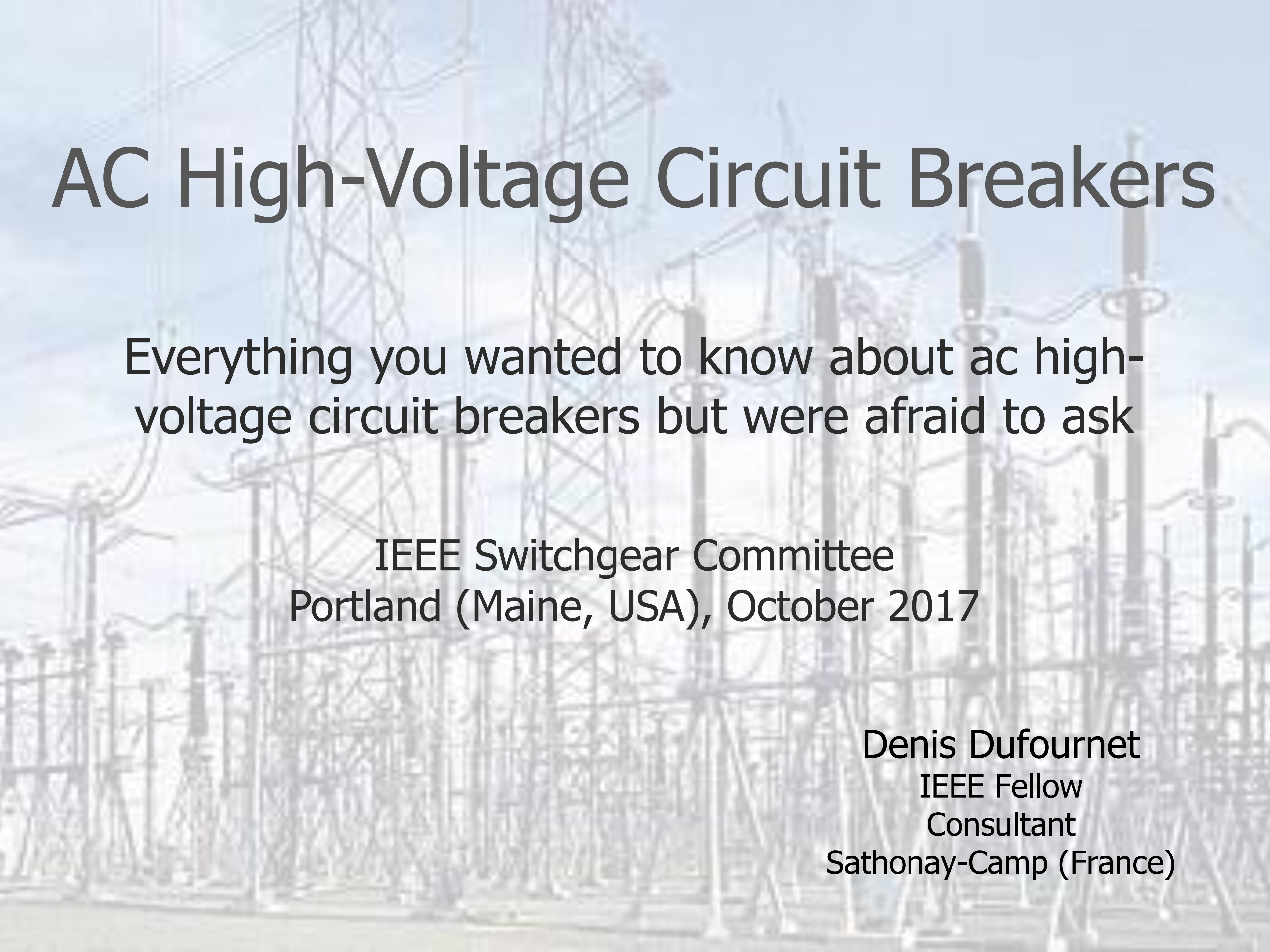


AC High-Voltage Circuit Breakers

Everything you wanted to know about ac high-voltage circuit breakers but were afraid to ask

IEEE Switchgear Committee
Portland (Maine, USA), October 2017

Denis Dufournet
IEEE Fellow
Consultant
Sathonay-Camp (France)

40 Years of Experience in HV Circuit Breakers

1989 GEC ALSTHOM

ALSTHOM

CGE

1985

ALSTHOM ATLANTIQUE

appareillage haute tension

DELLE-ALSTHOM

1980

CGE DELLE ALSTHOM A

1977

GEC ALSTHOM

T&D 1991

1998

ALSTOM

2004

AREVA

2010

ALSTOM

GRID SOLUTIONS

2015 - 2017

Content

Content

High-Voltage Circuit Breaker

Definition

A mechanical switching device, capable of

- making, carrying and breaking currents under normal circuit conditions and
- making, carrying for a specified time and breaking currents under specified abnormal circuit conditions such as those of short-circuit.

High-Voltage Circuit Breaker

The main task of a circuit breaker is to interrupt fault currents and to isolate faulted parts of the system.

A circuit breaker must also be able to interrupt a wide variety of other currents at system voltage such as capacitive currents, small inductive currents, and load currents.

The following is required from a circuit breaker:

- In the closed position it must be a good conductor;
- In the open position it must behave as a good isolator between system parts;
- It must be able to change from the closed to open position in a very short period of time (typically in less than 0.1 second);
- It does not cause overvoltages during switching;
- It is reliable in its operation.

HV Circuit Breaker - Type

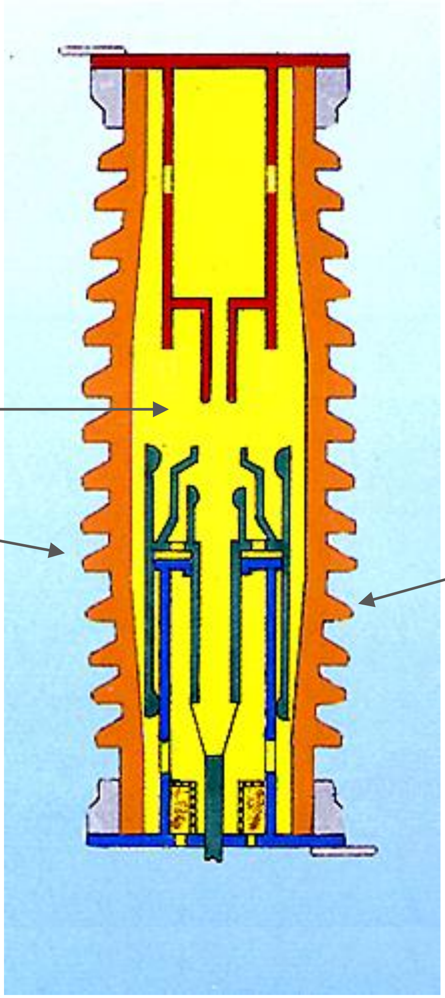
AIS SF_6 Circuit Breaker

AIS: Air Insulated Switchgear

AIS interrupting chamber has

- Internal voltage withstand in SF_6

- External voltage withstand in air



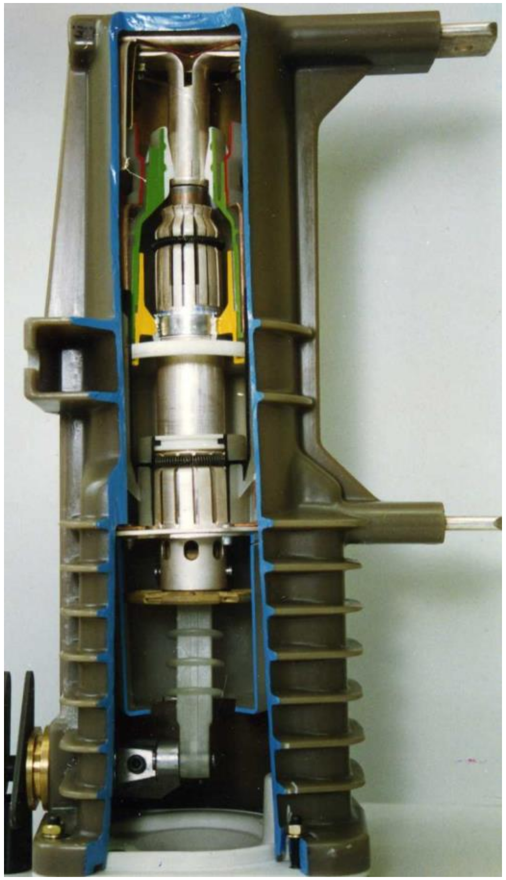
Insulator

Interrupting chamber
in open position

HV Circuit Breaker - Type

AIS SF_6 Circuit Breaker

Example of Medium Voltage Circuit breaker



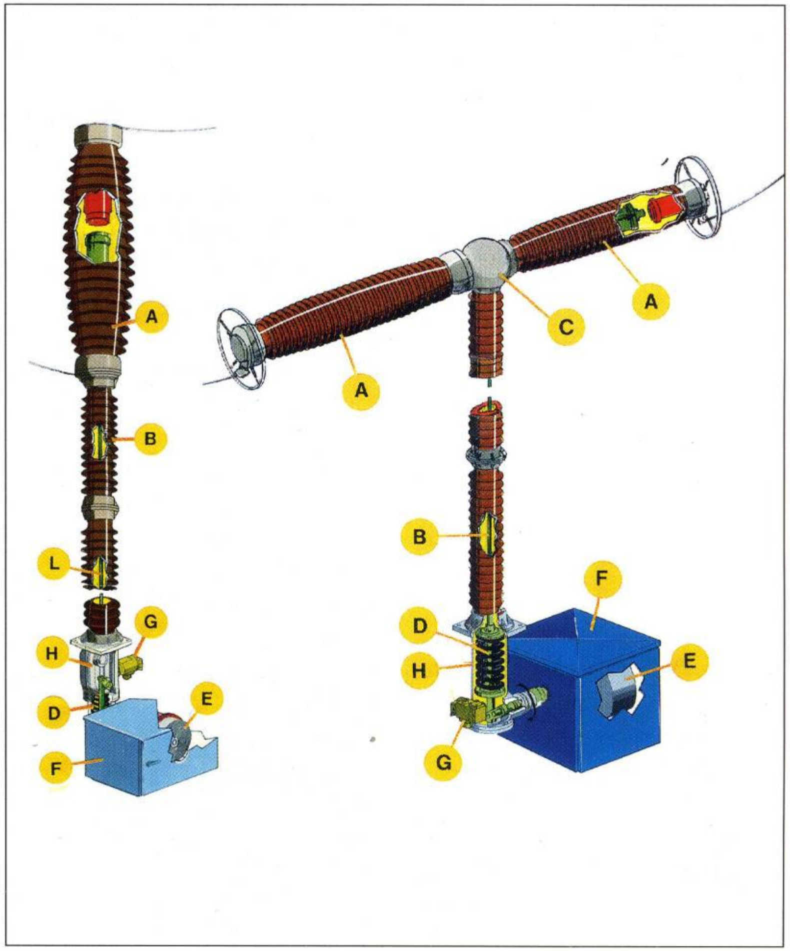
HV Circuit Breaker - Type

AIS SF_6 Circuit Breaker

Examples of HV circuit breaker
operated single-phase

- A: Interrupting chamber
- B: Insulating column
- C: Upper mechanism
- D: Tripping spring
- E: Closing spring
- F: Control cabinet
- G: SF_6 monitoring
- H: Lower mechanism
- L: Rod

These circuit breakers are also called LIVE TANK as the chambers are at system potential.

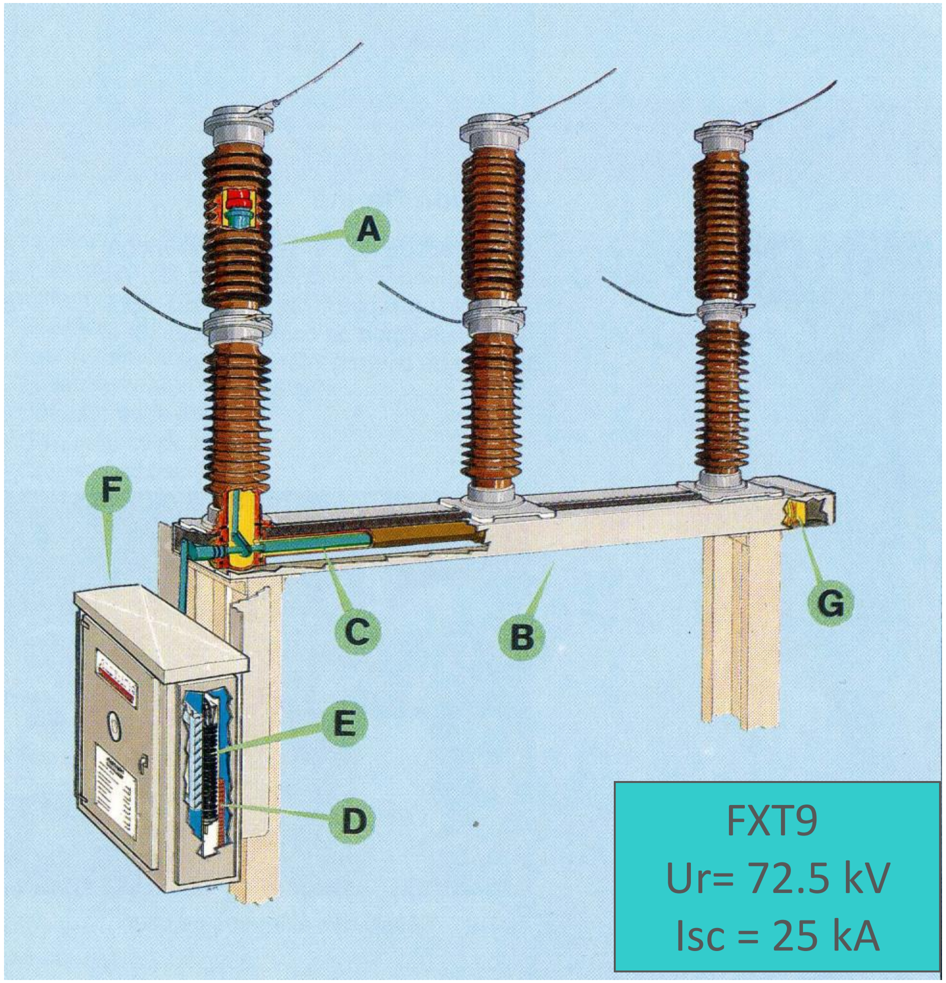


HV Circuit Breaker - Type

AIS SF_6 Circuit Breaker

Example of HV circuit breaker
operated three-phase

A: Interrupting chamber
B: Frame
C: Rotating rod
D: Tripping spring
E: Closing spring
F: Control cabinet
G: SF_6 monitoring



FXT9
Ur= 72.5 kV
Isc = 25 kA

HV Circuit Breaker - Type

AIS SF_6 Circuit Breaker

FX 800 kV 50 kA

4 chambers in series per pole

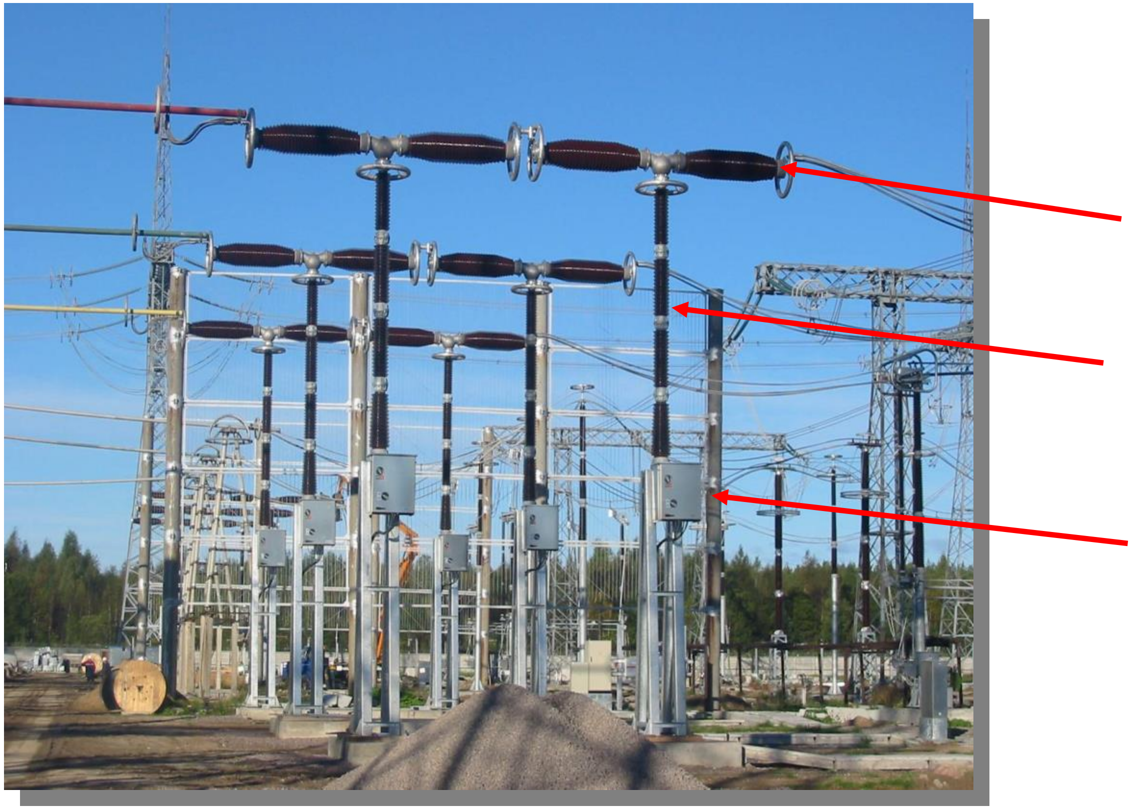
Modular range with vertical units (one mechanism per chamber)

Closing resistors

Grading capacitors

HV Circuit Breaker - Type

AIS SF_6 Circuit Breaker



Interrupting chambers

Insulating column

Operating mechanism

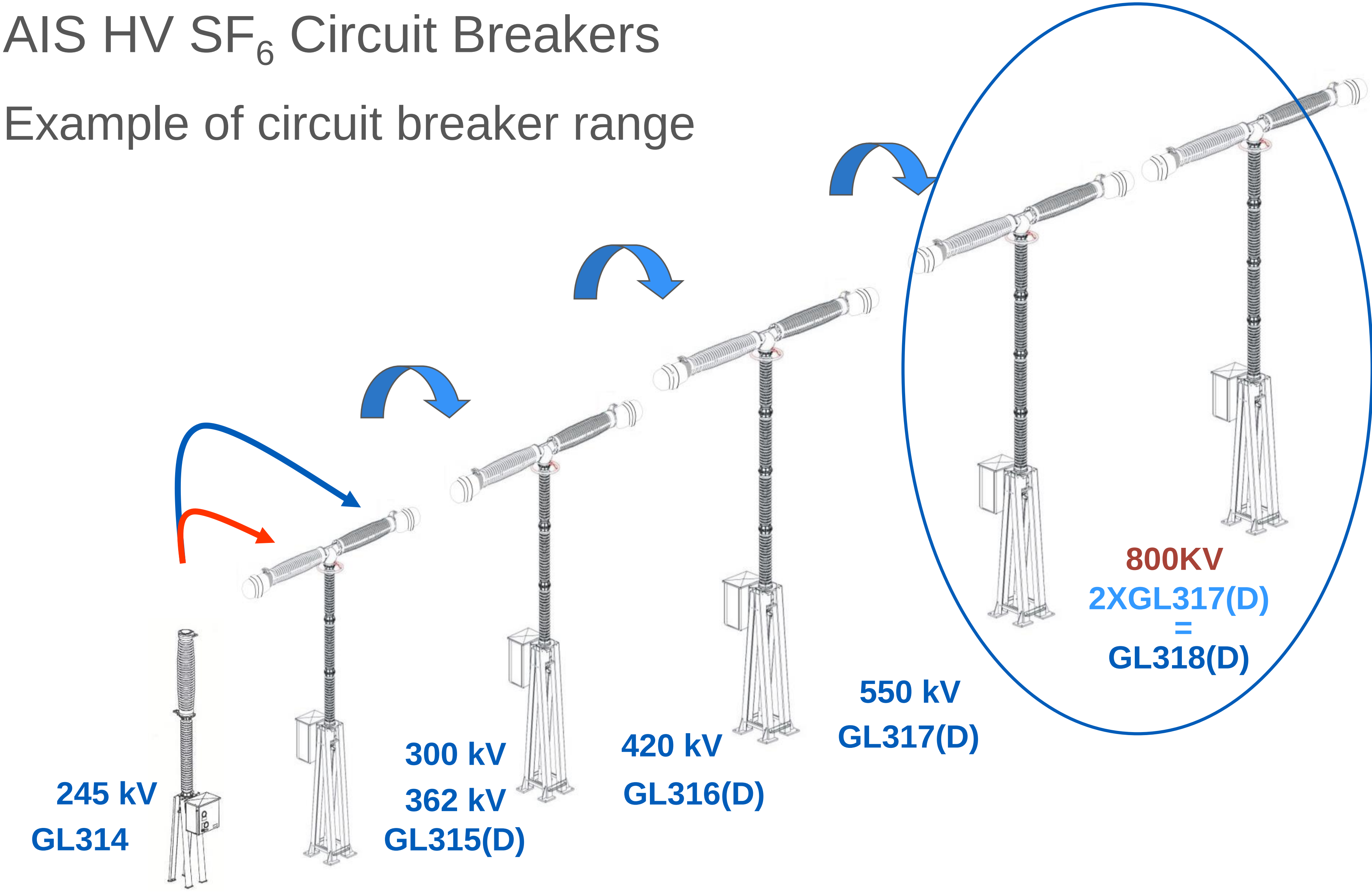
(one operates two chambers)

800 kV Circuit-breaker in Russia

HV Circuit Breakers - Type

AIS HV SF$_6$ Circuit Breakers

Example of circuit breaker range



245 kV
GL314

300 kV
362 kV
GL315(D)

420 kV
GL316(D)

550 kV
GL317(D)

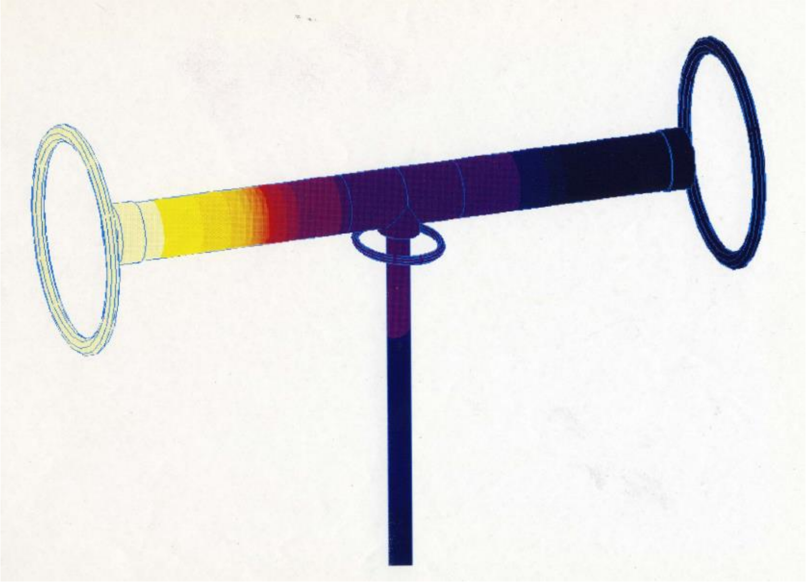
800KV
2XGL317(D)
=
GL318(D)

HV Circuit Breaker - Type

AIS SF_6 Circuit Breaker

Circuit breaker with several chambers in series per pole

- Open circuit-breaker: voltage distribution is done by
  - Grading capacitors, or
  - Rings

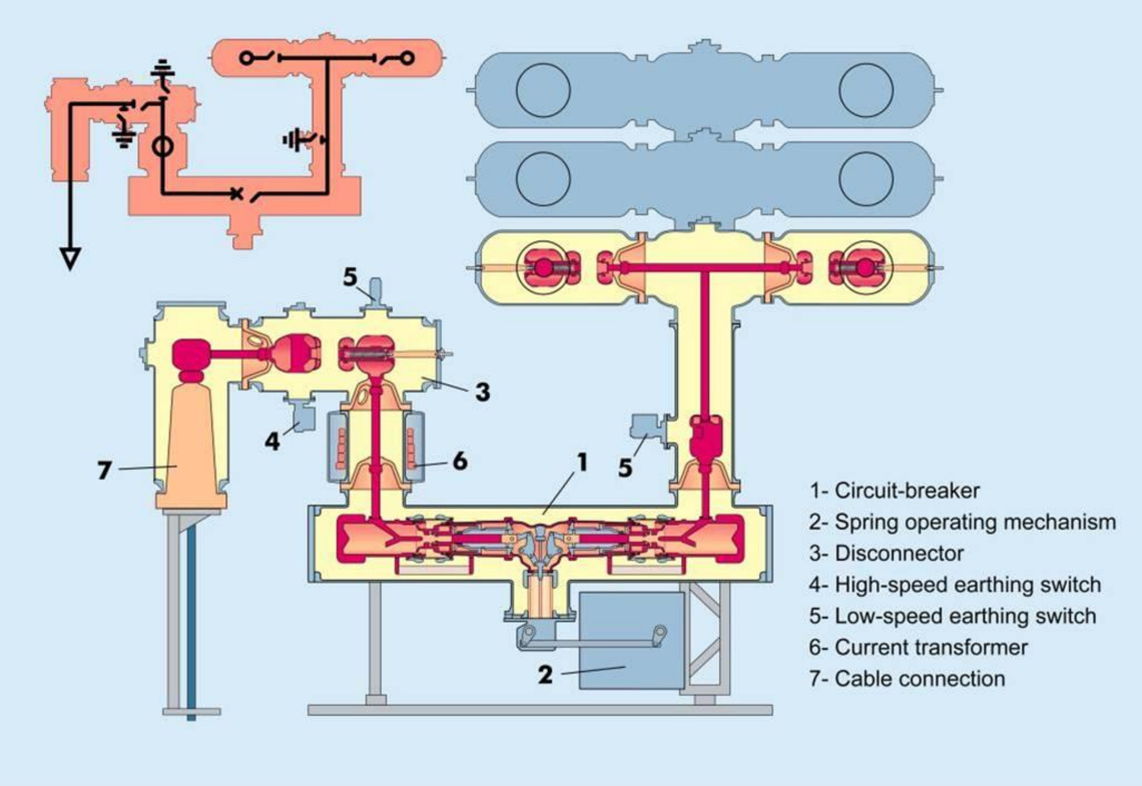


Colors illustrate the voltage distribution calculated by 3D simulation

HV Circuit Breaker - Type

GIS Circuit Breaker

GIS: Gas Insulated Switchgear



Voltage withstand of the interrupting chamber (between contacts and to ground) is fully in SF_6

1: Circuit breaker interrupting chamber

2 Circuit breaker operating mechanism

HV Circuit Breaker - Type

GIS Circuit Breaker

GIS 145 kV

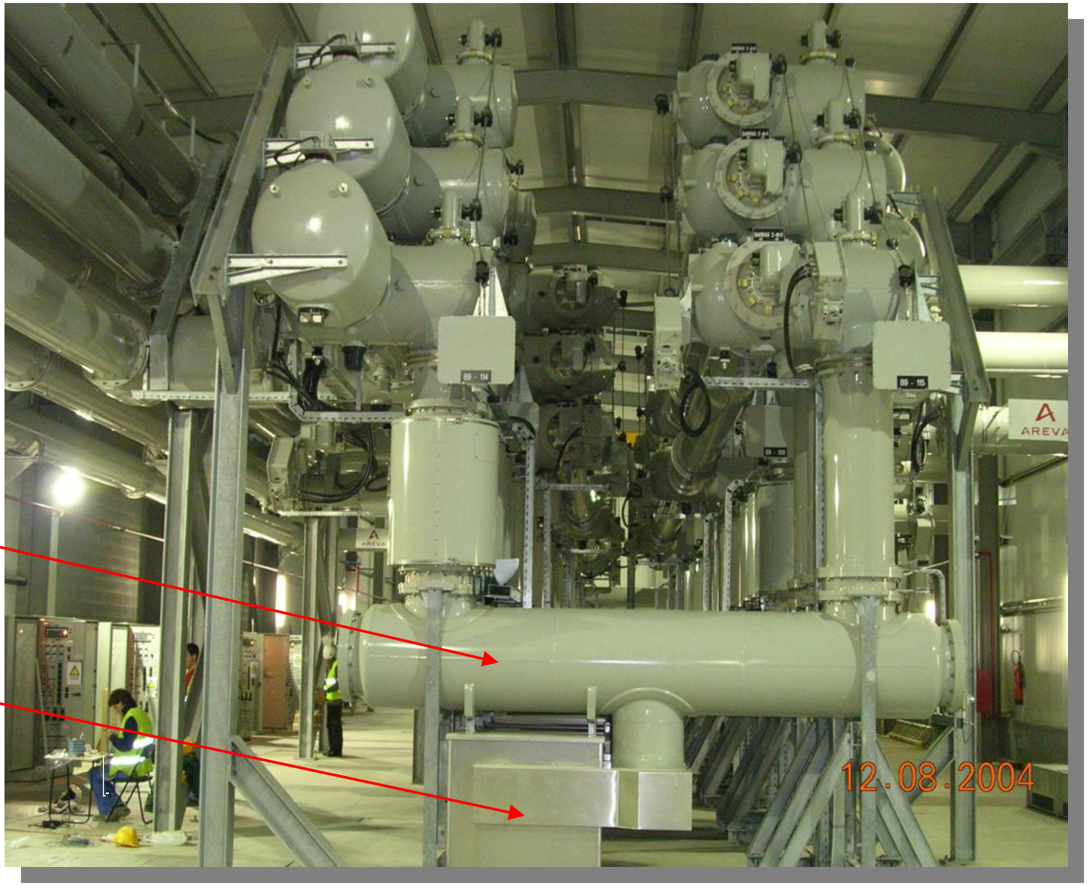
HV Circuit Breaker - Type

GIS Circuit Breaker

GIS 420 kV

Interrupting chambers

Operating mechanism



HV Circuit Breaker - Type

GIS Circuit Breaker

GIS 420 kV

HV Circuit Breaker - Type

GIS Circuit Breaker

Some advantages of GIS

- reduced size,
- not sensitive to environmental conditions,
- safety (active parts are in an enclosure at ground potential),
- no perturbation to surroundings,
- good seismic withstand.

