

Contents

1 Applications of Submarine Power Cables	1
1.1 Power Supply to Islands	1
1.2 Connection of Autonomous Grids	3
1.3 Offshore Wind Farms	4
1.4 Supply of Marine Platforms	5
1.5 Short-Haul Crossings	6
1.6 Other Applications of Submarine Power Cables	6
References	7
2 Submarine Power Cables and Their Design Elements	9
2.1 The Conductor	10
2.1.1 Solid Conductor	10
2.1.2 Conductors Stranded from Round Wires	11
2.1.3 Profiled Wire Conductors	12
2.1.4 Hollow Conductors for Oil-Filled Cables	13
2.1.5 Milliken Conductor	13
2.1.6 Conductor Resistance	15
2.1.7 Watertightness of Conductors	16
2.1.8 Superconducting Conductors	16
2.2 The Insulation System	17
2.2.1 Polyethylene	17
2.2.2 Cross-Linked Polyethylene	18
2.2.3 Conductor and Insulation Screen	19
2.2.4 The Influence of Ageing and Humidity on XLPE Insulation	20
2.2.5 Applications of XLPE Insulation	22
2.2.6 Extruded HVDC Cables	22
2.2.7 Other Extruded Insulation Systems	23
2.2.8 Paper-Insulated Oil-Filled Cables for a.c. or d.c.	23
2.2.9 Paper-Mass Insulation for HVDC	26
2.2.10 Gas-Filled Submarine Cables	28
2.2.11 Other Insulation Systems	29
2.3 The Water-Blocking Sheath	30

2.3.1	Lead Sheath	30
2.3.2	Aluminium Sheath	32
2.3.3	Copper Sheath	32
2.3.4	Polymeric Sheaths	33
2.4	Armoring	33
2.4.1	Corrosion Protection	37
2.5	Outer Serving	39
2.6	Three-Core Cables	40
2.6.1	Choice Between One Three-Core and Three Single-Core Cables	42
2.7	Two-Core Cables	43
2.8	Coaxial Cables	44
2.9	Optical Fibres Inside Submarine Power Cables	45
2.10	Five Generic Cable Types	47
	References	48
3	Design	51
3.1	Thermal Design	51
3.1.1	Single-Core HVDC Cables	52
3.1.2	a.c. Cables	59
3.1.3	Other Factors for the Thermal Design	64
3.1.4	The 2 K Criterion	73
3.1.5	Economic Aspects of the Thermal Design	75
3.2	Design of Mechanical Properties	78
3.2.1	Tensional Forces During Laying	79
3.2.2	The Cigré Test Recommendation	81
3.2.3	Distribution of Mechanical Stress Between Conductor and Armoring	83
3.2.4	Other Forces and Impacts	85
3.2.5	Vortex Induced Vibrations	88
3.3	Electric Design	90
3.3.1	The Concept of Electric Strength	90
3.3.2	The Weibull Distribution	91
3.3.3	Dielectric Design of a.c. Cables	94
3.3.4	Dielectric Design of d.c. Cables	97
3.3.5	Dielectric Design of Mass-Impregnated Cables	100
3.3.6	Impulse Stress	101
3.3.7	Availability and Reliability	102
	References	103
4	Accessories	105
4.1	Submarine Cable Joints	105
4.1.1	Factory Joints	106
4.1.2	Offshore Installation Joints	108
4.1.3	Miscellaneous Joint Designs	113
4.1.4	Beach Joints	114

4.2	Cable Terminations	116
4.2.1	On-Shore a.c. Cable Terminations	116
4.2.2	On-Shore d.c. Cable Terminations	116
4.2.3	Offshore Cable Terminations	118
4.3	Other Accessories	118
4.3.1	J-Tubes	118
4.3.2	Hang-Off	119
4.3.3	Bending Protection	120
4.3.4	Holding Devices	120
	References	120
5	Manufacturing and Testing	123
5.1	Manufacturing	123
5.1.1	The Conductor	124
5.1.2	XLPE Cables	125
5.1.3	Paper-Insulated Cables	126
5.1.4	Sheathing	129
5.1.5	Lay-up	130
5.1.6	Armoring	131
5.1.7	Storage of Submarine Cables	134
5.2	Testing	136
5.2.1	Development Tests	136
5.2.2	Type Tests	137
5.2.3	Routine Tests	144
5.2.4	Factory Acceptance Tests (FAT)	145
5.2.5	After-Installation Test	146
5.2.6	Non-electrical Tests	148
	References	148
6	Marine Survey	151
6.1	Scope of the Marine Survey	152
6.2	Bathymetry	153
6.3	Sub-bottom Profiling	156
6.4	Visual Inspection	157
6.5	Soil Sampling	157
6.6	Soil and Water Temperatures	158
	References	159
7	Installation and Protection of Submarine Power Cables	161
7.1	Installation	161
7.1.1	Cable Laying Vessels	162
7.1.2	Other Vessels	171
7.1.3	Loading and Logistics	173
7.1.4	Laying of Submarine Power Cables	174
7.1.5	Landing of Submarine Cables	177

