Table of Contents

Introduction	XV
Chapter 1. Synchronous motor controls, Problems and Modeling Jean-Paul LOUIS, Damien FLIELLER, Ngac Ky NGUYEN and Guy STURTZER	1
1.1. Introduction.	1
1.2. Problems on the synchronous motor control	2
1.2.1. The synchronous motor control, a vector control	2
1.2.2. Direct/inverse model and modeling hypotheses	3
1.2.3. Control properties	5
1.3. Descriptions and physical modeling of the synchronous motor	6
1.3.1. Description of the motor in preparation for its modeling	6
1.3.2. Hypotheses on the motor	8
1.3.3. Notations	9
1.3.4. Main transformation matrices.	9
1.3.5. Physical model of the synchronous motor	10
1.3.6. The two levels voltage inverter.	12
1.3.7. Model of the mechanical load	13
1.4. Modeling in dynamic regime of the synchronous motor in the	
natural three-phase <i>a-b-c</i> reference frame.	14
1.4.1. Model of the machines with non-salient poles and constant	
excitation	14
1.4.2. Exploitation of the model in the a-b-c reference frame in	
sinusoidal steady state, electromagnetic torque	18
1.4.3. Extensions to the case of non-sinusoidal field distribution	
machines	20

vi Control of Synchronous Motors

1.5. Vector transformations and dynamic models in the α - β and	
<i>d</i> - <i>q</i> reference frames (sinusoidal field distribution machines with	
non-salient and salient poles)	24
1.5.1. Factorized matrix modeling.	24
1.5.2. Concordia transformation: α - β reference frame	25
1.5.3. Park transformation, application to the synchronous salient	
pole motor	28
1.5.4. Note on the torque coefficients	30
1.6. Can we extend the Park transformation to synchronous motors	
with non-sinusoidal field distributions?	31
1.7. Conclusion	39
1.8. Appendices	39
1.8.1. Numerical values of the parameters	39
1.8.2. Nomenclature and notations	40
1.8.3. Acknowledgments	44
1.9. Bibliography	44
Chanter 2 Ontimal Supply and Synchronous Motors Torque	
Control: Designs in the <i>a-b-c</i> Reference Frame	49
Damien FLIELLER, Jean-Paul LOUIS, Guy STURTZER and Ngac Ky NGUYEN	.,
2.1. Introduction: problems of the controls in <i>a-b-c</i>	49
2.2. Model in the a - b - c reference frame: extension of the steady state	
approach in transient regime	50
2.2.1. Case of sinusoidal field distribution machines	50
2.2.2. Case of trapezoidal field distribution machines (brushless	
DC motor)	51
2.2.3. Note on the electromagnetic torque for non-sinusoidal	
machines	53
2.3. Structures of torque controls designed in the <i>a-b-c</i> reference	
frame	54
2.3.1. Case of the sinusoidal distribution machine	54
2.3.2. Extension to brushless DC motors (case of trapezoidal field	
distribution machines)	56
2.4. Performances and criticisms of the control approach in the	
a-b-c reference frame.	57
2.4.1. Case of a proportional control	57
2.4.2. Case of an integral and proportional (IP) current regulation	62
2.4.3. Interpretation in Park components of the IP controller	
designed in <i>a-b-c</i>	68
2.4.4. Advanced controllers: example of the resonant controller	72
2.4.5. Interpretation by Park transformation of the regulation	
by resonant controller	76