For voltages ≤ 145 kV, the more economical solution is to have the 3 poles in the same tank.

Higher ratings for a single-break GIS circuit breaker

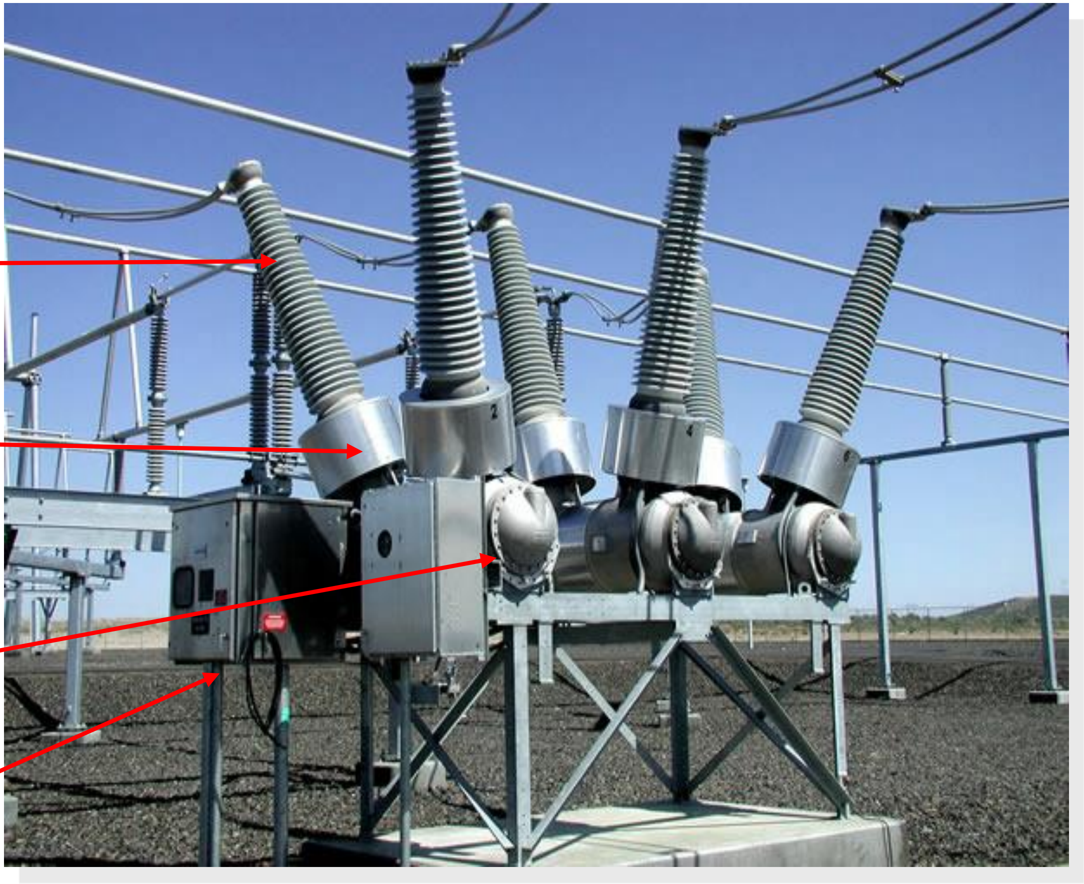
420 kV 63 kA with standard design of spring operated mechanism,

550 kV 63 kA with hydraulic mechanism.

HV Circuit Breaker - Type

Dead Tank Circuit Breaker

DT 245 kV 63 kA



Bushing

Current transformer

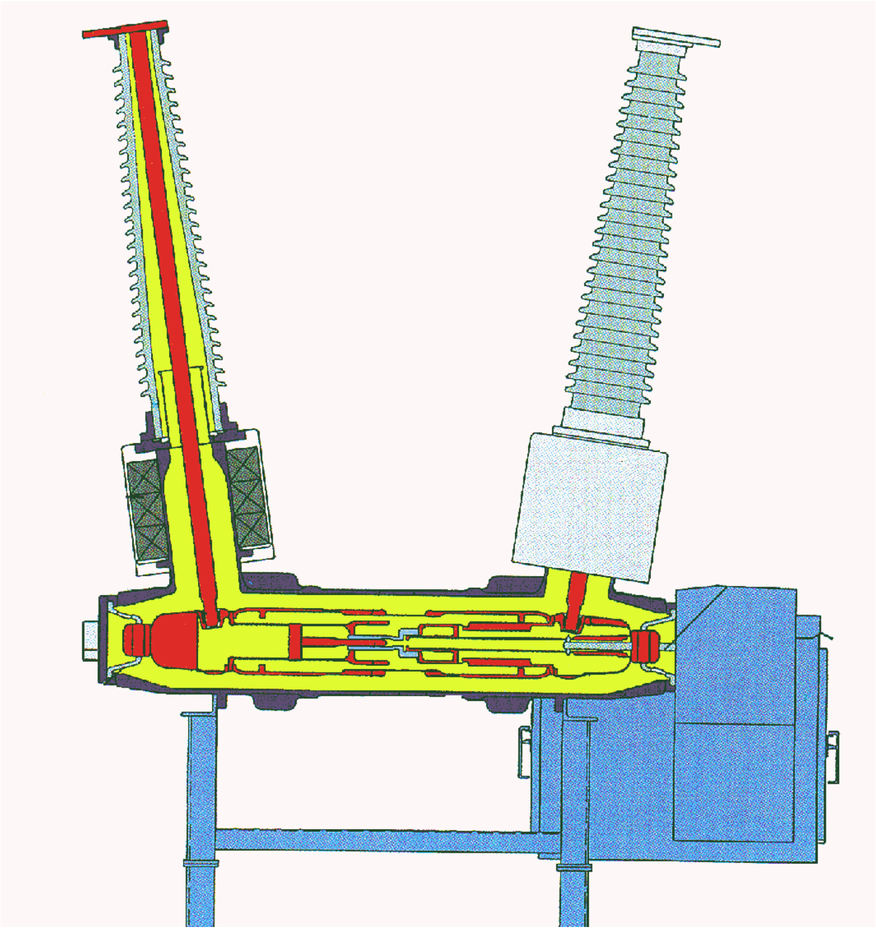
Interrupting chamber

Operating mechanism

HV Circuit Breaker - Type

Dead Tank Circuit Breaker

Voltage withstand of the interrupting chamber (between contacts and to ground) is fully in SF_6

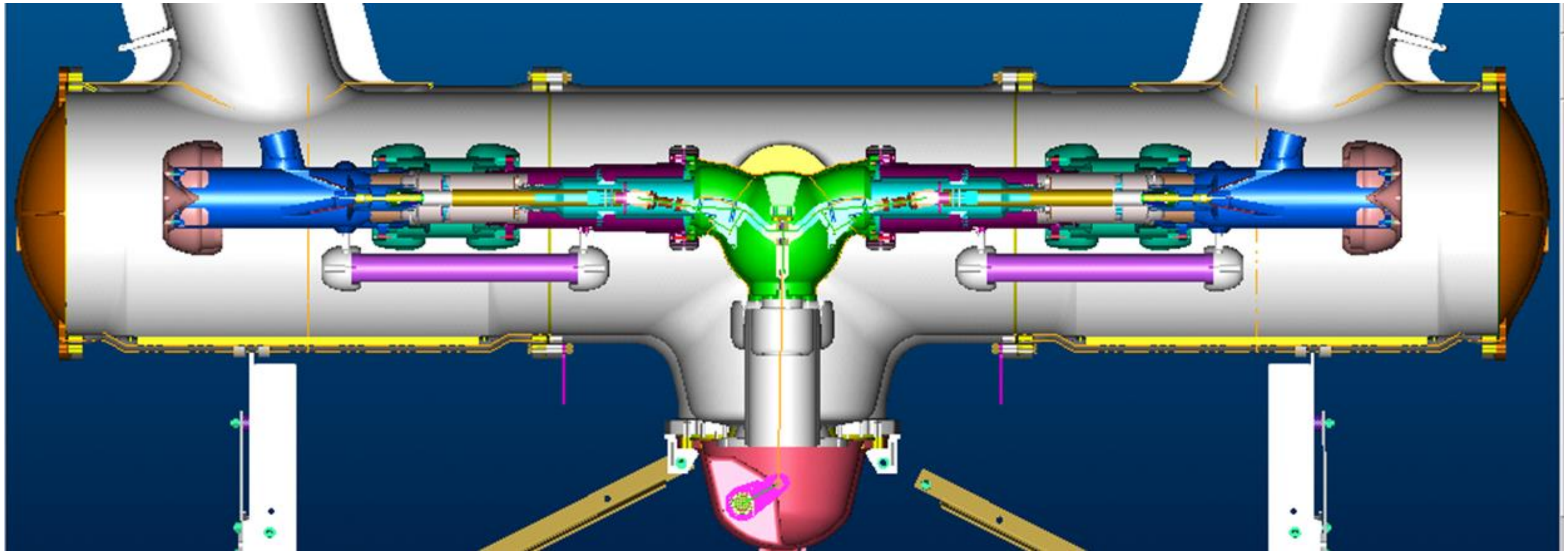


HV Circuit Breaker - Type

Dead Tank Circuit Breaker

Circuit breaker with several chambers in series per pole

Voltage distribution by grading capacitors



Dead Tank Circuit Breaker 550 kV
with grading capacitors

HV Circuit Breaker - Type

Hybrid switchgear (Compact switchgear assembly)

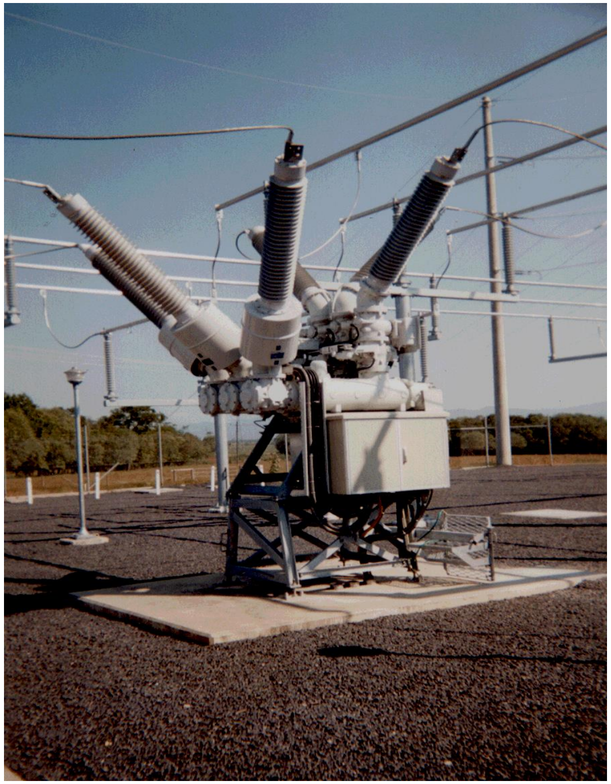
- It is a combination of open-type (AIS) and metal-enclosed equipment (GIS).
- Hybrid switchgear allows to reduce the size of substations and to combine the advantages of AIS and GIS.
- Specific IEC standard: IEC 62271-205.
- Circuit breaker is of GIS or Dead tank type
- Depending on the capacitance of the liaison to overhead lines, it is considered as a GIS or AIS circuit breaker.

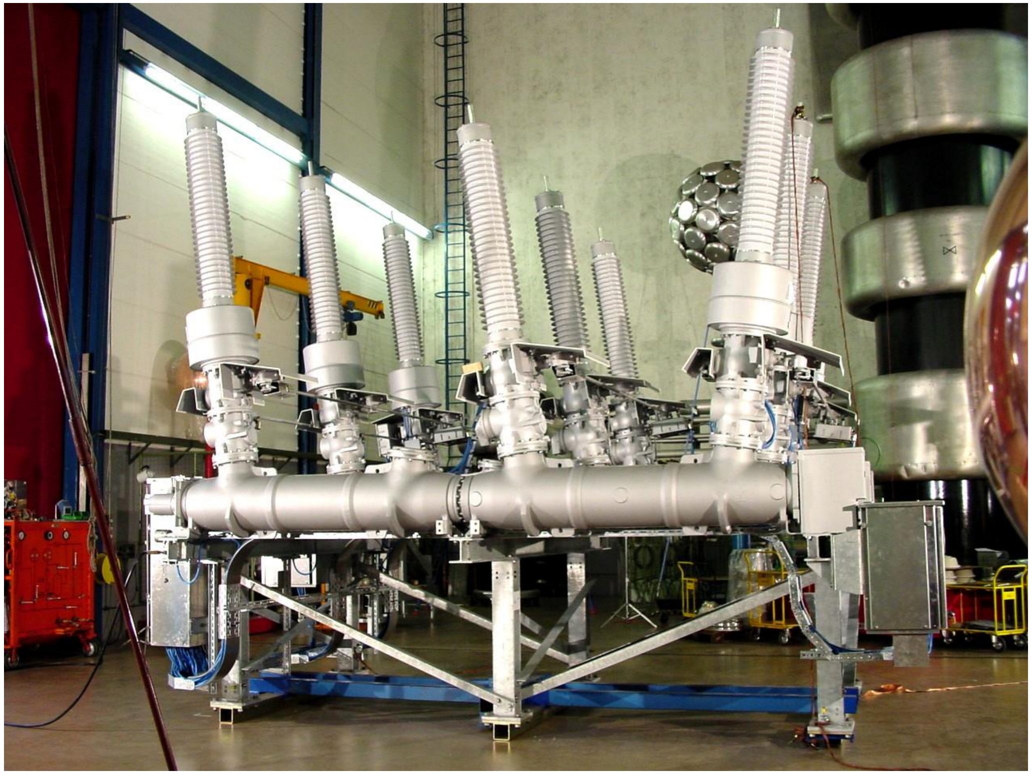
  In IEC it is considered to be AIS if the capacitance of the liaison between circuit breaker and a line is less than 1.2 nF.

HV Circuit Breaker - Type

Examples of hybrid switchgear

Compact switchgear assembly





HV Circuit Breaker - Type

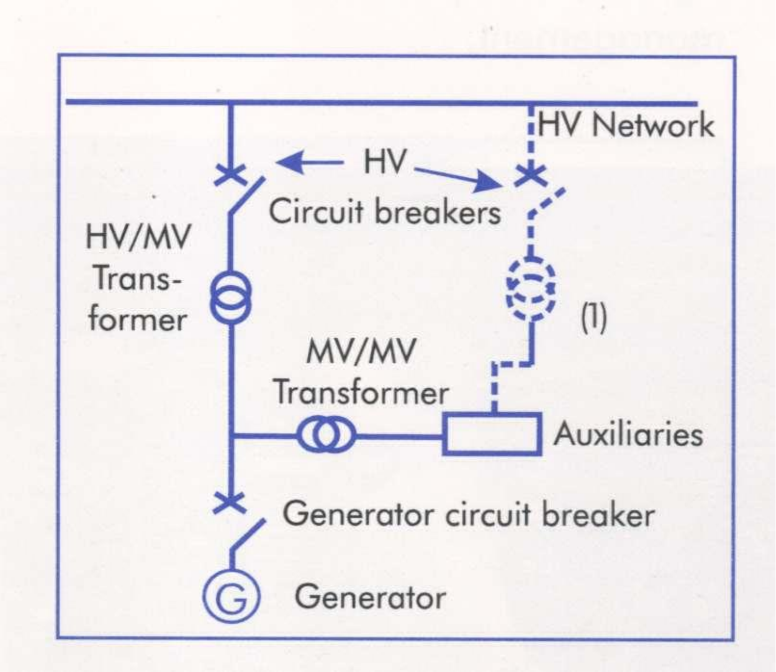
Example of hybrid switchgear (HGIS) 550 kV

Bushing ***Circuit breaker*** ***Disconnector***

HV Circuit Breaker - Type

Generator Circuit Breaker

Generator circuit breakers are located between a generator and the step-up transformer.



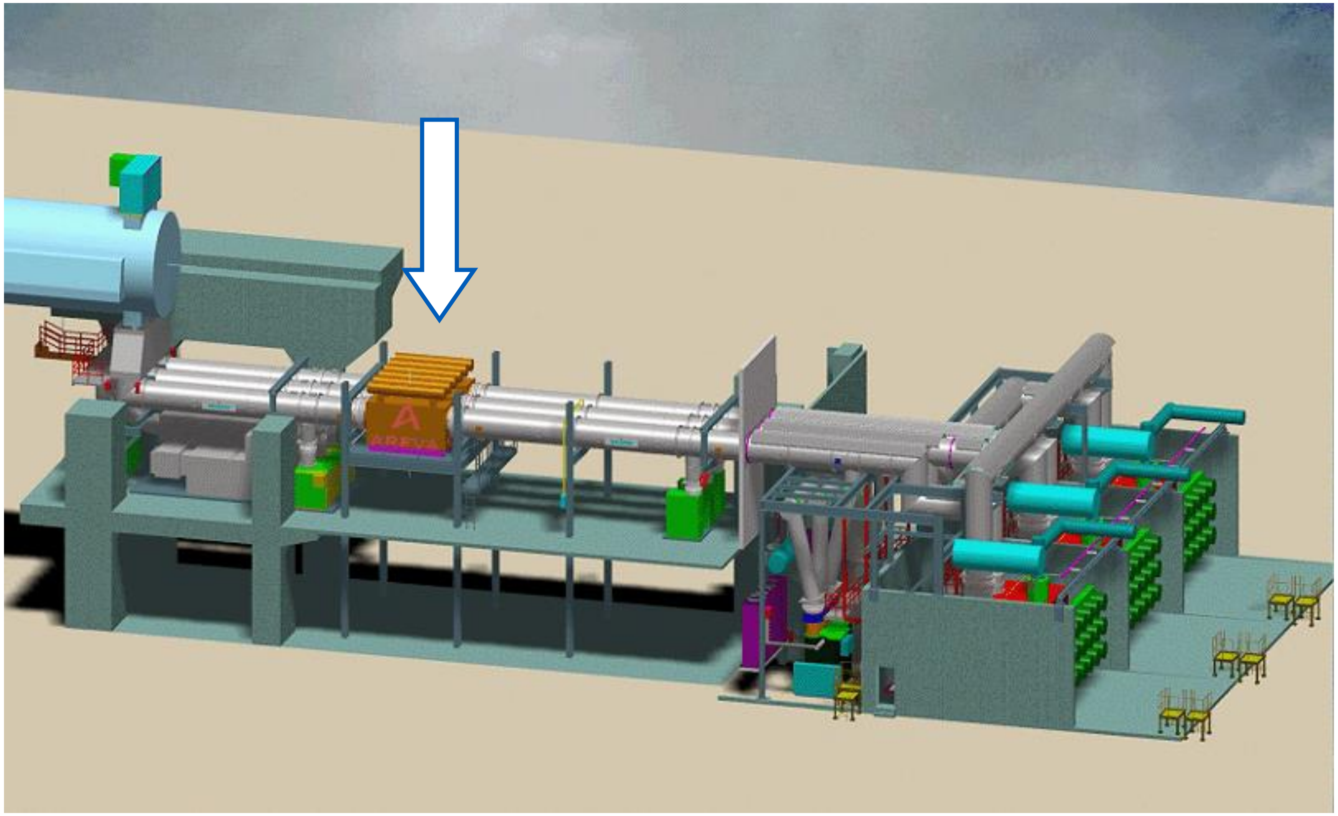
They are generally used with generators of high power (100MVA to 1800 MVA) in order to protect them safely, rapidly and in an economical way.

They must be able to carry high continuous currents (6300 A to 40000 A), and they must have a high short-circuit breaking current capability (63 kA to 275 kA).

HV Circuit Breaker - Type

Generator Circuit Breaker

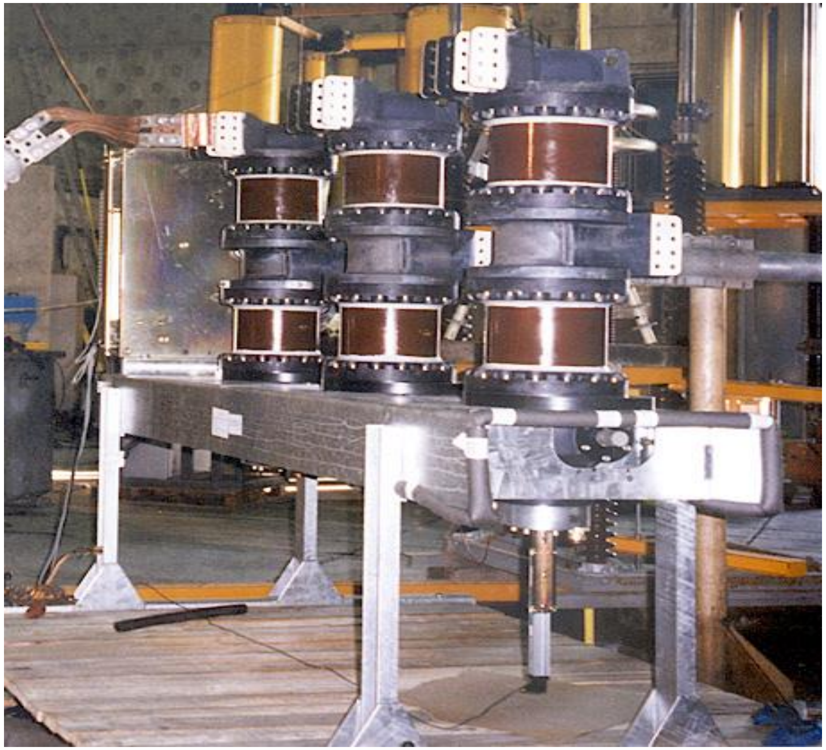
Circuit breaker located between a generator and the step-up transformer.



HV Circuit Breaker - Type

Generator Circuit Breaker

FKG2 17.5 kV 63 kA



Three-phase operation by
spring mechanism

Standard IEC/IEEE 62271-37-013 (2015)

HV Circuit Breaker - Type

Generator Circuit Breaker

FKGA8 Generator Circuit Breaker I_{sc} = 210 kA U_r = 33 kV

SF_6 circuit breaker

Designed for Power Plants from 700 to 1,500 MW

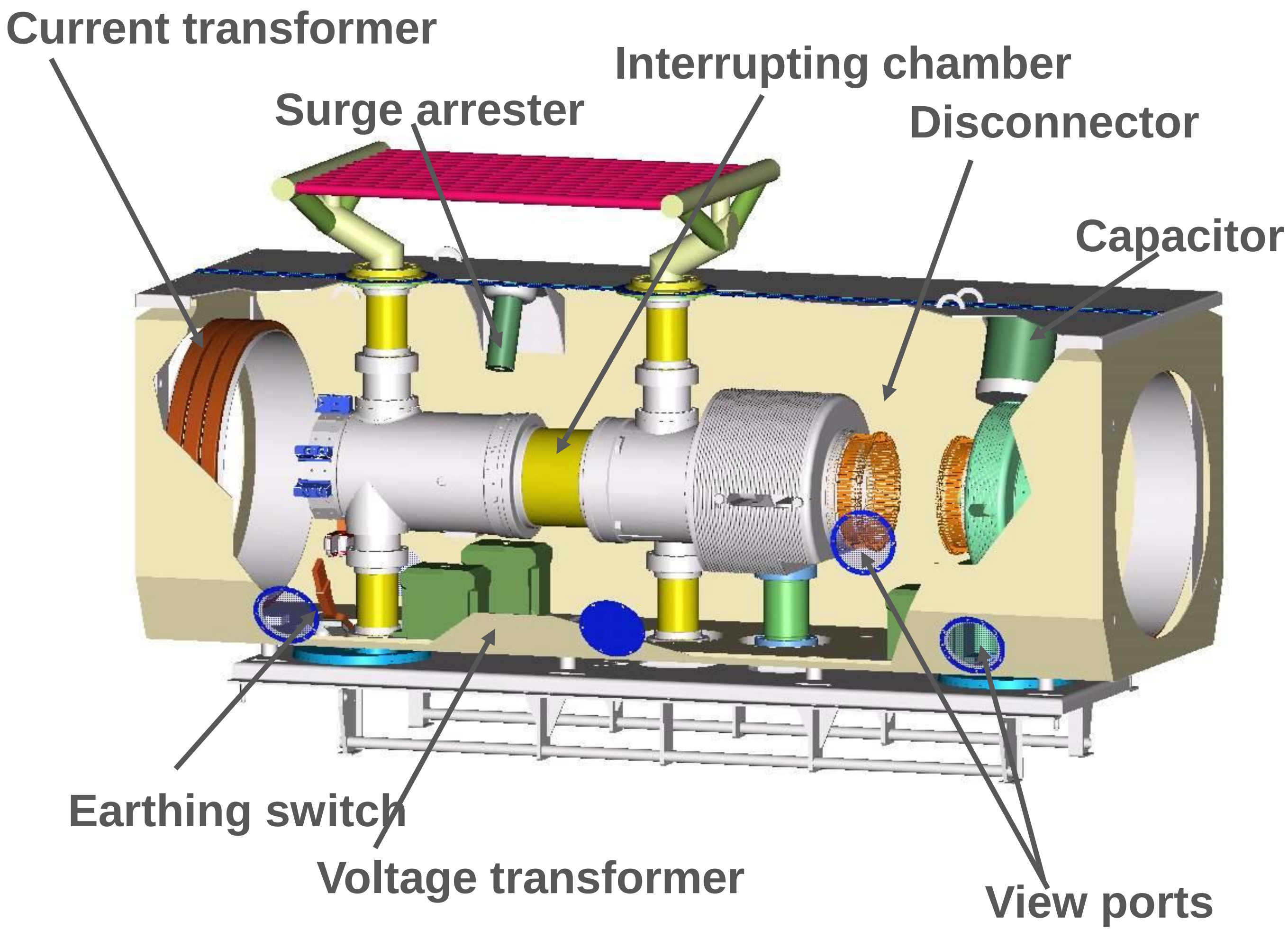
It is equipped with a spring-operated mechanism per pole.

30,000 A nominal current with natural cooling and up to 40,000 A nominal current with IPB forced air cooling.

IPB: Isolated phase bus ducts

HV Circuit Breaker - Type

Generator circuit breaker with associate equipment



HV Circuit Breaker – Service Conditions

Temperature in service / SF$_6$ pressure

Circuit breakers must function properly in the following normal service conditions:

- ambient temperature must not exceed 40°C and the average value, measured during 24h, does not exceed 35°C;
- minimum ambient temperature is not less than - 25°C according to IEC 62271-1, and - 30°C according to IEEE C37.100.1.

Other values of minimum ambient temperature can be specified in particular cases, such as - 40°C, -50°C in some countries such as Canada or even -60°C in Russia.

HV Circuit Breaker – Service Conditions

Temperature in service / SF$_6$ pressure

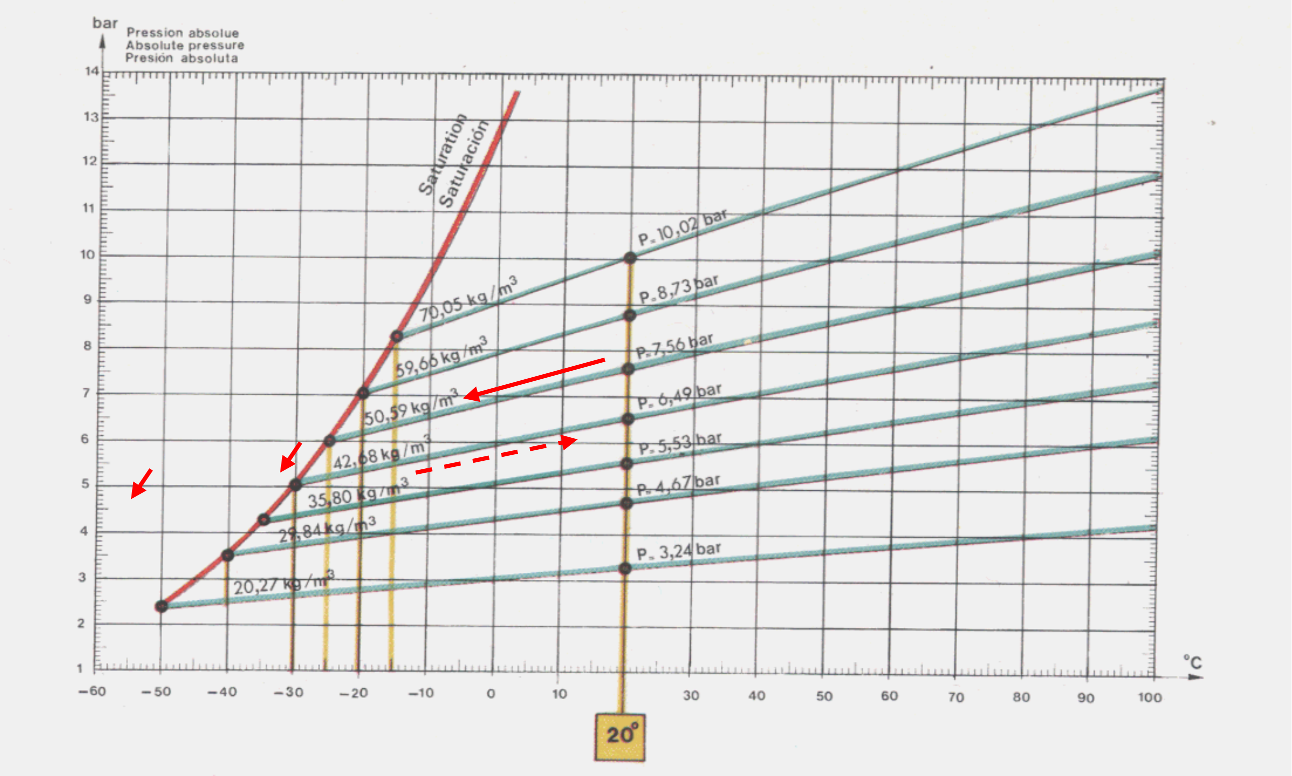


Diagram SF$_6$ – Pressure – Density Temperature

Considering a filling pressure of 7,5 bar (g). at 20°C, liquefaction occurs when temperature reaches -25°C, the residual gas density corresponds to 6.49 bar (g) at 20°C. Partial liquefaction is acceptable for AIS but generally not for GIS.

