Contents

Preface		Xi	
Pai	rt I	HVDC with Current Source Converters	1
1	Intr	roduction to Line-Commutated HVDC	3
	1.1	HVDC Applications	3
	1.2	Line-Commutated HVDC Components	5
	1.3	DC Cables and Overhead Lines	6
	1.4	LCC HVDC Topologies	7
	1.5	Losses in LCC HVDC Systems	9
	1.6	Conversion of AC Lines to DC	10
	1.7	Ultra-High Voltage HVDC	10
2	Thyristors		12
	2.1	Operating Characteristics	12
	2.2	Switching Characteristic	13
	2.3	Losses in HVDC Thyristors	17
	2.4	Valve Structure and Thyristor Snubbers	20
	2.5	Thyristor Rating Selection and Overload Capability	22
3	Six-	Pulse Diode and Thyristor Converter	23
	3.1	Three-Phase Uncontrolled Bridge	23
	3.2	Three-Phase Thyristor Rectifier	25
	3.3	Analysis of Commutation Overlap in a Thyristor Converter	26
	3.4	Active and Reactive Power in a Three-Phase Thyristor Converter	30
	3.5	Inverter Operation	31
4	HVDC Rectifier Station Modelling, Control and Synchronization		
	witl	h AC Systems	35
	4.1	HVDC Rectifier Controller	35
	42	Phase-Locked Loop (PLL)	36

5	HVDC Inverter Station Modelling and Control	40	
	5.1 Inverter Controller	40	
	5.2 Commutation Failure	42	
6	HVDC System V-I Diagrams and Operating Modes	45	
	6.1 HVDC-Equivalent Circuit	45	
	6.2 HVDC V-I Operating Diagram	45	
	6.3 HVDC Power Reversal	48	
7	HVDC Analytical Modelling and Stability	53	
	7.1 Introduction to Converters and HVDC Modelling	53	
	7.2 HVDC Analytical Model	54	
	7.3 CIGRE HVDC Benchmark Model	56	
	7.4 Converter Modelling, Linearization and Gain Scheduling	56	
	7.5 AC System Modelling for HVDC Stability Studies	58	
	7.6 LCC Converter Transformer Model	62	
	7.7 DC System Model	63	
	7.8 HVDC-HVAC System Model	65	
	7.9 Analytical Dynamic Model Verification	65	
	7.10 Basic HVDC Dynamic Analysis7.11 HVDC Second Harmonic Instability	66	
	7.12 Oscillations of 100 Hz on the DC Side	70	
	7.12 Osemations of 100 Hz oil the DC Side	71	
8	HVDC Phasor Modelling and Interactions with AC System	72	
	8.1 Converter and DC System Phasor Model	72	
	8.2 Phasor AC System Model and Interaction with the DC System	73	
	8.3 Inverter AC Voltage and Power Profile as DC Current is Increasing	75	
	8.4 Influence of Converter Extinction Angle	76	
	8.5 Influence of Shunt Reactive Power Compensation	78	
	8.6 Influence of Load at the Converter Terminals	78	
	8.7 Influence of Operating Mode (DC Voltage Control Mode)	78	
	8.8 Rectifier Operating Mode	80	
9	HVDC Operation with Weak AC Systems	82	
	9.1 Introduction	82	
	9.2 Short-Circuit Ratio and Equivalent Short-Circuit Ratio	82	
	9.3 Power Transfer between Two AC Systems	85	
	9.4 Phasor Study of Converter Interactions with Weak AC Systems	89	
	9.5 System Dynamics (Small Signal Stability) with Low SCR	90	
	9.6 HVDC Control and Main Circuit Solutions for Weak AC Grids 9.7 LCC HVDC with SVC (Static VAR Compensator)	90	
	= = " The Compensator)	91	
	•	93	
	9.9 AC System with Low Inertia	93	
10	Fault Management and HVDC System Protection		
	10.1 Introduction	98	
	10.2 DC Line Faults	98	
	10.3 AC System Faults	101	

