

Contents

Preface	<i>xv</i>
Acknowledgments	<i>xvii</i>
Symbols	<i>xix</i>
Abbreviations	<i>xxvii</i>

1	Introduction	<i>1</i>
2	Electrical Systems	<i>5</i>
2.1	High-Voltage Power Systems	<i>5</i>
2.2	Transformer Selection Depending on Load Profiles	<i>9</i>
2.3	Low-Voltage Power Systems	<i>10</i>
2.4	Examples of Power Systems	<i>17</i>
2.4.1	Example 1: Calculation of the Power	<i>17</i>
2.4.2	Example 2: Calculation of the Main Power Line	<i>17</i>
2.4.3	Example: Power Supply of a Factory	<i>17</i>
3	Design of DC Current Installations	<i>21</i>
3.1	Earthing Arrangement	<i>21</i>
3.2	Protection Against Overcurrent	<i>22</i>
3.3	Architecture of Installations	<i>23</i>
4	Smart Grid	<i>25</i>
5	Project Management	<i>27</i>
5.1	Guidelines for Contracting	<i>27</i>
5.2	Guidelines for Project Planning of Electrical Systems	<i>28</i>
6	Three-Phase Alternating Current	<i>31</i>
6.1	Generation of Three-Phase Current	<i>31</i>
6.2	Advantages of the Three-Phase Current System	<i>31</i>
6.3	Conductor Systems	<i>32</i>
6.4	Star Connection	<i>36</i>
6.5	Triangle Circuit	<i>37</i>
6.6	Three-Phase Power	<i>38</i>
6.7	Example: Delta Connection	<i>39</i>

6.8	Example: Star Connection	41
6.9	Example: Three-Phase Consumer	43
6.10	Example: Network Calculation	44
6.11	Example: Network	45
6.12	Example: Star Connection	47
7	Symmetrical Components	49
7.1	Symmetrical Network Operation	49
7.2	Unsymmetrical Network Operation	51
7.3	Description of Symmetrical Components	51
7.4	Examples of Unbalanced Short-Circuits	54
7.4.1	Example: Symmetrical Components	54
7.4.2	Example: Symmetrical Components	54
7.4.3	Example: Symmetrical Components	55
8	Short-Circuit Currents	57
8.1	Introduction	57
8.2	Fault Types, Causes, and Designations	60
8.3	Short-circuit with R - L Network	61
8.4	Calculation of the Stationary Continuous Short-circuit	63
8.5	Calculation of the Settling Process	64
8.6	Calculation of a Peak Short-Circuit Current	65
8.6.1	Impact Factor for Branched Networks	65
8.6.2	Impact Factor for Meshed Networks	65
8.7	Calculation of the Breaking Alternating Current	66
8.8	Near-Generator Three-Phase Short-circuit	66
8.9	Calculation of the Initial Short-Circuit Alternating Current	67
8.10	Short-Circuit Power	68
8.11	Calculation of Short-Circuit Currents in Meshed Networks	68
8.11.1	Superposition Method	68
8.11.2	Method of Equivalent Voltage Source	70
8.12	The Equivalent Voltage Source Method	72
8.13	Short-Circuit Impedances of Electrical Equipment	72
8.13.1	Network Feeders	73
8.13.2	Synchronous Machines	74
8.13.3	Transformers	75
8.13.4	Consideration of Motors	76
8.13.5	Overhead Lines, Cables, and Lines	78
8.13.6	Impedance Corrections	79
8.14	Calculation of Short-Circuit Currents	81
8.14.1	Three-Phase Short-circuits	81
8.14.2	Line-to-Line Short-circuit	82
8.14.3	Single-Phase Short-circuits to Ground	82
8.14.4	Calculation of Loop Impedance	83
8.14.5	Peak Short-Circuit Current	85
8.14.6	Symmetrical Breaking Current	85
8.14.7	Steady-State Short-circuit Current	87

