

Contents

Preface	V
Contents	IX
Symbols and Abbreviations	XIX
1 INTRODUCTION.....	1
1.1 The Function of High Voltage Technology	1
1.2 Applications of High Voltage Technology.....	1
1.3 Perspectives of High Voltage Engineering.....	2
1.4 Overview	3
2 ELECTRIC STRESSES.....	5
2.1 Basic Field Theory.....	5
2.1.1 Field Quantities	6
2.1.2 Equipotential Lines, Potential, Voltage and Capacitance	7
2.1.3 Maxwell's Equations.....	9
2.1.3.1 Maxwell's Main Field Equations	10
2.1.3.2 Maxwell's Continuity Equations	10
2.1.3.3 Material Equations	12
2.1.4 Classification of Fields.....	13
2.1.4.1 Static and Stationary Fields	14
2.1.4.2 Quasi-stationary (Inductive) Fields in Conductors	15
2.1.4.3 Quasi-stationary/ Quasi-static (Capacitive) Displacement Fields in Dielectrics	17
2.1.4.4 Non-stationary, Time-varying Fields (Electromagnetic Waves)	20
2.2 Electrical Stresses in High Voltage Engineering.....	21
2.2.1 DC Voltage Stress	22
2.2.2 AC Voltage Stress	23
2.2.3 Switching Impulse Voltage Stress ("Internal Overtvoltages")	25
2.2.4 Lightning Impulse Voltage Stress ("External Overtvoltages").....	25
2.2.5 Fast-rising Impulse Stresses ("Fast Transients")	26
2.2.6 Mixed-field Stresses.....	28
2.3 Conduction and Displacement Fields in Homogeneous Dielectrics.....	29
2.3.1 Analytic Evaluation of the Continuity Equation (Gauss's Law)	30
2.3.1.1 General Calculation Method	30

2.3.1.2 Spherically Symmetric Fields	31
2.3.1.3 Cylindrically Symmetric Fields	33
2.3.1.4 Uniform (Homogeneous) Fields	37
2.3.1.5 Field Distortions by Space Charges	38
2.3.2 Analytic Solution of Poisson's Equation	39
2.3.3 Graphical Field Mapping (for Plane Fields)	40
2.3.4 Conformal Mapping (for Plane Fields)	44
2.3.5 Charge Simulation Method	48
2.3.5.1 Conducting Spheres (Point Charges)	48
2.3.5.2 Field between Two Conducting Spheres (Sphere-to-sphere Gap)	54
2.3.5.3 Parallel Line Charges	58
2.3.5.4 Fields in the Vicinity of Cylindrical Conductors	60
2.3.6 Similarity Relations, Field Efficiency Factor (Schwaiger's Utilization Factor).....	71
2.3.7 Measurement of Stationary Conduction Fields.....	74
2.3.7.1 Analogy between Dielectric Displacement Field and Static Conduction Field	75
2.3.7.2 Measurements on Semi-conductive Paper ("Resistive Paper")	75
2.3.7.3 Measurements in Semi-conductive Liquids ("Electrolytic Tank")	76
2.4 Conduction and Displacement Fields in Inhomogeneous Dielectrics	76
2.4.1 Conductivity and Polarization.....	77
2.4.1.1 Conductivity	77
2.4.1.2 Polarization	78
2.4.2 Multi-dielectric Arrangements	81
2.4.2.1 Boundary Conditions at Interfaces	81
2.4.2.2 Interface Orthogonal (Normal) to the Field („Field Displacement“)	82
2.4.2.3 Interface Parallel to the Field (Tangential Interface)	84
2.4.2.4 Interface Inclined (at an Angle) to the Field ("Refraction Law")	85
2.4.3 Analytical Calculation of Multilayer Dielectric Arrangements	86
2.4.3.1 Plane, Cylindrically Symmetric and Spherically Symmetric Multi-layer Arrangements	87
2.4.3.2 Gaps and Cracks	92
2.4.3.3 Interstices (Triple-Points)	93
2.4.3.4 Dielectric Cavities and Spheres	97