HV Circuit Breaker – Service Conditions

Temperature in service / SF_6 pressure

Pressure scale

- The minimum (lock-out) pressure (at 20°C) for insulation and interruption is defined from the minimal temperature guaranteed.

  Performances are verified and guaranteed at this minimum pressure.

- Alarm pressure is 4% higher than the minimum pressure.
- Filling pressure is approximately 10% higher than the alarm pressure.

HV Circuit Breaker – Service Conditions

Temperature in service / SF_6 pressure

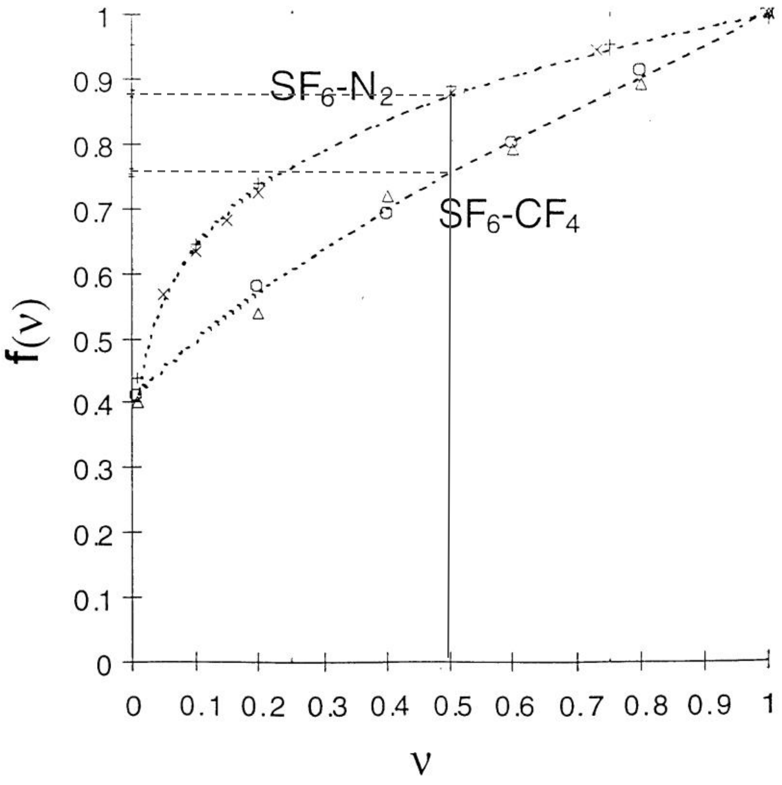
Gas mixture

- In the case of very low ambient temperatures (e.g. -50°C), it is difficult to obtain the required performances with pure SF_6.
- In these cases gas mixtures can be used with the acceptable pressure of SF_6 and the addition of another gas (SF_6-CF_4, SF_6-N_2).
- Another solution is to use heating belts (for Dead tank circuit breakers).

HV Circuit Breaker – Service Conditions

Dielectric Strength of SF_6 Gas Mixtures

In the case of SF_6-CF_4 and SF_6-N_2 gas mixtures, voltage withstand as function of the percentage of SF_6.



Content

Why use SF_6 ?

- **Electrical insulation**

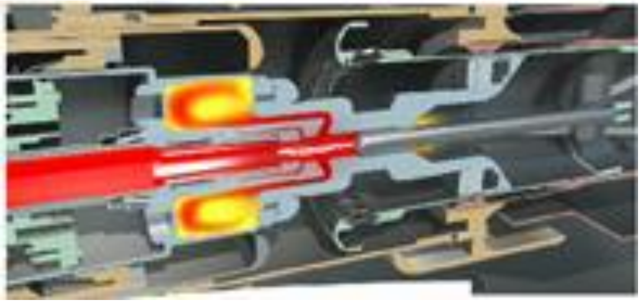
High dielectric strength, approx. 2.5 times that of air (depending on density)

- **Current breaking**

High electrical arc interrupting capacity approx. 10 times that of air (depending on density)

- **Heat transfer**

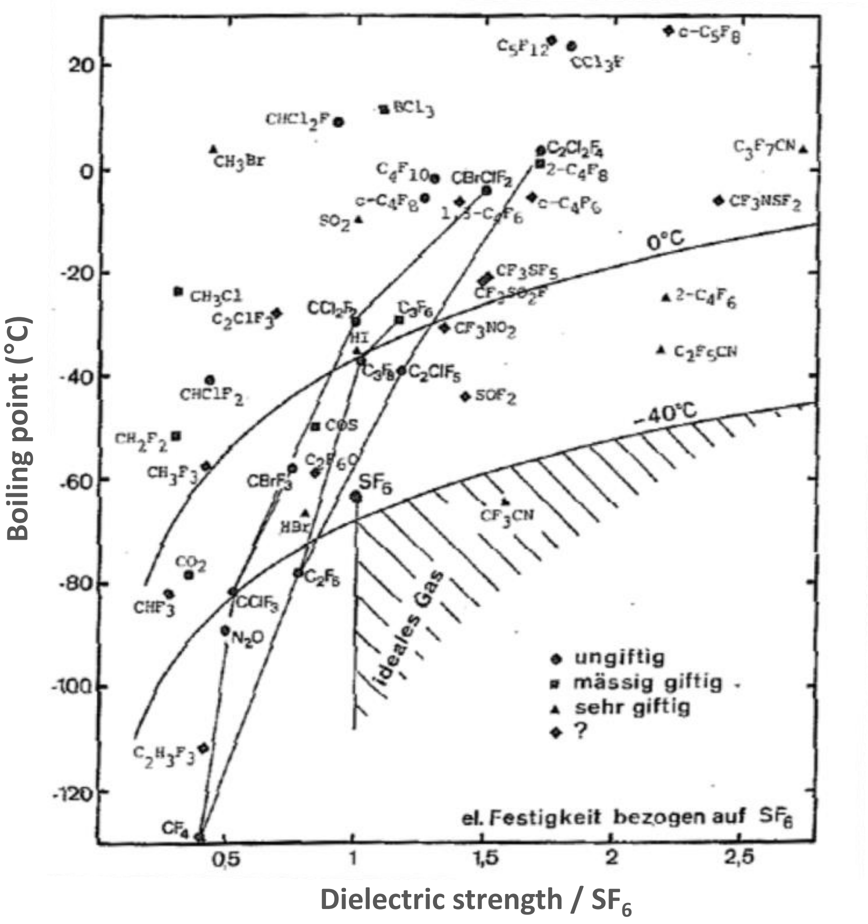
Twice better heat transfer than air



These properties make it possible to significantly reduce the size of electrical equipment and the operating energy of circuit breakers

Search for Alternatives to SF_6

1983



Source: ETH Zürich, Biasiutti & Zaengl, 1983

2014

Search for alternative gases started already in the 1980's

Alternatives to SF_6

- Vacuum is an alternative for MV applications, but limited to rated voltages up to 72.5 kV and possibly 145 kV.
- For HV applications it was necessary to find an alternative gas or gas mixture.
- Circuit breakers developed with CO_2 (and O_2) but limited to 31.5 kA.
- Grid Solutions alternative called g^3 is presented in the next slides. It can be used for -25°C applications.
- Gas mixtures including Fluroketone are also proposed but limited to a minimum temperature of 5°C (e.g. gas mixture with CO_2 and O_2 for GIS 170kV 40kA).

Alternatives to SF_6

More information to come in

IEEE Alternative Gases Task Force Technical Report

Nenad Uzelac (US), Chair

Karla Trost (US), Secretary

IEEE Power & Energy Society

IEEE Switchgear committee, ADSCOM Subcommittee

IEEE Substation committee

Alternative to SF_6 – g^3

1938

First experiments on SF_6 as quenching medium

1980

SF_6 is main gas for high voltage insulation and interruption

1997

SF_6 is listed in the Kyoto protocol as a Greenhouse Gas

2010

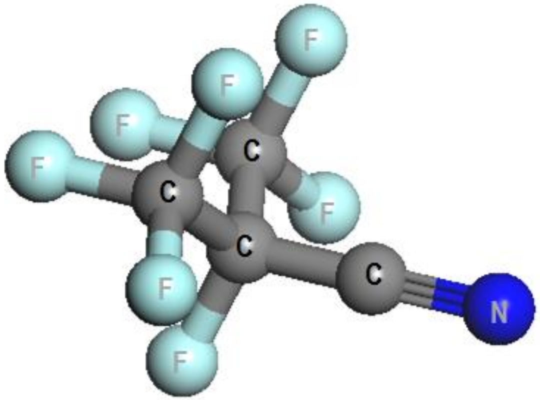
Grid Solutions cooperation with 3M

2014

g^3 green gas for grid

Alternative to SF_6 – g^3

A new compound
developed specifically for
switchgear applications



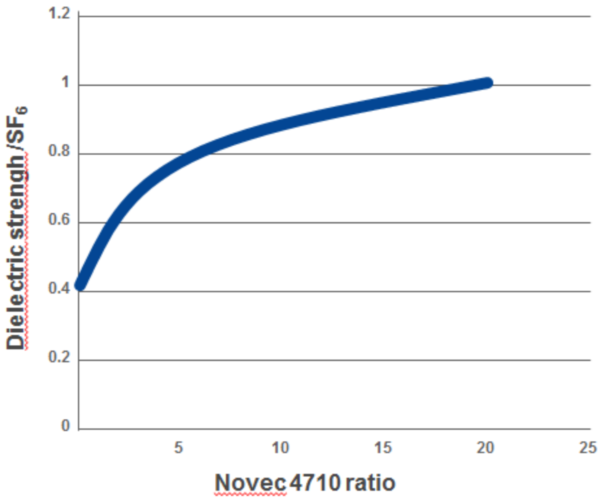
fluorinated nitrile
2,3,3,3-tetrafluoro-2-(trifluoromethyl) propanenitrile
heptafluoroisobutyronitrile
CAS # 42532-60-5

g^3
green
gas for
grid

A gas mixture of
3M^{TM} Novec^{TM} compound and CO_2

Alternative to SF_6 – g^3

Dielectric withstand is 85 to 100 % that of SF_6



Dielectric strength increase when Novec is added

Using g^3, Alstom's new solution, the gap between arcing contacts is significantly reduced

Gas: SF_6
Pressure: 0,15 Mpa
Breakdown Voltage: 72 kVeff
Contact gap: **22** mm

Gas: CO_2
Pressure: 0,15 Mpa
Breakdown Voltage: 72 kVeff
Contact gap: **60** mm

Gas: g^3 (-25 °C)
Pressure: 0,15 Mpa
Breakdown Voltage: 72 kVeff
Contact gap: **26** mm

Gas: g^3 (-15 °C)
Pressure: 0,17 Mpa
Breakdown Voltage: 72 kVeff
Contact gap: **22** mm

- Ratio of Novec molecule in g^3 depends on vapor pressure at minimum operating temperature
- For -25 °C, a slight overpressure allows to reach the SF_6 dielectric strength

Alternative to SF_6 – g^3

Voltage withstand
Test duties performed on GIS & AIS products

Temperature rise
Tests on GIS items

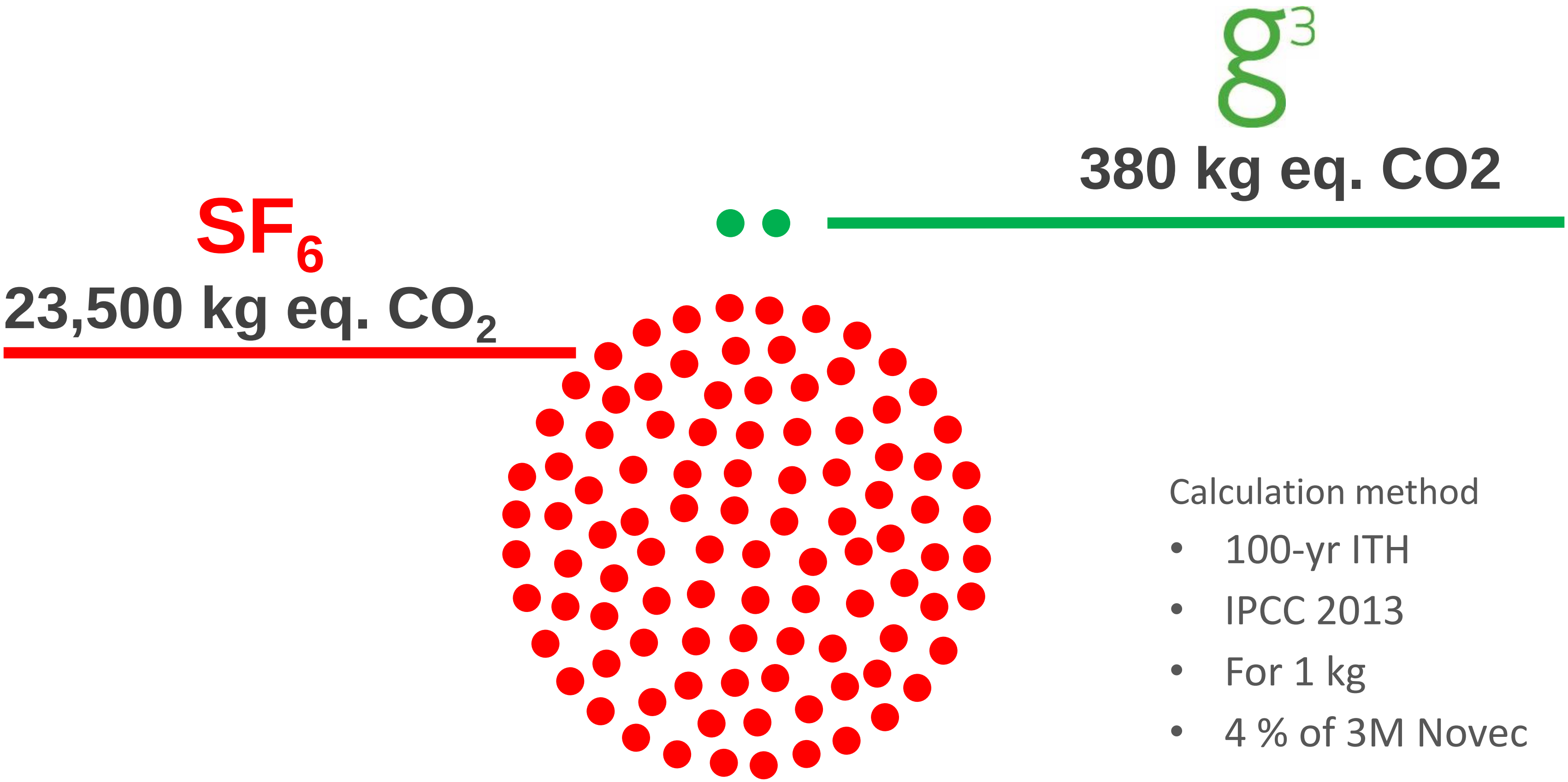
Interruption
Tests on 145 kV LT CB

Switching
Tests with GIS disconnectors

Alternative to SF_6 – g^3

Drastic reduction of global warming potential

98 % lower GWP than SF_6



g^3

380 kg eq. CO2

SF_6

23,500 kg eq. CO_2

Calculation method

- 100-yr ITH
- IPCC 2013
- For 1 kg
- 4 % of 3M Novec

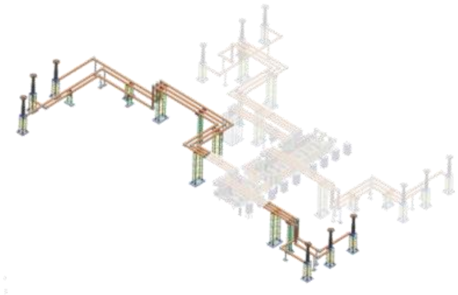
Alternative to SF$_6$ – g^3

420 kV GIL: Pilot project in UK

First pilot project with National Grid

- 300 m GIB at Sellindge substation, in Kent
- 420 kV, 63 kA, 4000 A

GIB	Gas emissions during 40 years (0.5 %/year)	Gas emissions during 40 years in equivalent carbon
SF$_6$ (GWP 23500)	0.50 tons of SF$_6$	11750 tons eq. CO$_2$
g^3 (GWP 327)	0.23 tons of g^3	74 tons eq. CO$_2$



Over both g^3 busducts:
11670 t eq. CO$_2$ will be saved during the operation period

Content

Circuit Breaker Rated Characteristics

- Rated maximum voltage
- Rated insulation level*
- Rated frequency
- Rated continuous current
- Rated short-time and peak current
- Rated short-circuit making and breaking current
- Rated operating sequence

The common ratings of switchgear are assigned by the manufacturer. They reflect the common specifications of the switchgear that are specified by the user and are necessary for operation on the user's network.

* In IEEE C37.100.1, but Rated dielectric withstand capabilities in IEEE C37.04

Rated Characteristics / Rated Maximum Voltage

The rated maximum voltage indicates the upper limit of the highest voltage of systems for which the circuit breaker is intended.

Rated values have been generally harmonized between IEC and ANSI/IEEE

- Medium voltage

  3,6 – 4.76* – 7.2 – 8.25* – 12 – 15* – 15.5* – 17.5 – 24 – 25.8* – 27* 36 – 38* – 48.3* – 52 kV.

* : values used in North America (15.5 and 27 kV are preferred to 15 and 25.8 kV)

- High voltage

  72.5 – 100** – 123 – 145 – 170 – 245 – 300** – 362 – 420** – 550 – 800 – 1100** – 1200** kV.

  ** : values in IEC only

IEEE values are given in 6.1 of IEEE C37.04-201x

Rated Characteristics / Insulation Level

The insulation level/dielectric withstand capability is given by

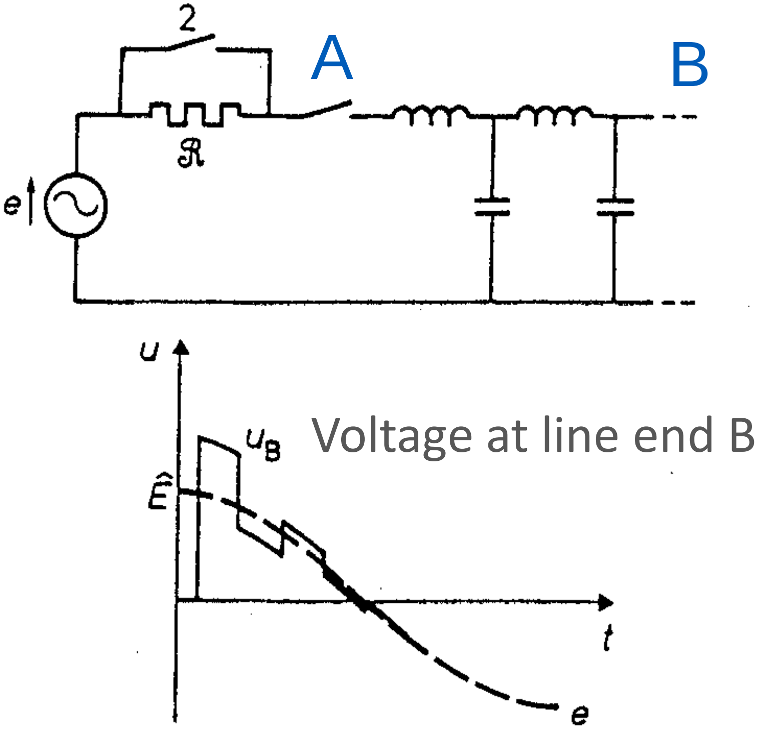
- the withstand voltage at power frequency (50 Hz or 60 Hz),
- the lightning impulse withstand voltage,
- the switching impulse withstand voltage ($U_r \geq 362$ kV).

These values characterize the dielectric stresses that the circuit breaker must withstand with a very high probability of success.

IEEE values are given in 5.3 of IEEE C37.100.1-201x and 6.1 of IEEE C37.04-201x

Rated Characteristics / Insulation Level

Origin of a switching impulse

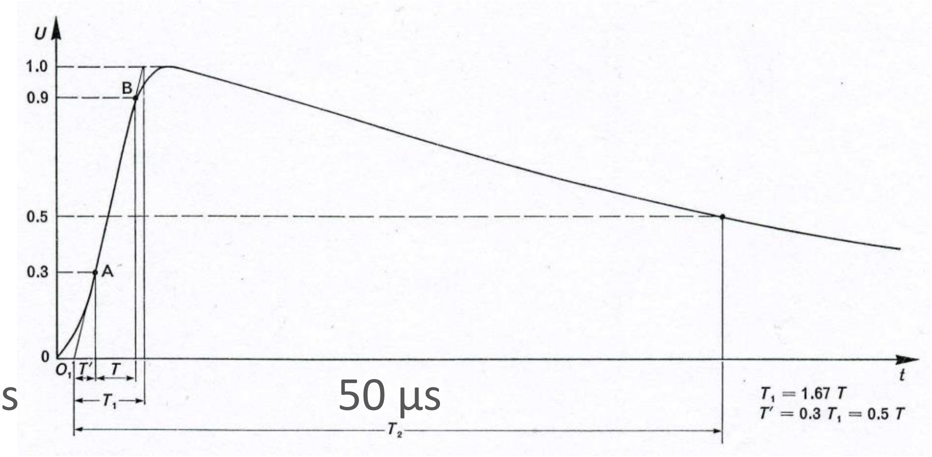


Closing operation by circuit-breaker (A) can produce an overvoltage (switching impulse) on circuit-breaker (B)

Rated Characteristics / Insulation Level

-

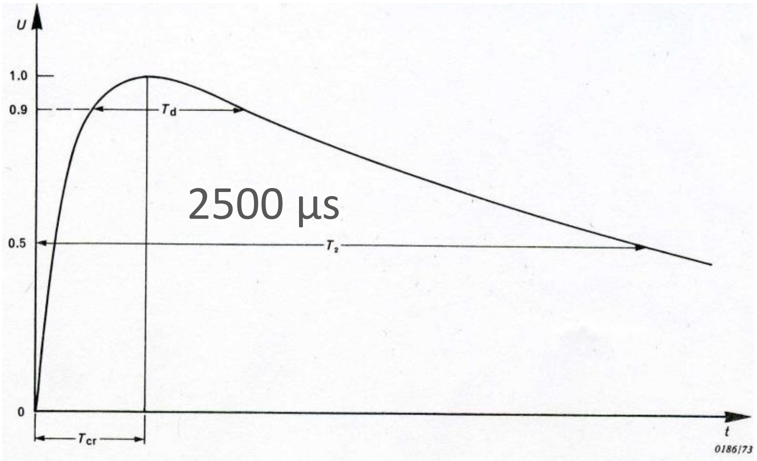
Lightning impulse voltage



1.2 µs

50 µs

Switching impulse voltage



2500 µs

250 µs

A lightning impulse voltage rises faster than a switching impulse

Rated Characteristics / Insulation Level

Insulation levels in IEEE C37.100.1 for rated voltages ≤ 245 kV

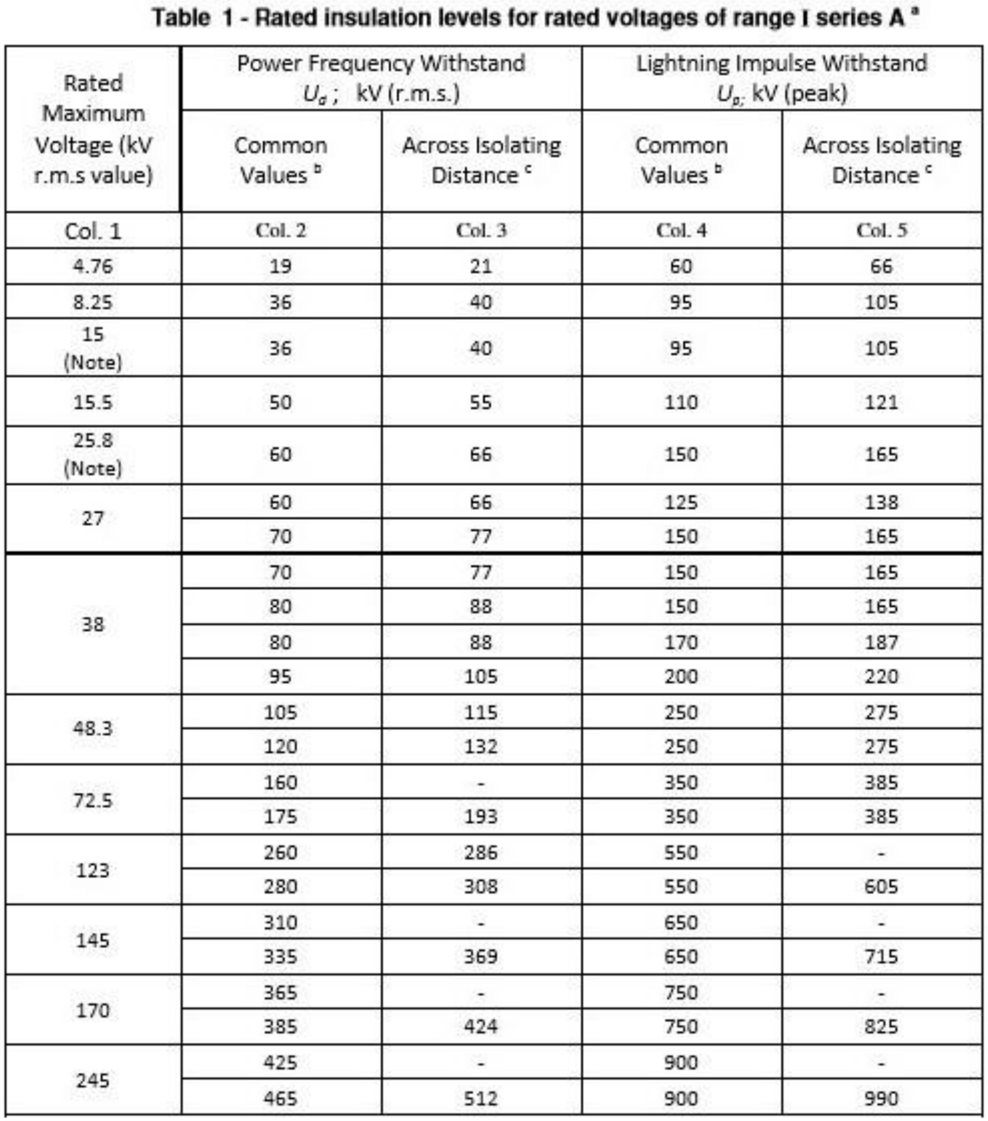


Table 1 - Rated insulation levels for rated voltages of range I series A [a]

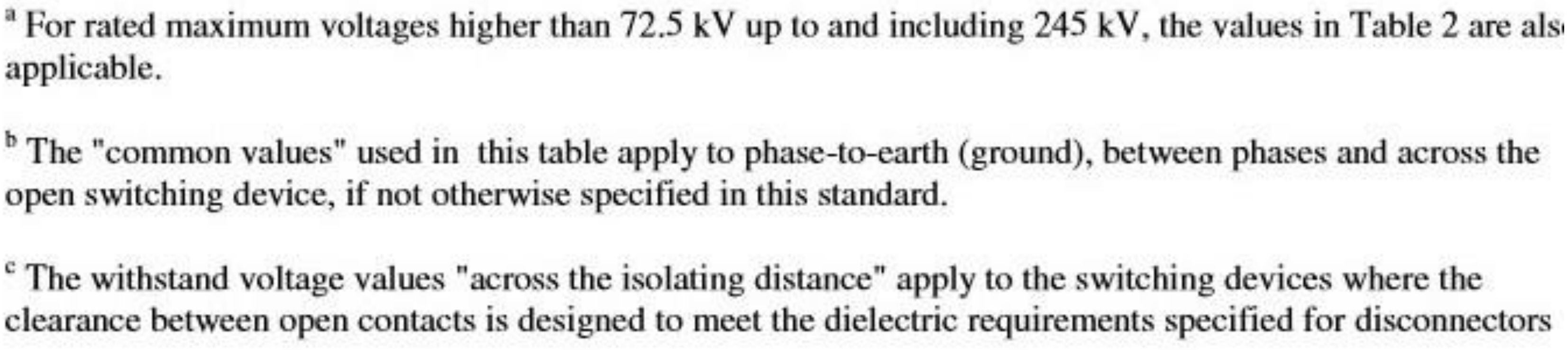
Rated Maximum Voltage (kV r.m.s value)	Power Frequency Withstand U_d; kV (r.m.s.)		Lightning Impulse Withstand U_p; kV (peak)	
	Common Values [b]	Across Isolating Distance [c]	Common Values [b]	Across Isolating Distance [c]
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5
4.76	19	21	60	66
8.25	36	40	95	105
15 (Note)	36	40	95	105
15.5	50	55	110	121
25.8 (Note)	60	66	150	165
27	60	66	125	138
	70	77	150	165
38	70	77	150	165
	80	88	150	165
	80	88	170	187
	95	105	200	220
48.3	105	115	250	275
	120	132	250	275
72.5	160	-	350	385
	175	193	350	385
123	260	286	550	-
	280	308	550	605
145	310	-	650	-
	335	369	650	715
170	365	-	750	-
	385	424	750	825
245	425	-	900	-
	465	512	900	990

IEEE C37.100.1 is the IEEE Standard of Common Requirements for High Voltage Power Switchgear Rated Above 1000 V

Rated Characteristics / Insulation Level

Insulation levels in IEEE C37.100.1 for rated voltages ≤ 245 kV

Notes to Table 1



[a] For rated maximum voltages higher than 72.5 kV up to and including 245 kV, the values in Table 2 are als applicable.