8.15	Thermal and Dynamic Short-circuit Strength	87
8.16	Examples for the Calculation of Short-Circuit Currents	89
8.16.1	Example 1: Calculation of the Short-Circuit Current in a DC System	89
8.16.2	Example 2: Calculation of Short-Circuit Currents in a Building Electrical System	91
8.16.3	Example 3: Dimensioning of an Exit Cable	92
8.16.4	Example 4: Calculation of Short-Circuit Currents with Zero-Sequence Resistances	93
8.16.5	Example 5: Complex Calculation of Short-Circuit Currents	94
8.16.6	Example 6: Calculation with Effective Power and Reactive Power	97
8.16.7	Example 7: Complete Calculation for a System	101
8.16.8	Example 8: Calculation of Short-Circuit Currents with Impedance Corrections	111
8.16.9	Example: Load Voltage and Zero Impedance	113
8.16.10	Example: Power Transmission	116
9	Relays	119
9.1	Terms and Definitions	119
9.2	Introduction	119
9.3	Requirements	121
9.4	Protective Devices for Electric Networks	121
9.5	Type of Relays	122
9.5.1	Electromechanical Protective Relays	122
9.5.2	Static Protection Relays	122
9.5.3	Numeric Protection Relays	122
9.6	Selective Protection Concepts	123
9.7	Overcurrent Protection	124
9.7.1	Examples for Independent Time Relays	126
9.8	Reserve Protection for IMT Relays with Time Staggering	126
9.9	Overcurrent Protection with Direction	126
9.10	Dependent Overcurrent Time Protection (DMT)	129
9.11	Differential Relays	131
9.12	Distance Protection	133
9.12.1	Method of Distance Protection	135
9.12.2	Distance Protection Zones	135
9.12.3	Relay Plan	135
9.13	Motor Protection	138
9.14	Busbar Protection	138
9.15	Saturation of Current Transformers	140
9.16	Summary	141
10	Power Flow in Three-Phase Network	143
10.1	Terms and Definitions	143
10.2	Introduction	143
10.3	Node Procedure	145
10.4	Simplified Node Procedure	148
10.5	Newton–Raphson Procedure	151

11	Substation Earthing	155
11.1	Terms and Definitions	155
11.2	Methods of Neutral Earthing	160
11.2.1	Isolated Earthing	162
11.2.2	Resonant Earthing	163
11.2.3	Double Earth Fault	164
11.2.4	Solid (Low-Impedance) Earthing	166
11.3	Examples for the Treatment of the Neutral Point	166
11.3.1	Example: Earth Fault Current When Operating with Free Neutral Point	166
11.3.2	Example: Calculation of Earth Fault Currents	167
11.3.3	Example: Ground Fault Current of a Cable	167
11.3.4	Example: Earth Leakage Coil	168
11.3.5	Example: Arc Suppression Coil	168
11.4	Dimensioning of Thermal Strength	168
11.5	Methods of Calculating Permissible Touch Voltages	169
11.6	Methods of Calculating Permissible Step Voltages	172
11.7	Current Injunction in the Ground	172
11.8	Design of Earthing Systems	173
11.9	Types of Earth Rods	175
11.9.1	Deep Rod	175
11.9.2	Earthing Strip	175
11.9.3	Mesh Earth	176
11.9.4	Ring Earth Electrode	177
11.9.5	Foundation Earthing	177
11.10	Calculation of the Earthing Conductors and Earth Electrodes	177
11.11	Substation Grounding IEEE Std. 80	178
11.11.1	Tolerable Body Current	178
11.11.2	Permissible Touch Voltages	179
11.11.3	Calculation of the Conductor Cross Section	180
11.11.4	Calculation of the Maximum Mesh Residual Current	181
11.12	Soil Resistivity Measurement	182
11.13	Measurement of Resistances and Impedances to Earth	184
11.14	Example: Calculation of a TR Station	184
11.15	Example: Earthing Resistance of a Building	186
11.15.1	Foundation Earthing R_{EF}	186
11.15.2	Ring Earth Electrode 1 R_{ER1}	187
11.15.3	Ring Earth Electrode 2 R_{ER2}	187
11.15.4	Deep Earth Electrode R_{ET}	187
11.15.5	Total Earthing Resistance R_{ETotal}	188
11.16	Example: Cross-Sectional Analysis	188
11.17	Example: Cross-Sectional Analysis of the Earthing Conductor	189
11.18	Example: Grounding Resistance According to IEEE Std. 80	190
11.19	Example: Comparison of IEEE Std. 80 and EN 50522	193
11.20	Example of Earthing Drawings and Star Point Treatment of Transformers	194
11.21	Software for Earthing Calculation	199
11.21.1	Numerical Methods for Grounding System Analysis	199
11.21.2	IEEE Std. 80 and EN 50522	203
11.21.3	Summary	217