2.4.3.5 Electric Forces at Interfaces	98
2.4.4 Direct Voltage and Transients.....	99
2.4.4.1 Analogies to the Dielectric Displacement Field	99
2.4.4.2 Typical DC fields	102
2.4.4.3 Transient Processes	105
2.4.5 Field Grading at Interfaces.....	110
2.5 Numerical Field Calculation	113
2.5.1 Overview	113
2.5.2 Charge Simulation Method	115
2.5.3 Finite Difference Method	116
2.5.4 Finite Element Method.....	119
2.6 Rapidly Changing Fields and Traveling Waves	124
2.6.1 Guided TEM Wave	125
2.6.2 Reflection Processes	129
2.6.2.1 Basics	129
2.6.2.2 Equivalent transmission-line circuit	131
2.6.2.3 Multiple Reflections	132
2.6.3 Examples	135
2.6.3.1 Gas-Insulated Switchgear ("Fast Transients")	135
2.6.3.2 Protection Zone of a Lightning Arrester	137
2.6.3.3 Traveling-Wave Generators (Transmission-Line Generators)	138

3 ELECTRIC STRENGTH.....	141
3.1 Introduction to Statistics	141
3.1.1 Statistical Descriptions of Discharge Processes.....	141
3.1.1.1 Random Variables	141
3.1.1.2 Cumulative Distribution Functions	142
3.1.1.3 Parameter Estimation	144
3.1.1.4 Example: Series of Measurements	145
3.1.2 Description of Discharge Processes by Distribution Functions.....	147
3.1.2.1 Comparison of Empirical and Theoretical Distribution Functions	147
3.1.2.2 Gaussian Normal Distribution	148
3.1.2.3 Weibull Distribution	150
3.1.2.4 Parameter Estimation	153
3.1.3 Statistical Size Effects.....	153
3.1.4 Correlation and Regression, Lifetime-stress Relationship.....	157
3.2 Gas Discharges.....	159
3.2.1 Gas Discharge Characteristics	159
3.2.1.1 Non-self-sustained and Self-sustaining Discharge	159
3.2.1.2 Gas Discharge Characteristic, Operating Points	160
3.2.1.3 Manifestations of Gas Discharges	162
3.2.2 Space-charge-free Discharge in a Uniform Field (Townsend and Paschen)	164
3.2.2.1 Townsend's Ignition Condition (Avalanche generations, Townsend Mechanism)	165
3.2.2.2 Ionization and Attachment	169
3.2.2.3 Electron Affinity and Electronegativity	173
3.2.2.4 Paschen's Law	174
3.2.3 Space-charge-dominated Discharge, Streamer Discharge	180
3.2.4 Impulse and High-frequency Breakdown	183
3.2.4.1 Statistical and Formative Time Lag (Discharge Delay)	183
3.2.4.2 Voltage-time Characteristics	186
3.2.4.3 High-frequency Breakdown	187
3.2.5 Discharges in Non-uniform Fields	188
3.2.5.1 Pre-discharges and Breakdown	188
3.2.5.2 Polarity Effect	189
3.2.5.3 Corona Inception, Pre-Discharges	192
3.2.5.4 Breakdown Voltages	194
3.2.5.5 Impact of Different Parameters	196
3.2.6 Surface Discharges.....	199
3.2.6.1 Arrangements with Surfaces	199
3.2.6.2 Ignition of Surface Discharges	200
3.2.6.3 Development of Surface Discharges	202
3.2.6.4 Pollution Flashover	203
3.2.7 Spark, Arc and Lightning Discharges	206
3.2.7.1 Spark discharge	206
3.2.7.2 Arc Discharge	208
3.2.7.3 Lightning Discharges	211
3.2.7.4 "Ball Lightning"	215
3.3 Discharges in Liquid and Solid Dielectrics	215
3.4 Discharges in Liquids.....	217
3.4.1 Discharge Mechanisms in Mineral Oil	217
3.4.1.1 Stages of Oil Breakdown	218
3.4.1.2 The Liquid before Ignition	220
3.4.1.3 Initial Processes	222
