

TECHNICAL REPORT



**High-voltage switchgear and controlgear –
Part 306: Guide to IEC 62271-100, IEC 62271-1 and other IEC standards related
to alternating current circuit-breakers**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.130.10

ISBN 978-2-83220-558-7

Warning! Make sure that you obtained this publication from an authorized distributor.

CONTENTS

FOREWORD	15
1 General	17
1.1 Scope.....	17
1.2 Normative references	17
2 Evolution of IEC standards for high-voltage circuit-breaker	18
3 Classification of circuit-breakers	22
3.1 General	22
3.2 Electrical endurance class E1 and E2.....	22
3.3 Capacitive current switching class C1 and C2	23
3.4 Mechanical endurance class M1 and M2	23
3.5 Class S1 and S2.....	24
3.5.1 General	24
3.5.2 Cable system.....	24
3.5.3 Line system	24
3.6 Conclusion	24
4 Insulation levels and dielectric tests	25
4.1 General	25
4.2 Longitudinal voltage stresses	28
4.3 High-voltage tests	28
4.4 Impulse voltage withstand test procedures	29
4.4.1 General	29
4.4.2 Application to high-voltage switching devices	29
4.4.3 Additional criteria to pass the tests	30
4.4.4 Review and perspective.....	30
4.4.5 Theory.....	33
4.4.6 Summary of 15/2 and 3/9 test methods.....	36
4.4.7 Routine tests	37
4.5 Correction factors.....	37
4.5.1 Altitude correction factor.....	37
4.5.2 Humidity correction factor.....	40
4.6 Background information about insulation levels and tests	41
4.6.1 Specification.....	41
4.6.2 Testing	43
4.6.3 Combined voltage tests of longitudinal insulation.....	43
4.7 Lightning impulse withstand considerations of vacuum interrupters	44
4.7.1 General	44
4.7.2 Conditioning during vacuum interrupter manufacturing	44
4.7.3 De-conditioning in service.....	45
4.7.4 Re-conditioning in service.....	45
4.7.5 Performing lightning impulse withstand voltage tests	45
5 Rated normal current and temperature rise.....	45
5.1 General	45
5.2 Load current carrying requirements	45
5.2.1 Rated normal current	45
5.2.2 Load current carrying capability under various conditions of ambient temperature and load.....	46

5.3	Temperature rise testing.....	49
5.3.1	Influence of power frequency on temperature rise and temperature rise tests	49
5.3.2	Test procedure	49
5.3.3	Temperature rise test on vacuum circuit-breakers.....	51
5.3.4	Resistance measurement	52
5.4	Additional information.....	52
5.4.1	Table with ratios I_a/I_r	52
5.4.2	Derivation of temperature rise equations	52
6	Transient recovery voltage	53
6.1	Harmonization of IEC and IEEE transient recovery voltages.....	53
6.1.1	General	53
6.1.2	A summary of the TRV changes.....	54
6.1.3	Revision of TRVs for rated voltages of 100 kV and above.....	57
6.1.4	Revision of TRVs for rated voltages less than 100 kV.....	60
6.2	Initial Transient Recovery Voltage (ITRV).....	62
6.2.1	Basis for specification.....	62
6.2.2	Applicability.....	63
6.2.3	Test duties where ITRV is required.....	63
6.2.4	ITRV waveshape	64
6.2.5	Standard values of ITRV.....	64
6.3	Testing.....	65
6.3.1	ITRV measurement.....	65
6.3.2	SLF with ITRV	66
6.3.3	Unit testing	67
7	Short-line faults	67
7.1	Short-line fault requirements	67
7.1.1	Basis for specification.....	67
7.1.2	Technical comment.....	68
7.1.3	Single-phase faults.....	68
7.1.4	Surge impedance of the line	68
7.1.5	Peak voltage factor.....	69
7.1.6	Rate-of-Rise of Recovery Voltage (RRRV) factor " s ".....	71
7.2	SLF testing.....	72
7.2.1	Test voltage.....	72
7.2.2	Operating sequence	72
7.2.3	Test duties	72
7.2.4	Test current asymmetry	73
7.2.5	Line side time delay.....	74
7.2.6	Supply side circuit	74
7.3	Additional explanations on SLF	75
7.3.1	Surge impedance evaluation.....	75
7.3.2	Influence of additional capacitors on SLF interruption.....	75
7.4	Comparison of surge impedances.....	80
7.5	Calculation of actual percentage of SLF breaking currents	81
7.6	TRV with parallel capacitance	82
8	Out-of-phase switching.....	85
8.1	Reference system conditions.....	85
8.1.1	General	85