12	Protection Against Electric Shock	219
12.1	Voltage Ranges	221
12.2	Protection by Cut-Off or Warning Messages	222
12.2.1	TN Systems	222
12.2.2	TT Systems	224
12.2.3	IT Systems	226
12.2.4	Summary of Cut-Off Times and Loop Resistances	228
12.2.5	Example 1: Checking Protective Measures	229
12.2.6	Example 2: Determination of Rated Fuse Current	231
12.2.7	Example 3: Calculation of Maximum Conductor Length	231
12.2.8	Example 4: Fault Current Calculation for a TT System	231
12.2.9	Example 5: Cut-Off Condition for an IT System	232
12.2.10	Example 6: Protective Measure for Connection Line to a House	232
12.2.11	Example 7: Protective Measure for a TT System	233
13	Equipment for Overcurrent Protection	235
13.1	Electric Arc	235
13.1.1	Electric Arc Characteristic	235
13.1.2	DC Cut-Off	237
13.1.3	AC Cut-Off	237
13.1.3.1	Cut-Off for Large Inductances	238
13.1.3.2	Cut-Off of Pure Resistances	239
13.1.3.3	Cut-Off of Capacitances	239
13.1.3.4	Cut-Off of Small Inductances	239
13.1.4	Transient Voltage	240
13.2	Low-Voltage Switchgear	241
13.2.1	Characteristic Parameters	241
13.2.2	Main or Load Switches	242
13.2.3	Motor Protective Switches	242
13.2.4	Contactors and Motor Starters	244
13.2.5	Circuit-Breakers	244
13.2.6	RCDs (Residual Current Protective Devices)	245
13.2.7	Main Protective Equipment	248
13.2.8	Meter Mounting Boards with Main Protective Switch	249
13.2.9	Fuses	251
13.2.9.1	Types of Construction	253
13.2.10	Power Circuit-Breakers	256
13.2.10.1	Short-Circuit Categories in Accordance with IEC 60947	258
13.2.10.2	Breaker Types	259
13.2.11	Load Interrupter Switches	260
13.2.12	Disconnect Switches	260
13.2.13	Fuse Links	261
13.2.14	List of Components	261
14	Current Carrying Capacity of Conductors and Cables	263
14.1	Terms and Definitions	263
14.2	Overload Protection	264
14.3	Short-Circuit Protection	265
14.3.1	Designation of Conductors	268

14.3.2	Designation of Cables	269
14.4	Current Carrying Capacity	270
14.4.1	Loading Capacity Under Normal Operating Conditions	270
14.4.2	Loading Capacity Under Fault Conditions	271
14.4.3	Installation Types and Load Values for Lines and Cables	273
14.4.4	Current Carrying Capacity of Heavy Current Cables and Correction Factors for Underground and Overhead Installation	276
14.5	Examples of Current Carrying Capacity	280
14.5.1	Example 1: Checking Current Carrying Capacity	280
14.5.2	Example 2: Checking Current Carrying Capacity	285
14.5.3	Example 3: Protection of Cables in Parallel	290
14.5.4	Example 4: Connection of a Three-Phase Cable	293
14.5.5	Example 5: Apartment Building Without Electrical Water Heating	294
14.6	Examples for the Calculation of Overcurrents	300
14.6.1	Example 1: Determination of Overcurrents and Short-Circuit Currents	300
14.6.2	Example 2: Overload Protection	302
14.6.3	Example 3: Short-Circuit Strength of a Conductor	303
14.6.4	Example 4: Checking Protective Measures for Circuit-Breakers	304
15	Selectivity and Backup Protection	309
15.1	Selectivity	309
15.2	Backup Protection	317
16	Voltage Drop Calculations	321
16.1	Consideration of the Voltage Drop of a Line	321
16.2	Example: Voltage Drop on a 10 kV Line	325
16.3	Example: Line Parameters of a Line	325
16.4	Example: Line Parameters of a Line	327
16.5	Voltage Regulation	328
16.5.1	Permissible Voltage Drop in Accordance With the Technical Conditions for Connection	328
16.5.2	Permissible Voltage Drop in Accordance With Electrical Installations in Buildings	329
16.5.3	Voltage Drops in Load Systems	329
16.5.4	Voltage Drops in Accordance With IEC 60364	330
16.5.5	Parameters for the Maximum Line Length	330
16.5.6	Summary of Characteristic Parameters	333
16.5.7	Lengths of Conductors With a Source Impedance	334
16.6	Examples for the Calculation of Voltage Drops	334
16.6.1	Example 1: Calculation of Voltage Drop for a DC System	334
16.6.2	Example 2: Calculation of Voltage Drop for an AC System	335
16.6.3	Voltage Drop for a Three-Phase System	336
16.6.4	Example 4: Calculation of Voltage Drop for a Distributor	338
16.6.5	Calculation of Cross Section According to Voltage Drop	338
16.6.6	Example 6: Calculation of Voltage Drop for an Industrial Plant	339
16.6.7	Example 7: Calculation of Voltage Drop for an Electrical Outlet	339
16.6.8	Example 8: Calculation of Voltage Drop for a Hot Water Storage Unit	339
16.6.9	Example 9: Calculation of Voltage Drop for a Pump Facility	339
16.6.10	Example: Calculation of Line Parameters	340

