

## Table of Contents

<b>Chapter 1. Introduction – Electric Drive Components . .</b>	<b>1</b>
1.1. Definition . . . . .	1
1.2. Electric drive components . . . . .	2
<b>Chapter 2. Driven Bodies . . . . .</b>	<b>5</b>
2.1. Function of the driven body . . . . .	5
2.2. Reference or rated running . . . . .	5
2.3. Transient behavior . . . . .	6
2.4. Specifications . . . . .	7
2.4.1. Basic data . . . . .	7
2.4.2. Characteristics of regulation . . . . .	8
2.4.3. Start-up and braking characteristics . . . . .	9
2.4.4. Transient characteristics . . . . .	10
2.4.5. Characteristics of the peripheral devices . . . . .	10
2.4.6. Thermal aspect . . . . .	11
2.4.7. Constraints . . . . .	12
2.4.8. Specification list . . . . .	12
<b>Chapter 3. Transmission . . . . .</b>	<b>15</b>
3.1. Transmission types and characterization . . . . .	15
3.1.1. Rotating-rotating transmissions . . . . .	15
3.1.2. Rotating-linear transmissions . . . . .	17
3.2. Resolution . . . . .	20
3.2.1. Characteristics . . . . .	20
3.2.2. Choice criteria . . . . .	21

vi	Electric Drives	
	3.2.3. Limits . . . . .	22
	3.3. Speed adaptation . . . . .	22
	3.4. Dynamic behavior. . . . .	23
	3.4.1. Aim. . . . .	23
	3.4.2. Dynamic equations . . . . .	23
	3.4.3. Mechanical time constant . . . . .	27
	3.4.4. Acceleration . . . . .	29
	3.5. Oscillatory torque. . . . .	31
	3.5.1. Aim. . . . .	31
	3.5.2. Smoothing the speed oscillations . . . . .	32
	3.5.3. Torque pulses . . . . .	33
	3.6. Position transfer . . . . .	36
	3.6.1. Aim. . . . .	36
	3.6.2. Speed profile. . . . .	37
	<b>Chapter 4. Motors . . . . .</b>	<b>41</b>
	4.1. Characterization . . . . .	41
	4.2. Rotating and linear motors . . . . .	42
	4.3. Induction motors . . . . .	42
	4.3.1. Structure . . . . .	42
	4.3.2. Equivalent electric scheme . . . . .	43
	4.3.3. Characteristics of current and torque with constant frequency . . . . .	44
	4.3.4. Two speed motor – Dahlander’s coupling . . . . .	48
	4.3.5. Characteristics of current and torque with variable frequency . . . . .	49
	4.3.6. Wound induction motor . . . . .	51
	4.3.7. Single-phase induction motor . . . . .	53
	4.3.8. Application fields. . . . .	54
	4.4. DC motors. . . . .	54
	4.4.1. Structure . . . . .	54
	4.4.2. Equivalent electric scheme . . . . .	55
	4.4.3. Torque and current characteristics. . . . .	56
	4.4.4. Collector motor . . . . .	61
	4.4.5. Applications . . . . .	61
	4.5. Synchronous motors . . . . .	62
	4.5.1. Structure . . . . .	62
	4.5.2. Equivalent circuit . . . . .	64
	4.5.3. Torque characteristics with imposed current . . . . .	65
	4.5.4. Torque characteristics with imposed voltage . . . . .	66