8.1.2	Case A	85
8.1.3	Case B	86
8.2	TRV parameters introduced into Tables 1b and 1c of the first edition of IEC 62271-100	87
8.2.1	General	87
8.2.2	Case A	87
8.2.3	Case B	88
8.2.4	TRV parameters for out-of-phase testing	88
9	Switching of capacitive currents	90
9.1	General	90
9.2	General theory of capacitive current switching	90
9.2.1	De-energisation of capacitive loads	90
9.2.2	Energisation of capacitive loads	103
9.3	Non-sustained disruptive discharge (NSDD)	121
9.4	General application considerations	124
9.4.1	General	124
9.4.2	Maximum voltage for application	124
9.4.3	Rated frequency	124
9.4.4	Rated capacitive current	124
9.4.5	Voltage and earthing conditions of the network	125
9.4.6	Restrike performance	126
9.4.7	Class of circuit-breaker	126
9.4.8	Transient overvoltages and overvoltage limitation	126
9.4.9	No-load overhead lines	128
9.4.10	Capacitor banks	130
9.4.11	Switching through transformers	137
9.4.12	Effect of transient currents	138
9.4.13	Exposure to capacitive switching duties during fault switching	140
9.4.14	Effect of load	140
9.4.15	Effect of reclosing	141
9.4.16	Resistor thermal limitations	141
9.4.17	Application considerations for different circuit-breaker types	141
9.5	Considerations of capacitive currents and recovery voltages under fault conditions	143
9.5.1	Voltage and current factors	143
9.5.2	Reasons for these specific tests being non-mandatory in the standard	144
9.5.3	Contribution of a capacitor bank to a fault	144
9.5.4	Switching overhead lines under faulted conditions	145
9.5.5	Switching capacitor banks under faulted conditions	146
9.5.6	Switching cables under faulted conditions	148
9.5.7	Examples of application alternatives	148
9.6	Explanatory notes regarding capacitive current switching tests	149
9.6.1	General	149
9.6.2	Restrike performance	149
9.6.3	Test programme	149
9.6.4	Subclause 6.111.3 of IEC 62271-100:2008 – Characteristics of supply circuit	149
9.6.5	Subclause 6.111.5 of IEC 62271-100:2008 – Characteristics of the capacitive circuit to be switched	149

9.6.6	Subclause 6.111.9.1.1 of IEC 62271-100:2008 – Class C2 test duties	149
9.6.7	Subclauses 6.111.9.1.1 and 6.111.9.2.1 of IEC 62271-100:2008 – Class C1 and C2 test duties	150
9.6.8	Subclauses 6.111.9.1.2 and 6.111.9.1.3 of IEC 62271-100:2008 – Single-phase and three-phase line- and cable-charging current switching tests	150
9.6.9	Subclauses 6.111.9.1.2. to 6.111.9.1.5 of IEC 62271-100:2008 – Three-phase and single-phase line, cable and capacitor bank switching tests	150
9.6.10	Subclauses 6.111.9.1.4 and 6.111.9.1.5 of IEC 62271-100:2008 – Three-phase and single-phase capacitor bank switching tests	150
10	Gas tightness	151
10.1	Specification	151
10.2	Testing	151
10.3	Cumulative test method and calibration procedure for type tests on closed pressure systems	152
10.3.1	Description of the cumulative test method	152
10.3.2	Sensitivity, accuracy and calibration	153
10.3.3	Test set-up and test procedure	153
10.3.4	Example: leakage rate measurement of a circuit-breaker during low temperature test	154
11	Miscellaneous provisions for breaking tests	155
11.1	Energy for operation to be used during demonstration of the rated operating sequence during short-circuit making and breaking tests	155
11.2	Alternative operating mechanisms	156
11.2.1	General	156
11.2.2	Comparison of the mechanical characteristics	157
11.2.3	Comparison of T100s test results	159
11.2.4	Additional test T100a	161
11.2.5	Conclusions	162
12	Rated and test frequency	162
12.1	General	162
12.2	Basic considerations	163
12.2.1	Temperature rise tests	163
12.2.2	Short-time withstand current and peak withstand current tests	163
12.2.3	Short-circuit making current	163
12.2.4	Terminal faults	163
12.2.5	Short-line fault	164
12.2.6	Capacitive current switching	164
12.3	Applicability of type tests at different frequencies	164
12.3.1	Temperature rise tests	164
12.3.2	Short-time withstand current and peak withstand current tests	165
12.3.3	Short-circuit making current test	165
12.3.4	Terminal faults (direct and synthetic tests)	165
12.3.5	Short-line fault (direct and synthetic tests)	166
12.3.6	Capacitive current switching	166
13	Terminal faults	167
13.1	General	167
13.2	Demonstration of arcing time	167
13.3	Demonstration of the arcing time for three-phase tests	168