[b] The "common values" used in this table apply to phase-to-earth (ground), between phases and across the open switching device, if not otherwise specified in this standard.

[c] The withstand voltage values "across the isolating distance" apply to the switching devices where the clearance between open contacts is designed to meet the dielectric requirements specified for disconnectors

Rated Characteristics / Insulation Level

Insulation levels in IEEE C37.100.1 for rated voltages ≤ 245 kV

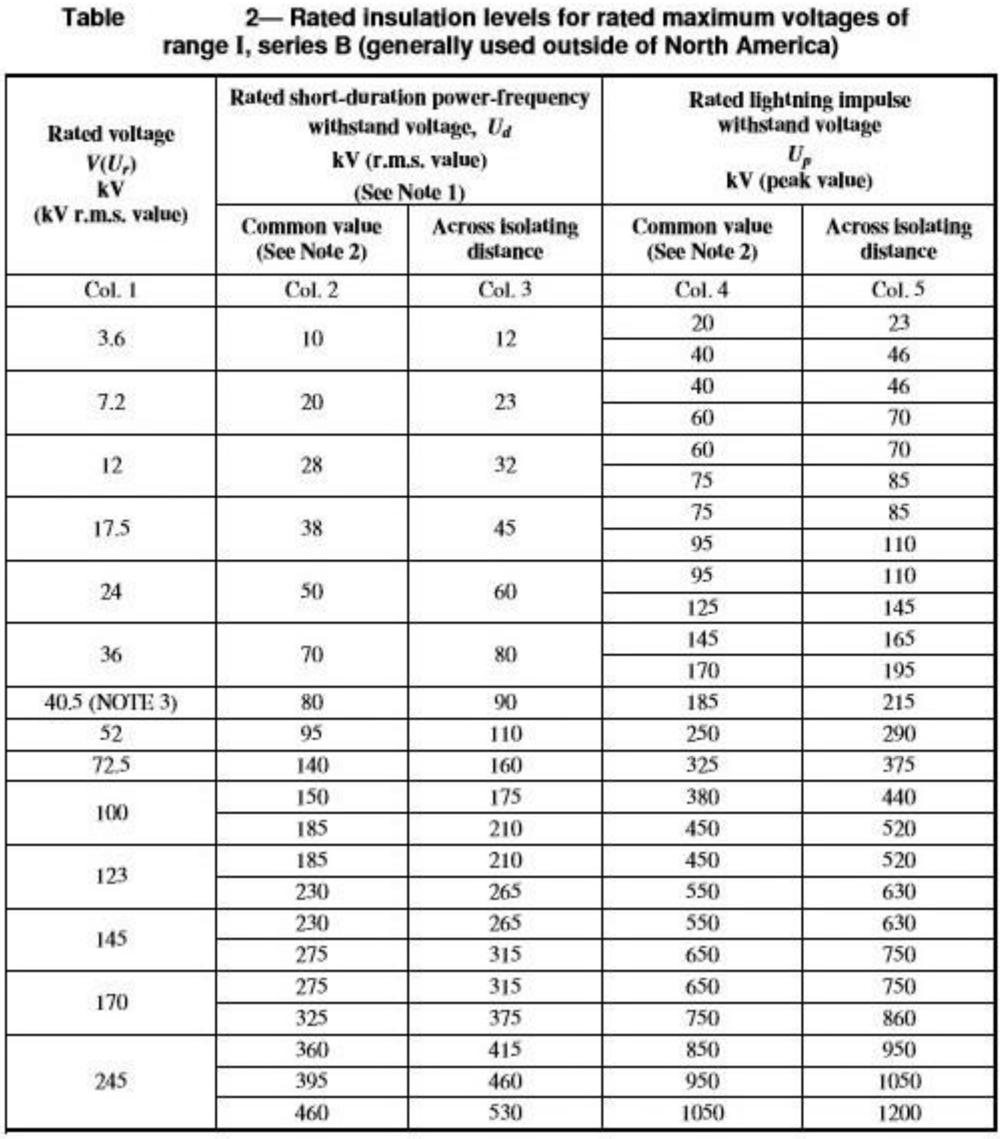


Table 2— Rated insulation levels for rated maximum voltages of range I, series B (generally used outside of North America)

Rated voltage $V(U_r)$ kV (kV r.m.s. value)	Rated short-duration power-frequency withstand voltage, U_d kV (r.m.s. value) (See Note 1)		Rated lightning impulse withstand voltage U_p kV (peak value)	
	Common value (See Note 2)	Across isolating distance	Common value (See Note 2)	Across isolating distance
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5
3.6	10	12	20	23
			40	46
7.2	20	23	40	46
			60	70
12	28	32	60	70
			75	85
17.5	38	45	75	85
			95	110
24	50	60	95	110
			125	145
36	70	80	145	165
			170	195
40.5 (NOTE 3)	80	90	185	215
52	95	110	250	290
72.5	140	160	325	375
100	150	175	380	440
	185	210	450	520
123	185	210	450	520
	230	265	550	630
145	230	265	550	630
	275	315	650	750
170	275	315	650	750
	325	375	750	860
245	360	415	850	950
	395	460	950	1050
	460	530	1050	1200

Rated Characteristics / Insulation Level

Power Frequency Tests for U_r = 245 kV

Explanation for standard value of 460 kV specified for wet test

Switching surge of 3 p.u. on one terminal: $3 \times 245\sqrt{2} / \sqrt{3} = 600$ kV

Equivalent power frequency value: $600 \times 0.75 / \sqrt{2} = 318$ kV

Power frequency voltage on opposite terminal: $245 / \sqrt{3} = 141$ kV

Power frequency voltage between terminals: $318 + 141 \approx 460$ kV

Power Frequency Tests for U_r = 145 kV

Explanation for standard value of 275 kV specified for wet test

Switching surge of 3 p.u. on one terminal: $3 \times 145\sqrt{2} / \sqrt{3} = 355$ kV

Equivalent power frequency value: $355 \times 0.75 / \sqrt{2} = 188$ kV

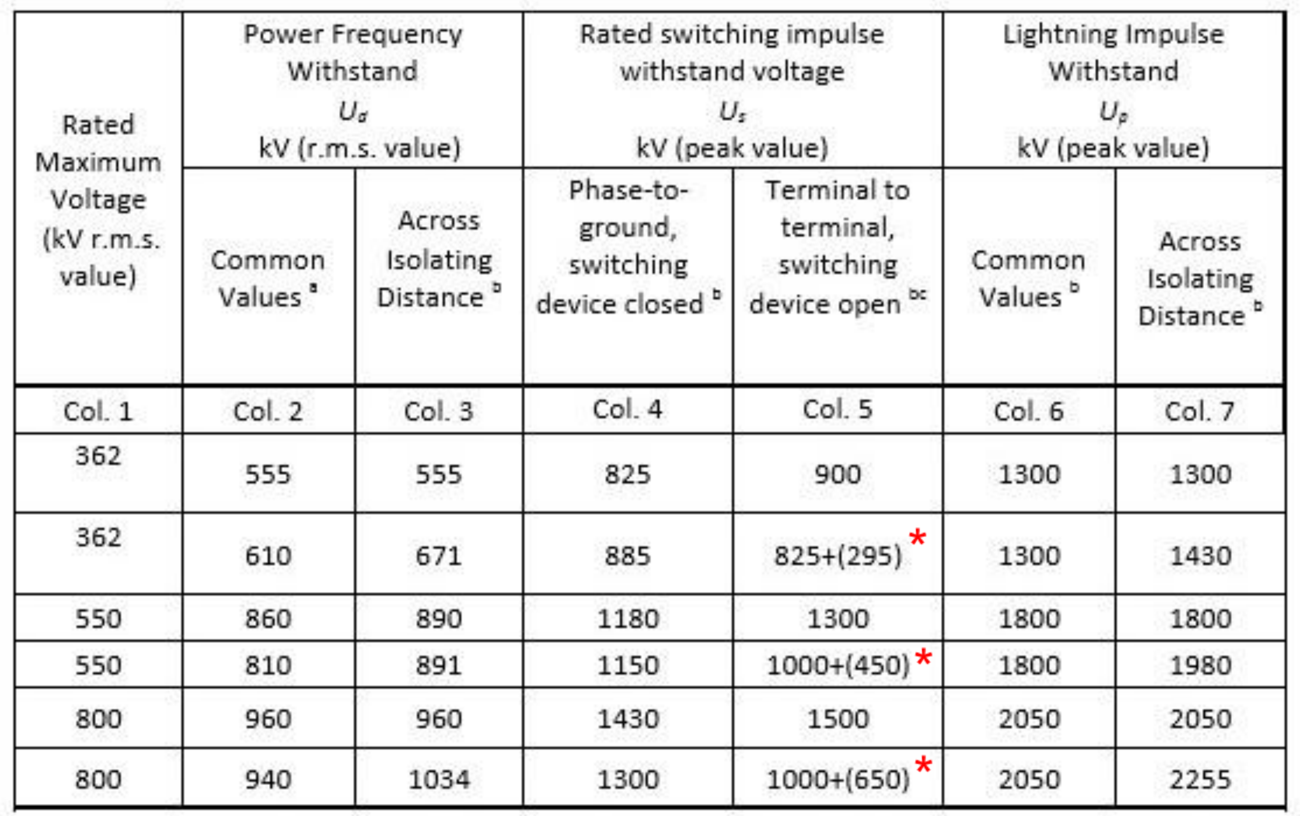
Power frequency voltage on opposite terminal: $145 / \sqrt{3} = 84$ kV

Power frequency voltage between terminals: $188 + 84 = 272$ kV ≈ 275 kV

Rated Characteristics / Insulation Level

Insulation levels in IEEE C37.100.1 for rated voltages ≥ 362 kV

Table 3—Rated insulation levels for range II



Rated Maximum Voltage (kV r.m.s. value)	Power Frequency Withstand U_d kV (r.m.s. value)		Rated switching impulse withstand voltage U_s kV (peak value)		Lightning Impulse Withstand U_p kV (peak value)	
	Common Values [a]	Across Isolating Distance [b]	Phase-to-ground, switching device closed [b]	Terminal to terminal, switching device open [bc]	Common Values [b]	Across Isolating Distance [b]
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7
362	555	555	825	900	1300	1300
362	610	671	885	825+(295) *	1300	1430
550	860	890	1180	1300	1800	1800
550	810	891	1150	1000+(450) *	1800	1980
800	960	960	1430	1500	2050	2050
800	940	1034	1300	1000+(650) *	2050	2255

* Values for combined test with switching impulse voltage applied on one terminal and power frequency voltage applied on the other terminal.

Rated Characteristics / Insulation Level

Insulation levels in IEEE C37.100.1 for rated voltages ≥ 362 kV

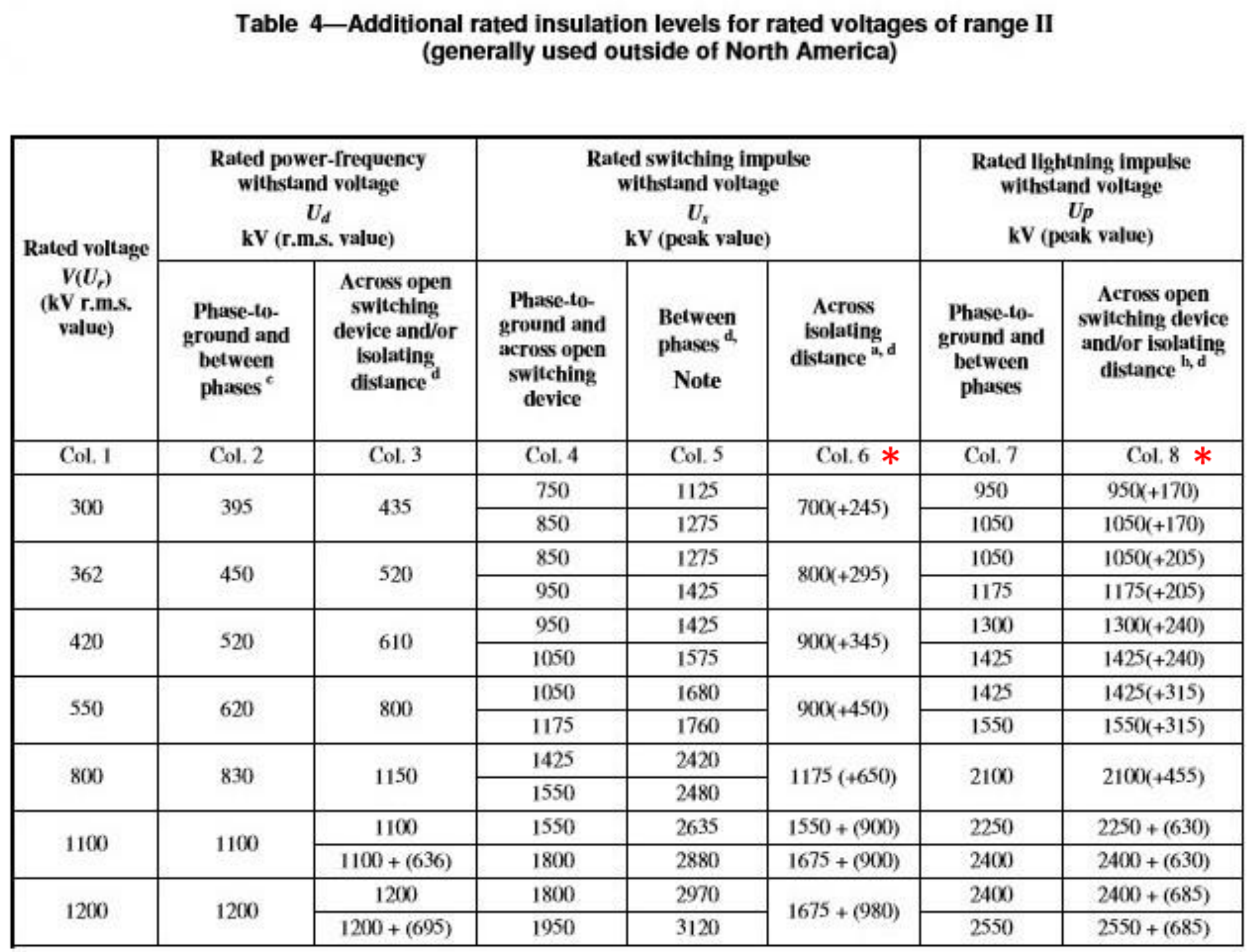


Table 4—Additional rated insulation levels for rated voltages of range II (generally used outside of North America)

Rated voltage $V(U_r)$ (kV r.m.s. value)	Rated power-frequency withstand voltage U_d kV (r.m.s. value)		Rated switching impulse withstand voltage U_s kV (peak value)			Rated lightning impulse withstand voltage Up kV (peak value)	
	Phase-to-ground and between phases[c]	Across open switching device and/or isolating distance[d]	Phase-to-ground and across open switching device	Between phases[d,] Note	Across isolating distance[a, d]	Phase-to-ground and between phases	Across open switching device and/or isolating distance[b, d]
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6 *	Col. 7	Col. 8 *
300	395	435	750	1125	700(+245)	950	950(+170)
			850	1275		1050	1050(+170)
362	450	520	850	1275	800(+295)	1050	1050(+205)
			950	1425		1175	1175(+205)
420	520	610	950	1425	900(+345)	1300	1300(+240)
			1050	1575		1425	1425(+240)
550	620	800	1050	1680	900(+450)	1425	1425(+315)
			1175	1760		1550	1550(+315)
800	830	1150	1425	2420	1175 (+650)	2100	2100(+455)
			1550	2480			
1100	1100	1100	1550	2635	1550 + (900)	2250	2250 + (630)
		1100 + (636)	1800	2880	1675 + (900)	2400	2400 + (630)
1200	1200	1200	1800	2970	1675 + (980)	2400	2400 + (685)
		1200 + (695)	1950	3120		2550	2550 + (685)

* Values for combined tests

Rated Characteristics / Insulation Level

Values in the draft revision of IEEE C37.04, coming from IEEE C37.06 (2009)

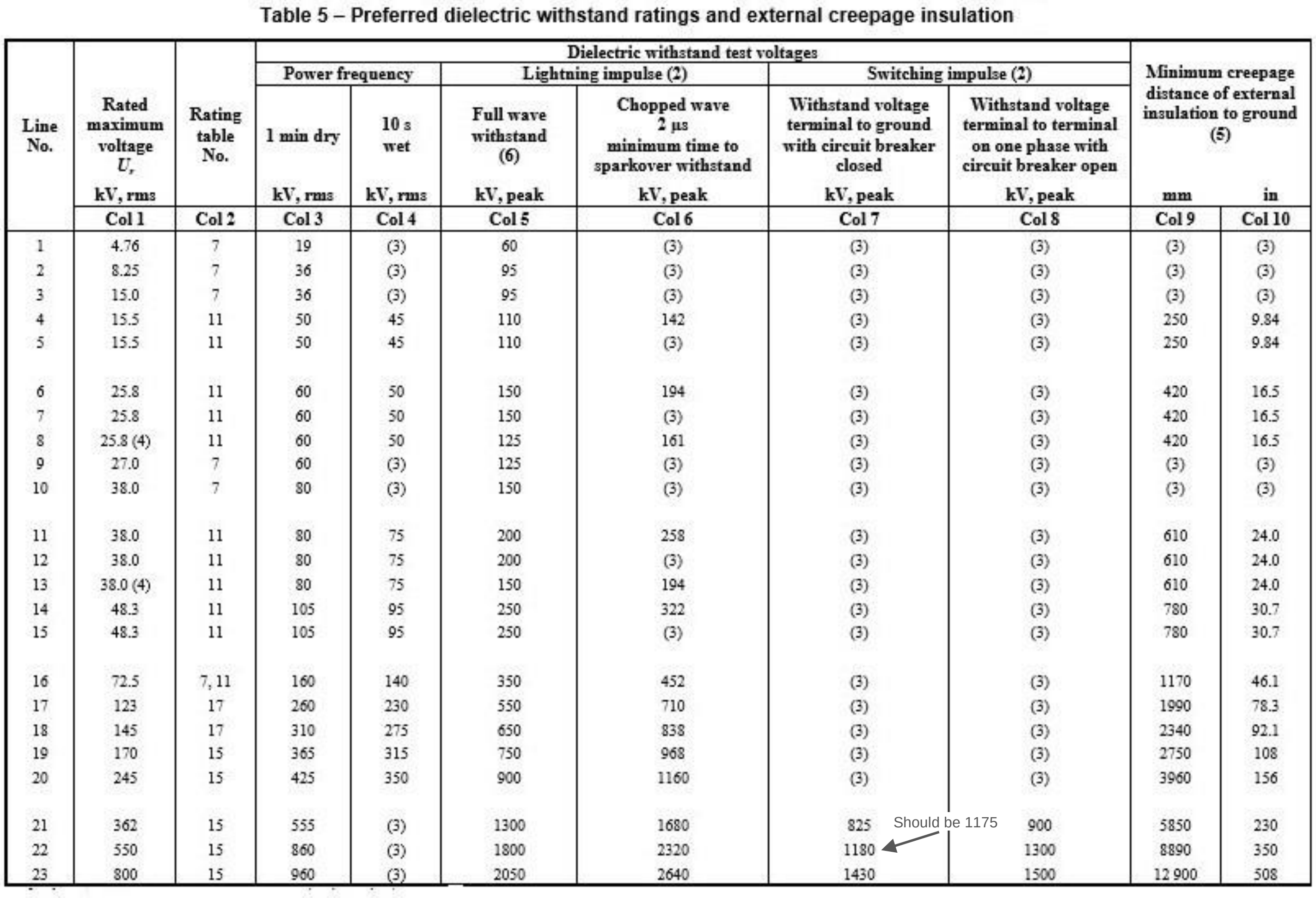


Table 5 – Preferred dielectric withstand ratings and external creepage insulation

Line No.	Rated maximum voltage U_r kV, rms	Rating table No.	Dielectric withstand test voltages						Minimum creepage distance of external insulation to ground (5)	
			Power frequency		Lightning impulse (2)		Switching impulse (2)			
			1 min dry kV, rms	10 s wet kV, rms	Full wave withstand (6) kV, peak	Chopped wave 2 µs minimum time to sparkover withstand kV, peak	Withstand voltage terminal to ground with circuit breaker closed kV, peak	Withstand voltage terminal to terminal on one phase with circuit breaker open kV, peak	mm	in
	Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9	Col 10
1	4.76	7	19	(3)	60	(3)	(3)	(3)	(3)	(3)
2	8.25	7	36	(3)	95	(3)	(3)	(3)	(3)	(3)
3	15.0	7	36	(3)	95	(3)	(3)	(3)	(3)	(3)
4	15.5	11	50	45	110	142	(3)	(3)	250	9.84
5	15.5	11	50	45	110	(3)	(3)	(3)	250	9.84
6	25.8	11	60	50	150	194	(3)	(3)	420	16.5
7	25.8	11	60	50	150	(3)	(3)	(3)	420	16.5
8	25.8 (4)	11	60	50	125	161	(3)	(3)	420	16.5
9	27.0	7	60	(3)	125	(3)	(3)	(3)	(3)	(3)
10	38.0	7	80	(3)	150	(3)	(3)	(3)	(3)	(3)
11	38.0	11	80	75	200	258	(3)	(3)	610	24.0
12	38.0	11	80	75	200	(3)	(3)	(3)	610	24.0
13	38.0 (4)	11	80	75	150	194	(3)	(3)	610	24.0
14	48.3	11	105	95	250	322	(3)	(3)	780	30.7
15	48.3	11	105	95	250	(3)	(3)	(3)	780	30.7
16	72.5	7, 11	160	140	350	452	(3)	(3)	1170	46.1
17	123	17	260	230	550	710	(3)	(3)	1990	78.3
18	145	17	310	275	650	838	(3)	(3)	2340	92.1
19	170	15	365	315	750	968	(3)	(3)	2750	108
20	245	15	425	350	900	1160	(3)	(3)	3960	156
21	362	15	555	(3)	1300	1680	825	900	5850	230
22	550	15	860	(3)	1800	2320	1180	1300	8890	350
23	800	15	960	(3)	2050	2640	1430	1500	12 900	508

Should be 1175

In accordance with the standard test procedure of IEEE Std 4, the duration of the wet test should be 1 min. As explained in this presentation, some power frequency values for dry tests (U_r = 123 kV, 145 kV & 170 kV) in Col 3 should be corrected (values in IEEE C37.122).

Rated Characteristics / Insulation Level

Power frequency test voltage in IEEE C37.06 for $U_r \geq 121$ kV

- With two exceptions (U_r = 170 kV and 362 kV), the power frequency test voltage U_d is approximately 0.472 times the BIL for dry conditions.

for example U_r = 121 kV BIL = 550 kV U_d = 0.472 x 550 = 260 kV

U_r = 145 kV BIL = 650 kV U_d = 0.477 x 650 = 310 kV

U_r = 245 kV BIL = 900 kV U_d = 0.472 x 900 = 425 kV

U_r = 550 kV BIL = 1800 kV U_d = 0.478 x 1800 = 860 kV

U_r = 800 kV BIL = 2050 kV U_d = 0.468 x 1800 = 960 kV

- The U_d value for U_r = 362 kV is 555 kV. It is based on a BIL of 1175 kV and was not changed when BIL was raised to 1300 kV. Experience in service confirmed that 555 kV can be kept, suggesting that the factor 0.472 is too high and should be reduced*.
- IEC values are based on a factor = 0.43 (e.g. U_d = 275 kV for U_r=145kV)
- Some IEC values having a different basis can be higher e.g. for U_r = 245 kV & BIL 1050 kV: U_d = 460 kV.

* See IEEE Tutorial Course "Application of power circuit breakers, - Insulation Considerations for AC High Voltage Circuit Breakers", by C.L.Wagner & R.A.York (1995).

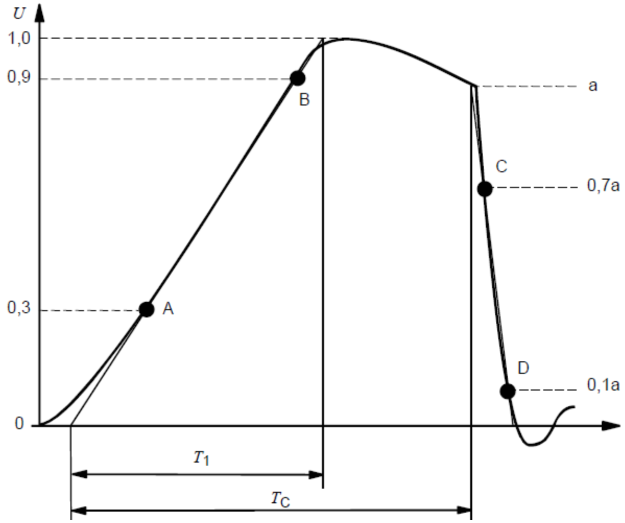
Rated Characteristics / Insulation Level

Values for circuit breakers in the draft revision of IEEE C37.04

From IEEE C37.06, a voltage withstand is specified with lightning impulse chopped waves, chopped at 2 µs, but not for GIS circuit breakers.

In practice it corresponds to the (rare) case of a second component of a lightning stroke with the circuit already opened, therefore not protected by the bus side surge arrester*.

As the surge voltage applied is often faster than the standard impulse wave, a higher peak value is specified: 1.29 times the lightning impulse withstand voltage value.



* Full explanation in IEEE Tutorial Course ″Application of power circuit breakers, - Insulation Considerations for AC High Voltage Circuit Breakers″, by C.L.Wagner & R.A.York (1995).

Rated Characteristics / Insulation Level

IEEE insulation levels: values for circuit breakers in GIS substations above 52 kV are given in IEEE C37.122-2011

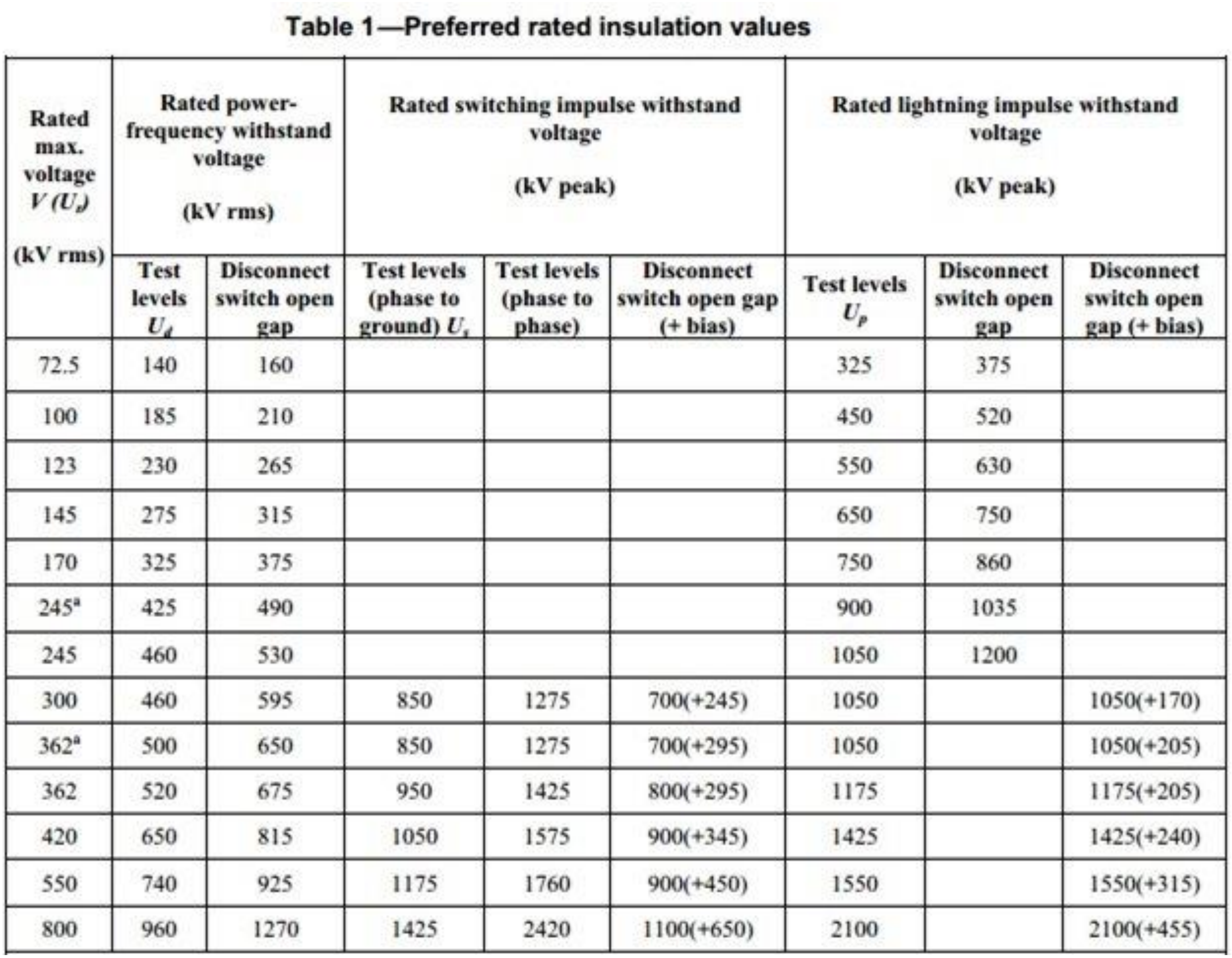


Table 1—Preferred rated insulation values

Rated max. voltage V (U_r) (kV rms)	Rated power-frequency withstand voltage (kV rms)		Rated switching impulse withstand voltage (kV peak)			Rated lightning impulse withstand voltage (kV peak)		
	Test levels U_d	Disconnect switch open gap	Test levels (phase to ground) U_s	Test levels (phase to phase)	Disconnect switch open gap (+ bias)	Test levels U_p	Disconnect switch open gap	Disconnect switch open gap (+ bias)
72.5	140	160				325	375	
100	185	210				450	520	
123	230	265				550	630	
145	275	315				650	750	
170	325	375				750	860	
245[a]	425	490				900	1035	
245	460	530				1050	1200	
300	460	595	850	1275	700(+245)	1050		1050(+170)
362[a]	500	650	850	1275	700(+295)	1050		1050(+205)
362	520	675	950	1425	800(+295)	1175		1175(+205)
420	650	815	1050	1575	900(+345)	1425		1425(+240)
550	740	925	1175	1760	900(+450)	1550		1550(+315)
800	960	1270	1425	2420	1100(+650)	2100		2100(+455)

Note: U_d = 275 kV for circuit breakers with U_r =145kV

Rated Characteristics / Insulation Level

Dielectric tests are done to verify the insulation level.