4.5.5. Self-commutated mode . . . . .	67
4.5.6. Angle $\varepsilon$ adaptation for a constant voltage supply . .	69
4.5.7. Applications . . . . .	72
4.6. Variable reluctance motors . . . . .	73
4.6.1. Structure and characteristics . . . . .	73
4.6.2. Driver and applications . . . . .	74
4.7. Linear motors . . . . .	75
4.7.1. Induction motors . . . . .	75
4.7.2. Synchronous motors . . . . .	76
4.7.3. Moving coil motors . . . . .	77
4.8. Piezoelectric motors and actuators . . . . .	81
4.8.1. Piezoelectric motors . . . . .	81
4.8.2. Applications . . . . .	83
4.8.3. Piezoelectric activators . . . . .	84
4.9. Appendix – BLDC motor characteristics . . . . .	84
<b>Chapter 5. Motors: Characterization . . . . .</b>	<b>87</b>
5.1. Characteristics . . . . .	87
5.1.1. Typology . . . . .	87
5.1.2. Aim of the scaling laws . . . . .	88
5.2. Scaling laws . . . . .	89
5.2.1. Copper losses . . . . .	89
5.2.2. Resistances and inductances . . . . .	89
5.2.3. Heating . . . . .	90
5.2.4. Induction and reluctance motors . . . . .	91
5.2.5. Permanent magnet motors . . . . .	93
5.2.6. Example . . . . .	94
5.3. Parametric expression . . . . .	96
5.3.1. Torque . . . . .	96
5.3.2. Comparison . . . . .	97
5.3.3. Inertia . . . . .	98
5.3.4. Acceleration . . . . .	98
<b>Chapter 6. Global Design of an Electric Drive . . . . .</b>	<b>101</b>
6.1. Introduction . . . . .	101
6.2. Dynamic equations . . . . .	102
6.2.1. Position transfer . . . . .	102
6.2.2. Movement equation with a transmission . . . . .	103
6.2.3. Solving . . . . .	105
6.3. Example . . . . .	107

6.3.1. Data . . . . .	107
6.3.2. Drive chosen by the manufacturer . . . . .	107
6.3.3. New drive with the same motor type. . . . .	110
6.3.4. Drive design with a motor of a given type . . . . .	114
6.3.5. High performance motor . . . . .	115
6.3.6. Average performance motor . . . . .	117
6.4. Conclusions . . . . .	117
<b>Chapter 7. Heating and Thermal Limits . . . . .</b>	<b>119</b>
7.1. Heating importance . . . . .	119
7.2. Thermal equations . . . . .	120
7.2.1. Conduction . . . . .	120
7.2.2. Convection and radiation . . . . .	120
7.2.3. Global phenomenon . . . . .	121
7.2.4. Resolution . . . . .	123
7.2.5. Measurement . . . . .	124
7.2.6. Start-up. . . . .	124
7.2.7. Variable behavior . . . . .	125
7.3. Energy dissipated at start-up . . . . .	126
7.3.1. Start-up conditions . . . . .	126
7.3.2. No load direct start-up – induction motor. . . . .	126
7.3.3. No load direct start up – DC motor. . . . .	127
7.3.4. Variable frequency start-up – induction motor . . . . .	129
7.3.5. Variable voltage start-up – DC motor . . . . .	129
7.3.6. Brushless DC motor start-up. . . . .	130
7.4. Cooling modes . . . . .	130
7.4.1. Techniques used . . . . .	130
7.4.2. Air cooling . . . . .	131
7.4.3. Water cooling . . . . .	133
<b>Chapter 8. Electrical Peripherals. . . . .</b>	<b>137</b>
8.1. Adaptation . . . . .	137
8.2. Sources. . . . .	137
8.3. Voltage adjustment. . . . .	138
8.3.1. Principle . . . . .	138
8.3.2. Autotransformer . . . . .	139
8.3.3. Star-triangle start-up. . . . .	142
8.4. Current adjustment devices . . . . .	143
8.4.1. Principle . . . . .	143
8.4.2. Start-up resistance . . . . .	143