3.4.1.4 Discharge Propagation	226
3.4.2 Important Parameters Influencing Breakdown in Mineral Oil	231

3.4.2.1 Water and Pollution	231
3.4.2.2 Temperature Dependence	233
3.4.2.3 Pressure Dependence	234
3.4.2.4 Barriers and Insulated Electrodes, Dependence on Gap Width	234
3.4.2.5 Time Dependences, Time Factors	236
3.4.3 Partial Discharges (PD) in Mineral Oil.....	238
3.4.4 Other Insulating Liquids	239
3.5 Discharges in Solids.....	240
3.5.1 Electrical Breakdown.....	241
3.5.2 Thermal Breakdown.....	242
3.5.3 Ageing, Erosion Breakdown and Lifetime	246
3.6 Partial Discharges (PD)	249
3.6.1 Causes of Partial Discharges.....	249
3.6.1.1 Corona Discharges	250
3.6.1.2 Internal Partial Discharges at AC Voltage	251
3.6.1.3 Internal Partial Discharges at DC Voltage	254
3.6.1.4 Surface Discharges	255
3.6.2 Sources of Partial Discharges	256
3.6.2.1 Sources of Partial Discharges in Gases	256
3.6.2.2 Sources of Partial Discharges in Liquids	256
3.6.2.3 Sources of Partial Discharges in Solids	257
3.6.3 Classical Interpretation of Partial Discharges	258
3.6.3.1 Classical Interpretation of Partial Discharges for AC Voltage	258
3.6.3.2 Interpretation of Partial Discharges for DC Voltage	262
3.7 Vacuum Breakdown.....	263
3.7.1 Physical Process	263
3.7.2 Technical Strengths.....	265
3.7.3 Applications	266
4 DIELECTRIC SYSTEM CHARACTERISTICS	269
4.1 Polarization in the Time and Frequency Domain	269
4.1.1 Description in the Time Domain.....	269
4.1.2 Description in the Frequency Domain	272
4.2 Dielectric Parameters.....	272
4.2.1 Permittivity ϵ_r	273
4.2.1.1 Polarization Mechanisms	273
4.2.1.2 Frequency Dependence (Dispersion)	274
4.2.1.3 Temperature Dependence	275
4.2.1.4 Field Strength Dependence	276
4.2.1.5 Mixed Dielectrics	276
4.2.2 Conductivity κ	276
4.2.2.1 Conductivity in Gases	277
4.2.2.2 Conductivity in Liquids	277
4.2.2.3 Conductivity in Solids	279
4.2.2.4 Influence of Field Strength and Temperature	281
4.2.3 Loss or Dissipation Factor $\tan \delta$	282
4.2.4 Complex Permittivity	284
4.3 Description of Dielectrics.....	287
4.3.1 Classic Parallel and Series Equivalent Circuits	287
4.3.2 Description of Dielectric Material Properties	289

4.3.2.1 Linear Polarization Equivalent Circuit for Solid Materials	290
4.3.2.2 Dependence on Temperature	291
4.3.2.3 Drift, Diffusion and Injection in Liquids	293
4.3.3 Description of Geometrical Properties	296
4.3.3.1 Maxwell's Two-layer Model	296
4.3.3.2 Simple Layered Arrangements	298
4.3.3.3 Complex Geometries	298
5 INSULATING MATERIALS	301
 5.1 Gases.....	301
5.1.1 Air	302
5.1.2 Sulfur Hexafluoride (SF ₆)	302
5.1.3 Alternative Insulating Gases	304
 5.2 Inorganic Solid Insulating Materials.....	306
5.2.1 Porcelain and Ceramics.....	306
5.2.2 Glass	308
5.2.3 Mica Products	309
 5.3 Highly Polymerized Plastics	309
5.3.1 Reactions of Formation and Cross-linking	310
5.3.2 Thermoplastic Insulating Materials	311
5.3.2.1 Polyethylene (PE and XLPE)	311
5.3.2.2 Polyvinyl Chloride (PVC)	313
5.3.2.3 Polypropylene (PP)	314
5.3.2.4 High-temperature Resistant Thermoplastics	315
5.3.2.5 Polyamides (PA) and Aramides	315