The dielectric withstand must be verified in the following cases:

- withstand between terminals, circuit breaker open
- withstand to ground, circuit breaker open
- withstand to ground, apparatus closed.

In all cases the aim is to verify the withstand of each pole and, when applicable, the withstand between poles.

Tests on switchgear filled with gas are done with the minimum gas pressure.

Rated Characteristics / Insulation Level

Power frequency withstand voltage tests

- These tests are required for all rated voltages.
- These tests are the only one performed as routine (production) tests.
- Tests values are defined to be equivalent to those for impulse tests.
- According to IEC, the withstand during 1 minute in dry and in wet conditions is required.

  No disruptive discharge is allowed during the dry test.

  The test in wet condition can be repeated if there is a disruptive discharge, but no other discharge is allowed.
- ANSI/IEEE has a similar procedure, with the exception of wet tests that have a duration of 10 seconds and the flow rate of rain is higher (5 mm/min).
- IEEE Std 4 (2013) has a new standard procedure with a precipitation rate (1 to 2 mm/min vertically and horizontally) and a duration of 60 s as in IEC.
- IEEE C37.09 should make reference to this new procedure of IEEE Std 4.

Rated Characteristics / Insulation Level

Lightning impulse withstand voltage tests

- These tests are required for all rated voltages. They are performed only with dry conditions.

- According to IEC, a series of 15 impulses is done for each test configuration and for each polarity of voltage; only 3 impulses according to IEEE, plus 9 if there is a disruptive discharge.

- IEC: for rated voltages higher than 245 kV, combined tests are required in open position with lightning impulse voltage applied on one terminal and power frequency voltage applied on the other terminal.

  Tests also given in Table 4 of IEEE C37.100.1

- IEC: tests are successful if the following conditions are met:
  - number of disruptive discharges does not exceed 2 in each series;
  - no disruptive discharge must occur on non self-restoring insulation (This is confirmed by 5 consecutive impulse withstands following the last disruptive discharge).

Rated Characteristics / Insulation Level

Switching impulse withstand voltage tests

- These tests are required for rated voltages higher than 245 kV.

- There are done in dry and wet conditions, with both polarities of voltage.

- According to IEC, a series of 15 impulses is applied for each configuration; only 3 impulses according to ANSI/IEEE plus 9 if there is a disruptive discharge.

  The circuit breaker being in closed and open position, the test voltage is applied with the rated switching impulse voltage withstand to ground specified.

- According to IEC: a second series of tests must be done with a switching impulse voltage applied on one terminal and a power frequency voltage applied on the other terminal.

Tests are also given in Table 4 of IEEE C37.100.1

- The criteria to pass the tests is the same as for lightning impulse voltage tests.

Rated Characteristics / Insulation Level

Internal insulation

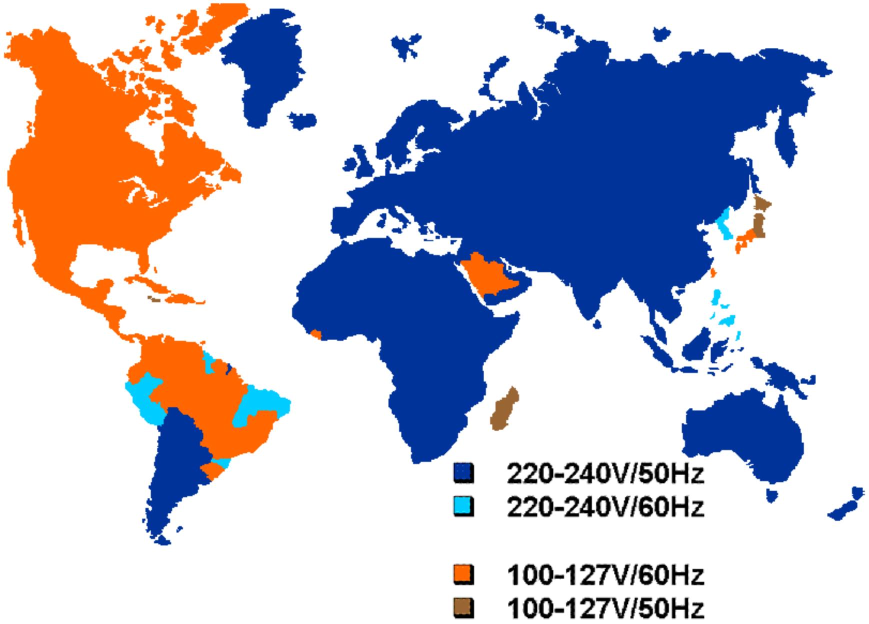
- Gas with good dielectric properties (e.g. SF_6) or vacuum.
- Good dimensioning of distances, metallic and insulating parts
- Avoid internal pollution or reduce it (during operations)

External insulation

- Insulators in porcelain or composite of appropriate length.
- Withstand in wet or polluted conditions, obtained by an appropriate choice of sheds (to have the required creepage distance)

Rated Characteristics / Rated Frequency

The rated values for HV switchgear are 50 Hz and 60 Hz.

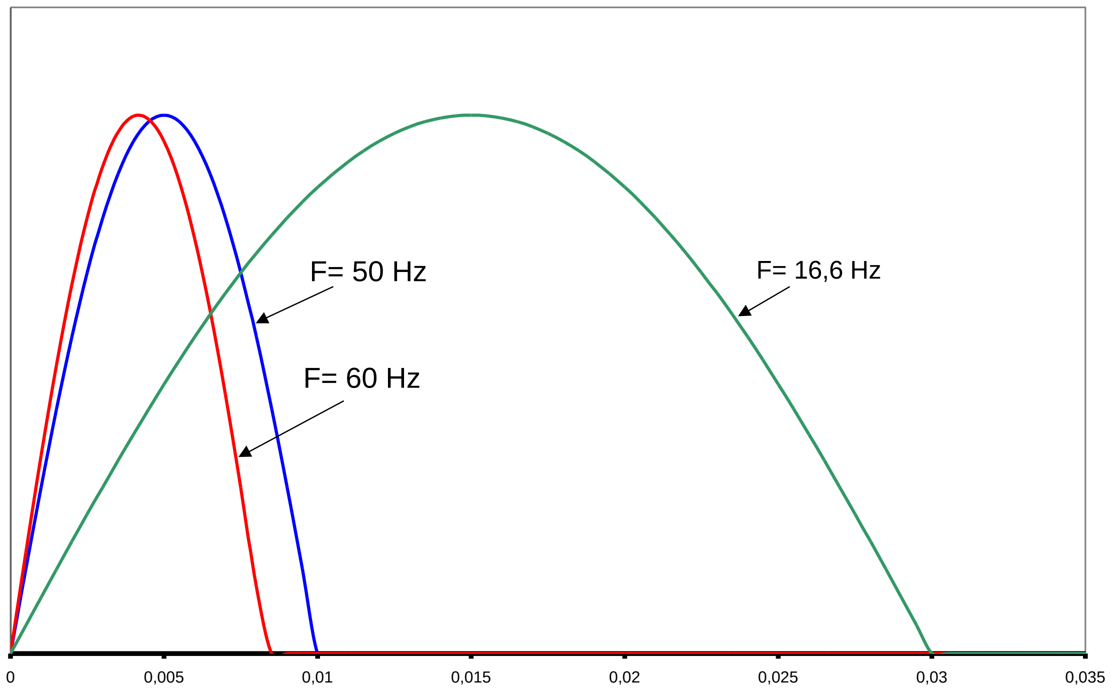


Other values are possible, for example 16 2/3 Hz and 25 Hz for railways applications.

Rated Characteristics / Rated Frequency

Applications at 16.6 Hz and 25 Hz

- These applications may require special types of circuit-breakers as the conditions for current interruption are different from those at 50Hz or 60Hz, and may be more severe.



Rated Characteristics / Continuous Current

The rated continuous (normal) current is the current that the circuit breaker can carry permanently under normal conditions of service.

When carrying the current, the temperature of parts rise but must not exceed values defined in the standards. These values are defined to ensure that the characteristics of materials will be kept.

Limits of temperature and temperature rise are given in IEC 62271-1 and IEEE C37.100.1.

Rated values defined in IEC are as follows:

630 - 800 - 1250 - 1600 - 2000 - 2500 - 3150 - 4000 - 5000 - 6300 A

These values are based on the R10 series of Renard with values proportional to $10^{n/10}$.

The present draft revision of IEEE C37.04 gives the following values of currents (taken from C37.06): 600 -1200 - 1600 - 2000 - 3000 - 4000 - 5000 A

IEEE C37.100.1 states that values should be selected from the R10 series. Note 2 indicates that relevant equipment standards may specify or grandfather other traditional values, e.g. 600 A, 900 A and 1200 A.

Rated Characteristics / Continuous Current

Renard’s Series R10

n	n/10	A=10**(n/10)	1000 A	In (A)	10A	Isc (kA)
1	0,1	1,259	1259	1250	12,6	12,5
2	0,2	1,585	1585	1600	15,8	16
3	0,3	1,995	1995	2000	20,0	20
4	0,4	2,512	2512	2500	25,1	25
5	0,5	3,162	3162	3150	31,6	31,5
6	0,6	3,981	3981	4000	39,8	40
7	0,7	5,012	5012	5000	50,1	50
8	0,8	6,310	6310	6300	63,1	63
9	0,9	7,943	7943	8000	79,4	80
10	1	10,000	10000	10000	100,0	100

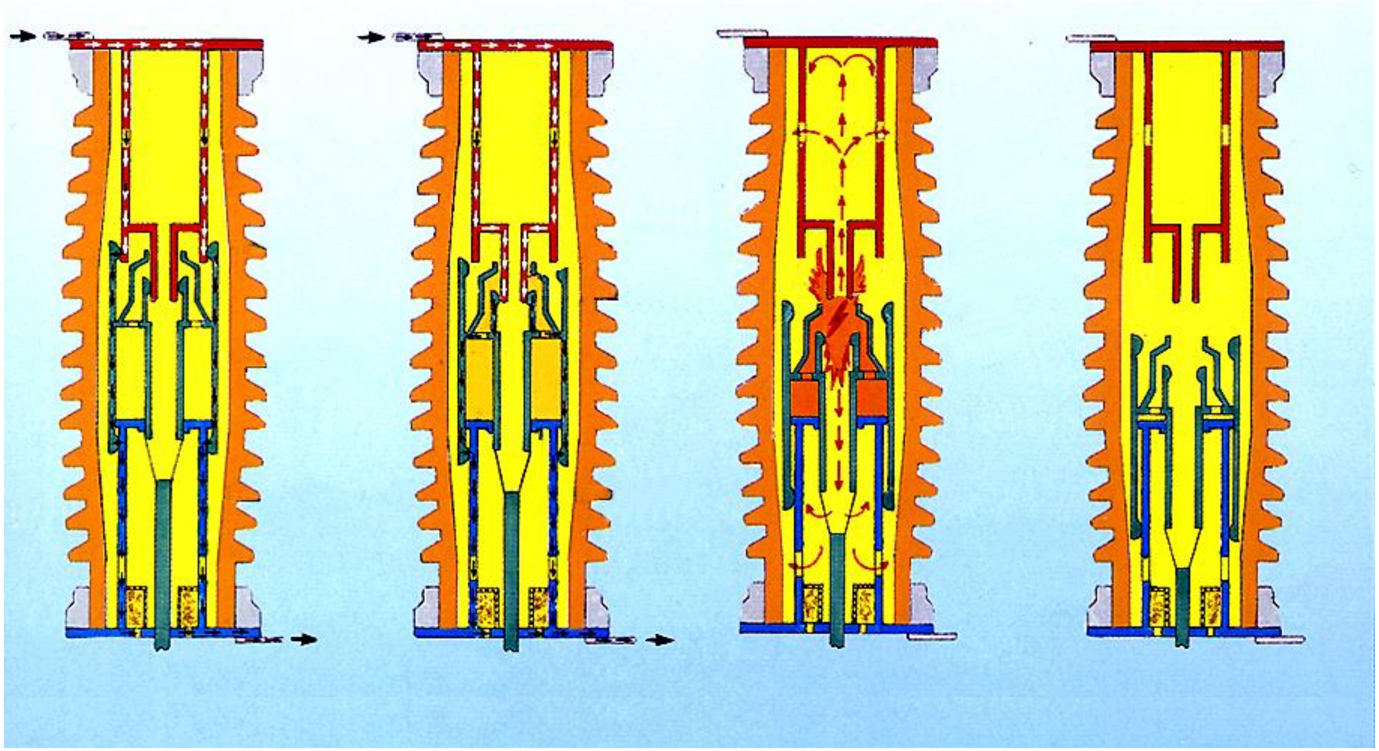
French engineer, inventor and balloonist Charles Renard (1847-1905)

Renard’s series were adopted by ISO in 1952, and later by IEC.

For GIS > 52 kV, IEEE C37.122 indicates that IEEE C37.100.1 applies (i.e. values in R10 series).

Rated Characteristics / Continuous Current

-



Closed position
current passes through the main contacts

After main contacts separation
current passes though arcing contacts

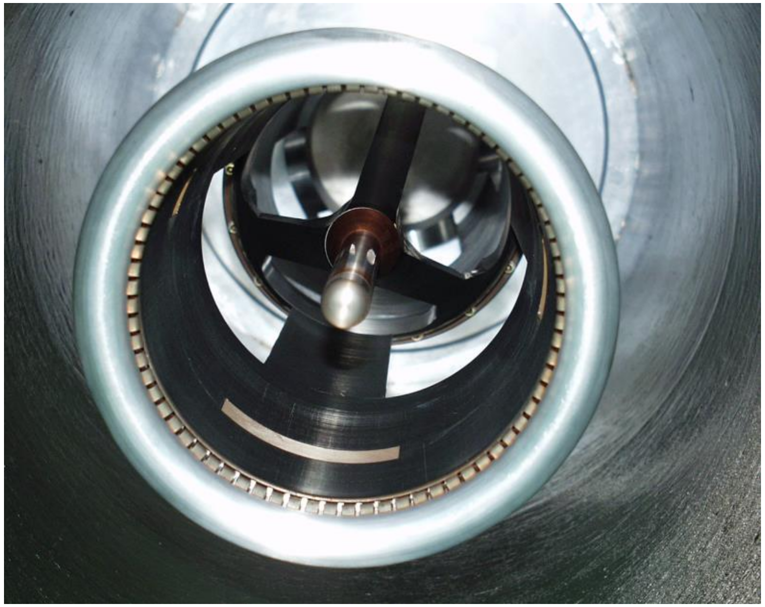
After arcing contacts separation
current carried by an arc between arcing contacts

Open position
current is interrupted

Rated Characteristics / Continuous Current

-

Moving arcing contact (tulip)



Stationary main and arcing contacts

Rated Characteristics / Rated Short-time Withstand Current and Peak Withstand Current

They are the currents that a circuit breaker must withstand in closed position:

- a short-circuit current (r.m.s.) during a given time (1 s, 2 s or 3 s) ;
- a peak current that it can withstand.

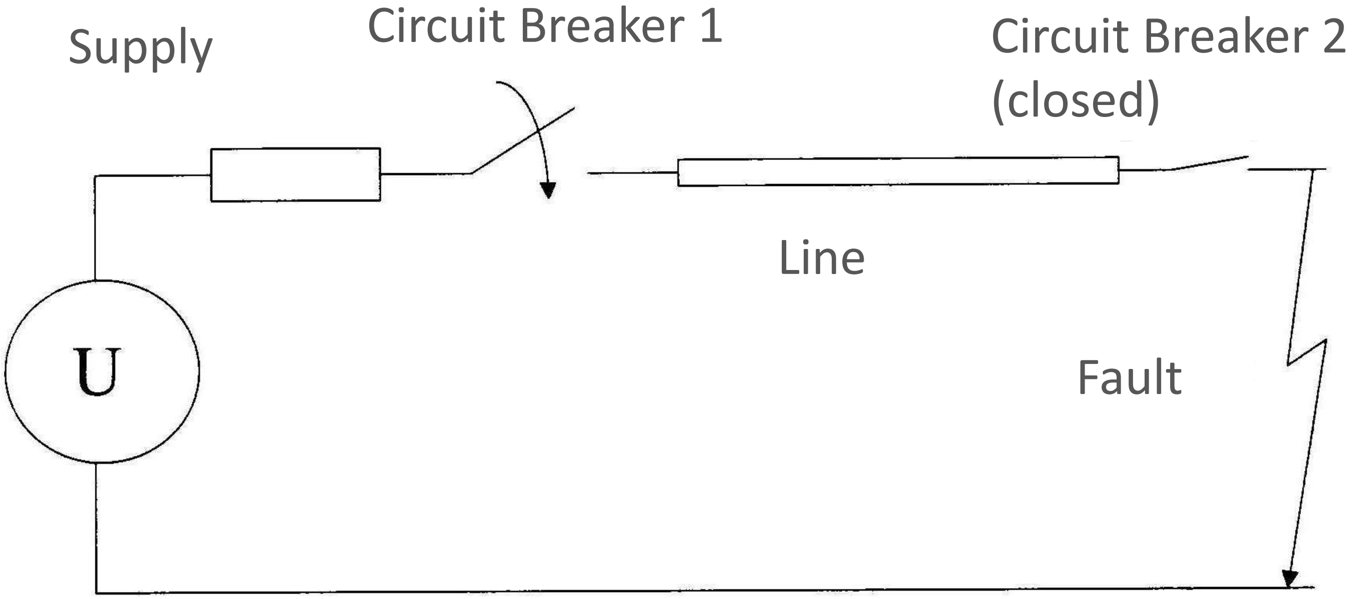
When a short-circuit occurs at a zero voltage, the current is said to be asymmetrical. It has a high peak that a circuit breaker must withstand.

The asymmetrical current is the sum of a periodical (a.c.) component and a d.c. component that is decreasing towards zero with a time constant that is function of the network characteristics.

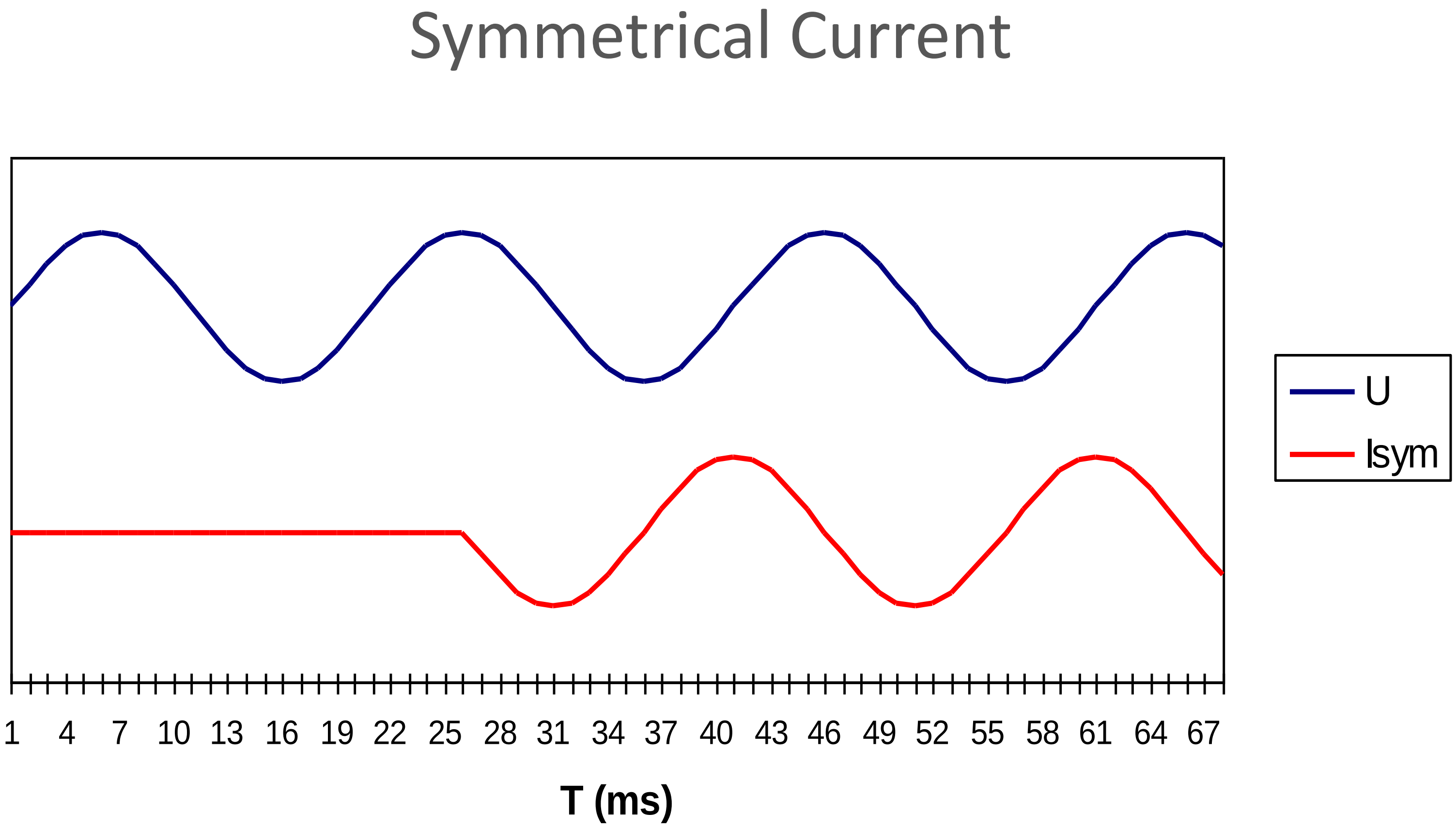
Ratings are given in 5.6 and 5.7 of IEEE C37.100.1
Tests are called STC in Table 1 of IEEE C37.09-201x

Rated Characteristics / Rated Short-time Withstand Current and Peak Withstand Current

Example of situation where a circuit-breaker 2 needs a short-time and peak withstand current capability

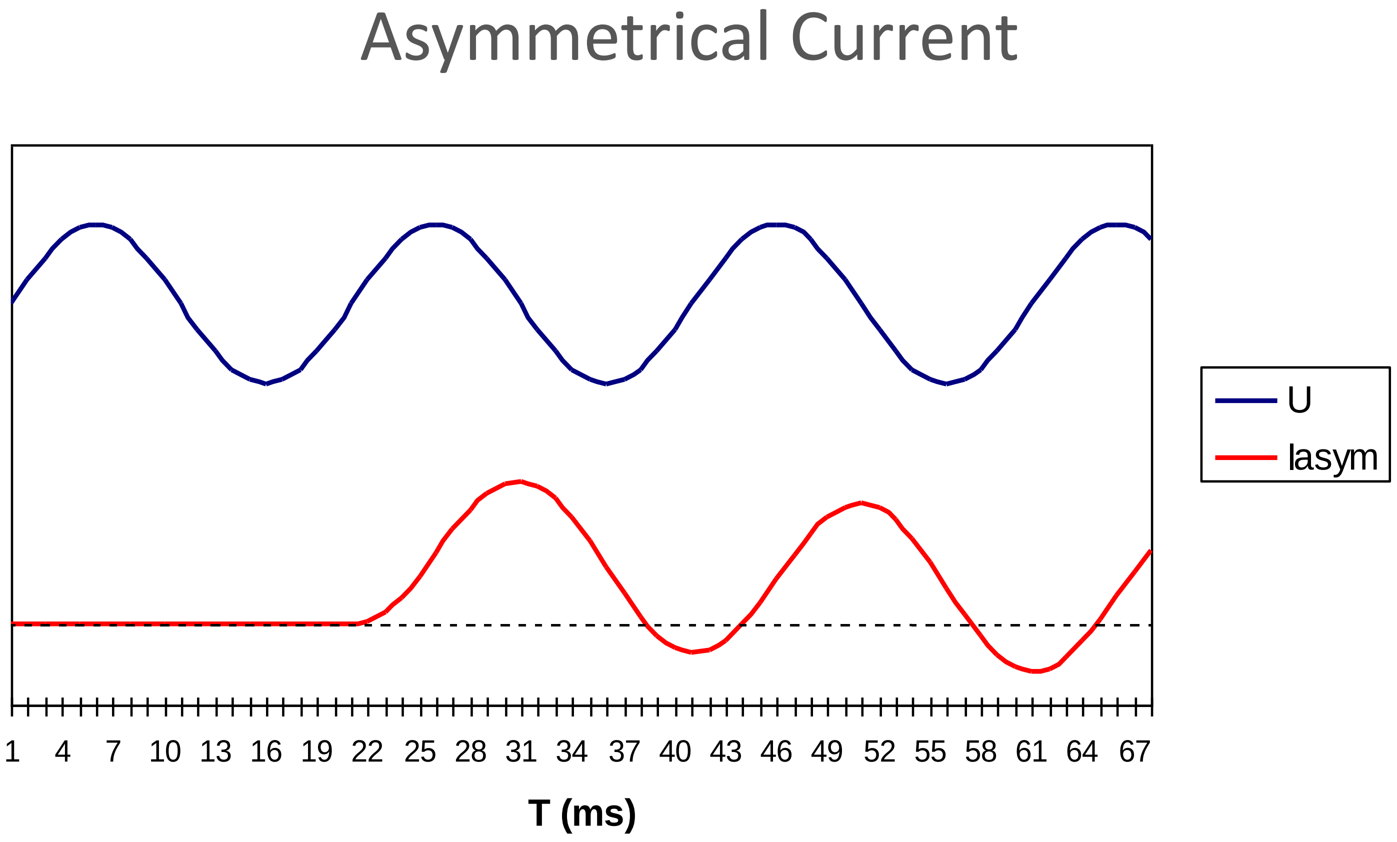


Rated Characteristics / Rated Peak Withstand Current



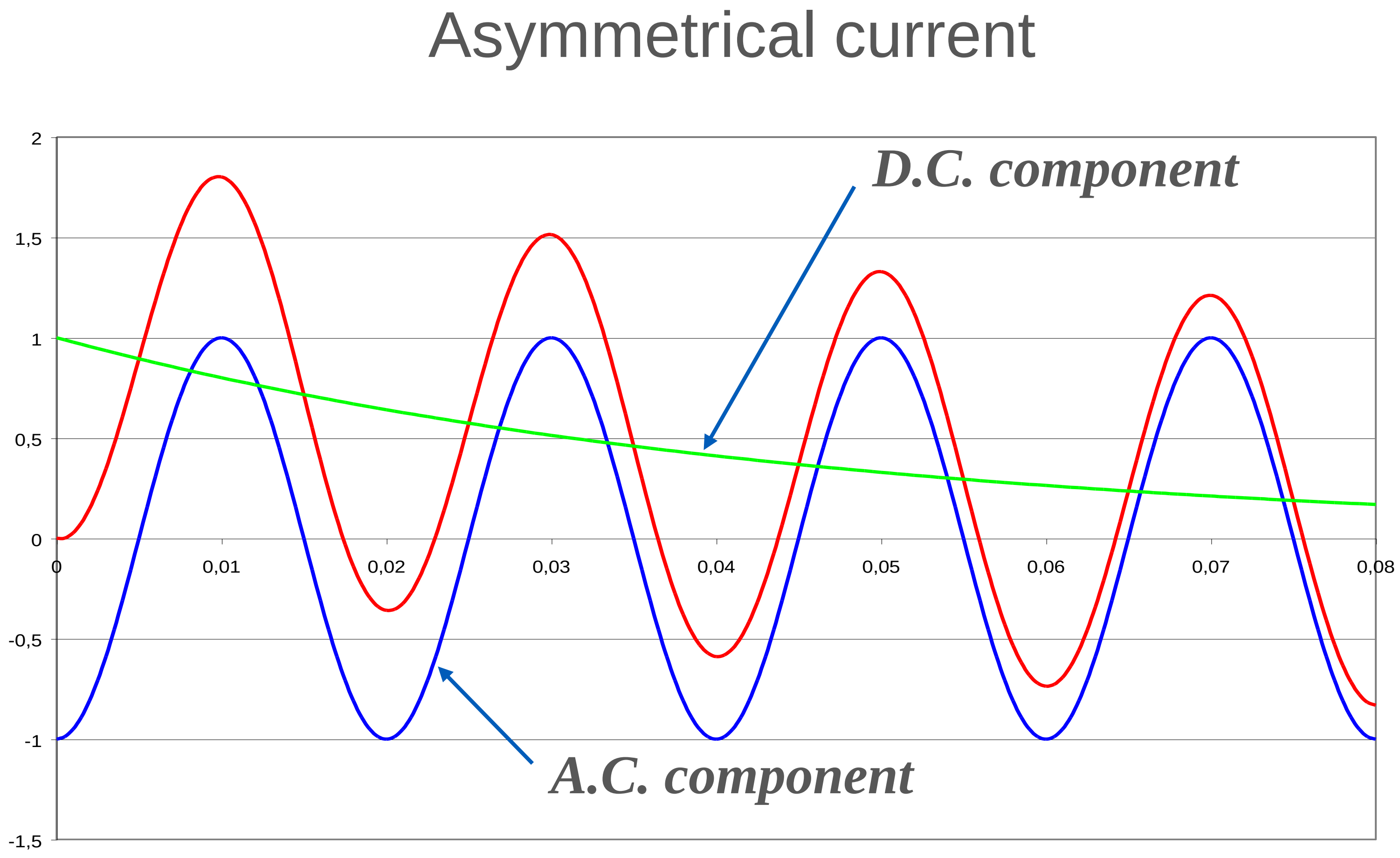
When the fault occurs at maximal voltage, the short-circuit current is symmetrical

Rated Characteristics / Rated Peak Withstand Current



When the fault occurs at zero voltage, the short-circuit current is asymmetrical

Rated Characteristics / Rated Peak Withstand Current



Rated Characteristics / Rated Peak Withstand Current

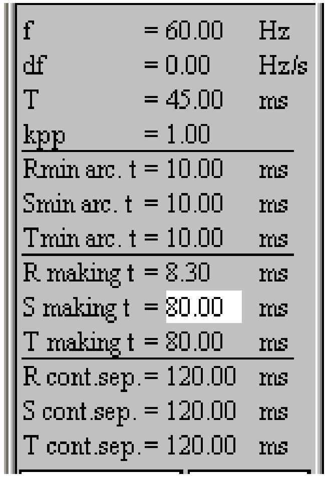
The peak value of the short-time withstand current is equal to the product of the rated short-circuit current by the following factor

2.5	for rated frequency 50Hz	$2.5 = 1.80 \times \sqrt{2}$
2.6	for rated frequency 60Hz	$2.6 = 1.83 \times \sqrt{2}$
2.7	for special applications (time constant > 45 ms)	

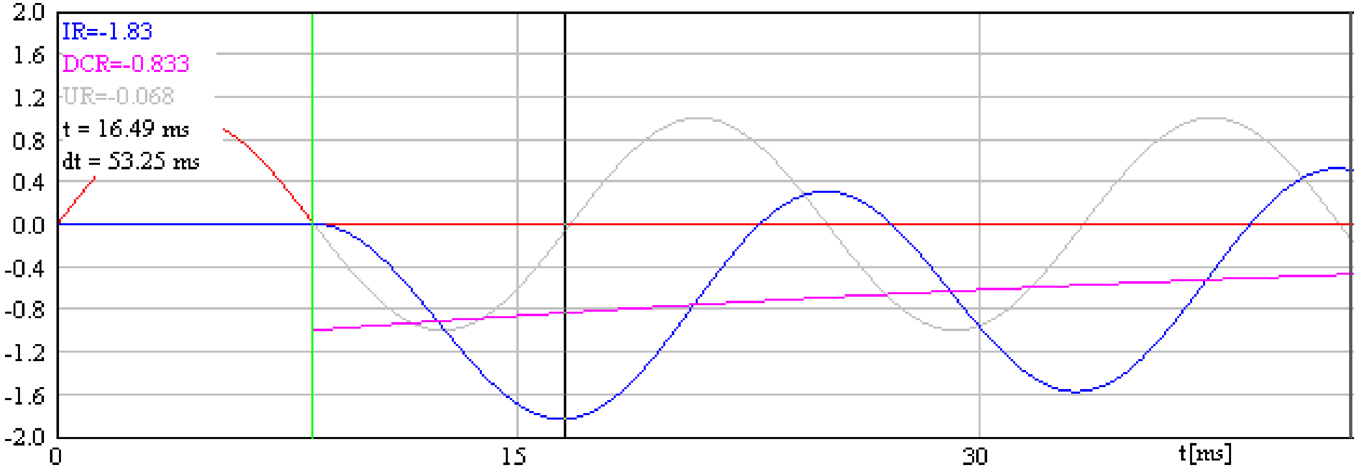
For example the peak current corresponding to 40 kA in a 60Hz network is 2.6 x 40 = 104 kA.

