CONTENTS

FC	REW	ORD	Xi
AC	CKNO	WLEDGMENTS	xv
LI	ST OF	F SYMBOLS AND ACRONYMS	xvii
IN	TROD	DUCTION	xxvii
1	INT	RODUCTION	1
	Refe	erences	8
2	FUN	NDAMENTALS OF HVDC CABLE TRANSMISSION	11
	2.1	Historical Evolution of HVDC Power Transmission	11
	2.2	Economic Comparison Between HVAC and HVDC Transmission S	ystems 18
	2.3	- · · · · · · · · · · · · · · · · · · ·	
	2.4		23
		2.4.1 Operation of a Line-Commutated Current Source	
		Converter (LCC-CSC)	23
		2.4.2 Operation of a Self-Commutated Voltage Source Converter ((VSC) 25
		2.4.3 CSC versus VSC: How Do They Affect Cable Insulation?	27
	2.5	Cables for HVDC Transmission	27
		2.5.1 Underground and Undersea Cable Transmission	27
		2.5.2 Different HVDC Cable Types	29
		2.5.2.1 Mass-Impregnated Nondraining (MIND) Cables	31
		2.5.2.2 Oil-Filled (OF) Cables	32
		2.5.2.3 Polypropylene Paper Laminate (known under a few	
		different acronyms, i.e., PPL, MI-PPL, PPLP) or La	
		Thin-Film Insulated Cable	33
		2.5.2.4 Polymer-Insulated or Extruded-Insulation Cable	33
		2.5.3 HVDC Cable Insulation	36
		2.5.3.1 Oil–Paper (or Lapped) Insulation	37
		2.5.3.2 Extruded Insulation	37
	Refe	erences	38
3	MAI	IN PRINCIPLES OF HVDC EXTRUDED CABLE DESIGN	41
	3.1	Differences Between HVAC and HVDC Extruded Cables	42
		3.1.1 Differences in the Structure	42
		3.1.2 Typical Formations of HVDC Extruded Cables	42
		3.1.2.1 Conductor	42
		3.1.2.2 Inner Semiconductive Layer	43

vi CONTENTS

			3.1.2.3	Insulation Layer	44
				Outer Semiconductive Layer	44
				Metallic Screen	45
				Water Sealing (or Blocking) Systems	46
				Protective Thermoplastic Sheath	47
				Armoring	47
				Jacketing (or External Sheath)	48
		3.1.3		ices in the Electric Field Distribution	48
	•		3.1.3.1	Electric Field Distribution Within the Insulation	
				of an HVAC Cable	48
			3.1.3.2	Steady Electric Field Distribution Within the Insulation	
				of an HVDC Cable	49
	3.2			ield Distribution	63
				Reach Steady-State DC Field Distribution	64
				on of Operational Stages of HVDC Cables	65
		3.2.3		istributions in the Various Stages	67
				Stage I: Raising the Voltage	68
				Stage II: After Raising the Voltage	68
				Stage III: Steady Resistive Field and Relevant Space Charge	71
		•		Stage IIIa: After Switching off the Load	73
				Stage IV: After Switching off the Voltage	74
				Stages at Polarity Reversal	75
	3.3			e Environment Temperature on the Steady Field of an HVDC	7.5
	2.4		ded Cable		75
				rimposed onto a DC Voltage	76
				roach to Impulse Voltage Test Levels for HVDC Cables	79
	3.6			f the Stress Distribution by Trapped Space Charge Effects	× 86
	3.7			HVDC Extruded Cables	92
	3.8 Dofo	rences	lology of	Polyethylene and Its Influence on Electrical Properties	95
	Kere	rences			73
4	SPA	CE CH	ARGE IN	I HVDC EXTRUDED INSULATION:	
•				TS, AND MEASUREMENT METHODS	99
	4.1			in HVDC Cable Insulation	100
	4.2			on and Transport in Insulating Polymers	107
		4.2.1		eld Conduction Mechanisms	107
				Ohmic Conduction	107
		400		Ionic Conduction	110
		4.2.2	_	ield Conduction Mechanisms	112
			4.2.2.1	Charge Injection From Electrodes Pully Controlled High Field Conduction Mechanisms	112
	4.2	Cmaaa	4.2.2.2	Bulk-Controlled High-Field Conduction Mechanisms	114
	4.3	Space 4.3.1		Accumulation Generation	118 119
		4.3.1	4.3.1.1	Electronic Charge Injection	119
			4.3.1.1	Field-Assisted Thermal Ionization of Impurities	119
			4.3.1.3		119
			4.3.1.4	Steady Direct Current Coupled with a Spatially	117
			7.3.1.4	Varying Ratio of Permittivity to Conductivity	122
				imping rand of a difficulty to conductivity	144