13.4	Power frequency recovery voltage and the selection of the first-pole-to-clear factors 1,0; 1,2; 1,3 and 1,5.....	168
13.4.1	General	168
13.4.2	Equations for the first, second and third-pole-to-clear factors	169
13.4.3	Standardised values for the second- and third- pole-to-clear factors	171
13.5	Characteristics of recovery voltage.....	171
13.5.1	Values of rate-of-rise of recovery voltage and time delays	171
13.5.2	Amplitude factors.....	172
13.6	Arcing window and k_p requirements for testing	172
13.7	Single-phase testing to cover three-phase testing requirements	176
13.8	Combination tests for $k_{pp} = 1,3$ and 1,5.....	176
13.9	Suitability of a particular short-circuit current rated circuit-breaker for use at an application with a lower short-circuit requirement.....	176
13.10	Basis for the current and TRV values of the basic short-circuit test-duty T10.....	177
14	Double earth fault.....	178
14.1	Basis for specification	178
14.2	Short-circuit current.....	179
14.3	TRV.....	179
14.4	Determination of the short-circuit current in the case of a double-earth fault.....	180
15	Transport, storage, installation, operation and maintenance	182
15.1	General	182
15.2	Transport and storage	183
15.3	Installation.....	184
15.4	Commissioning.....	184
15.5	Operation	186
15.6	Maintenance.....	186
16	Inductive load switching.....	186
16.1	General	186
16.2	Shunt reactor switching	187
16.2.1	General	187
16.2.2	Chopping overvoltages	187
16.2.3	Re-ignition overvoltages	194
16.2.4	Oscillation circuits	195
16.2.5	Overvoltage limitation.....	197
16.2.6	Circuit-breaker specification and selection.....	198
16.2.7	Testing	200
16.3	Motor switching	200
16.3.1	General	200
16.3.2	Chopping and re-ignition overvoltages.....	201
16.3.3	Voltage escalation	202
16.3.4	Virtual current chopping.....	202
16.3.5	Overvoltage limitation	203
16.3.6	Circuit-breaker specification and selection.....	204
16.3.7	Testing	204
16.4	Unloaded transformer switching	205
16.4.1	General	205
16.4.2	Oil-filled transformers	205
16.4.3	Dry type transformers	206
16.5	Shunt reactor characteristics	207

16.5.1	General	207
16.5.2	Shunt reactors rated 72,5 kV and above	207
16.5.3	Shunt reactors rated below 72,5 kV	208
16.6	System and station characteristics	209
16.6.1	General	209
16.6.2	System characteristics	209
16.6.3	Station characteristics	209
16.7	Current chopping level calculation	210
16.8	Application of laboratory test results to actual shunt reactor installations.....	215
16.8.1	General	215
16.8.2	Overvoltage estimation procedures.....	215
16.8.3	Case studies	217
16.9	Statistical equations for derivation of chopping and re-ignition overvoltages.....	222
16.9.1	General	222
16.9.2	Chopping number independent of arcing time	222
16.9.3	Chopping number dependent on arcing time	222
Annex A (informative)	Consideration of d.c. time constant of the rated short-circuit current in the application of high-voltage circuit-breakers.....	224
Annex B (informative)	Interruption of currents with delayed zero crossings	248
Annex C (informative)	Parallel switching	263
Annex D (informative)	Application of current limiting reactors.....	270
Annex E (informative)	Explanatory notes on the revision of TRVs for circuit-breakers of rated voltages higher than 1 kV and less than 100 kV.....	274
Annex F (informative)	Current and test-duty combination for capacitive current switching tests	278
Annex G (informative)	Grading capacitors.....	291
Annex H (informative)	Circuit-breakers with opening resistors.....	295
Annex I (informative)	Circuit-breaker history	318
Bibliography	320
Figure 1	– Probability of acceptance (passing the test) for the 15/2 and 3/9 test series.....	31
Figure 2	– Probability of acceptance at 5 % probability of flashover for 15/2 and 3/9 test series.....	32
Figure 3	– User risk at 10 % probability of flashover for 15/2 and 3/9 test series.....	32
Figure 4	– Operating characteristic curves for 15/2 and 3/9 test series	35
Figure 5	– α risks for 15/2 and 3/9 test methods	36
Figure 6	– β risks for 15/2 and 3/9 test methods.....	37
Figure 7	– Ideal sampling plan for AQL of 10 %	37
Figure 8	– Disruptive discharge mode of external insulation of switchgear and controlgear having a rated voltage above 1 kV up to and including 52 kV	41
Figure 9	– Temperature curve and definitions	51
Figure 10	– Evaluation of the steady state condition for the last quarter of the test duration shown in Figure 9.....	51
Figure 11	– Comparison of IEEE, IEC and harmonized TRVs, example for 145 kV at 100 % I_{SC} with $k_{pp} = 1,3$	56
Figure 12	– Comparison of IEEE, IEC and harmonized TRVs with compromise values of u_1 and t_1 , example for 145 kV at 100 % I_{SC} with $k_{pp} = 1,3$	59

