Control of Electric Machine Drive Systems

SEUNG-KI SUL







Mohamed E. El-Hawary, Series Editor

Contents

Preface	
1 Introduction	1
1.1 Introduction	1
1.1.1 Electric Machine Drive System	4
1.1.2 Trend of Development of Electric Machine Drive System	5
1.1.3 Trend of Development of Power Semiconductor	7
1.1.4 Trend of Development of Control Electronics	8
1.2 Basics of Mechanics	8
1.2.1 Basic Laws	9
1.2.2 Force and Torque	9
1.2.3 Moment of Inertia of a Rotating Body	11
1.2.4 Equations of Motion for a Rigid Body	13
1.2.5 Power and Energy	17
1.2.6 Continuity of Physical Variables	18
1.3 Torque Speed Curve of Typical Mechanical Loads 1.3.1 Fan, Pump, and Blower	18
1.3.2 Hoisting Load; Crane, Elevator	18
1.3.3 Traction Load (Electric Vehicle, Electric Train)	20 21
1.3.4 Tension Control Load	23
Problems	24
References	35
2 Basic Structure and Modeling of Electric Machines and Power Converters	36
2.1 Structure and Modeling of DC Maskins	
2.1 Structure and Modeling of DC Machine2.2 Analysis of Steady-State Operation	36
2.2.1 Separately Excited Shunt Machine	41 42
2.2.2 Series Excited DC Machine	42
2.3 Analysis of Transient State of DC Machine	46
2.3.1 Separately Excited Shunt Machine	47
2.4 Power Electronic Circuit to Drive DC Machine	50
2.4.1 Static Ward–Leonard System	51
2.4.2 Four-Quadrants Chopper System	52
2.5 Rotating Magnetic Motive Force	53
2.6 Steady-State Analysis of a Synchronous Machine	58

viii Contents

2.7	Linear Electric Machine	62
2.8	Capability Curve of Synchronous Machine	63
	2.8.1 Round Rotor Synchronous Machine with Field Winding	63
	2.8.2 Permanent Magnet Synchronous Machine	64
2.9	Parameter Variation of Synchronous Machine	66
	2.9.1 Stator and Field Winding Resistance	66
	2.9.2 Synchronous Inductance	66
	2.9.3 Back EMF Constant	67
2.10	Steady-State Analysis of Induction Machine	70
	2.10.1 Steady-State Equivalent Circuit of an Induction Machine	72
	2.10.2 Constant Air Gap Flux Operation	77
2.11	Generator Operation of an Induction Machine	79
2.12	Variation of Parameters of an Induction Machine	
2.12	2.12.1 Variation of Rotor Resistance, R_r	81
	2.12.1 Variation of Rotor Leakage Inductance, L_{lr}	81
	2.12.3 Variation of Stator Resistance, R_s	82
	2.12.4 Variation of Stator Leakage Inductance, L_{ls}	82
	2.12.5 Variation of Excitation Inductance, L_{ls}	83
	2.12.6 Variation of Resistance Representing Iron Loss, R_m	84
2 13	Classification of Induction Machines According	84
2.10	to Speed-Torque Characteristics	
2 14	Overi Transient Ctata A value	84
	Quasi-Transient State Analysis	87
2.13	Capability Curve of an Induction Machine	88
2.16	Comparison of AC Machine and DC Machine	90
	2.16.1 Comparison of a Squirrel Cage Induction Machine and a Separately	
	Excited DC Machine	90
	2.16.2 Comparison of a Permanent Magnet AC Machine and a Separately	
2 10	Excited DC Machine	92
2.17	Variable-Speed Control of Induction Machine Based on	
	Steady-State Characteristics	92
	2.17.1 Variable Speed Control of Induction Machine by Controlling	
	Terminal Voltage	93
	2.17.2 Variable Speed Control of Induction Machine Based on	
	Constant Air-Gap Flux ($\approx \frac{V}{F}$) Control	94
	2.17.3 Variable Speed Control of Induction Machine Based on Actual	
	Speed Feedback	95
	2.17.4 Enhancement of Constant Air-Gap Flux Control with Feedback	
2.10	of Magnitude of Stator Current	96
2.18	Modeling of Power Converters	96
	2.18.1 Three-Phase Diode/Thyristor Rectifier	97
	2.18.2 PWM Boost Rectifier	98
	2.18.3 Two-Quadrants Bidirectional DC/DC Converter	101
	2.18.4 Four-Quadrants DC/DC Converter	102
	2.18.5 Three-Phase PWM Inverter	103
	2.18.6 Matrix Converter	105
2.19	Parameter Conversion Using Per Unit Method	106
Probl		108
Refer	rences	114