5.3.2.6 Polytetrafluoroethylene (PTFE)	316
5.3.2.7 Polymethylmethacrylate (PMMA), Acrylic Glass	316
5.3.3 Thermosetting Materials and Elastomers.....	317
5.3.3.1 Epoxy Resins (EP)	317
5.3.3.2 Polyurethanes (PU)	322
5.3.3.3 Phenolic Resin and Resin-bonded Paper (RBP)	323
5.3.3.4 Elastomers and Shrinkable Sleevings	324
5.3.4 Silicones	325
5.3.4.1 Properties of Silicones	325
5.3.4.2 Hydrophobic Insulators	326
5.3.4.3 Other Applications of Silicones	329
5.3.5 Nano-dielectrics	330
5.3.5.1 Introduction	330
5.3.5.2 Principle of Nanostructuring	331
5.3.5.3 Dielectric Properties	331
5.3.5.4 Applications	332
 5.4 Insulating Liquids	333
5.4.1 Technology of Insulating Liquids	333
5.4.2 Mineral Oil	334
5.4.3 Synthetic Insulating Liquids	337
5.4.3.1 Polychlorinated Biphenyls (PCB)	337
5.4.3.2 Silicone Liquids ("Silicone Oils")	337
5.4.3.3 Other Organic Liquids	338
5.4.4 Vegetable Oils and "Natural Ester Liquids"	339
5.4.4.1 Vegetable Oils	340
5.4.4.2 Natural Ester Liquids	340
5.4.5 Water	341

5.4.6 Liquefied Gases.....	342
5.5 Fibrous Materials	345
5.5.1 Paper and Pressboard	345
5.5.1.1 Electric Strength	345
5.5.1.2 Dielectric Properties, Moisture and Ageing	346
5.5.1.3 Condition Assessment	349
5.5.1.4 Manufacture and Processing	349
5.5.2 Synthetic Fibrous Materials	354
6 TESTING, MEASURING AND DIAGNOSIS	355
6.1 Quality Assurance	355
6.1.1 Quality Assurance Systems.....	355
6.1.2 Certification and Accreditation.....	356
6.1.3 Calibration.....	356
6.1.4 Insulation Coordination.....	358
6.1.4.1 Principle of Insulation Coordination	358
6.1.4.2 High Voltage Tests	362
6.1.4.3 Surge Arresters	363
6.2 Generation of High Voltages	365
6.2.1 Generation of AC Voltages.....	367
6.2.1.1 Principles of Generation	367
6.2.1.2 Test Transformers	368
6.2.1.3 Cascade Arrangement	370
6.2.1.4 Capacitive Voltage Rise in Transformers	371
6.2.1.5 Series Resonance Test Systems	373
6.2.1.6 Requirements for Test Voltages in Laboratories and On-site	376
6.2.2 Generation of DC Voltages.....	379
6.2.2.1 High-voltage Rectifier	380
6.2.2.2 Rectifier Circuits	380
6.2.2.3 Switched-mode Power Supplies	383
6.2.2.4 Electrostatic Generators	384
6.2.3 Generation of Impulse Voltages	386
6.2.3.1 Impulse Voltage Waveforms	386
6.2.3.2 Single-stage Impulse Voltage Generators	389
6.2.3.3 Multi-stage Impulse Voltage Generators	391
6.2.3.4 Overshoot and Back Swing	394
6.2.3.5 Impulse-current Generators	396
6.2.3.6 Combined Test Circuits	397
6.2.3.7 Special Impulse Generators	398
6.3 High Voltage Measurement Techniques	401
6.3.1 Measuring Spark Gaps	401
6.3.1.1 Sphere-to-sphere Spark Gap	401
6.3.1.2 Rod-to-rod Spark Gap	404
6.3.2 Electrostatic Voltmeter	405
6.3.3 Field Sensors	406
6.3.3.1 Electrically Short Sensors	406
6.3.3.2 Electrically Long Sensors	407
6.3.3.3 Potential-free Probes	407
6.3.3.4 Generator-mode Sensors (“Field Mills”)	407
6.3.3.5 Electro-optical and Magneto-optical Field Sensors	408
6.3.4 Voltage Dividers	412
6.3.4.1 Response Characteristic	412
6.3.4.2 Divider Designs	413

6.3.4.3 Stray Capacitances	416
6.3.4.4 Low-voltage Arms	417