Rated Characteristics / Rated Peak Withstand Current

Simulation I_{asym} in case L/R = 45 ms & f_r = 60 Hz



f = 60.00 Hz
df = 0.00 Hz/s
T = 45.00 ms
kpp = 1.00
Rmin arc. t = 10.00 ms
Smin arc. t = 10.00 ms
Tmin arc. t = 10.00 ms
R making t = 8.30 ms
S making t = 80.00 ms
T making t = 80.00 ms
R cont.sep. = 120.00 ms
S cont.sep. = 120.00 ms
T cont.sep. = 120.00 ms



At 60 Hz, the peak value is 1.83 times the peak symmetrical current

The peak factor is then $1.83 \times \sqrt{2} = 2.6$

Rated Characteristics / Rated Short-Circuit Making & Breaking Current

Rated Short-Circuit Breaking Current

The rated short-circuit breaking current is the highest current that the circuit-breaker shall be capable of breaking under conditions of use and behaviour prescribed in the standard.

Rated Short-Circuit Making Current

The short-circuit making current is the product of the r.m.s. value of the a.c. component of its rated short-circuit breaking current by the factor

- 2.5 for rated frequency 50Hz
- 2.6 for rated frequency 60Hz
- 2.7 for special applications (time constant > 45 ms)

Ratings in 5.5 of IEEE C37.04-201x

Rated Characteristics / Operating Sequence

O - *t* - CO - *t*' – CO with *t*' = 3 min.

- *t* = 3 min for circuit-breakers not intended for rapid auto-reclosing;
- *t* = 0.3 s, for circuit-breakers intended for rapid auto-reclosing;

CO - *t*"- CO

- O represents an opening operation;
- CO represents a closing operation followed immediately by an opening operation.
- *t*" is 30 min for a generator circuit breaker

Ratings in 5.9 of IEEE C37.04-201x

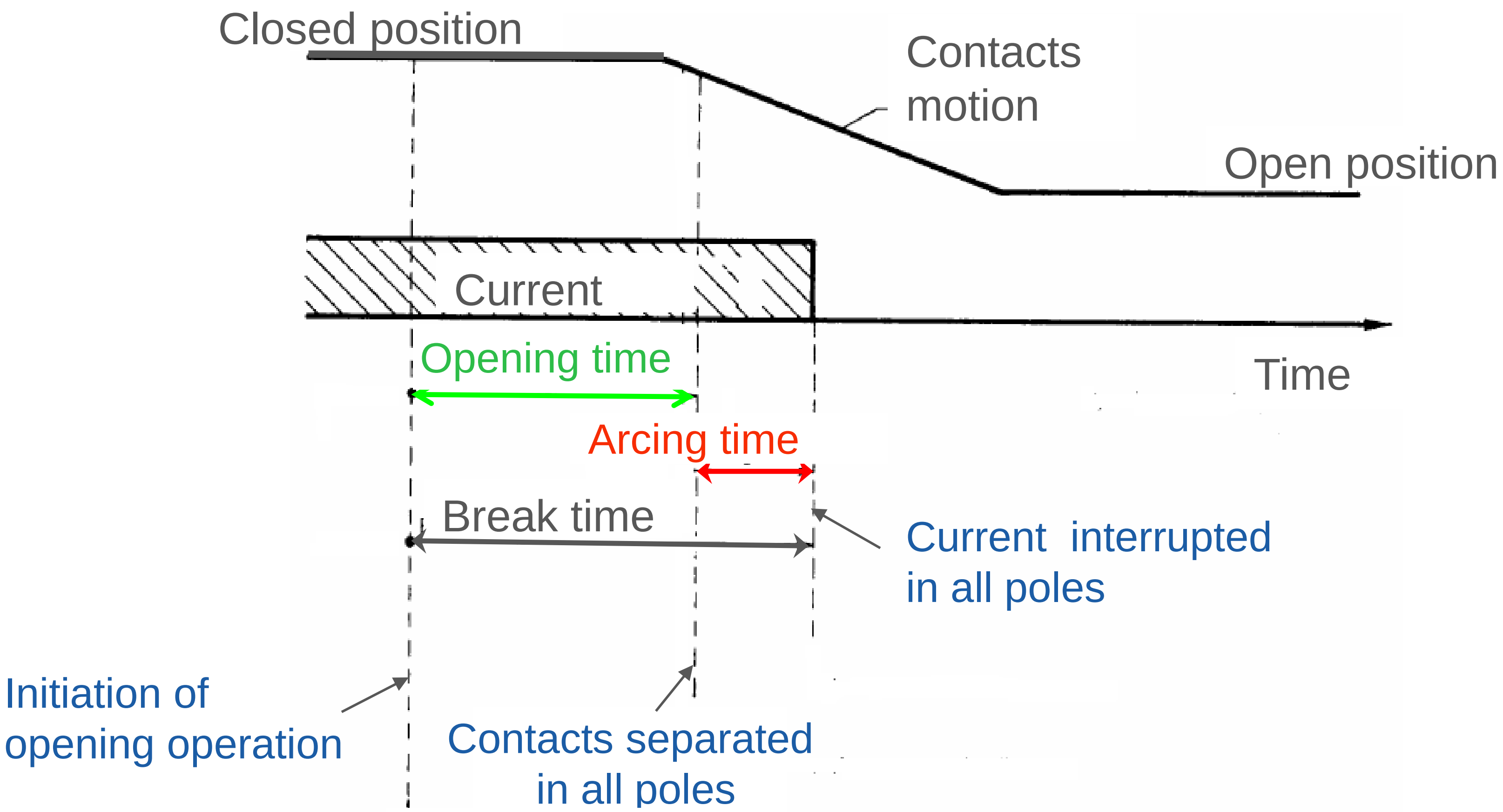
Rated Characteristics
Mechanical endurance

- Two classes are defined in IEC for mechanical endurance
  - Class M1 for normal mechanical endurance: 2000 CO
  - Class M2 for extended mechanical endurance: 10 000 CO

Operating sequence	**Supply voltage and operating pressure**	**Number of operating sequences**	
		Circuit-breakers for auto-reclosing	**Circuit-breakers not for auto-reclosing**
C-t_a-O-t_a	Minimum	500	500
	Rated	500	500
	Maximum	500	500
O-t-CO-t_a-C-t_a	Rated	250	-
CO-t_a	Rated	-	500

IEC tests for class M1 circuit breakers: 2000 C and 2000 O

Other Characteristics
Break Time / Interrupting Time



Other Characteristics
Break Time / Interrupting Time

IEC

- The break time (or interrupting time) is no longer a rating in IEC 62271-100.
- It is a value that can be derived from tests, but not tested as a rating because breaking tests are performed at minimum values of pressure and control voltage (not at rated values).
- The method to calculate the break time is given in IEC/TR 62271-306.

IEEE

- The interrupting time (or break time) is a rating in IEEE C37.04 “Standard Ratings and Requirements for AC HV Circuit Breakers”
- The method of calculation given in the draft revision of IEEE C37.09 “Test Procedures for AC HV Circuit Breakers” is the same as in IEC.

Interrupting time tests in 4.7 of IEEE C37.09-201x

Other Characteristics
Simultaneity of Operation

- Simultaneity of poles and interrupting chambers
  - Open operation
    - Less than 1/6 cycle between poles (IEC and IEEE)
    - Less than 1/8 cycle between chambers of same pole (IEC)
  - Closing operation
    - Less than 1/4 cycle between poles (IEC and IEEE)
    - Less than 1/6 cycle between chambers of same pole (IEC)

1/8 cycle at 60 Hz is 1/60 x 1/8 x 1000 = 2.1 ms

1/6 cycle at 60 Hz is 1/60 x 1/6 x 1000 = 2.8 ms

1/4 cycle at 60 Hz is 1/60 x 1/4 x 1000 = 4.2 ms

See 7.21 of IEEE C37.04-20xx and 5.101 of IEC 62271-100

Other Characteristics
Simultaneity of Operation

- Implication for short-circuit current making and breaking tests

  Unit testing is allowed

  - If contacts of a pole close within 1/4 cycle
  - If contacts of a pole open within 1/6 cycle

- Implication for capacitance current switching tests

  IEC: When the non-simultaneity of contact separation in the different poles of the circuit-breaker exceeds one sixth of the cycle of the rated frequency, it is recommended to raise further the voltage factor or to make only three-phase tests.

See 4.9.3.5.2 of IEEE C37.09-201x

Other Characteristics
Service Capability

- Requirements

  The circuit breaker shall be capable of interrupting a number of terminal faults where the sum of the service capabilities of the symmetrical breaking test currents is equivalent to the service capability duty of at least:

  a) 8 x the rated short-circuit breaking current (I_{rated}) when $U_r < 72.5$ kV

  b) 6 x I_{rated} for circuit breakers with $U_r \geq 72.5$ kV (see note)

  c) Option for circuit breakers with $U_r < 72.5$ kV: E2 Test Duty as defined in Table F1 of IEEE C37.04-201x

- Testing
  - $U_r < 72.5$ kV: T100s and T100a shall be included in tests.

    One test at I_{test} is counted as $[I_{\text{test}} / I_{\text{rated}}]^{1.8}$
  - $U_r \geq 72.5$ kV: T60 and T100s or T60 and T100a on the same pole in the case of single-phase tests or the same circuit breaker in the case of three-phase tests. Alternatively six interruptions at 100% rated short-circuit current.

Note: requirements based on CIGRE study reported in IEC 62271-310

See 5.5.2.5 of IEEE C37.04-201x and 4.9.5.4 of IEEE C37.09-201x

Content

Operating Mechanism

The operation of a circuit breaker is done by an operating mechanism that provide the energy necessary to open or close, or to perform operating cycles such as CO or OCO.

The operating mechanism must be able to perform the full operation of the circuit-breaker in all specified conditions.

Response time must be short enough to allow the interruption in the specified break (interrupting) time.

The order is given by a relay or network protection devices that are fed by instrument transformers.

The operation is obtained by sending an order (electric impulse) on a coil that releases a latch in the mechanism.

Operating Mechanism

The energy, previously stored in springs or in a fluid under pressure (oil or air), is released and used to operate the circuit breaker.

In the following two types of operating mechanism are presented

- Hydraulic mechanism
- Spring operated mechanism

Other types include

- Pneumatic mechanism
- Solenoid operated mechanism (MV)
- Bi-stable magnetic operating mechanism (MV)

Operating Mechanism

Hydraulic Mechanism

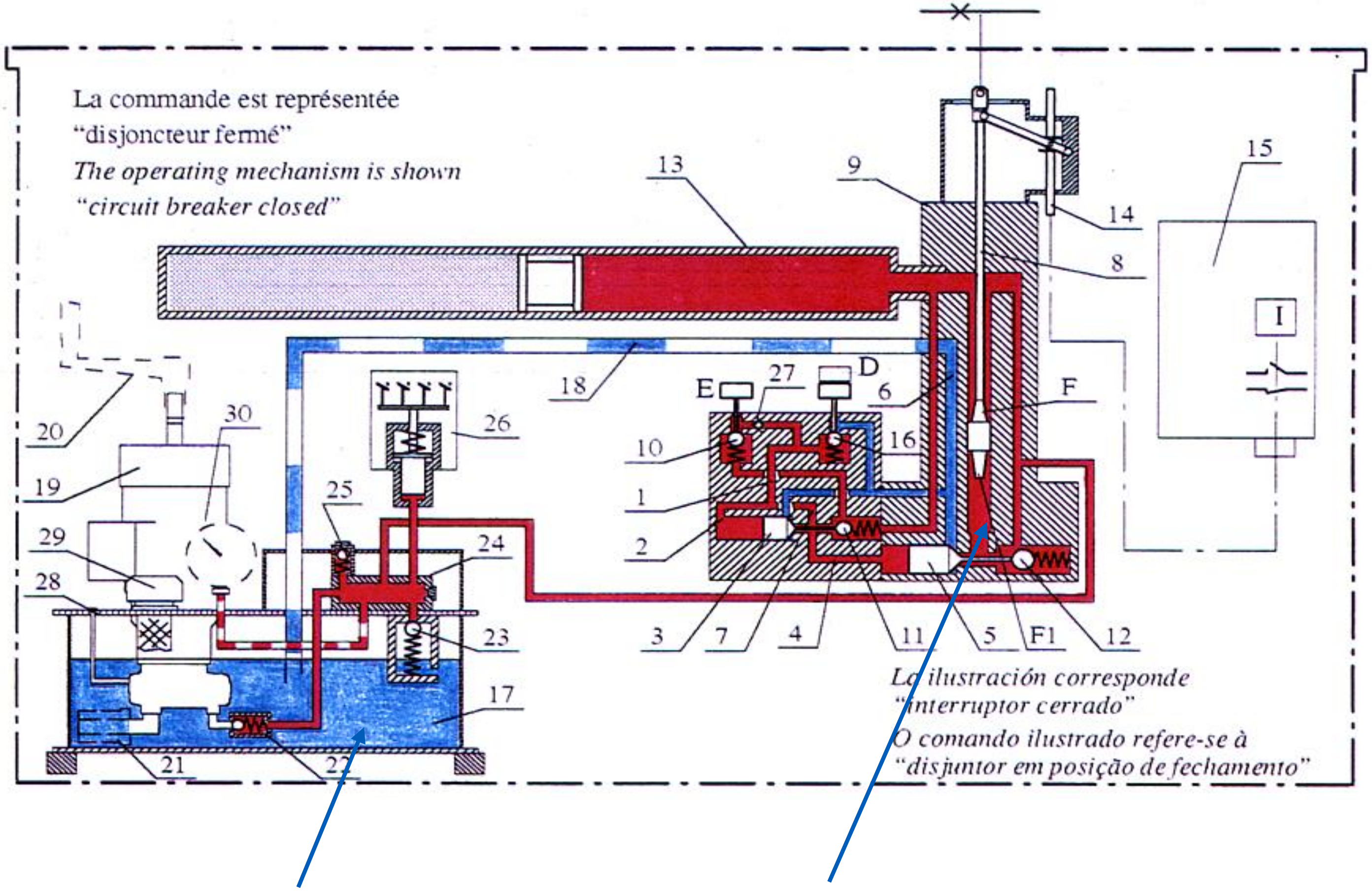
Until the mid 1980’s, hydraulic mechanisms were mainly used.

A high speed can be obtained rapidly, allowing to have more easily an interruption in 2 cycles at 60 Hz.

They can deliver high energies that for a long time were necessary to achieve high performances with Puffer type circuit breakers.

Operating Mechanism

Hydraulic Mechanism


La commande est représentée
"disjoncteur fermé"
The operating mechanism is shown
"circuit breaker closed"

Lo ilustración corresponde
"interruptor cerrado"
O comando ilustrado refere-se à
"disjuntor em posição de fechamento"

Low pressure oil

High-pressure oil: 335 bar

Operating Mechanism

Spring Mechanism

They operate now high-voltage circuit breakers up to 800 kV,

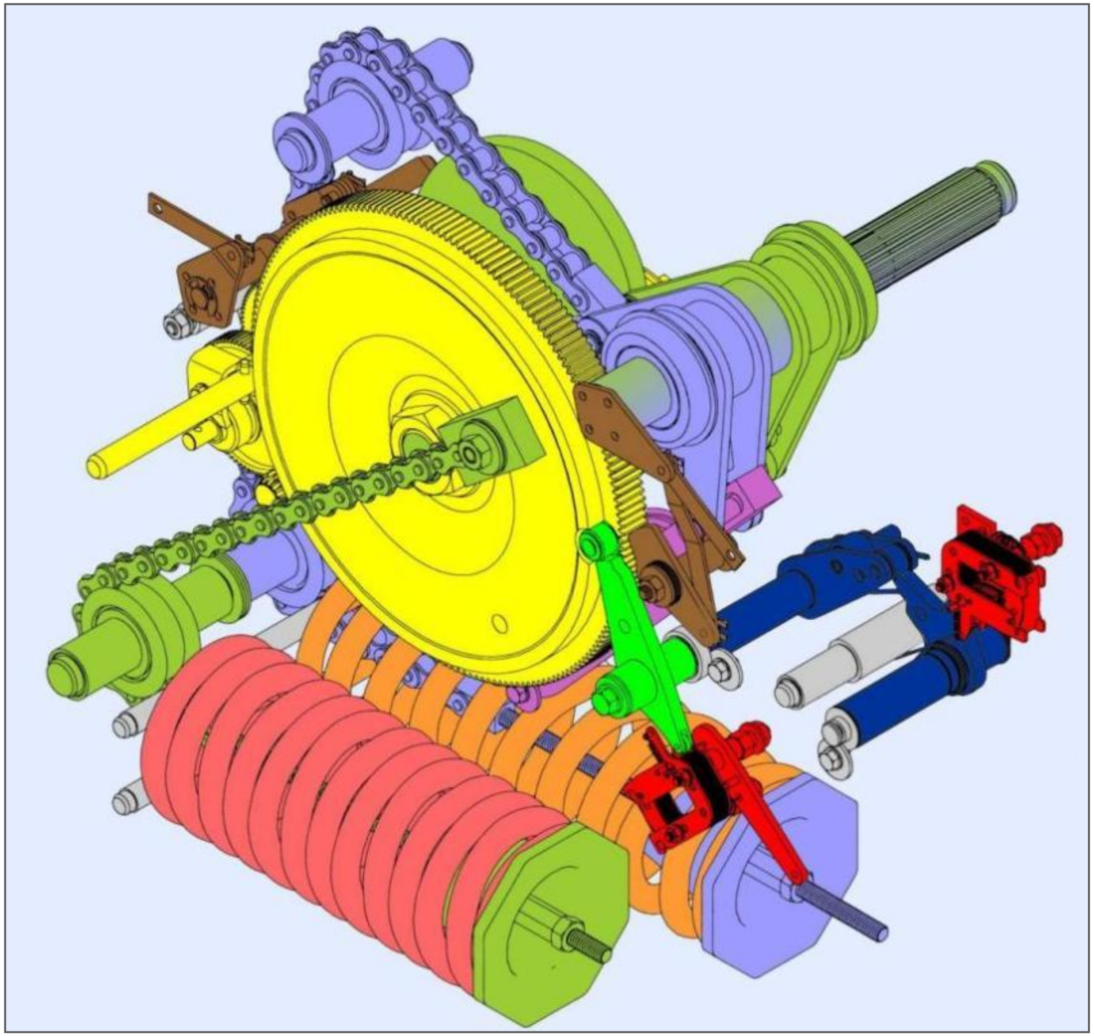
For operating energies of less than 8000 J they give the most economical solution.

Their use for high-voltage circuit breakers was possible due to

- the development of new interrupting principles that require low operating energies,
- the reduction of moving masses,
- the design of new spring-operating mechanisms.
- optimization of the linkage between poles and mechanism.

Operating Mechanism

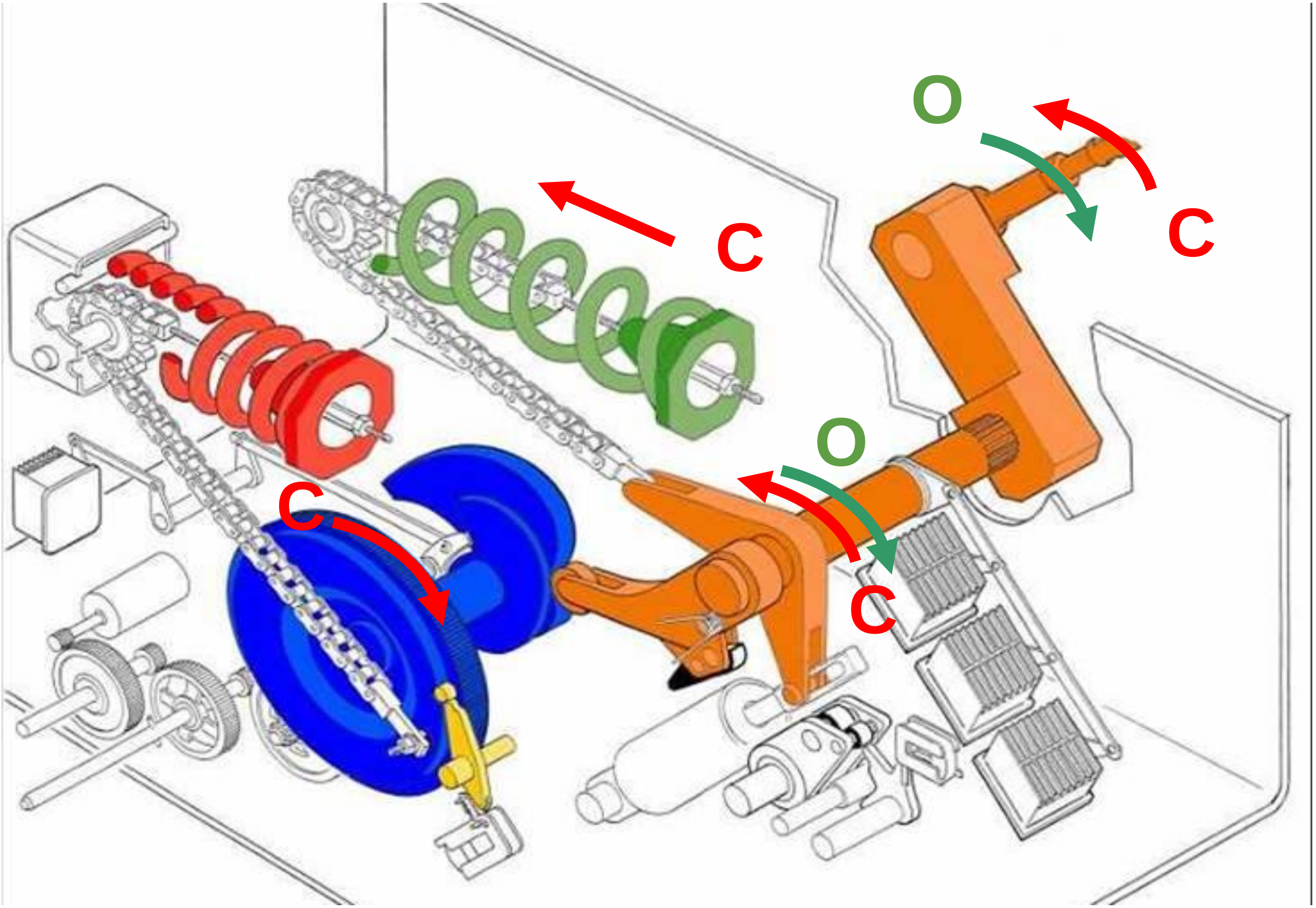
GE Spring Drive



- 🟥 closing spring
- 🟨 charging gearing
- 🟩 closing latching
- 🟩 closing system
- 🟧 trip spring
- 🟦 trip latching
- 🟪 opening system
- 🟪 opening and closing releases
- 🟫 auxiliary units