Contents	vii

	10.4 Internal Faults	102
	10.5 System Reconfiguration for Permanent Faults	102
	10.6 Overvoltage Protection	106
		700
11	LCC HVDC System Harmonics	107
	11.1 Harmonic Performance Criteria	107
	11.2 Harmonic Limits	108
	11.3 Thyristor Converter Harmonics	109
	11.4 Harmonic Filters	110
	11.5 Noncharacteristic Harmonic Reduction Using HVDC Controls	118
Bib	liography Part I Line Commutated Converter HVDC	119
Par	t II HVDC with Voltage Source Converters	121
12	VSC HVDC Applications and Topologies, Performance and	
14	Cost Comparison with LCC HVDC	123
	12.1 Voltage Source Converters (VSC)	123
	12.2 Comparison with Line-Commutated Converter (LCC) HVDC	125
	12.3 Overhead and Subsea/Underground VSC HVDC Transmission	126
	12.4 DC Cable Types with VSC HVDC	129
	12.5 Monopolar and Bipolar VSC HVDC Systems	129
	12.6 VSC HVDC Converter Topologies	130
	12.7 VSC HVDC Station Components	135
	12.8 AC Reactors	139
	12.9 DC Reactors	139
13	IGBT Switches and VSC Converter Losses	141
15	13.1 Introduction to IGBT and IGCT	141
	13.2 General VSC Converter Switch Requirements	142
	13.3 IGBT Technology	142
	13.4 High Power IGBT Devices	147
	13.5 IEGT Technology	148
	13.6 Losses Calculation	148
	13.7 Balancing Challenges in Series IGBT Chains	154
	13.8 Snubbers Circuits	155
14	Single-Phase and Three-Phase Two-Level VSC Converters	156
17	14.1 Introduction	156
	14.2 Single-Phase Voltage Source Converter	156
	14.3 Three-Phase Voltage Source Converter	159
	14.4 Square-Wave, Six-Pulse Operation	159
15	To a Land DWM VCC C	4 / 2
15	Two-Level PWM VSC Converters	167
	15.1 Introduction	167
	15.2 PWM Modulation	167
	15.3 Sinusoidal Pulse-Width Modulation (SPWM)	168
	15.4 Third Harmonic Injection (THI)	171

	15.5	Selective Harmonic Elimination Modulation (SHE)	172
	15.6	Converter Losses for Two-Level SPWM VSC	173
	15.7	Harmonics with Pulse-Width Modulation (PWM)	175
	15.8	Comparison of PWM Modulation Techniques	178
16		level VSC Converters	179
	16.1	Introduction	179
	16.2	Modulation Techniques for Multilevel Converters	181
	16.3	Neutral Point Clamped Multilevel Converter	182
	16.4	Flying Capacitor Multilevel Converter	184
	16.5	H-Bridge Cascaded Converter	185
	16.6	Half Bridge Modular Multilevel Converter (MMC)	186
	16.7	MMC Based on Full Bridge Topology	199
	16.8	Comparison of Multilevel Topologies	208
17	Two-	Level PWM VSC HVDC Modelling, Control and Dynamics	209
	17.1	PWM Two-Level Converter Average Model	209
	17.2	Two-Level PWM Converter Model in DQ Frame	210
	17.3	VSC Converter Transformer Model	212
	17.4	Two-Level VSC Converter and AC Grid Model in ABC Frame	213
	17.5	Two-Level VSC Converter and AC Grid Model in DQ Rotating	
		Coordinate Frame	213
	17.6	VSC Converter Control Principles	214
	17.7	The Inner Current Controller Design	215
	17.8	Outer Controller Design	218
	17.9	Complete VSC Converter Controller	221
	17.10	Small-Signal Linearized VSC HVDC Model	224
	17.11	Small-Signal Dynamic Studies	224
18	Two-l	Level VSC HVDC Phasor-Domain Interaction with AC Systems and	
		perating Diagrams	226
	18.1	Power Exchange between Two AC Voltage Sources	226
	18.2	Converter Phasor Model and Power Exchange with an AC System	230
	18.3	Phasor Study of VSC Converter Interaction with AC System	232
	18.4	Operating Limits	234
	18.5	Design Point Selection	235
	18.6	Influence of AC System Strength	236
	18.7	Influence of Transformer Reactance	236
	18.8	Operation with Very Weak AC Systems	239
19		Bridge MMC Converter: Modelling, Control and Operating PQ Diagrams	246
	19.1	Half Bridge MMC Converter Average Model in ABC Frame	246
	19.2	Half-Bridge MMC Converter-Static DQ Frame and Phasor Model	249
	19.3	Differential Current at Second Harmonic	254
	19.4	Complete MMC Converter DQ Model in Matrix Form	255
	19.5	Second Harmonic Circulating Current Suppression Controller	256
	19.6	DQ Frame Model of MMC with Circulating Current Controller	259
	19.7	Phasor Model of MMC with Circulating Current Suppression Controller	261
	19.8	Dynamic MMC Model Using Equivalent Series Capacitor C _{MMC}	262
	19.9	Full Dynamic Analytical MMC Model	265
	19.10	MMC Converter Controller	267