Figure 13 – Comparison of TRV's for cable-systems and line-systems.....	61
Figure 14 – Harmonization of TRVs for circuit-breakers < 100 kV.....	62
Figure 15 – Representation of ITRV and terminal fault TRV	64
Figure 16 – Typical graph of line side TRV with time delay and source side with ITRV.....	66
Figure 17 – Effects of capacitor size on the short-line fault component of recovery voltage with a fault 915 m from circuit-breaker	77
Figure 18 – Effect of capacitor location on short-line fault component of transient recovery voltage with a fault 760 m from circuit-breaker.....	78
Figure 19 – TRV obtained during a L_{90} test duty on a 145 kV, 50 kA, 60 Hz circuit-breaker	80
Figure 20 – TRV vs. ωLZ as function of t/t_{dL} when $t_L/t_{dL} = 4,0$	85
Figure 21 – Typical system configuration for out-of-phase breaking for case A	86
Figure 22 – Typical system configuration for out-of-phase breaking for Case B.....	86
Figure 23 – Voltage on both sides during CO under out-of-phase conditions.....	89
Figure 24 – Fault currents during CO under out-of-phase.....	89
Figure 25 – TRVs for out-of-phase clearing (enlarged).....	89
Figure 26 – Single-phase equivalent circuit for capacitive current interruption.....	91
Figure 27 – Voltage and current shapes at capacitive current interruption.....	92
Figure 28 – Voltage and current wave shapes in the case of a restrike	93
Figure 29 – Voltage build-up by successive restrikes	94
Figure 30 – Recovery voltage of the first-pole-to-clear at interruption of a three-phase non-effectively earthed capacitive load	95
Figure 31 – Cross-section of a high-voltage cable.....	96
Figure 32 – Screened cable with equivalent circuit.....	96
Figure 33 – Belted cable with equivalent circuit.....	96
Figure 34 – Recovery voltage peak in the first-pole-to-clear as a function of C_1/C_0 , delayed interruption of the second phase.....	99
Figure 35 – Typical current and voltage relations for a compensated line.....	100
Figure 36 – Half cycle of recovery voltage	101
Figure 37 – Recovery voltage on first-pole-to-clear for three-phase interruption: capacitor bank with isolated neutral	102
Figure 38 – Parallel capacitor banks	105
Figure 39 – Equivalent circuit of a compensated cable.....	109
Figure 40 – Currents when making at voltage maximum and full compensation.....	110
Figure 41 – Currents when making at voltage zero and full compensation.....	110
Figure 42 – Currents when making at voltage maximum and partial compensation.....	111
Figure 43 – Currents when making at voltage zero and partial compensation.....	112
Figure 44 – Typical circuit for back-to-back cable switching	114
Figure 45 – Equivalent circuit for back-to-back cable switching	116
Figure 46 – Bank-to-cable switching circuit	118
Figure 47 – Equivalent bank-to-cable switching circuit	118
Figure 48 – Energisation of no-load lines: basic phenomena.....	120
Figure 49 – Pre-insertion resistors and their function	120
Figure 50 – NSDD in a single-phase test circuit	121
Figure 51 – NSDD (indicated by the arrow) in a three-phase test	122

Figure 52 – A first example of a three-phase test with an NSDD causing a voltage shift in all three phases of the same polarity and magnitude	122
Figure 53 – A second example of three-phase test with an NSDD (indicated by the arrow) causing a voltage shift in all three phases of the same polarity and magnitude	123
Figure 54 – A typical oscillogram of an NSDD where a high resolution measurement was used to observe the voltage pulses produced by the NSDD	123
Figure 55 – Example of the recovery voltage across a filter bank circuit-breaker.....	126
Figure 56 – RMS charging current versus system voltage for different line configurations at 60 Hz	129
Figure 57 – Typical circuit for back-to-back switching	132
Figure 58 – Example of 123 kV system	135
Figure 59 – Voltage and current relations for capacitor switching through interposed transformer	138
Figure 60 – Station illustrating large transient inrush currents through circuit-breakers from parallel capacitor banks	139
Figure 61 – Fault in the vicinity of a capacitor bank.....	144
Figure 62 – Recovery voltages and currents for different interrupting sequences	146
Figure 63 – Reference condition	147
Figure 64 – Comparison of reference and alternative mechanical characteristics	158
Figure 65 – Closing operation outside the envelope	159
Figure 66 – Mechanical characteristics during a T100s test	160
Figure 67 – Arcing windows and k_p value for three-phase fault in a non-effectively earthed system	172
Figure 68 – Three-phase unearthed fault current interruption	173
Figure 69 – Arcing windows and k_p values for three-phase fault to earth in an effectively earthed system at 800 kV and below	174
Figure 70 – Arcing windows and k_p values for three-phase fault to earth in an effectively earthed system above 800 kV	175
Figure 71 – Simulation of three-phase to earth fault current interruption at 50 Hz	176
Figure 72 – Representation of a system with a double earth fault.....	179
Figure 73 – Representation of circuit with double-earth fault.....	180
Figure 74 – Fault currents relative to the three-phase short-circuit current	182
Figure 75 – General case for shunt reactor switching.....	188
Figure 76 – Current chopping phenomena	189
Figure 77 – General case first-pole-to-clear representation.....	189
Figure 78 – Single phase equivalent circuit for the first-pole-to-clear	190
Figure 79 – Voltage conditions at and after current interruption	191
Figure 80 – Shunt reactor voltage at current interruption.....	192
Figure 81 – Re-ignition at recovery voltage peak for a circuit with low supply side capacitance	194
Figure 82 – Field oscillogram of switching out a 500 kV 135 Mvar solidly earthed shunt reactor	195
Figure 83 – Single-phase equivalent circuit.....	196
Figure 84 – Motor switching equivalent circuit.....	202
Figure 85 – Unloaded transformer representation for TRV calculation.....	205
Figure 86 – TRV on switching out an unloaded 500 kV, 300 MVA transformer bank	206