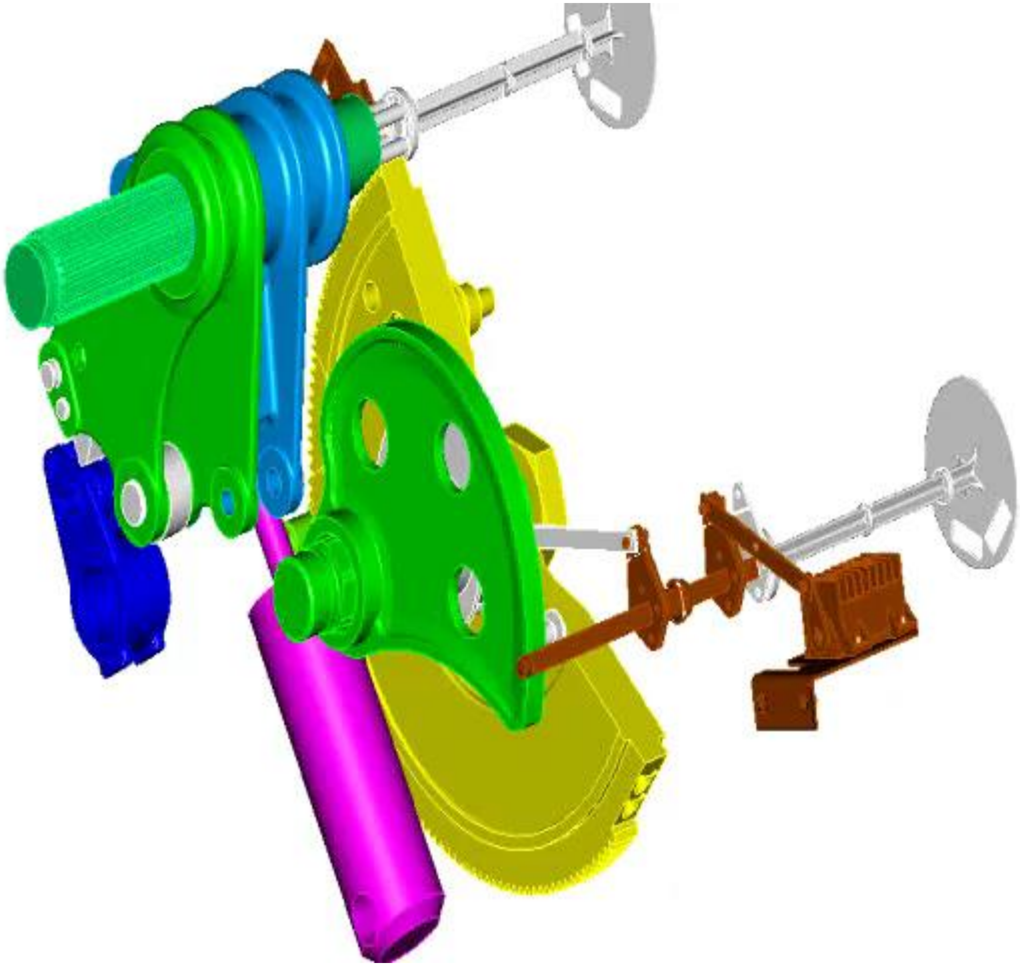
Operating Mechanism

Spring Mechanism



Operating Mechanism

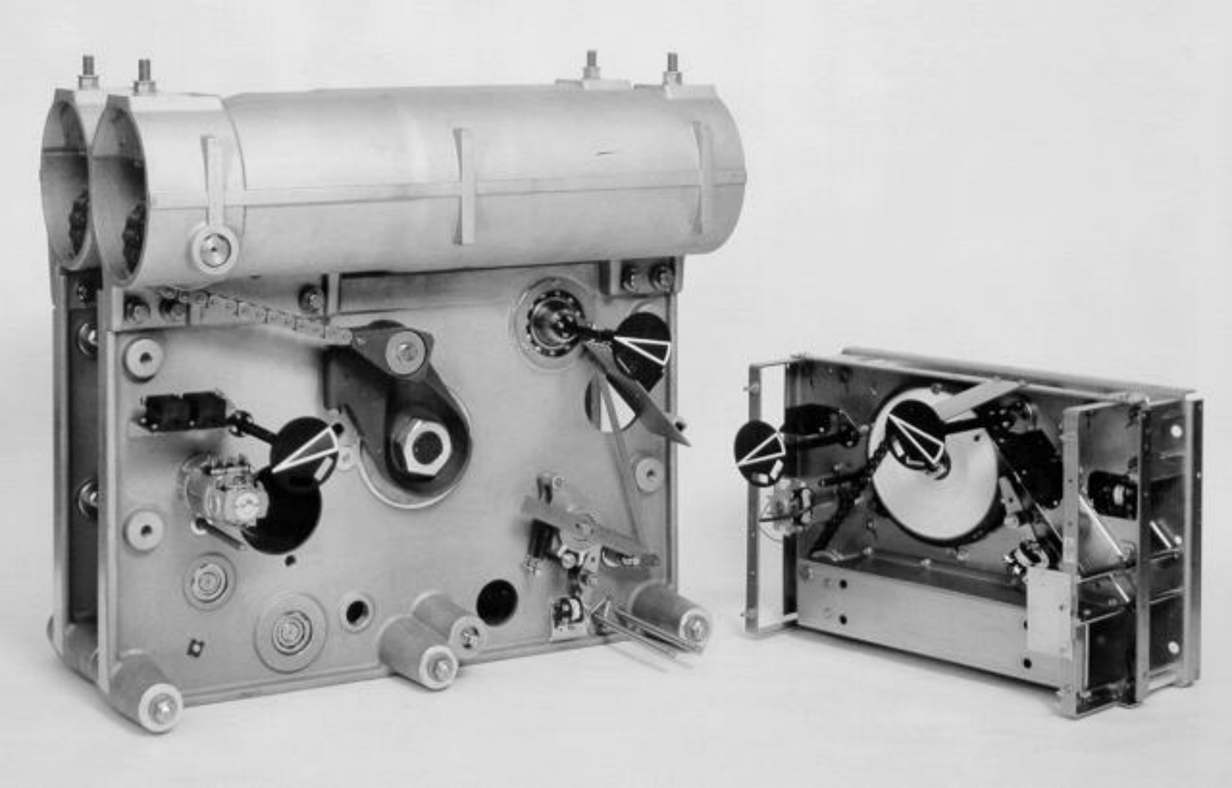
Spring Mechanism



Operating Mechanism

Spring Mechanism

FK range: 600 to 12000 Joules



Operating Mechanism

Reliability

The mechanism of a circuit breaker is responsible for

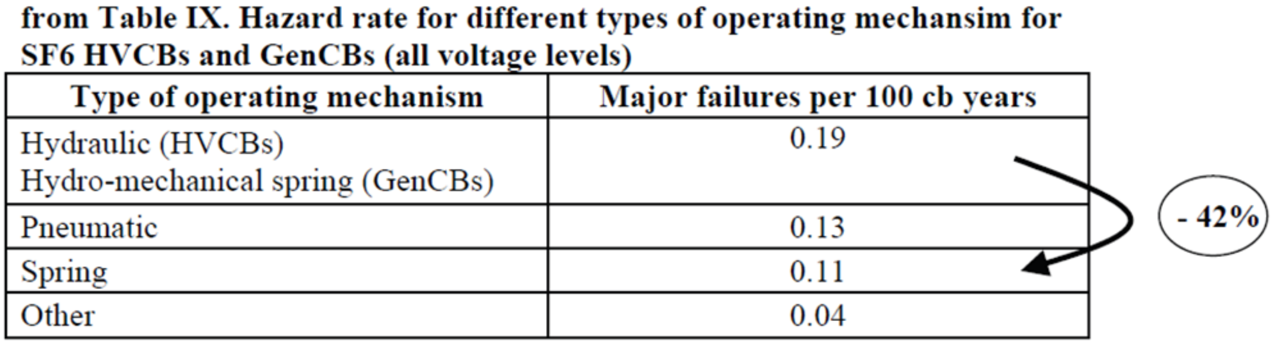
43 % of major outages

44 % of minor outages

Source: CIGRE 1994: 13-202 Second survey on reliability of CB.

The reliability of a circuit breaker depends mainly on the reliability of its mechanism.

A CIGRE study of 2012 has shown that the spring-operating mechanism has the highest reliability.



from Table IX. Hazard rate for different types of operating mechansim for SF6 HVCBs and GenCBs (all voltage levels)

Type of operating mechanism	Major failures per 100 cb years
Hydraulic (HVCBs) Hydro-mechanical spring (GenCBs)	0.19
Pneumatic	0.13
Spring	0.11
Other	0.04

AC High-Voltage Circuit Breakers

Everything you wanted to know about ac high-voltage circuit breakers but were afraid to ask

IEEE Switchgear Committee
Portland (Maine, USA), October 2017

Denis Dufournet
IEEE Fellow
Consultant
Sathonay-Camp (France)

Part 2

Content

Arcing Phenomena in HV Circuit Breakers

Current interruption in a high-voltage circuit breaker is obtained by separating two contacts in an insulating medium (air, oil, SF_6, mixtures of SF_6 with CF_4 or N_2 , vacuum).

When a circuit breaker is opened in a circuit where current is flowing, current is carried through an electric arc after contacts separation.

An electric arc is made up by a flux of electrons and a flux of ions which circulate in opposite directions between anode and cathode.

When the arc temperature decreases, ions and electrons recombine and the medium resumes its isolating properties.

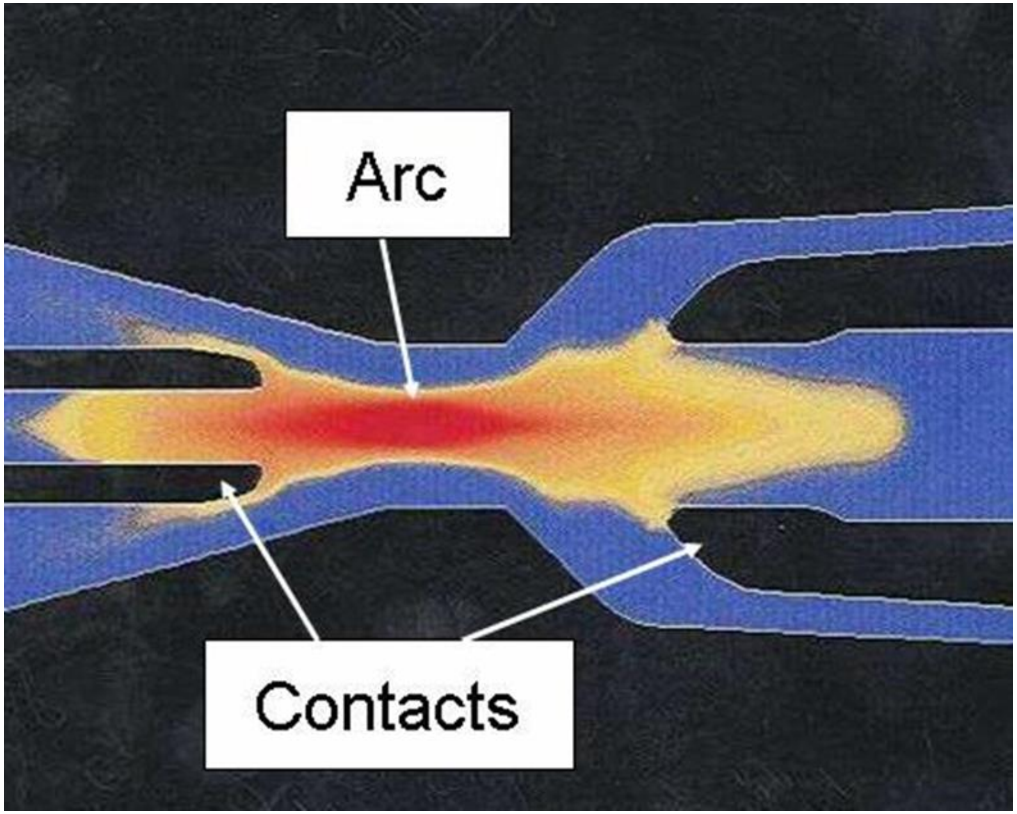
The arc core that has a very high temperature of 20 000 K to 25 000 K.

In a gas circuit breaker, a gaseous mantle surrounds the arc core. Its temperature decreases as the distance from the arc axis is increased.

Current is interrupted when an efficient blast is applied to cool the arc and extinguish it.

Arcing Phenomena in HV Circuit Breakers

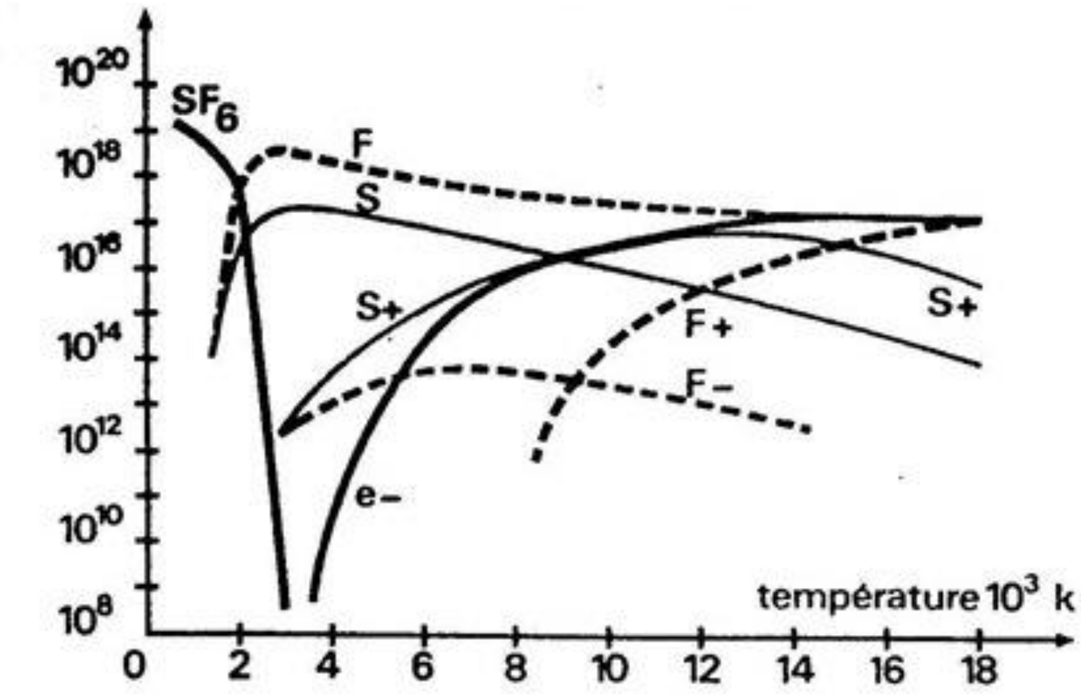
Temperature field between arcing contacts



The highest temperature (in red) is at the core of the arc

Arcing Phenomena in HV Circuit Breakers

SF_6 Circuit Breakers: when temperature decreases, due to cooling by the blast, electrons are attached to fluorine and the medium recovers its isolating properties.



Number of particles per cm^3 as function of temperature

Arcing Phenomena in HV Circuit Breakers

SF_6 Circuit Breakers: composition of SF_6 as function of temperature

Density of SF_6 decreases rapidly when temperature is higher than 1800 K.

Dielectric withstand decreases in the same way.

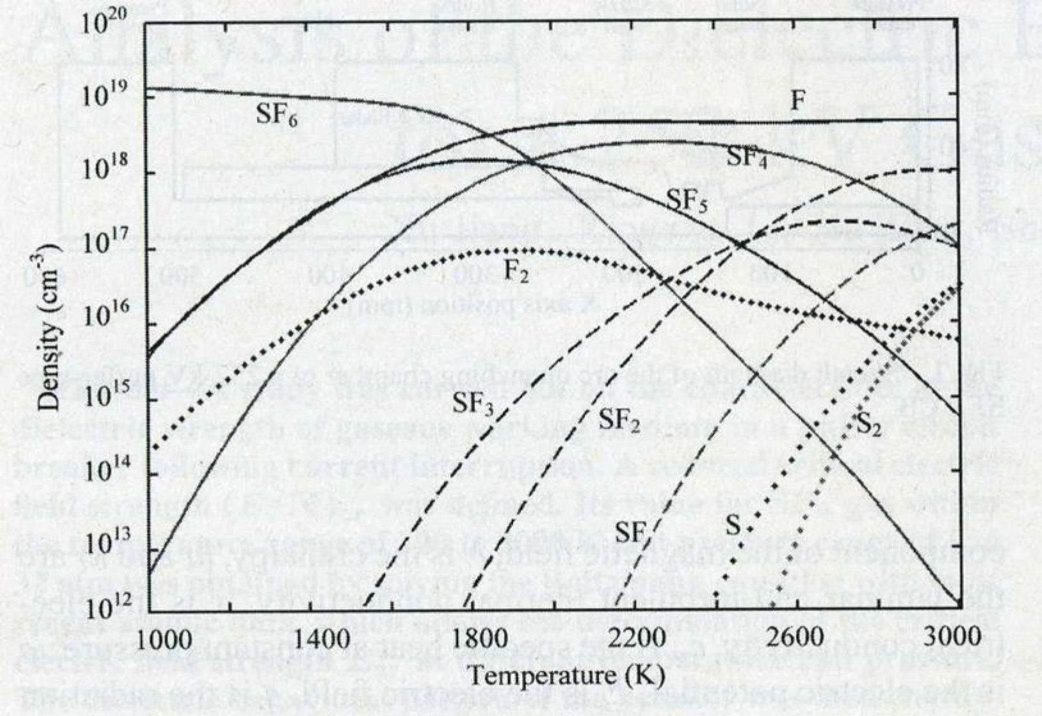


Fig. 2. Composition of SF_6 as a function of gas temperature at pressure 4 atm.

Arcing Phenomena in HV Circuit Breakers

AC circuit-breakers interrupt short-circuit currents at current zero because at this instant the input power from the system is zero ($U_{arc} \times I = 0$),

At current zero, it is possible to cool efficiently the arc so that its temperature decreases rapidly and the interval between contacts becomes non conductive.

Current interruption is successful if afterwards the withstand voltage between contacts is always higher than the recovery voltage applied by the system.

Arcing Phenomena in HV Circuit Breakers

Thermal Restrike

- If the gas blast is not sufficient, the input power in the arc (arc voltage U_{arc} multiplied by current) is higher than the power dissipated (P), therefore the arc resistance decreases and the interval between contacts stays conductive.
- Voltage between contacts does not exceed a few kilovolts before restrike. The restrike is said to be a thermal restrike.
- Black Box Arc Model

$$\frac{dR_{arc}}{dt} = \frac{R_{arc}}{\Theta} \times \left(1 - \frac{U_{arc} \times I}{P}\right)$$

R_{arc} = arc resistance P = dissipated power Θ = arc time constant

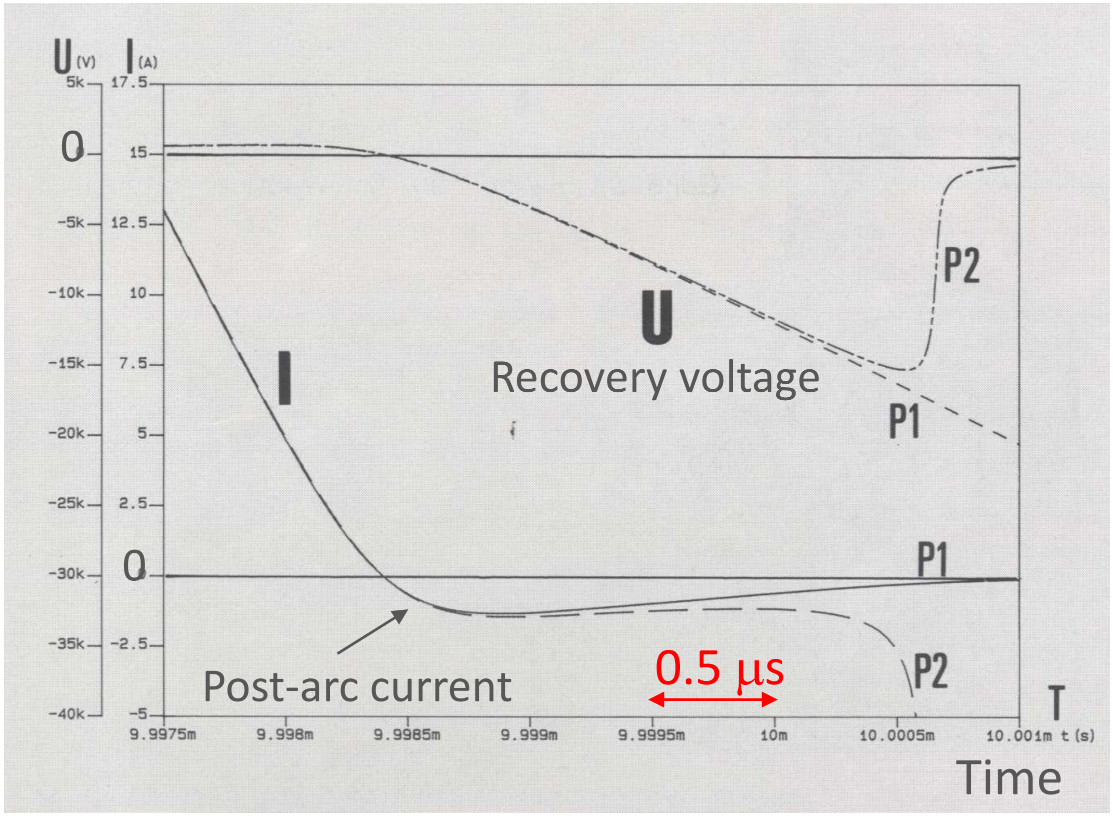
U_{arc} = arc voltage I = current

If P is higher than U_{arc} x I: R_{arc} increases

If P is less than U_{arc} x I: R_{arc} decreases

Arcing Phenomena in HV Circuit Breakers

Evolution of current and voltage near current zero



Simulation of short-line fault interruption

Power loss (or dissipated power) $P = P1$ leads to a successful interruption

Lower value of $P = P2$ leads to a thermal restrike

Arcing Phenomena in HV Circuit Breakers

Evolution of current and arc resistance after current zero

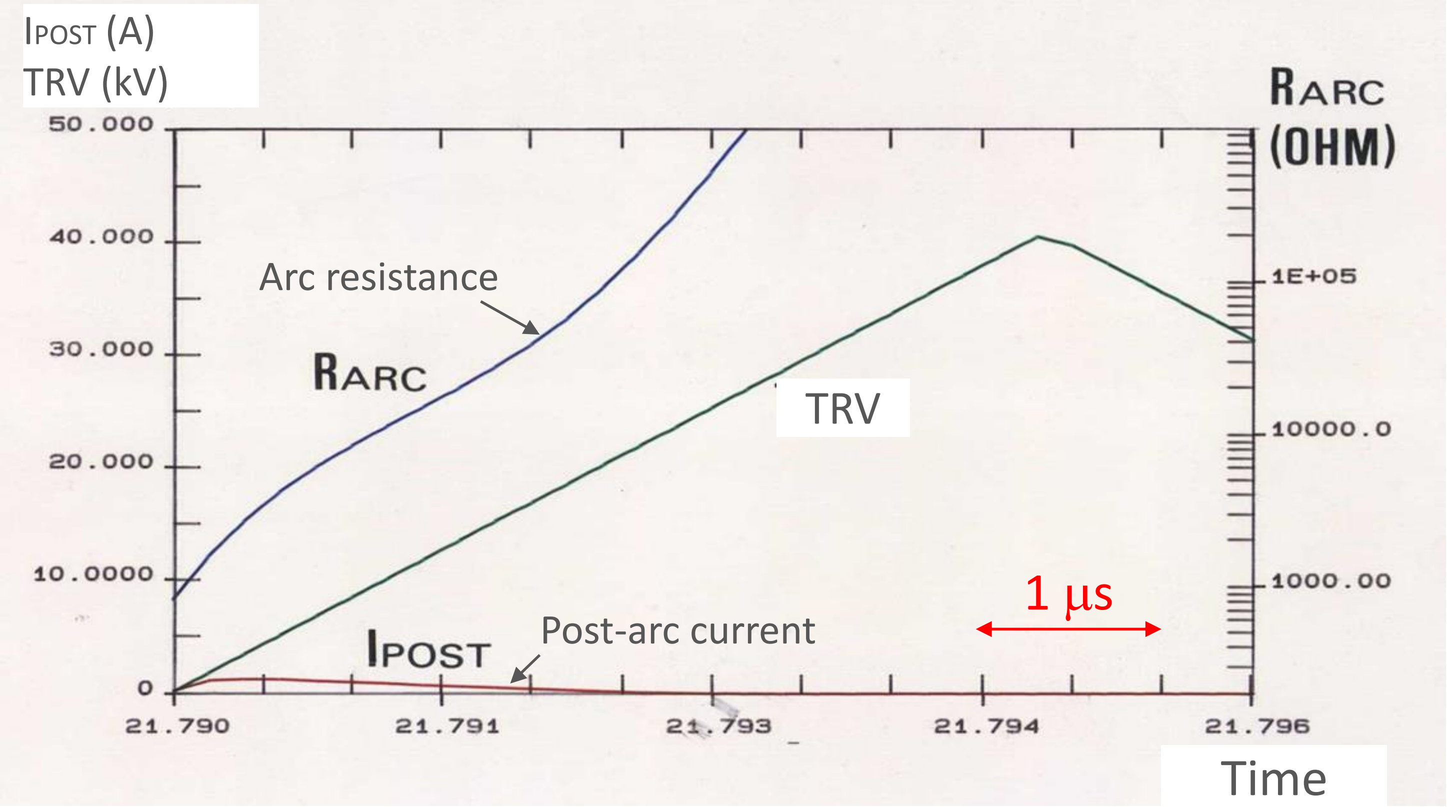


Illustration of a successful short-line fault current interruption

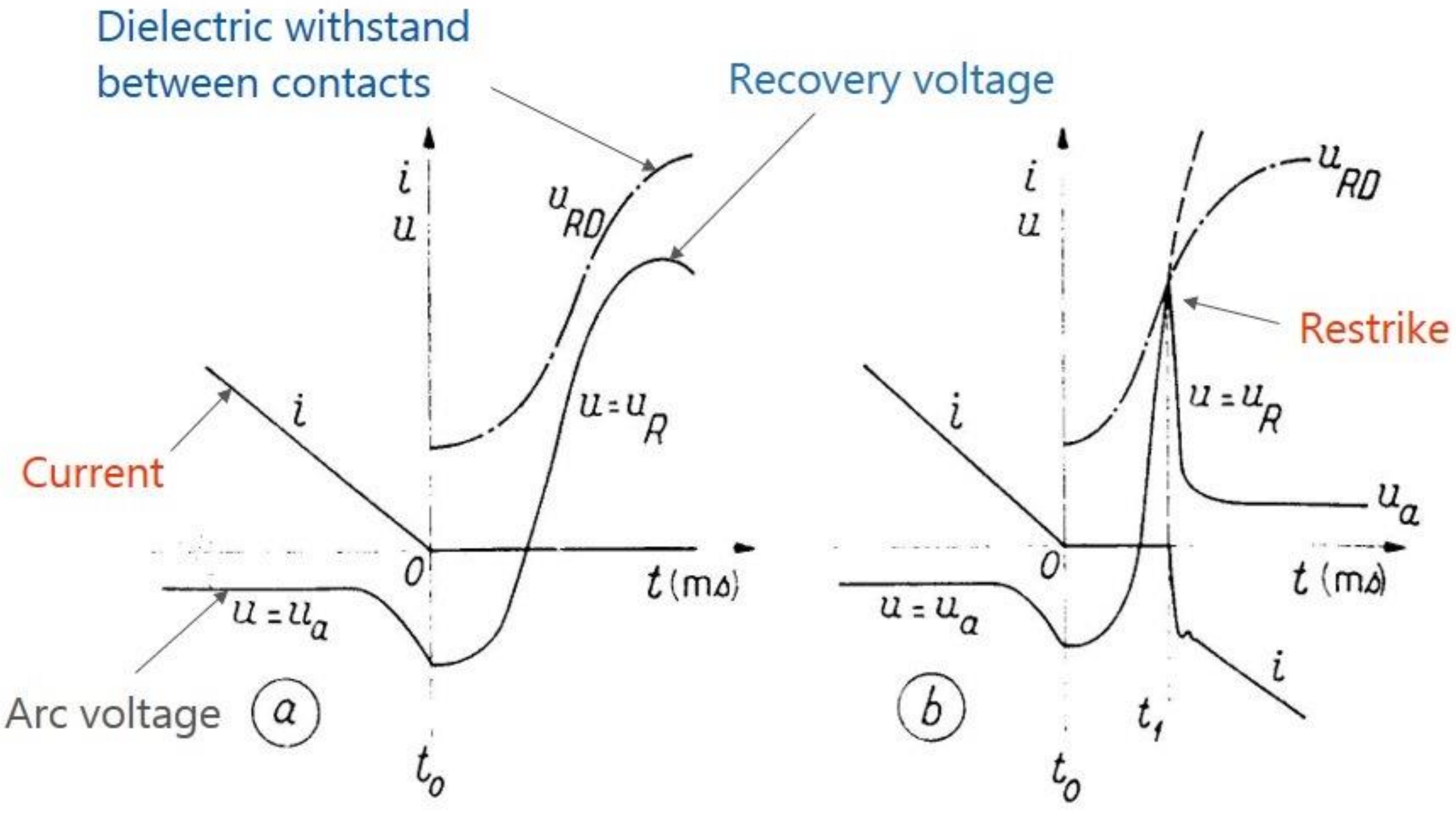
Arcing Phenomena in HV Circuit Breakers

Dielectric Restrike

- If the voltage withstand between contacts is lower than the recovery voltage from the network, there is a restrike, the arc is re-established and current flows again in the circuit.
- This restrike is called a dielectric restrike.
- The circuit-breaker can then try to interrupt at the next current zero.
- This type of restrike can happen tens or hundreds of micro-seconds after current interruption.

Arcing Phenomena in HV Circuit Breakers

Dielectric Restrike



Dielectric withstand between contacts

Recovery voltage

Current

Arc voltage

Restrike

Successful interruption

Dielectric restrike

Arcing Phenomena in HV Circuit Breakers

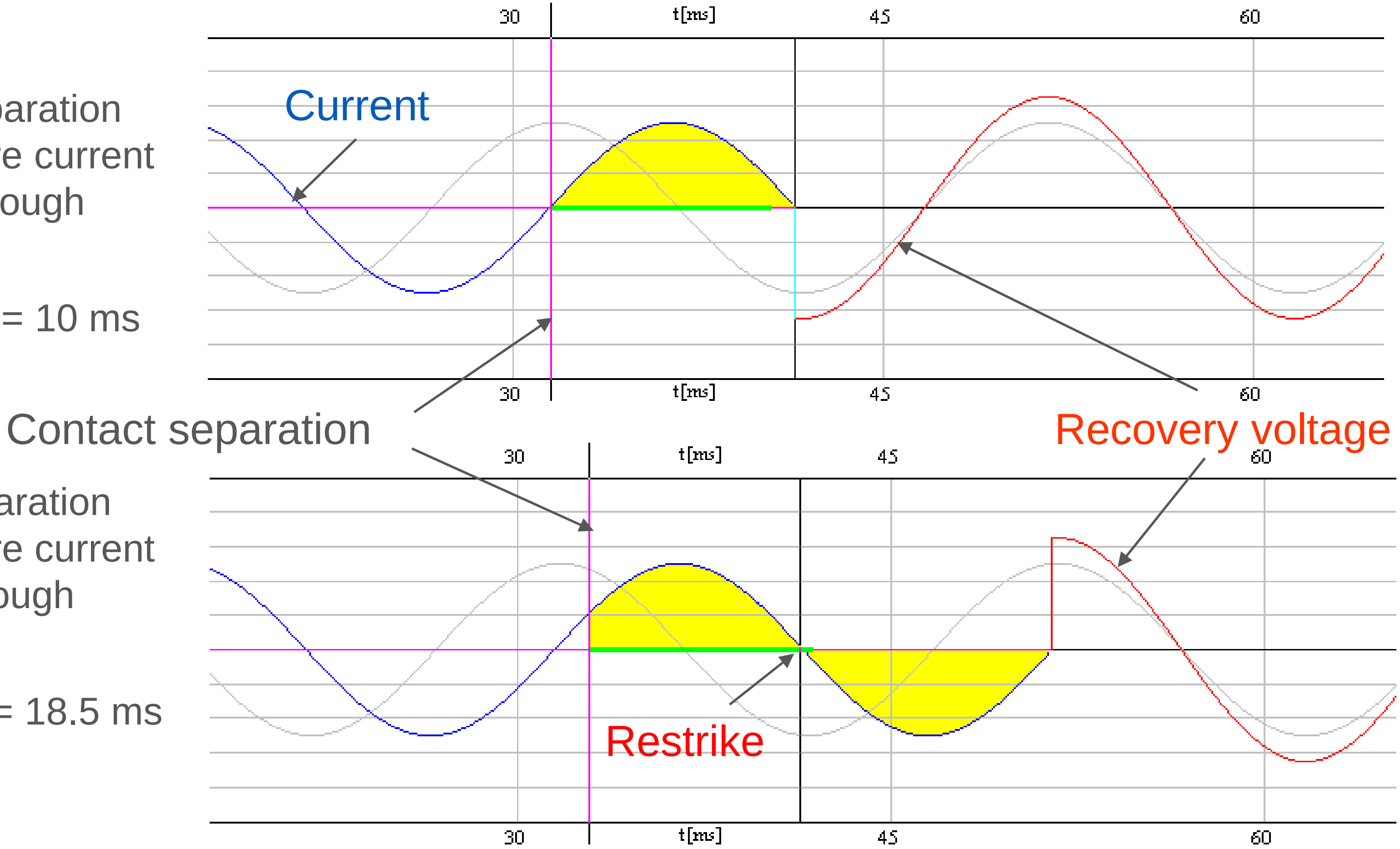
Example - Circuit breaker with minimum arcing time = 9 ms

Contact separation 10 ms before current passage through zero:

Arcing time = 10 ms

Contact separation 8.5 ms before current passage through zero:

Arcing time = 18.5 ms



Example with power frequency = 50 Hz

Arcing Phenomena in HV Circuit Breakers

Reignition - Restrike

- Reignition

Resumption of current between the contacts of a circuit breaker during a breaking operation with an interval of zero current of less than a 1/4 cycle of power frequency.

