

Contents

Summary	8
Streszczenie	9
Symbols and abbreviations	10
Introduction	13
I. IN-SERVICE STRESSES OF INSULATION SYSTEMS OF ELECTRICAL EQUIPMENT	
1. Characteristics of in-service voltage stresses of electrical insulation systems	19
1.1. Electrical exploitation stresses	19
1.2. Characteristics of overvoltages	20
1.2.1. External overvoltages	21
1.2.2. Internal overvoltages	22
1.3. Characteristics of shapes and duration of overvoltages	23
II. VERY FAST STRESSES OF MOTOR INSULATION SYSTEMS FED BY PULSE WIDTH MODULATION INVERTERS	
2. Characteristics of Pulse Width Modulation (PWM) supply voltage of electrical motors	29
2.1. Introduction	29
2.2. Inverter topology and switching sequence	31
2.3. Basics of PWM sequence	34
2.3.1. Sinusoidal PWM	34
2.3.2. Space-Vector PWM	37
3. Stresses of insulation systems of cables and motors fed by frequency inverters ..	41
3.1. Introduction	41
3.2. Fundamental principle of generation of inverter surge voltage	42
3.3. The stresses and deterioration processes for random and form-wound stator windings insulation system	44
3.3.1. The types of exploitation stresses	44
3.3.2. Random-wound insulation system	45
3.3.3. Form-wound insulation system	48

3.4. Partial discharges in motor insulation.....	49
3.4.1. Mechanism of PD initiation.....	50
3.5. The technical foundation for the evaluation of insulation systems of electrical machines fed by voltage inverters	52
3.5.1. The types of insulation systems.....	52
3.5.2. Qualification tests of insulation systems Type I and Type II.....	52
3.5.3. Partial discharge test for Type I insulation systems.....	53
4. Parameters identification of an equivalent circuit of induction motor.....	55
4.1. Introduction	55
4.2. High frequency equivalent circuit of induction motor.....	55
4.3. Parameters of equivalent scheme of the 3kW motor	59
5. Characteristics of impulse waveforms used for modelling of fast stresses impact	62
5.1. Introduction	62
5.2. Spectra of characteristic testing voltages.....	62
5.2.1. Lightning impulse (LI)	62
5.2.2. Very Fast Transient Overvoltages (VFTO)	65
5.2.3. Pulse Width Modulated voltages (PWM).....	66
6. Theoretical analysis of overvoltages generated in insulation systems of induction motors fed by <i>PWM</i> inverters	71
6.1. Introduction	71
6.2. Model of supplying of induction motors	72
6.3. Wave phenomena in cables at impulse supplying	74
6.3.1. Development in frequency domain	74
6.3.2. Development in time domain – lossless cable	76
6.4. Simulation results of overvoltages on insulation system of the induction motor ..	78
7. Modelling of fast stresses in insulation systems of induction motors fed by <i>PWM</i> inverters.....	80
7.1. Introduction	80
7.2. High frequency modelling of induction motors supplied by use of <i>PWM</i>	81
8. Measurements of overvoltages in motor windings.....	85
8.1. Introduction	85
8.2. Laboratory measurements of motor terminal overvoltages	87
8.3. Overvoltage distribution in windings of induction motors at surge stresses.....	91
8.3.1. Characteristic of the experimental motor.....	91
8.3.2. Results of investigations for overvoltages in windings	92
9. Mechanism of partial discharges in insulation systems.....	96
9.1. Classification of partial discharges	96
9.2. Physical mechanism of partial discharges	97
9.3. Structural changes of dielectric materials exposed to partial discharges	98
9.4. Partial discharge pulses	99

9.5. Partial discharge model at sinusoidal voltage	102
9.6. Partial discharge model at trapezoidal voltage	105
9.7. Partial discharge model at overvoltages generated by semi-square voltage.....	107
9.8. Partial discharge model at impulse voltage.....	107
9.9. Partial discharges in insulation system of motor fed by frequency inverter.....	108
10. Detection and measurements of partial discharges in insulation systems	111
10.1. Introduction	111
10.2. Partial discharges detection and acquisition	113
10.3. Partial discharge detection in VHF/UHF range.....	121
10.4. Application of correlation techniques during PD pulses digital acquisition....	124
10.5. Selected non-electrical PD detection methods	127
11. Generation of testing voltage waveforms for laboratory research.....	130
11.1. Introduction	130
11.2. High voltage arbitrary waveform generator	131
11.3. Rectangular pulse testing voltage systems	132
11.3.1. Bipolar IPM-based pulse voltage generator.....	132
11.3.2. Bipolar pulse voltage generator with LC resonant circuit.....	133
11.3.3. Unipolar/bipolar IGBT-based PWM system	134
11.4. Parameters of testing voltage waveforms generated by systems used in experiments	137
12. Breakdown characteristics of models representing motor winding insulation systems at PWM-like and sinusoidal voltages	139
12.1. Modelling of random-wound windings	139
12.2. Generation of semi-square and PWM-like voltage with different rise time....	142
12.3. Breakdown voltage in twisted-pair samples with different number of twists... <td>143</td>	143
12.4. The influence of semi-square voltage rise time on breakdown voltage of twisted-pair samples.....	145
12.5. Time to breakdown of twisted-pair samples at PWM-like voltage at two frequencies.....	148
12.6. Time to breakdown of twisted-pair samples at PWM-like voltage and sinusoidal voltage at 50 Hz frequency	151
12.7. Summary	152
13. Partial discharges of models representing motor winding insulation systems at PWM-like and sinusoidal voltage.....	153
13.1. Partial discharge measurements in twisted-pair samples.....	153
13.2. Corona discharges in twisted-pair samples with parallel wires	155
13.3. The comparison of partial discharge patterns at sinusoidal and semi-square wave shape	160
13.4. Partial discharge pulse acquisition at semi-square voltage.....	165
13.5. Acquisition and analysis of partial discharge signals in time domain	167
13.6. Partial discharge pulse registration at semi-square voltage with different frequency	170

