the correct application settings	227
8.6.3	Selecting the correct parameter settings	227
<hr/>		
<b>9</b>	<b>Special topics and new developments</b>	<b>229</b>
<hr/>		
9.1	Soft-switching	229
9.2	The matrix converter	231
<hr/>		
<b>Appendix A</b> Motor protection – direct temperature sensing		<b>233</b>
<hr/>		
<b>Appendix B</b> Current measurement transducers		<b>244</b>
<hr/>		
<b>Appendix C</b> Speed measurement transducers		<b>248</b>
<hr/>		
<b>Appendix D</b> International and national standards		<b>262</b>
<hr/>		
<b>Appendix E</b> Glossary		<b>266</b>
<hr/>		
<b>Index</b>		<b>277</b>