6.3.4.5 Coupling Circuits	418
6.3.5 Instrument Transformers.....	419
6.3.5.1 Voltage Transformers	419
6.3.5.2 Current Transformers	420
6.3.6 Measurements of R.m.s. Value, Peak Value and Harmonics	422
6.3.7 Current Measurement.....	424
6.3.8 Electromagnetic Compatibility (EMC).....	425
6.4 Diagnosis and Monitoring	426
6.4.1 Dielectric Measurements.....	426
6.4.1.1 Dissipation Factor and Capacitance	426
6.4.1.2 Insulation Resistance, Conductivity	429
6.4.1.3 Dielectric System Response	431
6.4.2 Partial Discharge (PD) Measurement and Diagnosis.....	433
6.4.2.1 Partial Discharge Measurement Circuit	434
6.4.2.2 Apparent Charge, Partial Discharge Energy	435
6.4.2.3 Sensitivity and Calibration	437
6.4.2.4 Signal Processing and Signal Evaluation	438
6.4.2.5 Interference-free measurement	441
6.4.2.6 Partial Discharge Diagnosis	443
6.4.2.7 Synchronous Multi-channel Partial Discharge Measurement	447
6.4.2.8 UHF Partial discharge Diagnosis	452
6.4.2.9 Non-electrical Methods of Partial Discharge Diagnosis	453
6.4.3 Chemical Analyses.....	454
6.4.3.1 Determination of Water Content	454
6.4.3.2 Gas-in-oil Analysis	455
6.4.3.3 High-pressure Liquid Chromatography (HPLC)	460
6.4.3.4 Determination of Degree of Polymerization of Cellulose	461
6.4.4 Insulating Material Tests.....	461
6.4.4.1 Dielectric Measurements	461
6.4.4.2 Breakdown measurements	461
6.4.4.3 Creepage Currents and Tracking Resistance	464
6.4.4.4 Arc Resistance	465
6.4.4.5 Additional Tests for Insulating Materials	466
6.4.5 Optical and Acoustic Diagnosis Methods	466
6.4.5.1 Optical Waveguides	466
6.4.5.2 Visual Diagnostics	467
6.4.5.3 Acoustic Diagnostics	467
6.4.6 Determination of System Properties	468
6.4.6.1 Impulse-current Waveshapes	468
6.4.6.2 Transfer Functions, Frequency Response Analysis FRA	468
6.4.6.3 Frequency Response Measurements	470
6.4.6.4 Reflectometry	470
6.4.7 Dielectric Diagnosis	470
6.4.7.1 Time and Frequency Domain	471
6.4.7.2 Selective Measurements	472
6.4.7.3 Discharge-voltage Measurement	474
6.4.7.4 IRC Analysis	474
6.4.7.5 Recovery Voltage Analysis	475
6.4.7.6 PDC Analysis	477
6.4.7.7 Frequency Domain Analysis	485
6.4.7.8 Dielectric Diagnosis in Time Domain and Frequency Domain	486
6.4.8 Online monitoring	487
6.4.8.1 Monitoring of Transformers	488
6.4.8.2 Monitoring of Bushings	490

6.4.8.3 Monitoring of Rotating Machines	492
6.4.8.4 Monitoring of XLPE Cables and Fittings	493
6.4.8.5 Monitoring Other Equipment	494
7 APPLICATIONS.....	497
 7.1 Typical Insulation Systems for AC Voltages	497
7.1.1 Cables and Accessories	497
7.1.1.1 Paper-insulated Cables	497
7.1.1.2 Plastic-insulated Cables	499
7.1.1.3 Gas-insulated Lines (GIL)	501
7.1.1.4 Cable Accessories (Cable Fittings)	501
7.1.1.5 Testing Cable Systems	505
7.1.2 Bushings.....	507
7.1.2.1 Field Grading or Potential Grading	508
7.1.2.2 Calculation of Capacitive Grading	508
7.1.2.3 Designs	510
7.1.3 Transformers	512
7.1.3.1 Oil-filled Transformers and Dry-type Transformers, Reactors	513
7.1.3.2 Windings and On-load Tap Changer	514
7.1.3.3 Design of Oil-board Insulation	517