Figure 87 – Arc characteristic	211
Figure 88 – Rizk’s equivalent circuit for small current deviations from steady state	211
Figure 89 – Single phase equivalent circuit	212
Figure 90 – Circuit for calculation of arc instability	213
Figure 91 – Initial voltage versus arcing time	218
Figure 92 – Suppression peak overvoltage versus arcing time	218
Figure 93 – Calculated chopped current levels versus arcing time	218
Figure 94 – Calculated chopping numbers versus arcing time	218
Figure 95 – Linear regression for all test points	219
Figure A.1 – Simplified single-phase circuit.....	225
Figure A.2 – Percentage d.c. component in relation to the time interval from the initiation of the short-circuit for the standard time constants and for the alternative special case time constants (from IEC 62271-100).....	226
Figure A.3 – First valid operation in case of three-phase test ($\tau = 45$ ms) on a circuit-breaker exhibiting a very short minimum arcing time.....	236
Figure A.4 – Second valid operation in case of three-phase test on a circuit-breaker exhibiting a very short minimum arcing time.....	236
Figure A.5 – Third valid operation in case of three-phase test on a circuit-breaker exhibiting a very short minimum arcing time.....	237
Figure A.6 – Plot of 60 Hz currents with indicated d.c. time constants.....	240
Figure A.7 – Plot of 50 Hz currents with indicated d.c. time constants.....	240
Figure A.8 – Three-phase testing of a circuit-breaker with a rated d.c. time constant of the rated short-circuit breaking current longer than the test circuit time constant.....	242
Figure A.9 – Single phase testing of a circuit-breaker with a rated d.c. time constant of the rated short-circuit breaking current shorter than the test circuit time constant	244
Figure A.10 – Single-phase testing of a circuit-breaker with a rated d.c. time constant of the rated short-circuit breaking current longer than the test circuit time constant	246
Figure B.1 – Single line diagram of a power plant substation	249
Figure B.2 – Performance chart (power characteristic) of a large generator	250
Figure B.3 – Circuit-breaker currents i and arc voltages u_{ARC} in case of a three-phase fault following underexcited operation: Non-simultaneous fault inception	250
Figure B.4 – Circuit-breaker currents i and arc voltages u_{ARC} in case of a three-phase fault following underexcited operation: Simultaneous fault inception at third phase voltage zero.....	251
Figure B.5 – Circuit-breaker currents i and arc voltages u_{ARC} in case of a three-phase fault following underexcited operation: Simultaneous fault inception at third phase voltage crest.....	251
Figure B.6 – Circuit-breaker currents i and arc voltages u_{ARC} under conditions of a non-simultaneous three-phase fault, underexcited operation and failure of a generator transformer	252
Figure B.7 – Circuit-breaker currents i and arc voltages u_{ARC} under conditions of a non-simultaneous three-phase fault following full load operation.....	253
Figure B.8 – Circuit-breaker currents i and arc voltages u_{ARC} under conditions of a non-simultaneous three-phase fault following no-load operation	254
Figure B.9 – Circuit-breaker currents i and arc voltages u_{ARC} under conditions of unsynchronized closing with 90° differential angle	255
Figure B.10 – Prospective (inherent) current.....	256
Figure B.11 – Arc voltage-current characteristic for a SF ₆ puffer type interrupter	257