14. Impact of fast transient stresses on insulation systems of electrical machines based on twisted-pair samples in long-term tests	171
14.1. Characteristic of long-term tests	171
14.1.1. Researches methodology.....	172
14.1.2. Measured PD attributes	172
14.1.3. Derived PD dependences	173
14.2. The long-term test at <i>PWM</i> -like voltage	173
14.2.1. Measurement results.....	173
14.2.2. Analysis of breakdown mechanism in TP samples	182
14.2.3. PD patterns and charge distributions.....	185
14.3. The long-term test at AC voltage.....	189
14.3.1. Research methodology	189
14.3.2. Measurements results	189
14.4. Final remarks	193
15. Analysis of electrical field distributions in elements of motor windings for assessment of partial discharge conditions.....	194
15.1. The exposition of twisted pair samples to electric field.....	194
15.2. Simulations of electric field in parallel configuration of wires in twisted pair sample	196
15.3. Electric field distribution in twist configuration of twisted pair samples	200
15.4 Impact of wire insulation conductivity on electric field distribution in twisted-pair samples	203
16. Mechanisms of deterioration processes in polymer insulation of electric motors caused by partial discharges	205
16.1. Basic physical phenomena of partial discharges in polymers	205
16.2. The stages in deterioration test of partial discharge action in elements of motor windings.....	207
16.3. The initial stage in partial discharge mechanism	208
16.3.1. PD inception mechanism in gaseous contents.....	208
16.3.2. The role of space charge in PD mechanism	213
16.3.3. Electron injection from electrode	214
16.4. The aging stage	215
16.4.1. Erosion of polymer surface.....	215
16.4.2. Changes of insulation surface conductivity.....	216
16.5. The model of partial discharge mechanism in elements of motor windings....	218
17. Deterioration processes of polymer cable insulation by partial discharges.....	221
17.1. Characteristic of power cable insulation	221
17.2. Electric field distribution in polymer cable insulation with local defects	223
17.3. Laboratory investigations of partial discharges action on XLPE and EPR insulation	227
17.3.1. Methods and aging conditions.....	227
17.3.2. Partial discharge inception voltage.....	228
17.3.3. Partial discharge phase-resolved patterns	230

17.3.4. Amplitude charge distributions	237
17.3.5. Partial discharge phase range.....	237
17.3.6. Transformation of PD impulse sets in long-term test.....	241
17.3.7. Mechanism of surface partial discharges	246
17.3.8. Microscopic assessment of erosion processes of polymeric materials....	249
18. Very fast voltage stresses of transformers insulating systems.....	253
18.1. Transient overvoltages in transformer	253
18.2. Stress of insulation systems of windings from overvoltages	258
19. Analysis of transient voltage distributions in transformer windings at different voltage stimuli.....	264
19.1. Introduction	264
19.2. Initial voltage distributions in transformer windings at ultra fast stresses.....	265
19.3. Impact of oil and temperature on initial voltage distributions in transformer windings at ultra fast stresses	271
19.4. Influence of oil temperature on frequency characteristics of disc and layer transformer windings.....	276
20. Impact of resonance overvoltages in transformers on internal insulation systems	281
20.1. Introduction	281
20.2. Test object and stimuli description	282
20.3. Experimental waveforms of internal resonance overvoltages in the winding ..	284
21. Application of transfer function to recognition of resonance overvoltages in transformer winding.....	288
21.1. Introduction	288
21.2. Investigation results of resonance overvoltages in windings.....	290
21.3. Transfer function based recognition of resonance overvoltage prone zones	293
IV. ASSESSMENT OF INFLUENCE OF FAST STRESSES ON DEGRADATION PROCESSES IN INSULATION SYSTEMS	
22. Assessment of fast stresses influence on degradation processes in electrical insulation systems	299
Literature	305
Index	323