2.5. Generalization: extension of the supplies to the case of	
non-sinusoidal distribution machines	78
2.5.1. Generalization of the modeling.	79
2.5.2. A first (heuristic) approach of the solution	80
2.5.3. First generalization: optimization of the Joule losses	
(without constraint on the zero-sequence component current)	81
2.5.4. Application of this approach: optimization in the case where	
electromotive forces are sinusoidal	83
2.5.5. Second generalization: optimization of the Joule losses with	
constraint (the zero-sequence component current must be	
equal to zero)	84
2.5.6. Geometrical interpretation of the two optimal currents.	86
2.6. Use of Fourier expansion to obtain optimal currents.	90
2.6.1. Interest of the Fourier expansion (FS).	90
2.6.2. Modeling by Fourier series (with complex coefficients)	91
2.6.3. Properties of the results by the Fourier expansion.	92
2.6.4. First important case: the back-EMF only contains uneven	
order harmonics.	93
2.6.5. Second important case: the back-EMF only contain even	
order harmonics.	93
2.6.6. General case, even and uneven order harmonics	94
2.6.7. Rules: to impose the torque, it is necessary to impose its	
different harmonics.	94
2.6.8. General approach for the optimization (heuristic	
demonstration in one example).	95
2.6.9. General formulation of the optimization method	99
2.6.10. An important example: the sinusoidal field distribution	
machine	106
2.6.11. Application: obtaining a constant torque	107
2.6.12. Some results	108
2.7. Conclusion	112
2.8. Appendices	113
2.8.1. Digital parameters values	113
2.8.2. Nomenclature and notations	113
2.9. Bibliography	114
Chapter 3. Optimal Supplies and Synchronous Motors Torque	
Controls. Design in the <i>d-q</i> Reference Frame	119
2.1 Introductions on the controls designed in the Dark d	
reference frame	119

viii Control of Synchronous Motors

3.2. Dynamic model (case of the salient pole machine and constant	
excitation)	120
3.3. First approach to determine of optimal current references $(d-q)$	
reference frame)	122
3.4. Determination of the current controls designed in the d - q	
reference frame	124
3.4.1. Principle of control by model inversion: example of the	
proportional controller with compensations	124
3.4.2. Self-control	126
3.4.3. Some properties of efficient current regulation	128
3.4.4. Robustness problems of a proportional controller of the	
currents	133
3.5. New control by model inversion: example of an IP controller with	
compensations.	135
3.5.1. Principle	135
3.5.2. Performances of the IP regulations for current loops	137
3.5.3. Robustness of the IP controllers for the current loops	140
3.5.4. Conclusion on the controls performances in the $d-q$	
reference frame	143
3.6 Optimal supply of the salient poles synchronous motors:	
geometrical approach of the isotorque curves	143
3.6.1 General information: a general approach with the torque	1.0
surfaces	143
3.6.2 Preliminaries 1: case of synchronous machines with	115
magnets, with non-salient poles and with spatial distribution of	
the sinusoidal field	148
3 6 3 Preliminaries 2: case of synchronous machines with	140
magnets, with non-salient poles and with spatial distribution	
of a non-sinusoidal field – first extension of the Park	
transformation	150
2.6.4 Demark: Analogy with the n a theory	153
2.6.5 2D visualization area of non soliont nole mechines	155
2.6.6. Comparalization to the solicit noise machinest ages of	134
5.0.0. Generalization to the salient pole machines. case of	155
synchronous magnet machines with sinusoidal field distribution	155
3.6./. Visualization: case of an excited synchronous machine	1.70
	158
3.6.8. Case of a reluctance synchronous machine.	159
3.6.9. Case of synchronous machines with variable reluctance and	
non-sinusoidal spatial field distribution: second extension of the	1 (1
Park transformation	161
3.6.10. Visualization: torque surface of a reluctance	1.66
synchronous machine	166

3.7. Conclusion	166 167
3.8.1 Numerical parameters values	167
3.8.2. Nomenclature and notations	167
3.9. Bibliography	169
Chapter 4. Drive Controls with Synchronous Motors Jean-Paul LOUIS, Damien FLIELLER, Ngac Ky NGUYEN and Guy STURTZER	173
4.1. Introduction.	173
4.2. Principles adopted for speed controls: case of IP controllers	176
4.3. Speed controls designed in the <i>a-b-c</i> reference frame (application	
to a non-salient pole machine)	179
4.3.1. General information	179
<i>a-b-c</i> reference frame	180
4.3.3. IP speed controller with a resonant current controller	183
reference frame (application to a salient pole machine)	184
4.4.1. General information	184
4.4.2. Introductory example: speed control with compensation	
or decoupling	185
4.4.3. Discussion on the speed controls.	188
4.4.4. Examples of regulation choices. The interest of an IP	
controller: its limits	192
4.4.5. Examples of the regulation choices: IP controller with	
an anti-windup device	194
4.4.6. Examples of regulation choices: IP controller with	100
limited dynamics	196
4.4./. Example of an advanced regulation: P controller associated	200
4.5 Note on position regulations	200
4.5. Note on position regulations	211
4.0. Conclusion	215
4.7. Appendices	210
4.7.2 Nomenclature and notations	216
4.8 Ribliography	210
4.0. Diologiuphy	217
Chapter 5. Digital Implementation of Vector Control of Synchronous Motors	221
5.1. Introduction	221