Figure B.12 – Assessment function $e(t)$	257
Figure B.13 – Network with contribution from generation and large motor load.....	258
Figure B.14 – Computer simulation of a three-phase simultaneous fault with contribution from generation and large motor load	259
Figure B.15 – Short-circuit at voltage zero of phase A (maximum d.c. component in phase A) with transition from three-phase to two-phase fault	260
Figure B.16 – Short-circuit at voltage crest of phase B (phase B totally symmetrical) and transition from three-phase to two-phase fault.....	261
Figure C.1 – Equivalent circuit for parallel switching analysis.....	264
Figure C.2 – Parallel switching between transmission lines with disconnecter.....	266
Figure D.1 – TRV for three-phase ungrounded fault on 25 kV feeder with current limiting reactor (1 p.u. = 30,6 kV peak)	271
Figure D.2 – EMTP simulation for case in Figure D.1 with and without parallel capacitance (1 p.u. = 20,4 kVpeak).....	271
Figure D.3 – TRV for three-phase ungrounded fault on 66 kV shunt capacitor bank with 10 mH current limiting reactor.....	272
Figure D.4 – Initial part of TRV for three-phase ungrounded fault on 66 kV shunt capacitor bank with 10 mH current limiting reactor	272
Figure D.5 – Initial part of TRV for three-phase ungrounded fault on 66 kV shunt capacitor bank with 10 mH current limiting reactor with parallel 20 nF capacitor	273
Figure F.1 – Test-duty 2 combination for Case 1	280
Figure F.2 – TD1 combination for case a)	281
Figure F.3 – TD1 combination for case b)	281
Figure F.4 – TD1/TD2 combination for Case 1	282
Figure F.5 – TD2 combination for Case 2.....	285
Figure F.6 – TD1 combination.....	286
Figure F.7 – TD1/TD2 combination for Case 2	286
Figure F.8 – TD2 combination for Case 3.....	289
Figure F.9 – TD1 combination for Case 3.....	289
Figure G.1 – Equivalent circuit of a grading capacitor	291
Figure G.2 – Equivalent circuit for determination of $\tan\delta$, power factor and quality factor	292
Figure G.3 – Vector diagram of capacitor impedances	292
Figure H.1 – Typical system configuration for breaking with opening resistors	295
Figure H.2 – Circuit diagram used for the RLC method, ramp current injection.....	296
Figure H.3 – Relationship between TRV peak and critical damping	297
Figure H.4 – Approximation by superimposed ramp elements	298
Figure H.5 – Results of calculations done with RLC method.....	300
Figure H.6 – Example of a calculation of the TRV across the main interrupter for T100 using 700 Ω opening resistors.....	302
Figure H.7 – Example of a calculation of the TRV across the main interrupter for T10 using 700 Ω opening resistors.....	303
Figure H.8 – Typical TRV waveshapes in the time domain using the Laplace transform	303
Figure H.9 – TRV plots for resistor interrupter for a circuit-breaker with opening resistor in the case of terminal faults.....	305
Figure H.10 – Typical waveforms for out-of-phase interruption – Network 1 without opening resistor	306

Figure H.11 – Typical waveforms for out-of-phase interruption – Network 1 with opening resistor (700 Ω)	307
Figure H.12 – Typical waveforms for out-of-phase interruption – Network 2 without opening resistor	308
Figure H.13 – Typical waveforms for out-of-phase interruption – Network 2 with opening resistor (700 Ω)	309
Figure H.14 – Typical recovery voltage waveshape of capacitive current switching on a circuit-breaker equipped with opening resistors.....	311
Figure H.15 – Recovery voltage waveforms across the resistor interrupter during capacitive current switching by a circuit-breaker with opening resistors	312
Figure H.16 – Timing sequence of a circuit-breaker with opening resistor	313
Figure H.17 – Voltage waveshapes for line-charging current breaking operations	314
Figure I.1 – Manufacturing timelines of different circuit-breaker types	319
Table 1 – Classes and shapes of stressing voltages and overvoltages (from IEC 60071-1:2006, Table 1).....	27
Table 2 – 15/2 and 3/9 test series attributes	30
Table 3 – Summary of theoretical analysis	36
Table 4 – Values for m for the different voltage waveshapes	38
Table 5 – Maximum ambient temperature versus altitude (IEC 60943)	49
Table 6 – Some examples of the application of acceptance criteria for steady state conditions	50
Table 7 – Ratios of I_a/I_r for various ambient temperatures based on Table 3 of IEC 62271-1:2007.....	52
Table 8 – Summary of recommended changes to harmonize IEC and IEEE TRV requirements.....	57
Table 9 – Recommended u_1 values	57
Table 10 – Standard values of initial transient recovery voltage – Rated voltages 100 kV and above.....	65
Table 11 – Comparison of typical values of surge impedances for a single-phase fault (or third pole to clear a three-phase fault) and the first pole to clear a three-phase fault	81
Table 12 – Actual percentage short-line fault breaking currents	82
Table 13 – Voltage factors for single-phase capacitive current switching tests.....	102
Table 14 – Inrush current and frequency for switching capacitor banks	133
Table 15 – Typical values of inductance between capacitor banks	134
Table 16 – Results of the calibration of the enclosure	155
Table 17 – Temperature rise tests	165
Table 18 – Short-time withstand current tests	165
Table 19 – Peak withstand current tests.....	165
Table 20 – Short-circuit making current tests	165
Table 21 – Terminal faults: symmetrical test duties	166
Table 22 – Terminal faults: asymmetrical test duties	166
Table 23 – Short-line faults.....	166
Table 24 – Capacitive current switching.....	166
Table 25 – First-pole-to-clear factors k_{pp}	170
Table 26 – Pole-to-clear factors for each clearing pole.....	170

