

Contents

Preface	9
 CHAPTER 1	
Exploitation stresses of high-voltage insulating systems of power equipment	13
 CHAPTER 2	
Physical aspects of partial discharge mechanism	22
2.1. Introduction	22
2.2. Discharge development and propagation	25
 CHAPTER 3	
Impulse character of partial discharges	34
3.1. Introduction	34
3.2. Partial discharge signals	35
3.3. Partial discharge models	38
3.3.1. Partial discharges at AC voltage	38
3.3.2. Partial discharges at DC voltage	46
3.4. Simulation of discharge mechanism in stochastic model	59
3.5. Multi-source PD model	64
 CHAPTER 4	
Partial discharge detection, acquisition, and processing methods	67
4.1. Introduction	67
4.2. PD detection and acquisition methods	69
4.2.1. Optical PD detection	72
4.2.2. Electric PD detection	72
4.2.3. Acoustic PD detection	75
4.2.4. UHF PD detection	76
4.3. Phase-resolved partial discharge acquisition	78
4.4. Calibration of partial discharge measurements	83

CHAPTER 5

Partial discharges at AC, DC, PWM, and impulse voltages	85
5.1. Influence of high-voltage harmonics on partial discharge images	85
5.1.1. Introduction	85
5.1.2. Influence of harmonics on partial discharge mechanism	87
5.1.3. Simulation of partial discharges at distorted voltage	91
5.1.4. Investigations of partial discharges at distorted voltage by higher harmonics	99
5.1.5. Influence of harmonics on partial discharges in aging processes	114
5.1.6. Harmonic evaluation of high voltage	116
5.1.7. Partial discharges in HVDC insulation with superimposed AC harmonics	122
5.1.7.1. Measurement methodology	124
5.1.7.2. Specimen and measurement setup	125
5.1.7.3. Evaluation techniques and results	127
5.2. Mechanism of partial discharges in non-homogeneous electric field at higher pressure	138
5.2.1. Introduction	138
5.2.2. Electric field distribution in non-homogenous configuration	140
5.2.3. Discharges in compressed gases	142
5.2.4. Influence of pressure on PD inception and breakdown voltages	146
5.3. Partial discharge forms for DC insulating systems at higher air pressure	154
5.3.1. Introduction	154
5.3.2. Experimental setup, specimens, and data acquisition	155
5.3.3. Influence of pressure on partial discharges at DC.....	157
5.4. Partial discharges in PWM-based power electronics applications	169
5.4.1. Introduction	169
5.4.2. Partial discharge model at semi-square voltage waveform	172
5.4.3. Influence of PWM parameters on partial discharges	176
5.4.4. Simulations of electric field in insulation of twisted-pair wires	192
5.4.5. Partial discharges in twisted-pair magnet wires subjected to multi-level PWM stresses	199
5.5. Accumulative effect of partial discharges at impulse-voltage wave tail	214
5.5.1. Introduction	214
5.5.2. Partial discharges at impulse voltage	216
5.5.3. Influence of rise and fall times of impulse voltage on PD	219
5.5.4. Mechanism of PDs at impulse-voltage tail	230

CHAPTER 6

Non-continuous partial discharge sequencing and PD echo	234
6.1. Chopped partial discharge sequence	234
6.1.1. Introduction	234
6.1.2. Methodology of chopped sequence	234
6.1.3. Charge behavior in voids	237
6.1.4. Specimens, instrumentation, and measurement setup	239
6.1.5. Partial discharges at chopped sequence	240
6.2. Investigations on post-partial discharge charge decay in void using chopped sequence	254
6.2.1. Introduction	254
6.2.2. Calculation methodology of charge decay in void	255
6.2.3. Evaluation of PD charge decay in various insulating materials	263
6.3. Partial discharge echo obtained by chopped sequence	268
6.3.1. Introduction	268
6.3.2. Measuring sequence and PD echo	269
6.3.3. Instrumentation for PD echo acquisition	274
6.3.4. Observations of PD echo in dielectric void applying chopped sequence	275

CHAPTER 7

Partial discharge effects on high-voltage insulating materials	295
7.1. Interaction of conductor with polymeric materials exposed to partial discharges	295
7.1.1. Introduction	295
7.1.2. Assessment techniques and experimental conditions	297
7.2. Metal migration at conductor/XLPE interface subjected to partial discharges at different electrical stresses	312
7.2.1. Introduction	312
7.2.2. Metal migration process	313
7.3. Mapping of discharge channels in voids	323
7.3.1. Introduction	323
7.3.2. Aging procedure and evaluation technique	324
7.3.3. Mapping of surface resistance and discharge channels	326
7.3.4. Comparison of surface resistance mapping on various aged insulating materials	334
7.4. Hyperspectral imaging of insulating materials subjected to partial discharges	339
7.4.1. Introduction	339

7.4.2. Hyperspectral analysis of void surface subjected to PD	342
7.4.3. Terahertz-based inspection of HV insulating materials	349
7.5. PD imaging in non-uniform electric field	351
7.5.1. Introduction to discharge imaging	351
7.5.2. Partial discharge mechanism in strongly non-uniform electric field	352
7.5.2.1. Electrical discharges in air	352
7.5.2.2. Dielectric barrier discharges	365
7.5.2.3. Discharges in solid dielectrics	366
7.5.3. Experimental setup, instrumentation, and specimens	369
7.5.4. Imaging of corona and dielectric-barrier discharges and correspondence with PD phase-resolved patterns	372
7.5.4.1. Point-plane electrode configuration with dielectric barrier on plane side	373
7.5.4.2. Point-plane electrode configuration with inclined dielectric barrier	384
CHAPTER 8	
PD signal and image processing and artificial intelligence	389
8.1. Wavelet-based partial discharge signal and image denoising	389
8.1.1. Introduction	389
8.1.2. Application of wavelets to partial discharge images	396
8.2. Phase-resolved rise time-based discrimination of partial discharge forms	409
8.2.1. Introduction	409
8.2.2. Phase-resolved rise-time method	410
8.3. Artificial intelligence applied to partial discharges	418
8.3.1. Introduction	418
8.3.2. Machine learning and PD pattern recognition	418
8.3.3. Features extraction, clustering and segmentation of PD images	424
8.3.4. Anomaly detection in partial discharge images	429
8.3.5. Neural networks	431
8.3.5.1. Multi-layer perceptron-based recognition of partial discharge forms	432
8.3.5.2. Classification of PD images using deep convolutional neural networks	450
8.4. Autonomous tracking of PD pattern evolution	462
8.4.1. Introduction	462
8.4.2. Detection of motion in image processing	463
8.4.3. Motion detection in partial discharge images	468

CHAPTER 9

Partial discharge-based diagnostics of high voltage equipment	475
9.1. Introduction	475
9.2. Condition-assessment strategies in electric power	479
9.3. Partial discharges in electrical insulation of power apparatus	484
9.3.1. Gas-insulated substations	487
9.3.2. Power transformers	492
9.3.3. Rotating machines	494
9.3.4. Power cables	502
List of selected symbols and abbreviations	507
References	511
Index	567