x Control of Synchronous Motors

5.2. Classical, analog and ideal torque control of a synchronous		
motor		223
5.2.1. Calculation of the current regulators.		223
5.2.2. Determination of the current references.		224
5.2.3. Parameters of the studied synchronous motor		225
5.2.4. Simulation results of the ideal analog vector control of		
synchronous motors		226
5.3. Digital implementation problem of the synchronous motor		
vector control		227
5.3.1. The interfaces, sources of restrictions		227
5.3.2. Time diagram		228
5.3.3. Digital implementation constraints of the vector control of a		
synchronous motor		230
5.4. Discretization of the control system		230
5.4.1. Choice of the sampling period		231
5.4.2. Choice of the sampling instant		232
5.4.3. Implementation of the digital control		233
5.4.4. Simulation of the control with discrete regulators.		236
5.5. Study of the delays introduced by the digital implementation of		
the vector control of the synchronous motor		237
5.5.1. Simulation results after introduction of the delays in the		
system		237
5.5.2. Calculation of the new regulators after taking into account		
the delays		239
5.5.3. Simulation after delays correction and system discretization .		240
5.6. Quantization problems		241
5.6.1. Quantization affecting the current measures		241
5.6.2. Quantization at the level of the position measure		244
5.6.3. Calculation of the speed by digital differentiation.		245
5.6.4. Quantization in the vector PWM of the voltage inverter		246
5.7. Delays in the reverse Park transformation		248
5.8. Conclusion		248
5.9. Bibliography		249
Chapter 6. Direct Control of a Permanent Magnet Synchronous		
Machine		251
Jean-Marie RÉTIF		
6.1 Introduction	,	251
6.2 Model of the permanent magnet synchronous machine in the		
d_{-a} reference frame	,	252
6.2.1 State modeling		253

6.3. Conventional DTC with free switching frequency	253
6.3.1. General principle	253
6.3.2. Experimental application of DTC	256
6.4. DTC at a fixed switching frequency	258
6.4.1. Principle of the control.	258
6.4.2. Development of the reference vector $\Psi^{\#}$	261
6.4.3. Experimental results of DTC on a period of fixed	
calculation	263
6.5. Predictive direct control	264
6.5.1. Introduction	264
6.5.2. General principle of predictive direct control	264
6.5.3. Application to the permanent magnet synchronous motor	265
6.5.4. Experimental results	270
6.5.5. Predictive direct control by model inversion	272
6.6. Conclusion	279
6.7. Bibliography	280
Chapter 7. Synchronous Machine and Inverter Fault Tolerant	
Predictive Controls	283
Caroline DOC, Vincent LANFRANCHI and Nicolas PATIN	
7.1 Introduction	283
7.2 Topologies of three phase fault tolerant machines	285
7.2.1 Restriction of the short circuit current of permanent magnet	204
machines	284
7.2.2. Restriction of the fault to the phase at fault alone	284
7.3. Topologies of fault tolerant converters	285
7.4 Fault tolerant controls	285
7.4.1 Modeling synchronous machines in preparation for fault	207
tolerant control	287
7.4.2 Simulation of synchronous machines with fault tolerant	207
control	288
7 4 3 Predictive control	200
7.4.4 Application	204
7.5. Conclusion	302
7.6 Bibliography	302
	505
Chapter & Characterization of Control without a Mechanical Sensor	
in Permanent Magnet Synchronous Machines	305
Maurice FADEL	505
8.1. Introduction.	305
8.1.1. State observation and disturbance observer	306