Table 27 – Pole-to-clear factors for various types of faults	171
Table 28 – Example of comparison of rated values against application ($U_r = 420$ kV)	177
Table 29 – Circuit-breaker chopping numbers	193
Table 30 – Chopping and re-ignition overvoltage limitation method evaluation for shunt reactor switching.....	197
Table 31 – Re-ignition overvoltage limitation method evaluation for motor switching	203
Table 32 – Typical shunt reactor electrical characteristics.....	207
Table 33 – Connection characteristics for shunt reactor installations	209
Table 34 – Capacitance values of various station equipment	210
Table 35 – Laboratory test parameters.....	217
Table 36 – 500 kV circuit-breaker TRVs.....	221
Table 37 – 1 000 kV circuit-breaker transient recovery voltages.....	221
Table 38 – 500 kV circuit-breaker: maximum re-ignition overvoltage values	221
Table A.1 – X/R values	227
Table A.2 – I_{peak} values	227
Table A.3 – Comparison of last major current loop parameters, case 1	231
Table A.4 – Comparison of last major current loop parameters, case 1: test parameters used for the reference case set at the minimum permissible values	232
Table A.5 – Comparison of last minor current loop parameters, case 1	233
Table A.6 – Comparison of last major current loop parameters, case 2	234
Table A.7 – Comparison of last major current loop parameters, case 2: test parameters used for the reference case set at the minimum permissible values	235
Table A.8 – 60 Hz comparison between the integral method and the method prescribed by IEC 62271-100.....	238
Table A.9 – 50 Hz comparison between the integral method and the method prescribed by IEC 62271-100.....	238
Table A.10 – Example showing the test parameters obtained during a three-phase test when the d.c. time constant of the test circuit is shorter than the rated d.c. time constant of the rated short-circuit current.....	241
Table A.11 – Example showing the test parameters obtained during a single-phase test when the d.c. time constant of the test circuit is longer than the rated d.c. time constant of the rated short-circuit current.....	243
Table A.12 – Example showing the test parameters obtained during a single-phase test when the d.c. time constant of the test circuit is shorter than the rated d.c. time constant of the rated short-circuit current.....	245
Table C.1 – Current transfer direction for parallel circuit-breakers with same contact parting instant and based on arc voltage.....	267
Table C.2 – Analysis of actual parallel switching tests	268
Table C.3 – Current transfer directions for parallel circuit breakers with inherent opening times and arc voltages.....	269
Table F.1 – Summary of required test-duties for covering the capacitive current switching without any test-duty combination.....	279
Table F.2 – Case where TD2 covers LC2, CC2 and BC2.....	280
Table F.3 – Combination values for the case where TD2 covers only CC2 and BC2.....	280
Table F.4 – Combination values for case a): the combined TD1 covers CC1 and BC1	281
Table F.5 – Combination values for case b): the combined TD1 covers LC1 and CC1.....	282
Table F.6 – Combination values for a TD2 covering LC2, CC1 and BC1.....	282

Table F.7 – Summary of the possible test-duty combination for a 145 kV circuit-breaker, tested single-pole according to class C2	283
Table F.8 – Neutral connection prescriptions for three-phase capacitive tests.....	284
Table F.9 – Summary of required test-duties for covering the capacitive current switching without any test duty combination.....	284
Table F.10 – Combination values for a TD2 covering LC2, CC2 and BC2.....	285
Table F.11 – Values for the additional TD2 for covering only BC2.....	285
Table F.12 – Values for the three a TD1 that shall be performed since no combination is possible	286
Table F.13 – Combination values for a TD2 covering LC2, CC2 and BC1.....	287
Table F.14 – Summary of the possible test-duty combination for a 36 kV circuit-breaker tested under three-phase conditions according to class C2	287
Table F.15 – Summary of required test-duties for covering the capacitive current switching without any test-duty combination.....	288
Table F.16 – Combination values for a TD2 covering LC2, CC2 and BC2.....	289
Table F.17 – Combination values for a TD1 covering LC1, CC1 and BC1.....	290
Table F.18 – Summary of the possible test-duty combination for a 245 kV circuit-breaker, tested single-phase according to class C1	290
Table H.1 – Summary of TRV between main and resistor interrupters after out-of-phase interruption with/without opening resistor.....	309
Table H.2 – TRV on main interrupter with opening resistor for T100,T60,T30, T10, OP and SLF $U_r = 1\ 100\text{ kV}$, $I_{SC} = 50\text{ kA}$, $R = 700\ \Omega$	310
Table H.3 – TRV on resistor interrupter for T100s, T60, T30, T10, OP2 and SLF with opening resistor of $700\ \Omega$	310
Table H.4 – Example of calculated values on main and resistor interrupter	317