8.4.3. Start-up inductance . . . . .	144
8.4.4. Example . . . . .	146
<b>Chapter 9. Electronic Peripherals . . . . .</b>	<b>149</b>
9.1. Power electronic . . . . .	149
9.2. Simple switch . . . . .	150
9.2.1. Basic structure . . . . .	150
9.2.2. Active switch . . . . .	151
9.3. H bridge . . . . .	151
9.3.1. Basic structure . . . . .	151
9.3.2. Active H bridge . . . . .	152
9.3.3. Half-H bridge . . . . .	153
9.4. Element bridge . . . . .	154
9.4.1. Basic structure . . . . .	154
9.4.2. Six transistor active bridge . . . . .	155
9.4.3. 120 degree commutation . . . . .	155
9.4.4. 180 degree commutation . . . . .	157
<b>Chapter 10. Sensors . . . . .</b>	<b>159</b>
10.1. Functions and types . . . . .	159
10.1.1. Functions . . . . .	159
10.1.2. Position and speed . . . . .	159
10.1.3. Sensor types . . . . .	160
10.2. Optical position sensors . . . . .	161
10.2.1. Principle . . . . .	161
10.2.2. Performances . . . . .	162
10.3. Hall sensors . . . . .	163
10.3.1. Principle . . . . .	163
10.3.2. Applications . . . . .	163
10.4. Inductive position sensors . . . . .	164
10.4.1. Principle . . . . .	164
10.4.2. Applications: simple sensor with variable self- inductance . . . . .	164
10.4.3. Linear variable differential transformer . . . . .	165
10.5. Resolver-type rotating, inductive, contactless sensors . . . . .	168
10.5.1. Principle . . . . .	168
10.6. Other position sensors . . . . .	170
10.6.1. Inductosyn sensors . . . . .	170
10.6.2. Capacitive sensors . . . . .	172

x	Electric Drives	
	10.6.3. Sensors by potentiometer . . . . .	174
	10.7. The motor as a position sensor . . . . .	175
	10.7.1. Principle . . . . .	175
	10.7.2. Back-EMF . . . . .	175
	10.7.3. Saturation level measurement . . . . .	176
	10.7.4. Detection of the third harmonic . . . . .	178
	10.8. Sensor position. . . . .	179
	10.8.1. Problems . . . . .	179
	10.8.2. Plays . . . . .	180
	10.8.3. Elasticity . . . . .	180
	10.9. Current sensors . . . . .	181
	10.9.1. Principle . . . . .	181
	10.9.2. Resistance in series . . . . .	181
	10.9.3. Current transformer. . . . .	181
	10.9.4. Current measurement per Hall probe . . . . .	182
	10.10. Protection sensors . . . . .	183
	10.10.1. Aim . . . . .	183
	10.10.2. Over-current and over-voltage . . . . .	183
	10.10.3. Over-heating . . . . .	184
	10.10.4. Other protections . . . . .	184
	<b>Chapter 11. Direct Drives . . . . .</b>	<b>187</b>
	11.1. Performance limits . . . . .	187
	11.1.1. Methodology . . . . .	187
	11.1.2. Specific surface force . . . . .	188
	11.1.3. Permanent magnet motors . . . . .	189
	11.1.4. Induction motor. . . . .	192
	11.1.5. Comparison . . . . .	195
	11.1.6. Linear PM motor . . . . .	196
	11.1.7. Conclusions . . . . .	199
	11.2. Motor with external rotor. . . . .	200
	11.2.1. Specifications . . . . .	200
	11.2.2. Torque . . . . .	200
	11.3. Example . . . . .	203
	11.3.1. Specifications . . . . .	203
	11.3.2. External wheel-motor. . . . .	204
	11.3.3. Classic motor with gearbox . . . . .	204
	11.3.4. Choice . . . . .	206

<b>Chapter 12. Integrated Drives</b> . . . . .	207
12.1. Principle . . . . .	207
12.2. Realization . . . . .	208
12.2.1. Motor and electronics . . . . .	208
12.2.2. System . . . . .	209
12.2.3. Transmission integration. . . . .	211
12.2.4. Applications . . . . .	212
<b>Symbols</b> . . . . .	213
<b>Indices</b> . . . . .	217
<b>Bibliography</b> . . . . .	221
<b>Index</b> . . . . .	223