3		rence Frame Transformation and Transient State Analysis nree-Phase AC Machines	116
	3.1	Complex Vector	117
		d- q - n Modeling of an Induction Machine Based on Complex	117
	5,2	Space Vector	119
		3.2.1 Equivalent Circuit of an Induction Machine at $d-q-n$ AXIS	120
		3.2.2 Torque of the Induction Machine	125
	3.3	d– q – n Modeling of a Synchronous Machine Based on Complex	
		Space Vector	128
		3.3.1 Equivalent Circuit of a Synchronous Machine at $d-q-n$ AXIS	128
		3.3.2 Torque of a Synchronous Machine	138
		3.3.3 Equivalent Circuit and Torque of a Permanent Magnet	
		Synchronous Machine	140
	ъ	3.3.4 Synchronous Reluctance Machine (SynRM)	144
		blems	146
	Rei	Serences Serences	153
4	Desig	gn of Regulators for Electric Machines and Power Converters	154
	4.1	Active Damping	157
	4.2	Current Regulator	158
		4.2.1 Measurement of Current	158
		4.2.2 Current Regulator for Three-Phase-Controlled Rectifier	161
		4.2.3 Current Regulator for a DC Machine Driven by a PWM Chopper	166
		4.2.4 Anti-Wind-Up	170
	4.2	4.2.5 AC Current Regulator	173
	4.3	Speed Regulator	179
		4.3.1 Measurement of Speed/Position of Rotor of an Electric Machine	179
		4.3.2 Estimation of Speed with Incremental Encoder4.3.3 Estimation of Speed by a State Observer	182 189
		4.3.4 PI/IP Speed Regulator	198
		4.3.5 Enhancement of Speed Control Performance with Acceleration	170
		Information	204
		4.3.6 Speed Regulator with Anti-Wind-Up Controller	206
	4.4	Position Regulator	208
		4.4.1 Proportional–Proportional and Integral (P–PI) Regulator	208
		4.4.2 Feed-Forwarding of Speed Reference	
		and Acceleration Reference	209
	4.5	Detection of Phase Angle of AC Voltage	210
		4.5.1 Detection of Phase Angle on Synchronous Reference Frame	210
		4.5.2 Detection of Phase Angle Using Positive Sequence Voltage	010
	16	on Synchronous Reference Frame	213
	4.0	Voltage Regulator 4.6.1 Voltage Regulator for DC Link of PWM Boost Rectifier	215
	Pro	blems	215
		erences	218
	I C	OI OILOUS	228

5 Vector Control	230
5.1 Instantaneous Torque Control	231
5.1.1 Separately Excited DC Machine	231
5.1.2 Surface-Mounted Permanent Magnet Synchronous Motor (SMPMSN	
5.1.2 Surface-Mounted Permanent Magnet Synchronous Motor (IPMSM)	235
5.2 Vector Control of Induction Machine	236
5.2.1 Direct Vector Control	237
5.2.2 Indirect Vector Control	243
5.2 Rotor Flux Linkage Estimator	245
5.3.1 Voltage Model Based on Stator Voltage Equation of an	24.
Induction Machine	245
5.3.2 Current Model Based on Rotor Voltage Equation of an	47.
Induction Machine	246
5.3.3 Hybrid Rotor Flux Linkage Estimator	247
5.3.4 Enhanced Hybrid Estimator	248
5.4 Flux Weakening Control	249
5.4.1 Constraints of Voltage and Current to AC Machine	249
5.4.2 Operating Region of Permanent Magnet AC Machine in Current	2.,,
Plane at Rotor Reference Frame	250
5.4.3 Flux Weakening Control of Permanent Magnet Synchronous	
Machine	257
5.4.4 Flux Weakening Control of Induction Machine	262
5.4.5 Flux Regulator of Induction Machine	267
Problems	269
References	281
6 Position/Speed Sensorless Control of AC Machines	283
6.1 Sensorless Control of Induction Machine	286
6.1.1 Model Reference Adaptive System (MRAS)	286
6.1.2 Adaptive Speed Observer (ASO)	291
6.2 Sensorless Control of Surface-Mounted Permanent Magnet	
Synchronous Machine (SMPMSM)	297
6.3 Sensorless Control of Interior Permanent Magnet Synchronous	491
Machine (IPMSM)	299
6.4 Sensorless Control Employing High-Frequency Signal Injection 6.4.1. Inherently Salient Rotor Machine	302
6.4.2 AC Machine with Nonsalient Rotor	304
Problems	305
	317
References	320
7 Practical Issues	324
7.1 Output Voltage Distortion Due to Dead Time and Its	
Compensation	324
7.1.1 Compensation of Dead Time Effect	325
I	

Contents	ХÌ
7.1.2 Zero Current Clamping (ZCC)	327
7.1.3 Voltage Distortion Due to Stray Capacitance of Semiconductor	
Switches	327
7.1.4 Prediction of Switching Instant	330
7.2 Measurement of Phase Current	334
7.2.1 Modeling of Time Delay of Current Measurement System	334
7.2.2 Offset and Scale Errors in Current Measurement	337
7.3 Problems Due to Digital Signal Processing of Current	
Regulation Loop	342
7.3.1 Modeling and Compensation of Current Regulation Error	
Due to Digital Delay	342
7.3.2 Error in Current Sampling	346
Problems	350
References	353
Appendix A Measurement and Estimation of Parameters of Electric	
Machinery	354
Widelinery	
A.1 Parameter Estimation	354
A.1.1 DC Machine	355
A.1.2 Estimation of Parameters of Induction Machine	357
A.2 Parameter Estimation of Electric Machines Using Regulators	
of Drive System	361
A.2.1 Feedback Control System	361
A.2.2 Back EMF Constant of DC Machine, K	363
A.2.3 Stator Winding Resistance of Three-Phase AC Machine, R_s	363
A.2.4 Induction Machine Parameters	365
A.2.5 Permanent Magnet Synchronous Machine	370
A.3 Estimation of Mechanical Parameters	374
A.3.1 Estimation Based on Mechanical Equation	374
A.3.2 Estimation Using Integral Process	376
References	380
Appendix B d-q Modeling Using Matrix Equations	381
B.1 Reference Frame and Transformation Matrix	381
B.2 $d-q$ Modeling of Induction Machine Using Transformation	201
	296
Matrix D. 2. A. a. Markelina of Samahanana Manhina Using Transformation	386
B.3 d-q Modeling of Synchronous Machine Using Transformation	390
Matrix	390
Index	391
IEEE Press Series on Power Engineering	401