7.1.6	Jointing of Submarine Power Cables	181
7.1.7	Weather	186
7.1.8	Organisation	193
7.2	Protection of Submarine Power Cables	194
7.2.1	Selection of a Suitable Cable Route	195
7.2.2	Design of a Suitable Cable Armoring	196
7.2.3	External Protection	198
7.2.4	After-Installation Protection	205
7.3	Appendix: The Catenary Line	206
	References	208
8	Damages and Repair	211
8.1	Damages	211
8.1.1	Causes of Damages	212
8.1.2	Statistic Distribution of Damages	213
8.1.3	Damage by Fishing Equipment	213
8.1.4	Damage by Anchors	215
8.1.5	Damage During the Installation	218
8.1.6	Other Damage	219
8.1.7	Spontaneous Damage	220
8.1.8	Failures of Joints	221
8.2	Repair	222
8.2.1	Spare Cable	222
8.2.2	Repair Vessel	223
8.2.3	Repair Crew	223
8.2.4	Repair Operation	224
8.3	Fault Location	225
8.3.1	TDR	225
8.3.2	Bridge Measurements	228
8.3.3	Fine Localisation	229
8.3.4	Optical Time Domain Reflectrometry	230
8.3.5	Other Methods	231
8.4	Repair Example	232
	References	235
9	Operation and Maintenance: Reliability	237
9.1	Operation of Submarine Cables	237
9.1.1	Common Measures for All Kind of Submarine Power Cables	237
9.1.2	Instrumentation	238
9.1.3	Mass-Impregnated Cables and XLPE Cables	240
9.1.4	LPOF, SCOF and SCFF Cables	240
9.1.5	Cable Terminations	241
9.2	Reliability of Submarine Cables	241
9.2.1	The Cigré Studies	241

9.2.2	Failure Statistics for Large HVDC Cable Projects	242
9.2.3	Definition of Reliability Terms	244
9.2.4	Reliability of Some Specific Submarine Power Cables	244
	References	247
10	Environmental Issues	249
10.1	Environmental Assessment	249
10.2	The Influence of Cable Losses	251
10.3	Environmental Aspects Related to Cable Design	252
10.3.1	Conductor Materials	252
10.3.2	Choice of Other Cable Materials	252
10.4	Environmental Aspects of Cable Installation	255
10.5	Environmental Impacts from the Operation of Submarine Power Cables	258
10.5.1	Thermal Impact	258
10.5.2	The 2 k Criterion	258
10.5.3	Electromagnetic Impact	261
10.5.4	Chemical Impact	266
10.6	Recycling of Submarine Power Cables	266
	References	267
11	Anecdotes	269
11.1	The Floating Hospital S/S Castalia	270
11.2	HVDC Cable Between Lydd, UK and Boulogne, F	270
11.3	The Pilot	271
11.4	S-Lay and Coiling Direction	271
11.5	Edible Insulation	273
11.6	Flipper	273
11.7	Stamps	274
11.8	Unusual Cable Ships	274
11.9	Master Teredo	276
11.10	Krauts at War Searching for a Cable Break	276
11.11	Even More Damages	277
11.12	Loops	277
11.13	Cable Ship Reefs	277
11.14	Poetry	278
11.14.1	The Journey of Mrs. Florence Kimball Russel	279
	References	280
12	Useful Tables	281
12.1	Dielectric Properties of Cable Insulation Material	281
12.2	Lead Alloys	282
12.3	Non-metric Conductor Size: kcmil	283
12.4	Non-metric Wire Diameter	283
12.5	The Galvanic Series of Metals and Alloys in Seawater	285

12.6	Classification of Submarine Soil in Different Countries	286
12.7	Non-metric Units	287
12.8	Tidal Terms	288
	References	288
Index		289