Contents

	19.11 MMC Total Series Reactance in the Phasor Model	267
	19.12 MMC VSC Interaction with AC System	
	and PQ Operating Diagrams	269
20	VSC HVDC under AC and DC Fault Conditions	271
	20.1 Introduction	271
	20.2 Faults on the AC System	271
	20.3 DC Faults with Two-Level VSC	272
	20.4 Influence of DC Capacitors	276
	20.5 VSC Converter Modelling under DC Faults and VSC Diode Bridge	277
	20.6 Converter-Mode Transitions as DC Voltage Reduces	284
	20.7 DC Faults with Half-Bridge Modular Multilevel Converter	286
	20.8 DC Faults with Full-Bridge Modular Multilevel Converter	287
21	VSC HVDC Application for AC Grid Support and Operation with	
	Passive AC Systems	291
	21.1 VSC HVDC High-Level Controls and AC Grid Support	291
	21.2 HVDC Embedded inside an AC Grid	292
	21.3 HVDC Connecting Two Separate AC Grids	293
	21.4 HVDC in Parallel with AC	293
	21.5 Operation with a Passive AC System and Black Start Capability	294
	21.6 VSC HVDC Operation with Offshore Wind Farms	294
	21.7 VSC HVDC Supplying Power Offshore and Driving a MW-Size	
	Variable-Speed Motor	296
Bib	oliography Part II Voltage Source Converter HVDC	298
Par	rt III DC Transmission Grids	301
22	Introduction to DC Grids	303
	22.1 DC versus AC Transmission	303
	22.2 Terminology	304
	22.3 DC Grid Planning, Topology and Power-Transfer Security	304
	22.4 Technical Challenges	305
	22.5 DC Grid Building by Multiple Manufacturers	306
	22.6 Economic Aspects	306
23	DC Grids with Line-Commutated Converters	307
23	DC Grids with Line-Commutated Converters 23.1 Multiterminal HVDC	307 307
23		
23	23.1 Multiterminal HVDC	307
23	 23.1 Multiterminal HVDC 23.2 Italy–Corsica–Sardinia Multiterminal HVDC Link 23.3 Connecting LCC Converter to a DC Grid 23.4 Control of LCC Converters in DC Grids 	307 308
23	 23.1 Multiterminal HVDC 23.2 Italy–Corsica–Sardinia Multiterminal HVDC Link 23.3 Connecting LCC Converter to a DC Grid 23.4 Control of LCC Converters in DC Grids 23.5 Control of LCC DC Grids through DC Voltage Droop Feedback 	307 308 309
23	 23.1 Multiterminal HVDC 23.2 Italy–Corsica–Sardinia Multiterminal HVDC Link 23.3 Connecting LCC Converter to a DC Grid 23.4 Control of LCC Converters in DC Grids 23.5 Control of LCC DC Grids through DC Voltage Droop Feedback 23.6 Managing LCC DC Grid Faults 	307 308 309 311
23	 23.1 Multiterminal HVDC 23.2 Italy–Corsica–Sardinia Multiterminal HVDC Link 23.3 Connecting LCC Converter to a DC Grid 23.4 Control of LCC Converters in DC Grids 23.5 Control of LCC DC Grids through DC Voltage Droop Feedback 23.6 Managing LCC DC Grid Faults 23.7 Reactive Power Issues 	307 308 309 311 311
23	 23.1 Multiterminal HVDC 23.2 Italy–Corsica–Sardinia Multiterminal HVDC Link 23.3 Connecting LCC Converter to a DC Grid 23.4 Control of LCC Converters in DC Grids 23.5 Control of LCC DC Grids through DC Voltage Droop Feedback 23.6 Managing LCC DC Grid Faults 	307 308 309 311 311 313
23	 23.1 Multiterminal HVDC 23.2 Italy-Corsica-Sardinia Multiterminal HVDC Link 23.3 Connecting LCC Converter to a DC Grid 23.4 Control of LCC Converters in DC Grids 23.5 Control of LCC DC Grids through DC Voltage Droop Feedback 23.6 Managing LCC DC Grid Faults 23.7 Reactive Power Issues 23.8 Large LCC Rectifier Stations in DC Grids DC Grids with Voltage Source Converters and Power-Flow Model 	307 308 309 311 311 313 315
	 23.1 Multiterminal HVDC 23.2 Italy–Corsica–Sardinia Multiterminal HVDC Link 23.3 Connecting LCC Converter to a DC Grid 23.4 Control of LCC Converters in DC Grids 23.5 Control of LCC DC Grids through DC Voltage Droop Feedback 23.6 Managing LCC DC Grid Faults 23.7 Reactive Power Issues 23.8 Large LCC Rectifier Stations in DC Grids DC Grids with Voltage Source Converters and Power-Flow Model 24.1 Connecting a VSC Converter to a DC Grid 	307 308 309 311 311 313 315 315
	 23.1 Multiterminal HVDC 23.2 Italy-Corsica-Sardinia Multiterminal HVDC Link 23.3 Connecting LCC Converter to a DC Grid 23.4 Control of LCC Converters in DC Grids 23.5 Control of LCC DC Grids through DC Voltage Droop Feedback 23.6 Managing LCC DC Grid Faults 23.7 Reactive Power Issues 23.8 Large LCC Rectifier Stations in DC Grids DC Grids with Voltage Source Converters and Power-Flow Model 	307 308 309 311 311 313 315 315