			CONTENTS	vii
		4.3.2 Charge Trapping		125
		4.3.2.1 Physical Defects		128
		4.3.2.2 Chemical Defects		. 128
	4.4	Review of Space-Charge Measurement Methods for HVDC	Extruded	
		Insulation		130
		4.4.1 Thermal Methods		133
		4.4.1.1 Thermal Pulse Method		134
		4.4.1.2 Laser Intensity Modulation Method (LIMM	()	135
		4.4.1.3 Thermal Step Method (TSM)		137
		4.4.2 Pressure Pulse Methods		142
		4.4.2.1 Pressure Wave Propagation Method		145
		4.4.2.2 Laser-Induced Pressure Pulse (LIPP) Metho	od	146
		4.4.2.3 Pulsed Electroacoustic (PEA) Method		148
		4.4.3 Techniques for Estimating the Trap Depth and the M	obility	
		of Space Charges		159
	4.5	Up-to-Date Developments of the Best Techniques for Meast	ıring	
		Space Charges		164
		4.5.1 Space-Charge Measurements in HVDC Cables with	the TSM	
		Technique		164
		4.5.1.1 Experimental Facility		164
		4.5.1.2 Cable 1: Under Field Measurements		167
		4.5.1.3 Study of Cable 2: Volt-Off Measurements		169
		4.5.2 Space-Charge Measurements in HVDC Cables with		
		the PEA Technique		171
		4.5.2.1 Space-Charge Measurements Related to the	;	
		Semicon-Insulation Interface		172
		4.5.2.2 Space-Charge Measurements Related to the	;	
		Insulation-Insulation Interface		176
		4.5.2.3 Space-Charge Measurements Related to the	;	
		Effect of Temperature Gradient		183
		4.5.3 Recent Developments in the Pressure Wave Propaga	tion Method	191
	4.6	Final Comparison between the Best Space-Charge Measure	ment Methods	
		for Power Cables: PEA versus TSM		193
	Refe	erences		200
5	<i>IMP</i>	PROVED DESIGN OF HVDC EXTRUDED CABLE SYSTEMS	S	209
_	5.1	R&D Trends in Improving Extruded Polymeric Insulation		
	5.1	for HVDC Cables		210
		5.1.1 Problems to be Solved for Improving HVDC Extrud	ed Insulation	210
		5.1.2 Optimum Characteristics of Polymeric Insulating M		210
		for HVDC Cables	accitais	212
		5.1.3 Historical Development Activities of HVDC Extrude	ed Insulation	213
	5.2	Use of AC LDPE, XLPE, or HDPE Cable Compounds for H		213
	٠.٢	Applications without any Modifications		215
	5.3	Stress Inversion-Free or -Limited DC Cable		217
	5.4	Suppression of Space Charge in the Polymer		218
	۶.¬	5.4.1 Modification of the Characteristics of the Electrode-	-Insulation	210
		Interfaces	moutanoli	218
		5.4.1.1 Traditional Approaches		218
		- · · · · · · · · · · · · · · · · · · ·		0

viii CONTENTS

			5.4.1.2	Effect of Surface Fluorination on the Space-Charge	210
		5 4 0	N # 11 C	Behavior of PE	219
		5.4.2		ation of Bulk Insulation Characteristics	220
				Blending PE with Another Polymer	221
				Using Additives or Fillers in PE-Based Compounds	221 227
				Additives and the Morphology of Polyethylene Effect of Nanostructuration	
	<i>E E</i>	Donath o			228
	5.6			ements for the Improvement of HVDC Extruded Cable Design gn of HVDC Extruded Cables	229 232
	3.0			ample of Improved Design of HVDC Extruded Cables	232
				Design Relevant to the Gotland Project	232
				Design Relevant to the Murraylink Project	234
				Design Relevant to the Trans Bay Project	236
				nproved Cable Designs	237
	5.7			gn of Accessories for HVDC Extruded Cable Systems	239
	3.7			ories Design Relevant to the Gotland Project	243
		3.7.1		Joints for the Gotland Project	243
				Terminations for the Gotland Project	243
		5.7.2		ories Design Relevant to the Murraylink Project	244
		3.1.2		Joints for the Murraylink Project	244
				Terminations for the Murraylink Project	246
		5.7.3		the Art of HVDC Extruded Cable Accessories	246
		5.7.5		Prefabricated Joints	247
				Terminations	249
				Electric Fields in Accessories	249
				Installation of Accessories	250
	5.8	Impro		e System Design	251
	5.9			OC Extruded Cable Systems	252
		erences	6		256
6	LIFI	E MOD	ELING C	OF HVDC EXTRUDED CABLE INSULATION	265
	6.1	Funda	mentals o	of Life Modeling and Reliability Estimates of Power Cables	266
		6.1.1		onal Approach to Insulation Life Modeling	268
		6.1.2		listic Framework of HVDC Extruded Insulation Life Modeling	277
				Basic Aspects of Probabilistic Life Modeling	277
				Probabilistic Life Models for HVDC Extruded Cable	
				Insulation	279
			6.1.2.3	Life Models for HVDC Extruded Cables under Single	
				and Combined Stress	286
	6.2	Space	-Charge-	Based Life Models for Extruded HVDC Cables	293
		6.2.1		imited Space-Charge Model	294
		6.2.2		Charge DMM Model	296
			6.2.2.1	The DC DMM Model	297
			6.2.2.2	Application of the DC DMM Model to HVDC Extruded	
				Insulation	298
	6.3	From	Space Ch	narges to Partial Discharges: Life Model Based on Damage	
		Growt	th from M	Microvoids	300
		6.3.1	Charge	Storage at PE-Void Interface and Injection into the Void	302
		6.3.2	Hot-Ele	ectron Avalanche Formation inside the Void	303

				CONTENTS	ki
		6.3.3	Damage at Void-PE Interface Growing into the Polymer		304
		6.3.4	Fitting the Model to Extruded HVDC Insulation Times to Fai	lure	305
6.	.4	Space	Charge: Cause or Effect of Aging?		308
R	efer	ences			315
- 14	6 A 7 N	IPFAI	LIZATIONS OF HVDC EXTRUDED CABLE SYSTEMS		
	IN THE WORLD				
7.	.1	Overv	iew		323
7.	.2	Extruc	led Systems in Service		327
		7.2.1	Gotland Link		328
		7.2.2	Murraylink		330
		7.2.3	Cross Sound Cable (CSC)		332
		7.2.4	Troll A Platform		333
		7.2.5	Estlink		334
		7.2.6	BorWin 1		335
		7.2.7	The Trans Bay Project		336
		7.2.8	The Hokkaido-Honshu Intertie		339
R	efei	ences			340
INDE	X				343