xii Control of Synchronous Motors

8.1.2. Interaction of the dynamics of control and observation	307
8.1.3. Poles placement for control and observation.	310
8.2. Sensorless control of PMSM, thanks to an extended Kalman	
filter	313
8.2.1. A brief reminder on the Kalman filter (KF)	313
8.2.2. Application to the PMSM case	315
8.2.3. Simulation results.	318
8.3. Comparison with the MRAS (model reference adaptive system)	
method	321
8.4. Experimental results comparison	323
8.5. Control without sensor of the PMSM with load torque	
observation	325
8.5.1. Control by state feedback on the currents.	331
8.6. Starting the PMSM without a mechanical sensor	334
8.6.1. Equilibriums of the system without a mechanical sensor	335
8.6.2. Analysis by simulation.	338
8.6.3. Modification of the control law for a global convergence	341
8.7. Conclusion	344
8.8. Bibliography	345
Chapter 9. Sensorless Control of Permanent Magnet Synchronous	
Chapter 9. Sensorless Control of Permanent Magnet Synchronous Machines: Deterministic Methods, Convergence and Robustness	347
Chapter 9. Sensorless Control of Permanent Magnet Synchronous Machines: Deterministic Methods, Convergence and Robustness Farid MEIBODY-TABAR and Babak NAHID-MOBARAKEH	347
Chapter 9. Sensorless Control of Permanent Magnet Synchronous Machines: Deterministic Methods, Convergence and Robustness Farid MEIBODY-TABAR and Babak NAHID-MOBARAKEH	347
Chapter 9. Sensorless Control of Permanent Magnet Synchronous Machines: Deterministic Methods, Convergence and Robustness Farid MEIBODY-TABAR and Babak NAHID-MOBARAKEH 9.1. Introduction.	347 347
Chapter 9. Sensorless Control of Permanent Magnet Synchronous Machines: Deterministic Methods, Convergence and Robustness Farid MEIBODY-TABAR and Babak NAHID-MOBARAKEH 9.1. Introduction. 9.2. Modeling PMSMs for mechanical sensorless control 9.2. Is the sensorless control	347 347 350
Chapter 9. Sensorless Control of Permanent Magnet Synchronous Machines: Deterministic Methods, Convergence and Robustness Farid MEIBODY-TABAR and Babak NAHID-MOBARAKEH 9.1. Introduction. 9.1. Introduction.	 347 347 350 352 254
Chapter 9. Sensorless Control of Permanent Magnet Synchronous Machines: Deterministic Methods, Convergence and Robustness Farid MEIBODY-TABAR and Babak NAHID-MOBARAKEH 9.1. Introduction. 9.2. Modeling PMSMs for mechanical sensorless control 9.2.1. State model 9.2.2. Reduced-order model	 347 347 350 352 354 256
Chapter 9. Sensorless Control of Permanent Magnet Synchronous Machines: Deterministic Methods, Convergence and Robustness Farid MEIBODY-TABAR and Babak NAHID-MOBARAKEH 9.1. Introduction. 9.2. Modeling PMSMs for mechanical sensorless control 9.2.1. State model 9.2.2. Reduced-order model 9.3. Convergence analysis of mechanical sensorless control laws 9.2.1. Provide analysis of mechanical sensorless control laws	347 347 350 352 354 356
Chapter 9. Sensorless Control of Permanent Magnet Synchronous Machines: Deterministic Methods, Convergence and Robustness Farid MEIBODY-TABAR and Babak NAHID-MOBARAKEH 9.1. Introduction. 9.2. Modeling PMSMs for mechanical sensorless control 9.2.1. State model 9.2.2. Reduced-order model 9.3. Convergence analysis of mechanical sensorless control laws 9.3.1. Proportional-type control law.	347 347 350 352 354 356 356
Chapter 9. Sensorless Control of Permanent Magnet Synchronous Machines: Deterministic Methods, Convergence and Robustness Farid MEIBODY-TABAR and Babak NAHID-MOBARAKEH 9.1. Introduction. 9.2. Modeling PMSMs for mechanical sensorless control 9.2.1. State model 9.2.2. Reduced-order model 9.3. Convergence analysis of mechanical sensorless control laws 9.3.1. Proportional-type control law. 9.3.2. Variable structure control law	347 350 352 354 356 356 364 271