7.1.3.4 Manufacture	524
7.1.3.5 Transformer Testing	525
7.1.3.6 Operation, Diagnosis and Maintenance	533
7.1.4 Capacitors.....	537
7.1.4.1 Structure of the Dielectric	537
7.1.4.2 Drying and Impregnation	538
7.1.4.3 Capacitor Designs	539
7.1.4.4 Measuring Capacitors	539
7.1.5 Circuit-breakers.....	540
7.1.5.1 Development of Switching Devices	540
7.1.5.2 SF ₆ Compressed-gas Circuit-Breaker	541
7.1.5.3 Vacuum Circuit-breaker	544
7.1.6 Electrical Machines	546
7.1.6.1 Low-voltage Motors	547
7.1.6.2 Machines for High Powers	548
7.1.6.3 Cable Generators, Cable Machines	551
 7.2 Typical Insulation Systems for DC Voltages	552
7.2.1 Electrical Stress, Strength and Design for DC Voltage.....	552
7.2.1.1 Dielectric Stresses at DC Voltage	553
7.2.1.2 Dielectric Strength at DC Voltage	553
7.2.1.3 Dielectric Properties of Materials	554
7.2.1.4 Design of Insulation Systems for DC Voltage	559
7.2.2 Capacitors for Direct Voltage (DC Capacitors).....	560
7.2.3 HVDC Transformers.....	561
7.2.3.1 Dielectric Stresses	561
7.2.3.2 AC and Steady-state DC Voltage Stresses	564
7.2.3.3 Stresses during Voltage Variations	567
7.2.3.4 Transition Processes (Transients)	568
7.2.4 HVDC Bushings	571
7.2.4.1 Internal Insulation	571
7.2.4.2 External Insulation	572
7.2.5 HVDC Cables and Accessories.....	574
7.2.5.1 DC Cables	574
7.2.5.2 Paper-insulated HVDC Cables	576
7.2.5.3 Plastic-insulated HVDC Cables	576

7.2.5.4 Emerging HVDC Cable Technologies	578
7.2.5.5 HVDC Cable Accessories	578
7.2.5.6 HVDC Cable Testing	580
7.2.6 High-frequency Chopped DC Voltages	580
7.2.6.1 Applications	580
7.2.6.2 Insulation Problems	581
7.2.6.3 Test Techniques	581
7.3 Typical Insulation Systems for Impulse Voltages	581
7.3.1 Electrical Stress and Strength	581
7.3.2 Energy Storage.....	582
7.3.3 Impulse Capacitors (Energy Storage or Surge Capacitors)	583
7.3.3.1 Capacitor Design	583
7.3.3.2 The so-called “Capacitor Inductance”	584
7.3.3.3 Dielectric and Service Life	584
7.3.4 Barrier Systems	585
7.4 Other Applications	587
7.4.1 Lightning Protection	587
7.4.1.1 Ensuring EMC	587
7.4.1.2 External Lightning Protection	588
7.4.1.3 Internal Lightning Protection	590
7.4.1.4 Lightning Protection Zone Concept	591
7.4.2 Pulsed Power Technology	592
7.4.2.1 Impulse current circuits	592
7.4.2.2 Acoustic Shock Waves	592
7.4.2.3 Pulsed Particle Beams and Laser Beams	593
7.4.2.4 Electrodynamic Generation of Nanocrystalline Materials	594
7.4.2.5 Electrodynamic Fragmentation	594
7.4.2.6 Electrohydraulic Fragmentation	595
7.4.2.7 Electroporation in Biological Cells	595
7.4.3 Light Technology and Laser Technology	596
7.4.4 X-ray Technology	597
7.4.5 Electrostatic Particle Precipitation, Ionization.....	597
7.4.6 Spark Plug	598
7.5 Superconducting Equipment.....	600
7.5.1 Superconductivity	600
7.5.2 HTSC Conductor Materials	602
7.5.3 Insulation and Cooling with LN ₂	603
7.5.4 Applications	604
7.5.4.1 SMES Superconducting Magnetic Energy Storage	604
7.5.4.2 Fault Current Limiter, Switch	605
7.5.4.3 Cables	606
7.5.4.4 Motors, Generators	607
7.5.4.5 Transformers	607
8 REFERENCES	611
9 INDEX	631