INTERNATIONAL ELECTROTECHNICAL COMMISSION

HIGH-VOLTAGE SWITCHGEAR AND CONTROLGEAR –**Part 306: Guide to IEC 62271-100, IEC 62271-1 and other IEC standards related to alternating current circuit-breakers**

FOREWORD

- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
- 2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
- 3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
- 4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
- 5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
- 6) All users should ensure that they have the latest edition of this publication.
- 7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
- 8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
- 9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC 62271-306, which is a technical report, has been prepared by subcommittee 17A: High-voltage switchgear and controlgear, of IEC technical committee 17: Switchgear and controlgear.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
17A/1003A/DTR	17A/1021/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62271 series, published under the general title *High-voltage switchgear and controlgear*, can be found on the IEC website.

The document follows the structure of IEC 62271-1 and IEC 62271-100. The topics addressed appear in the order they appear in IEC 62271-1 and IEC 62271-100.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

HIGH-VOLTAGE SWITCHGEAR AND CONTROLGEAR –

Part 306: Guide to IEC 62271-100, IEC 62271-1 and other IEC standards related to alternating current circuit-breakers

1 General

1.1 Scope

This part of IEC 62271 is applicable to a.c. circuit-breakers designed for indoor or outdoor installation and for operation at frequencies of 50 Hz and 60 Hz on systems having voltages above 1 000 V.

NOTE While this technical report mainly addresses circuit-breakers, some clauses (e.g. Clause 5) apply to switchgear and controlgear.

This technical report addresses utility, consultant and industrial engineers who specify and apply high-voltage circuit-breakers, circuit-breaker development engineers, engineers in testing stations, and engineers who participate in standardization. It is intended to provide background information concerning the facts and figures in the standards and provide a basis for specification for high-voltage circuit-breakers. Thus, its scope will cover the explanation, interpretation and application of IEC 62271-100 and IEC 62271-1 as well as related standards and technical reports with respect to high-voltage circuit-breakers.

Rules for circuit-breakers with intentional non-simultaneity between the poles are covered by IEC 62271-302.

This technical report does not cover circuit-breakers intended for use on motive power units of electrical traction equipment; these are covered by the IEC 60077 series.

Generator circuit-breakers installed between generator and step-up transformer are not within the scope of this technical report.

This technical report does not cover self-tripping circuit-breakers with mechanical tripping devices or devices which cannot be made inoperative.

Disconnecting circuit-breakers are covered by IEC 62271-108.

By-pass switches in parallel with line series capacitors and their protective equipment are not within the scope of this technical report. These are covered by IEC 62271-109 and IEC 60143-2.

In addition, special applications (among others parallel switching, delayed current zero crossings) are treated in annexes to this document.

1.2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60060-1:2010, *High-voltage test techniques – Part 1: General definitions and test requirements*

IEC 60071-1:2006, *Insulation co-ordination – Part 1: Definitions, principles and rules*

IEC 60071-2:1996, *Insulation co-ordination – Part 2: Application guide*

IEC 60376, *Specification of technical grade sulfur hexafluoride (SF₆) for use in electrical equipment*

IEC 60480, *Guidelines for the checking and treatment of sulfur hexafluoride (SF₆) taken from electrical equipment and specification for its re-use*

IEC 62146-1, *Grading capacitors for high-voltage alternating current circuit-breakers*¹

IEC 62271-1:2007, *High-voltage switchgear and controlgear – Part 1: Common specifications*

IEC 62271-4, *High-voltage switchgear and controlgear – Part 4: Handling procedures for sulphur Hexafluoride (SF₆)*²

IEC 62271-100:2008, *High-voltage switchgear and controlgear – Part 100: Alternating-current circuit-breakers*
Amendment 1:2012³

IEC 62271-101, *High-voltage switchgear and controlgear – Part 101: Synthetic testing*

IEC 62271-102:2001, *High-voltage switchgear and controlgear – Part 102: Alternating current disconnector and earthing switches*

IEC 62271-110, *High-voltage switchgear and controlgear – Part 110: Inductive load switching*

IEC 62271-310, *High-voltage switchgear and controlgear – Part 310: Electrical endurance testing for circuit-breakers above a rated voltage of 52 kV*

¹ To be published.

² To be published.

³ To be published.