Chapter 9. Sensorless Control of Permanent Magnet Synchronous Machines: Deterministic Methods, Convergence and Robustness Farid MEIBODY-TABAR and Babak NAHID-MOBARAKEH 9.1. Introduction. 9.2. Modeling PMSMs for mechanical sensorless control 9.2.1. State model 9.3. Convergence analysis of mechanical sensorless control laws 9.3.1. Proportional-type control law. 9.3.2. Variable structure control law 9.4. Estimation of the back-EMF vector	 347 347 350 352 354 356 356 364 371
Chapter 9. Sensorless Control of Permanent Magnet Synchronous Machines: Deterministic Methods, Convergence and Robustness Farid MEIBODY-TABAR and Babak NAHID-MOBARAKEH 9.1. Introduction. 9.2. Modeling PMSMs for mechanical sensorless control 9.2.1. State model 9.2.2. Reduced-order model 9.3. Convergence analysis of mechanical sensorless control laws 9.3.1. Proportional-type control law. 9.3.2. Variable structure control law 9.4. Estimation of the back-EMF vector 9.5. Robustness of sensorless control of PMSM with respect to	347 347 350 352 354 356 356 364 371
Chapter 9. Sensorless Control of Permanent Magnet Synchronous Machines: Deterministic Methods, Convergence and Robustness Farid MEIBODY-TABAR and Babak NAHID-MOBARAKEH 9.1. Introduction. 9.2. Modeling PMSMs for mechanical sensorless control 9.2.1. State model 9.2.2. Reduced-order model 9.3. Convergence analysis of mechanical sensorless control laws 9.3.1. Proportional-type control law. 9.3.2. Variable structure control law 9.4. Estimation of the back-EMF vector 9.5. Robustness of sensorless control of PMSM with respect to parameter uncertainties.	 347 347 350 352 354 356 364 371 373
Chapter 9. Sensorless Control of Permanent Magnet Synchronous Machines: Deterministic Methods, Convergence and Robustness Farid MEIBODY-TABAR and Babak NAHID-MOBARAKEH 9.1. Introduction. 9.2. Modeling PMSMs for mechanical sensorless control 9.2.1. State model 9.2.2. Reduced-order model 9.3. Convergence analysis of mechanical sensorless control laws 9.3.1. Proportional-type control law. 9.3.2. Variable structure control law 9.4. Estimation of the back-EMF vector 9.5. Robustness of sensorless control of PMSM with respect to parameter uncertainties. 9.5.1. Uncertainty on the stator inductances	 347 347 350 352 354 356 364 371 373 375
Chapter 9. Sensorless Control of Permanent Magnet Synchronous Machines: Deterministic Methods, Convergence and Robustness Farid MEIBODY-TABAR and Babak NAHID-MOBARAKEH 9.1. Introduction. 9.2. Modeling PMSMs for mechanical sensorless control 9.2.1. State model 9.2.2. Reduced-order model 9.3. Convergence analysis of mechanical sensorless control laws 9.3.1. Proportional-type control law. 9.3.2. Variable structure control law 9.4. Estimation of the back-EMF vector 9.5. Robustness of sensorless control of PMSM with respect to parameter uncertainties. 9.5.1. Uncertainty on the stator inductances 9.5.2. Uncertainty on the torque coefficient	 347 347 350 352 354 356 364 371 373 375 377 270
Chapter 9. Sensorless Control of Permanent Magnet Synchronous Machines: Deterministic Methods, Convergence and Robustness Farid MEIBODY-TABAR and Babak NAHID-MOBARAKEH 9.1. Introduction. 9.2. Modeling PMSMs for mechanical sensorless control 9.2.1. State model 9.3. Convergence analysis of mechanical sensorless control laws 9.3.1. Proportional-type control law. 9.3.2. Variable structure control law 9.4. Estimation of the back-EMF vector 9.5. Robustness of sensorless control of PMSM with respect to parameter uncertainties. 9.5.1. Uncertainty on the stator inductances 9.5.2. Uncertainty on the stator resistance	 347 347 350 352 354 356 364 371 373 375 377 378