X	Contents
	

25	DC G	rid Control	324
	25.1	Introduction	324
	25.2	Fast Local VSC Converter Control in DC Grids	324
	25.3	DC Grid Dispatcher with Remote Communication	326
	25.4	Primary, Secondary and Tertiary DC Grid Control	327
	25.5	DC Voltage Droop Control for VSC Converters in DC Grids	328
	25.6	Three-Level Control for VSC Converters with Dispatcher Droop	329
	25.7	Power Flow Algorithm When DC Powers are Regulated	330
	25.8	Power Flow and Control Study of CIGRE DC Grid-Test System	334
26	DC Grid Fault Management and DC Circuit Breakers		
	26.1	Introduction	339
	26.2	Fault Current Components in DC Grids	340
	26.3	DC System Protection Coordination with AC System Protection	342
	26.4	Mechanical DC Circuit Breaker	342
	26.5	Semiconductor Based DC Circuit Breaker	345
	26.6	Hybrid DC Circuit Breaker	349
	26.7	DC Grid-Protection System Development	351
	26.8	DC Grid Selective Protection System Based on Current Derivative or	
		Travelling Wave Identification	352
	26.9	Differential DC Grid Protection Strategy	353
		DC Grid Selective Protection System Based on Local Signals	354
	26.11	DC Grids with DC Fault-Tolerant VSC Converters	355
27	High Power DC/DC Converters and DC Power-Flow Controlling Devices		
	27.1	Introduction	362
	27.2	Power Flow Control Using Series Resistors	363
	27.3	Low Stepping-Ratio DC/DC Converters	366
	27.4	DC/DC Converters with DC Polarity Reversal	371
	27.5	High Stepping Ratio Isolated DC/DC Converter	373
	27.6	High Stepping Ratio LCL DC/DC Converter	373
	27.7	Building DC Grids with DC/DC Converters	375
	27.8	DC Hubs	377
	27.9	Developing DC Grids Using DC Hubs	380
	27.10	North Sea DC Grid Topologies	380
Bibl	liograp	hy Part III DC Transmission Grids	384
App	endix	A Variable Notations	386
Арр	endix	B Analytical Background for Rotating DQ Frame	388
App	endix	C System Modelling Using Complex Numbers and Phasors	399
Арр	endix	D Simulink Examples	401
Index		419	