17	Switchgear Combinations	343
17.1	Terms and Definitions	343
17.2	Design of the Switchgear	347
17.2.1	Data for Design	347
17.2.2	Design of the Distributor and Proof of Construction	348
17.2.3	Short-Circuit Resistance Proofing	348
17.2.4	Proof of Heating	349
17.2.5	Determination of an Operating Current	349
17.2.6	Determination of Power Losses	350
17.2.7	Determination of a Design Loading Factor RDF	350
17.2.8	Determination of an Operating Current	350
17.2.9	Check of Short-Circuit Variables	351
17.2.10	Construction and Manufacturing of the Distribution	351
17.2.11	CE Conformity	352
17.3	Proof of Observance of Boundary Overtemperatures	352
17.4	Power Losses	353
18	Compensation for Reactive Power	355
18.1	Terms and Definitions	355
18.2	Effect of Reactive Power	358
18.3	Compensation for Transformers	358
18.4	Compensation for Asynchronous Motors	359
18.5	Compensation for Discharge Lamps	359
18.6	c/k Value	360
18.7	Resonant Circuits	360
18.8	Harmonics and Voltage Quality	360
18.8.1	Compensation With Nonchoked Capacitors	362
18.8.2	Inductor–Capacitor Units	363
18.8.3	Series Resonant Filter Circuits	365
18.9	Static Compensation for Reactive Power	365
18.9.1	Planning of Compensation Systems	368
18.10	Examples of Compensation for Reactive Power	368
18.10.1	Example 1: Determination of Capacitive Power	368
18.10.2	Example 2: Capacitive Power With k Factor	369
18.10.3	Example 3: Determination of Cable Cross Section	369
18.10.4	Example 4: Calculation of the c/k Value	370
19	Lightning Protection Systems	371
19.1	Lightning Protection Class	373
19.2	Exterior Lightning Protection	374
19.2.1	Air Terminal	374
19.2.2	Down Conductors	375
19.2.3	Grounding Systems	379
19.2.3.1	Minimum Length of Ground Electrodes	385
19.2.4	Example 1: Calculation of Grounding Resistances	386
19.2.5	Example 2: Minimum Lengths of Grounding Electrodes	387
19.2.6	Exposure Distances in the Wall Area	387
19.2.7	Grounding of Antenna Systems	389
19.2.8	Examples of Installations	389