Chapter 9. Sensorless Control of Permanent Magnet Synchronous Machines: Deterministic Methods, Convergence and Robustness Farid MEIBODY-TABAR and Babak NAHID-MOBARAKEH 9.1. Introduction. 9.2. Modeling PMSMs for mechanical sensorless control 9.2.1. State model 9.3. Convergence analysis of mechanical sensorless control laws 9.3.1. Proportional-type control law. 9.3.2. Variable structure control law. 9.4. Estimation of the back-EMF vector 9.5. Robustness of sensorless control of PMSM with respect to parameter uncertainties. 9.5.1. Uncertainty on the stator inductances 9.5.2. Uncertainty on the stator resistance 9.5.3. Uncertainty on the stator resistance 9.6. Sensorless control of PMSMs in the presence of uncertainties	 347 347 350 352 354 356 364 371 373 375 377 378
Chapter 9. Sensorless Control of Permanent Magnet Synchronous Machines: Deterministic Methods, Convergence and Robustness Farid MEIBODY-TABAR and Babak NAHID-MOBARAKEH 9.1. Introduction. 9.2. Modeling PMSMs for mechanical sensorless control 9.2.1. State model 9.2.2. Reduced-order model 9.3. Convergence analysis of mechanical sensorless control laws 9.3.1. Proportional-type control law. 9.3.2. Variable structure control law 9.4. Estimation of the back-EMF vector 9.5. Robustness of sensorless control of PMSM with respect to parameter uncertainties. 9.5.1. Uncertainty on the stator inductances 9.5.2. Uncertainty on the stator resistance 9.5.3. Uncertainty on the stator resistance 9.6. Sensorless control of PMSMs in the presence of uncertainties 9.6. Sensorless control of PMSMs in the presence of uncertainties	 347 347 350 352 354 356 364 371 373 375 377 378 387
Chapter 9. Sensorless Control of Permanent Magnet Synchronous Machines: Deterministic Methods, Convergence and Robustness Farid MEIBODY-TABAR and Babak NAHID-MOBARAKEH 9.1. Introduction. 9.2. Modeling PMSMs for mechanical sensorless control 9.2.1. State model 9.2.2. Reduced-order model 9.3. Convergence analysis of mechanical sensorless control laws 9.3.1. Proportional-type control law. 9.3.2. Variable structure control law 9.4. Estimation of the back-EMF vector 9.5. Robustness of sensorless control of PMSM with respect to parameter uncertainties. 9.5.1. Uncertainty on the stator inductances 9.5.2. Uncertainty on the stator resistance 9.6. Sensorless control of PMSMs in the presence of uncertainties 0.6.1. Online estimation of the resistance	 347 347 350 352 354 356 364 371 373 375 377 378 387 387
Chapter 9. Sensorless Control of Permanent Magnet Synchronous Machines: Deterministic Methods, Convergence and Robustness Farid MEIBODY-TABAR and Babak NAHID-MOBARAKEH 9.1. Introduction. 9.2. Modeling PMSMs for mechanical sensorless control 9.2.1. State model 9.2.2. Reduced-order model 9.3. Convergence analysis of mechanical sensorless control laws 9.3.1. Proportional-type control law. 9.3.2. Variable structure control law 9.4. Estimation of the back-EMF vector 9.5. Robustness of sensorless control of PMSM with respect to parameter uncertainties. 9.5.1. Uncertainty on the stator inductances 9.5.2. Uncertainty on the stator resistance 9.5.3. Uncertainty on the stator resistance 9.6.1. Online estimation of the resistance 9.6.1. Online estimation of the sensitivity of the sensorless control	 347 347 350 352 354 356 364 371 373 375 377 378 387 387

Table of Contents xiii

9.7. Conclusion																											
9.8. Appendix 1																											
9.9. Appendix 2																											
9.10. Bibliography .						•											•										
List of Authors																											
	• •	·	·	• •	·	•	• •	·	·	• •	•	·	• •	•	•	·	•	•••	•	·	·	·	·	·	•	•••	