19.3	Interior Lightning Protection	392
19.3.1	The EMC Lightning Protection Zone Concept	392
19.3.2	Planning Data for Lightning Protection Systems	395
20	Lighting Systems	399
20.1	Interior Lighting	399
20.1.1	Terms and Definitions	399
20.2	Types of Lighting	400
20.2.1	Normal Lighting	400
20.2.2	Normal Workplace-Oriented Lighting	400
20.2.3	Localized Lighting	400
20.2.4	Technical Requirements for Lighting	401
20.2.5	Selection and Installation of Operational Equipment	401
20.2.6	Lighting Circuits for Special Rooms and Systems	402
20.3	Lighting Calculations	403
20.4	Planning of Lighting with Data Blocks	405
20.4.1	System Power	405
20.4.2	Distribution of Luminous Intensity	405
20.4.3	Luminous Flux Distribution	405
20.4.4	Efficiencies	406
20.4.5	Spacing Between Lighting Elements	407
20.4.6	Number of Fluorescent Lamps in a Room	407
20.4.7	Illuminance Distribution Curves	407
20.4.8	Maximum Number of Fluorescent Lamps on Switches	407
20.4.9	Maximum Number of Discharge Lamps Per Circuit-Breaker	408
20.4.10	Mark of Origin	408
20.4.11	Standard Values for Planning Lighting Systems	409
20.4.12	Economic Analysis and Costs of Lighting	409
20.5	Procedure for Project Planning	412
20.6	Exterior Lighting	413
20.7	Low-Voltage Halogen Lamps	415
20.8	Safety and Standby Lighting	416
20.8.1	Terms and Definitions	416
20.8.2	Circuits	417
20.8.3	Structural Types for Groups of People	417
20.8.4	Planning and Configuring of Emergency Symbol and Safety Lighting	417
20.8.5	Power Supply	421
20.8.6	Notes on Installation	422
20.8.7	Testing During Operation	422
20.9	Battery Systems	423
20.9.1	Central Battery Systems	423
20.9.2	Grouped Battery Systems	427
20.9.3	Single Battery Systems	429
20.9.4	Example: Dimensioning of Safety and Standby Lighting	432
21	Generators	435
21.1	Generators in Network Operation	437
21.2	Connecting Parallel to the Network	438
21.3	Consideration of Power and Torque	438

21.4	Power Diagram of a Turbo Generator	439
21.5	Example 1: Polar Wheel Angle Calculation	440
21.6	Example 2: Calculation of the Power Diagram	440
22	Transformer	441
22.1	Introduction	441
22.2	Core	445
22.3	Winding	446
22.4	Constructions	446
22.5	AC Transformer	446
22.5.1	Construction	446
22.5.2	Mode of Action	447
22.5.3	Idling Stress	448
22.5.4	Voltage and Current Translation	448
22.5.5	Operating Behavior of the Transformer	449
22.6	Three-phase Transformer	452
22.6.1	Construction	452
22.6.2	Windings	452
22.6.3	Circuit Groups	452
22.6.4	Overview of Vector Groups	454
22.6.5	Parallel Connection of Transformers	454
22.7	Transformers for Measuring Purposes	457
22.7.1	Current Transformers	457
22.7.2	Voltage Transformer	457
22.7.3	Frequency Transformer	458
22.8	Transformer Efficiency	459
22.9	Protection of Transformers	459
22.10	Selection of Transformers	459
22.11	Calculation of a Continuous Short-Circuit Current on the NS Side of a Transformer	461
22.12	Examples of Transformers	462
22.12.1	Example 1: Calculation of the Continuous Short-Circuit Current	462
22.12.2	Example: Calculation of a Three-phase Transformer	462
23	Asynchronous Motors	467
23.1	Designs and Types	467
23.1.1	Principle of Operation (No-Load)	468
23.1.1.1	Motor Behavior	469
23.1.1.2	Generator Behavior	469
23.1.2	Typical Speed-Torque Characteristics	469
23.2	Properties Characterizing Asynchronous Motors	471
23.2.1	Rotor Frequency	471
23.2.2	Torque	471
23.2.3	Slip	472
23.2.4	Gear System	472
23.3	Startup of Asynchronous Motors	473
23.3.1	Direct Switch-On	473
23.3.2	Star Delta Startup	474
23.4	Speed Adjustment	479

23.4.1	Speed Control by the Slip	479
23.4.2	Speed Control by Frequency	479
23.4.3	Speed Control by Pole Changing	480
23.4.4	Soft Starters	481
23.4.5	Example: Calculation of Overload and Starting Conditions	483
23.4.6	Example: Calculation of Motor Data	484
23.4.7	Example: Calculation of the Belt Pulley Diameter and Motor Power	485
23.4.8	Example: Dimensioning of a Motor	485
24	Questions About Book	487
24.1	Characteristics of Electrical Cables	487
24.2	Dimensioning of Electric Cables	487
24.3	Voltage Drop and Power Loss	488
24.4	Protective Measures and Earthing in the Low-voltage Power Systems	488
24.5	Short Circuit Calculation	488
24.6	Switchgear	489
24.7	Protection Devices	489
24.8	Electric Machines	489
	References	491
	Index	495