- Restrike

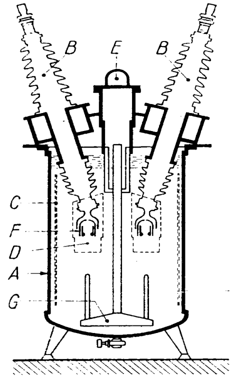
Resumption of current between the contacts of a mechanical switching device during a breaking operation with an interval of zero current of a 1/4 cycle of power frequency or longer.

Content

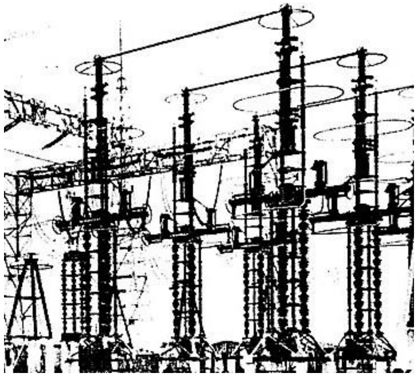
Arc Extinction Principles

Air

Oil



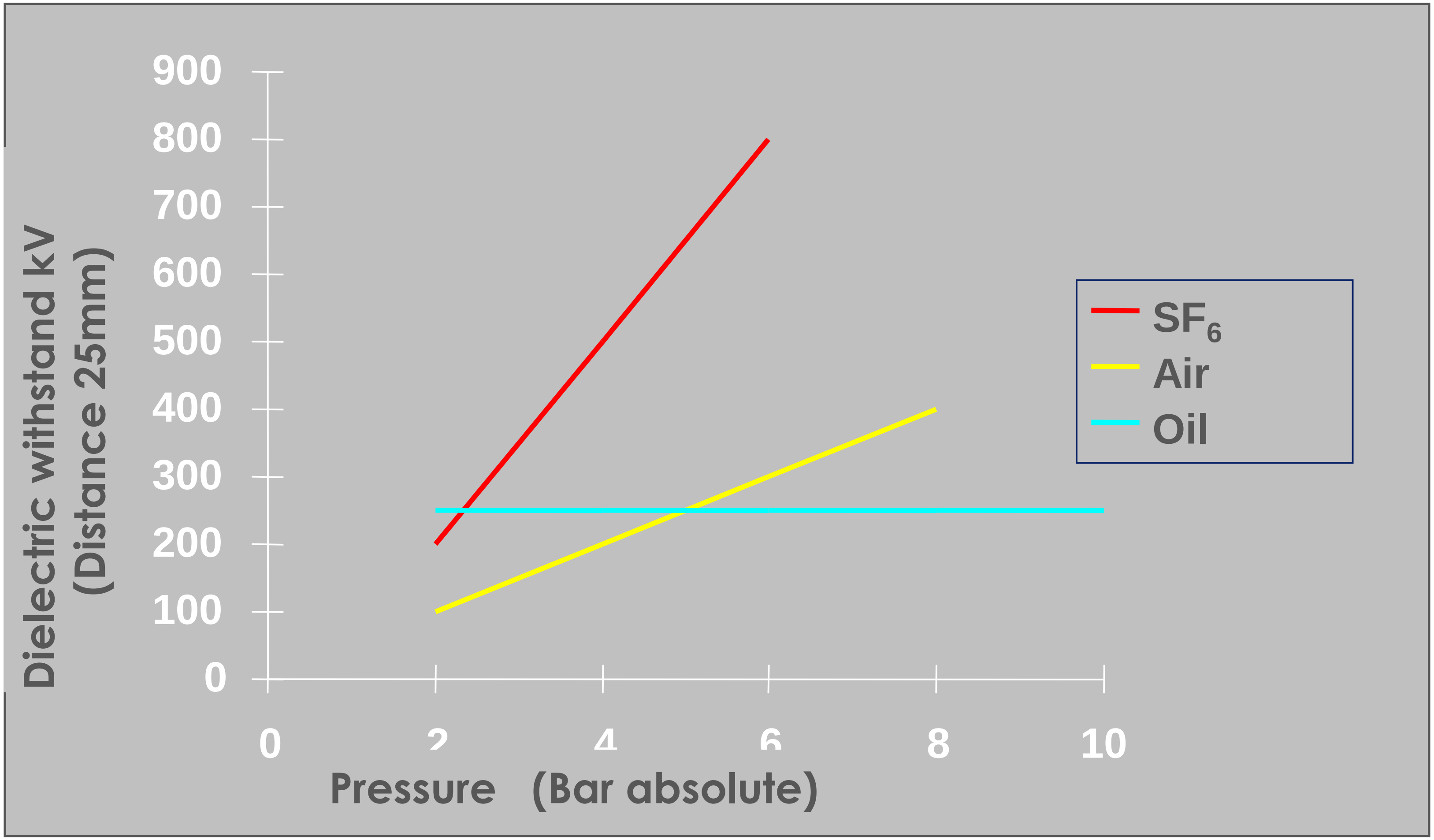
Air blast



SF_6

Vacuum

Arc Extinction Principles



Arc Extinction Principles

SF_6 Circuit Breaker

The use of SF_6 for insulation was patented by Franklin Cooper (General Electric) in 1938.

First high-voltage circuit breaker with high rated short-circuit current in 1959 by Westinghouse: 41.8 kA under 138 kV and 37.6 kA under 230 kV.

This three-phase circuit breaker of the Dead tank type had 3 interrupting chambers in series per pole

- SF_6 pressure of 13.5 bar rel. for interruption
- SF_6 pressure of 3 bar for insulation.

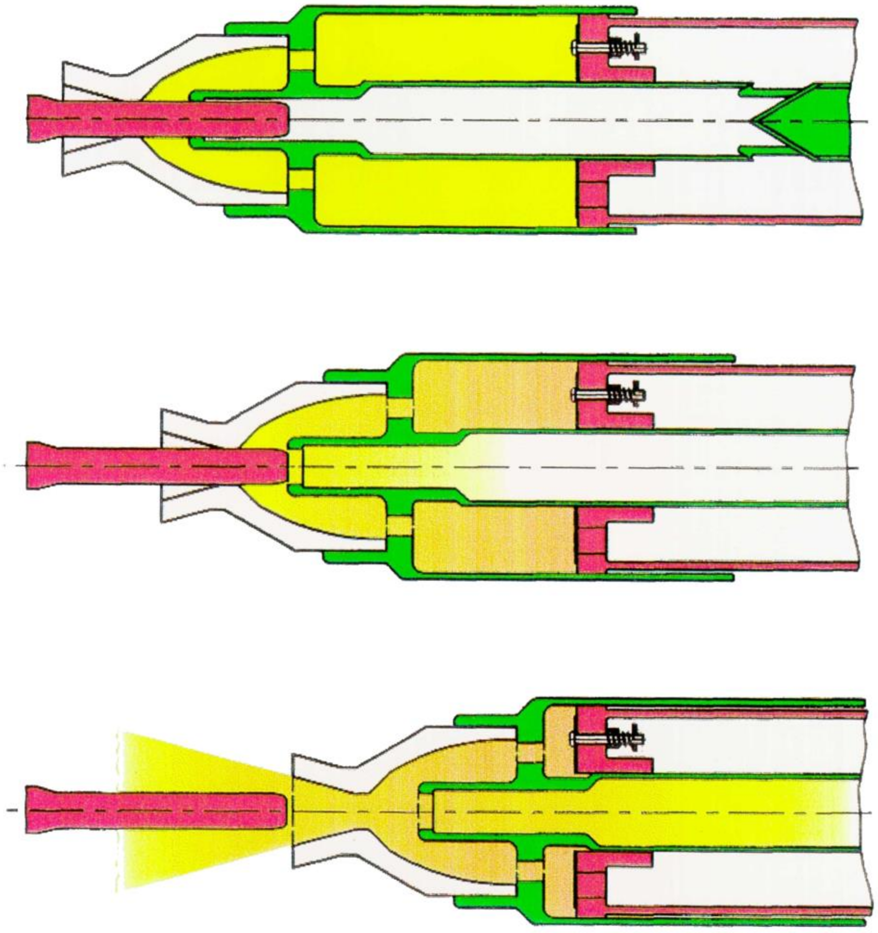
It is called a double (or dual) pressure circuit breaker.

Drawbacks of this technique: need of a compressor, risk of liquefaction of SF_6 at temperatures lower than -5°C.

More simple and efficient designs were developed in the 1960’s: puffer circuit breakers.

Arc Extinction Principles

Puffer Circuit Breaker



Closed position

Gas is compressed when the moving part (in green) moves toward the open position

After contacts separation, an arc is established between contacts.

Arc is cooled by the blast produced by the pressure differential between the puffer cylinder and the downstream region

Arc Extinction Principles

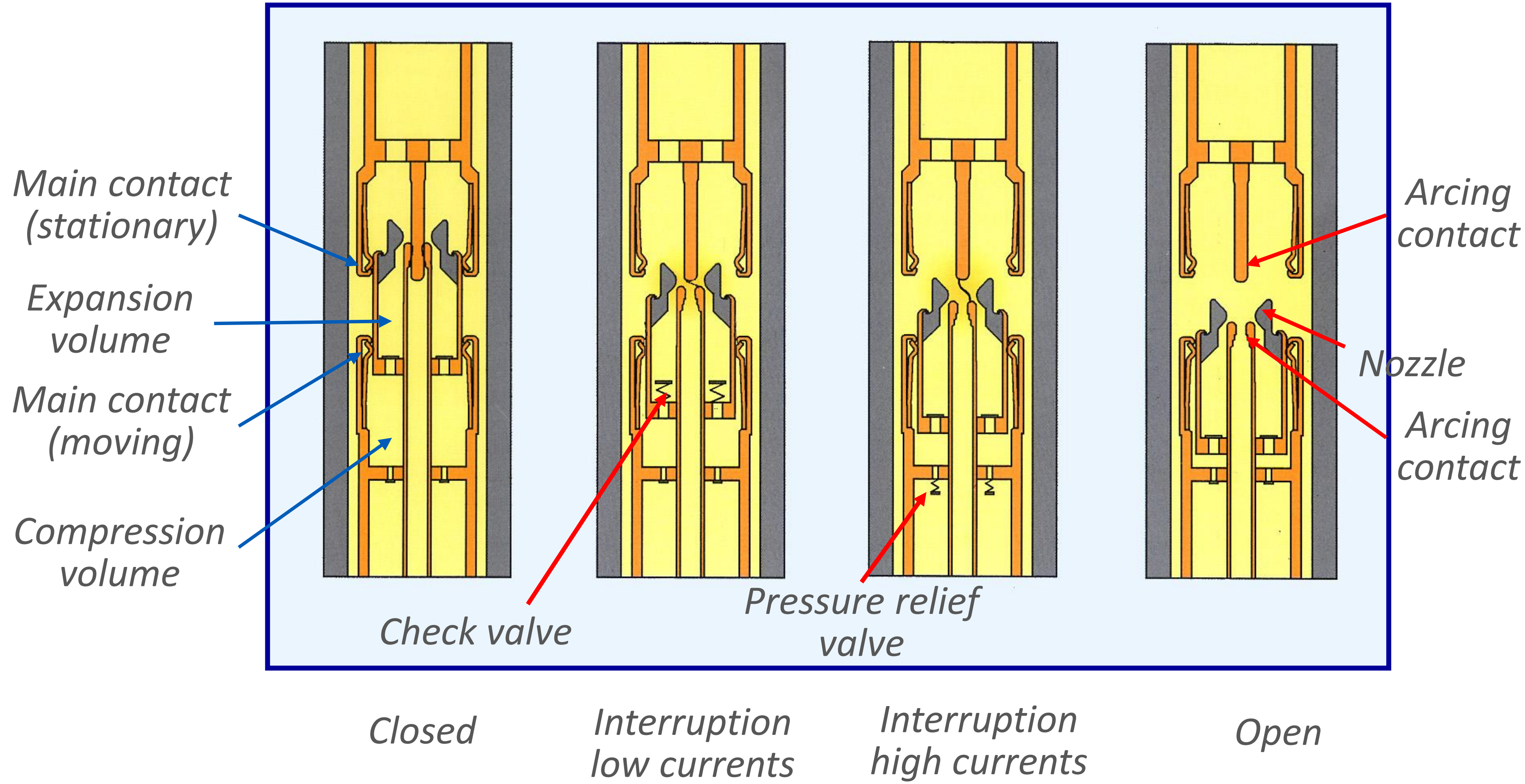
Puffer Circuit Breaker

Several characteristics of SF_6 circuit breakers can explain their success:

- The simplicity of the interrupting chamber which does not necessitate an auxiliary chamber to assist current interruption ;
- The autonomy brought about by the pressure puffer technique (no gas compressor) ;
- The possibility of obtaining the highest performances, up to 63 kA, with a reduced number of interrupting chambers: a single chamber is necessary at 245 kV to interrupt 50 kA, one or two at 420 kV, two at 550 kV and four at 800kV ;
- A short break time of 2 or 2.5 cycles ;
- A high electrical endurance that allows at least 25 years in service life.

Arc Extinction Principles

Self Blast Circuit Breaker



Arc Extinction Principles

Self Blast Circuit Breaker

Low current interruption

Gas is compressed in the compression volume.

As the pressure is higher in the compression volume, the check valve between the two volumes is opened.

Arc quenching by compressed gas as in a puffer circuit breaker.

High current interruption

A high pressure is generated by gas heating in the thermal volume.

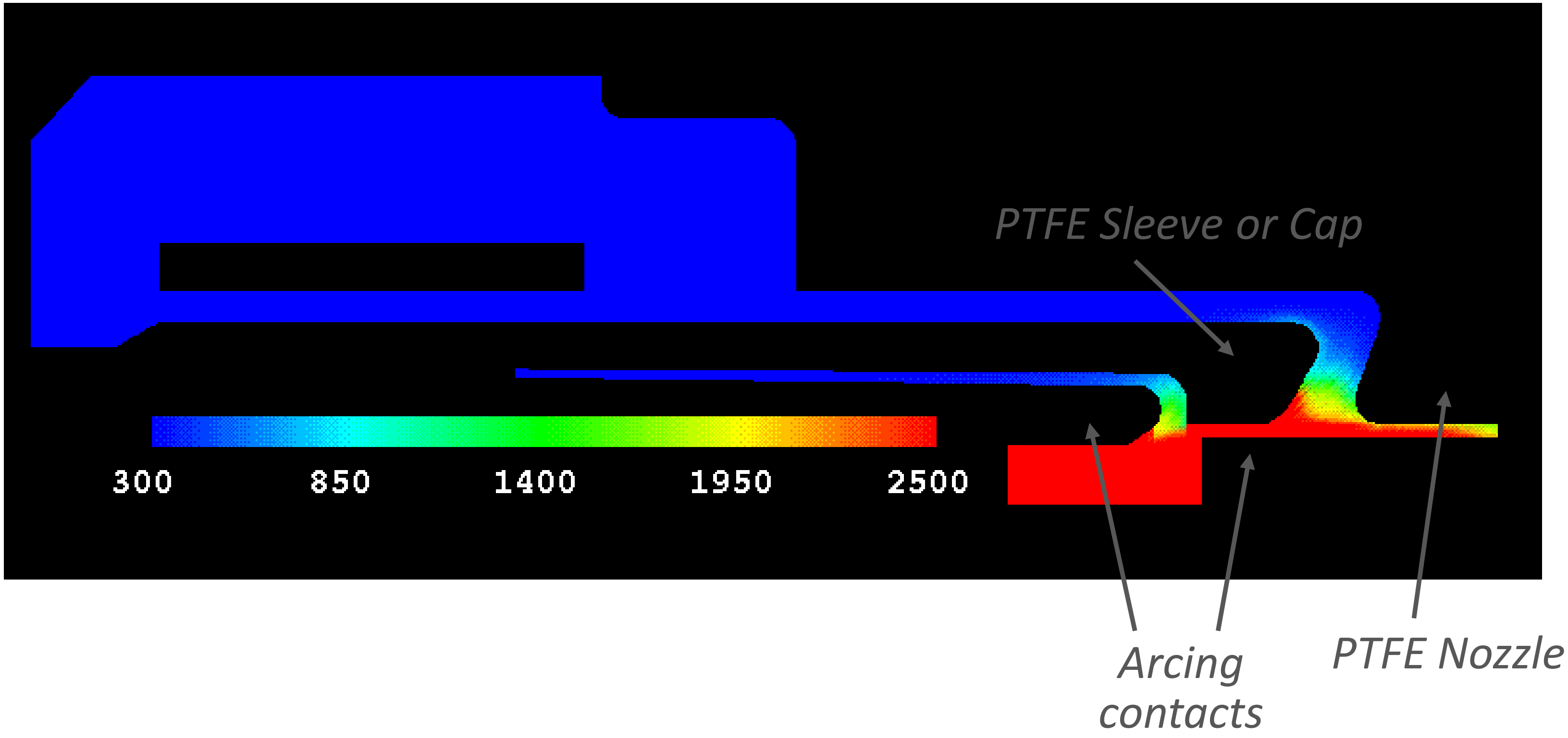
The valve between thermal and compression volumes is closed.

Arc quenching by thermal blast.

A pressure relief valve fitted on the piston limits the pressure in the compression volume.

Arc Extinction Principles

Self Blast Circuit Breaker – Gas flow simulation



PTFE Sleeve or Cap

Arcing contacts

PTFE Nozzle

Temperature field in arcing region and expansion volume during high current interruption - Simulation by CFD code

CFD = Computational Fluid Dynamics

Arc Extinction Principles

Self Blast Circuit Breaker

Self Blast interrupting chambers have many design parameters

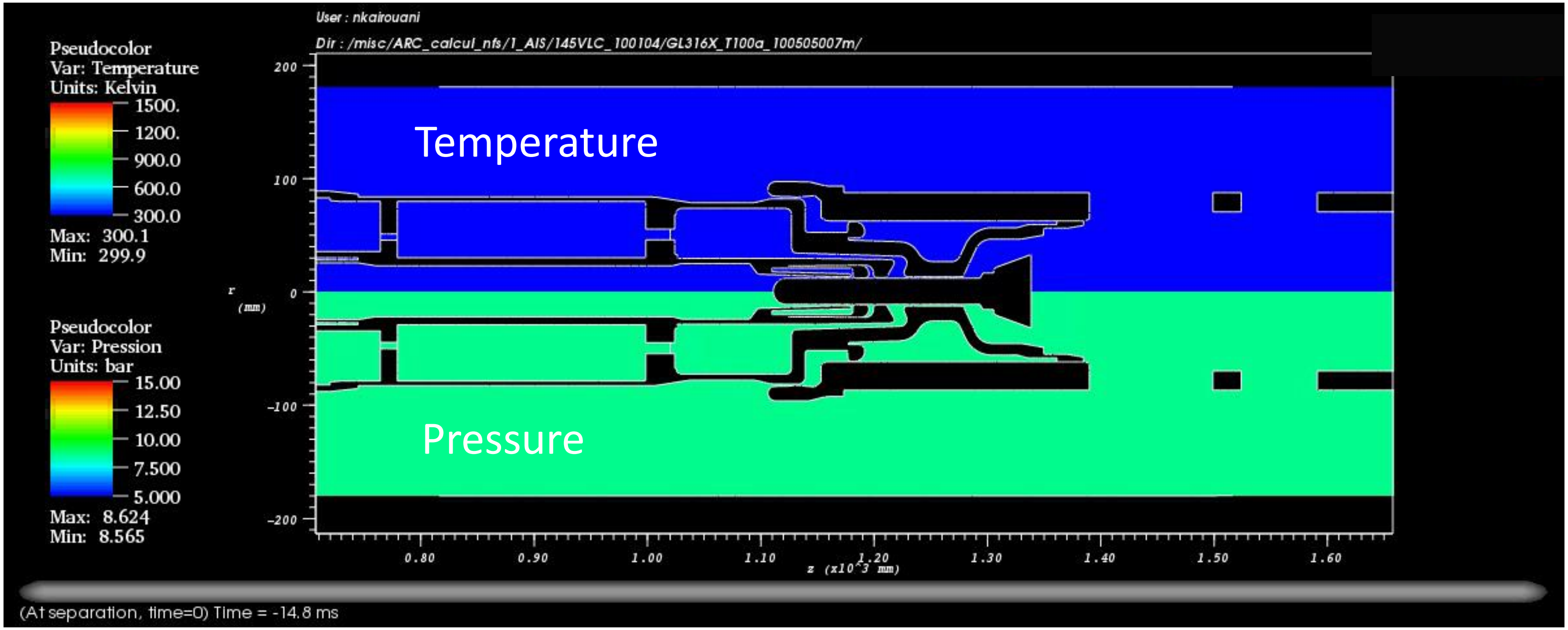
Optimized dimensioning can only be obtained through the use of software taking into account

- Arcing between contacts
- Fluid dynamics
- Interaction with mechanism
- Voltage withstand after contact separation.

GE’s codes MC3 and AMASIS were developed for this purpose.

Arc Extinction Principles

Self Blast Circuit Breaker – CFD Gas Flow Simulation

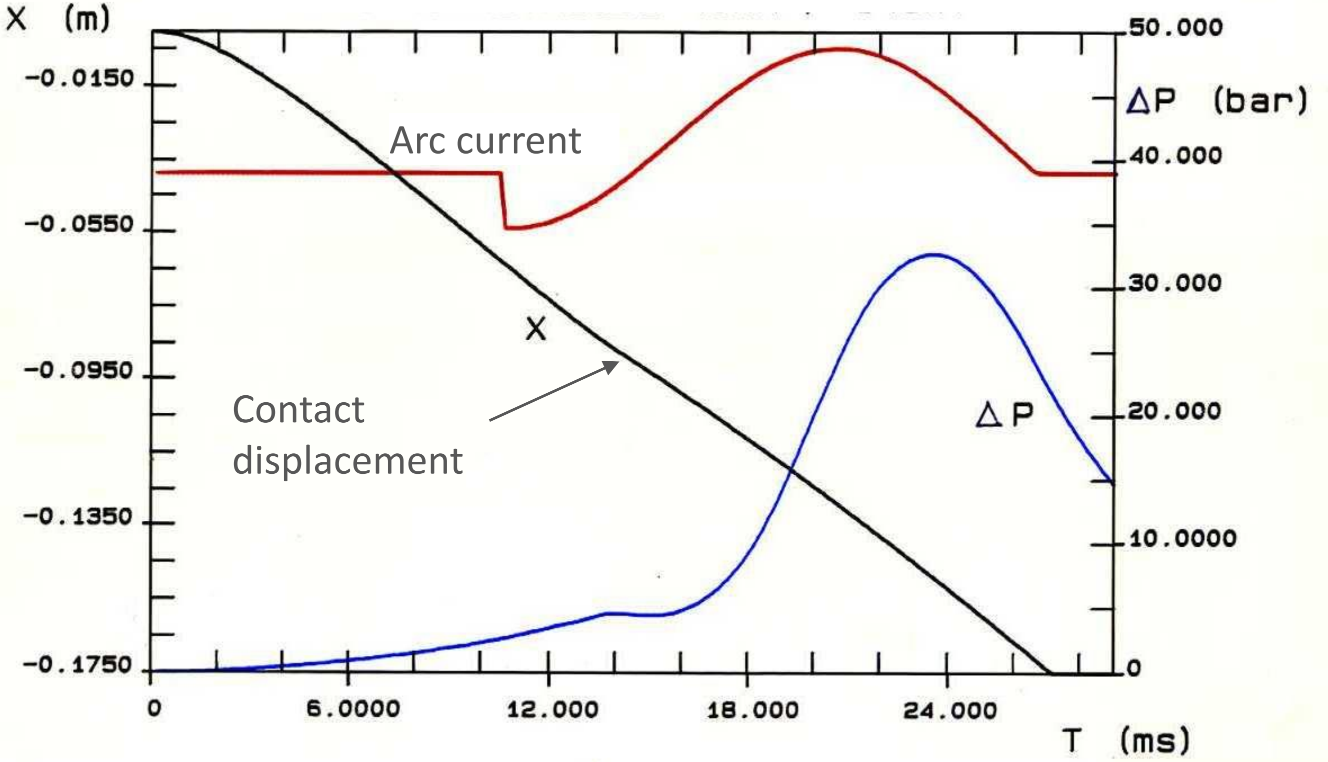


Calculation of temperature field and pressure field during a breaking operation

Arc Extinction Principles

Self Blast Circuit Breaker – 1D Simulation

Interruption of 40kA asymmetrical current by a 145kV circuit breaker

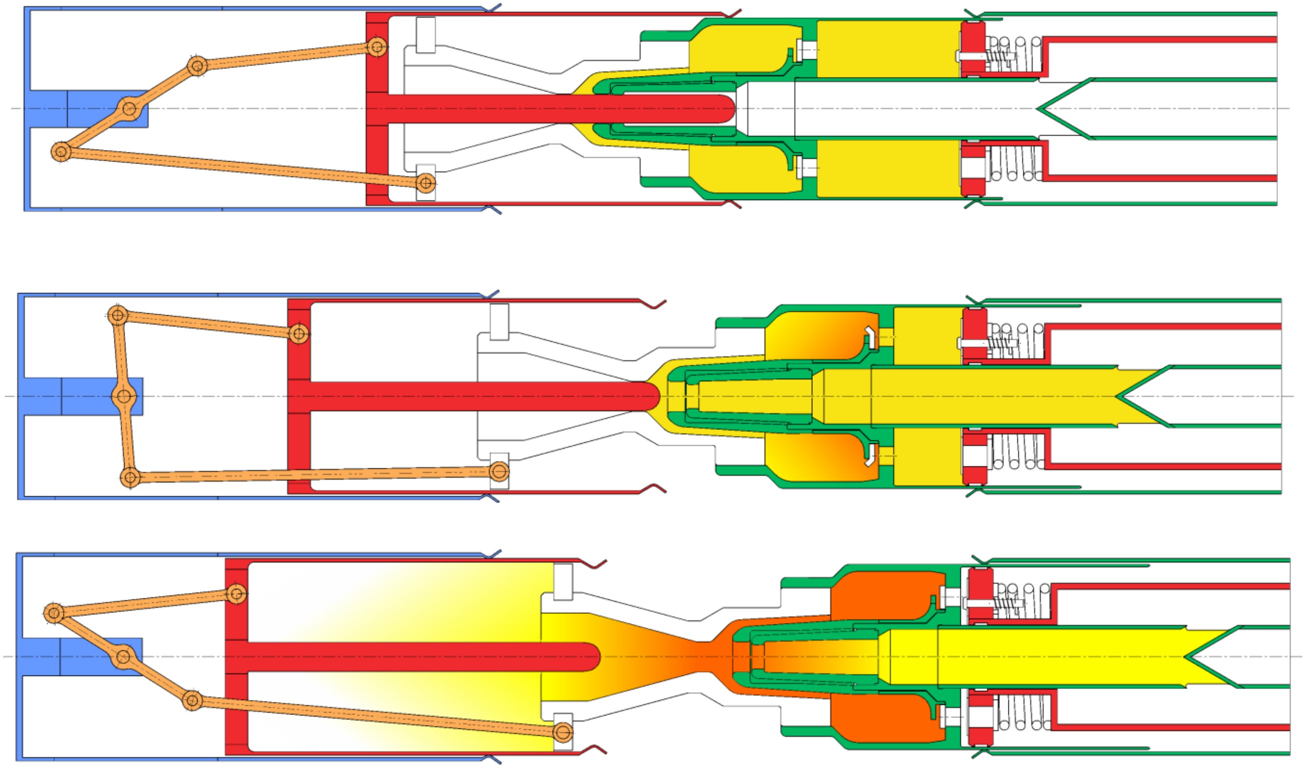


ΔP = Pressure rise in the expansion volume

Arc Extinction Principles

Self Blast Circuit Breaker

Self-blast chamber with double motion of contacts



Arcing contacts move in opposite directions.

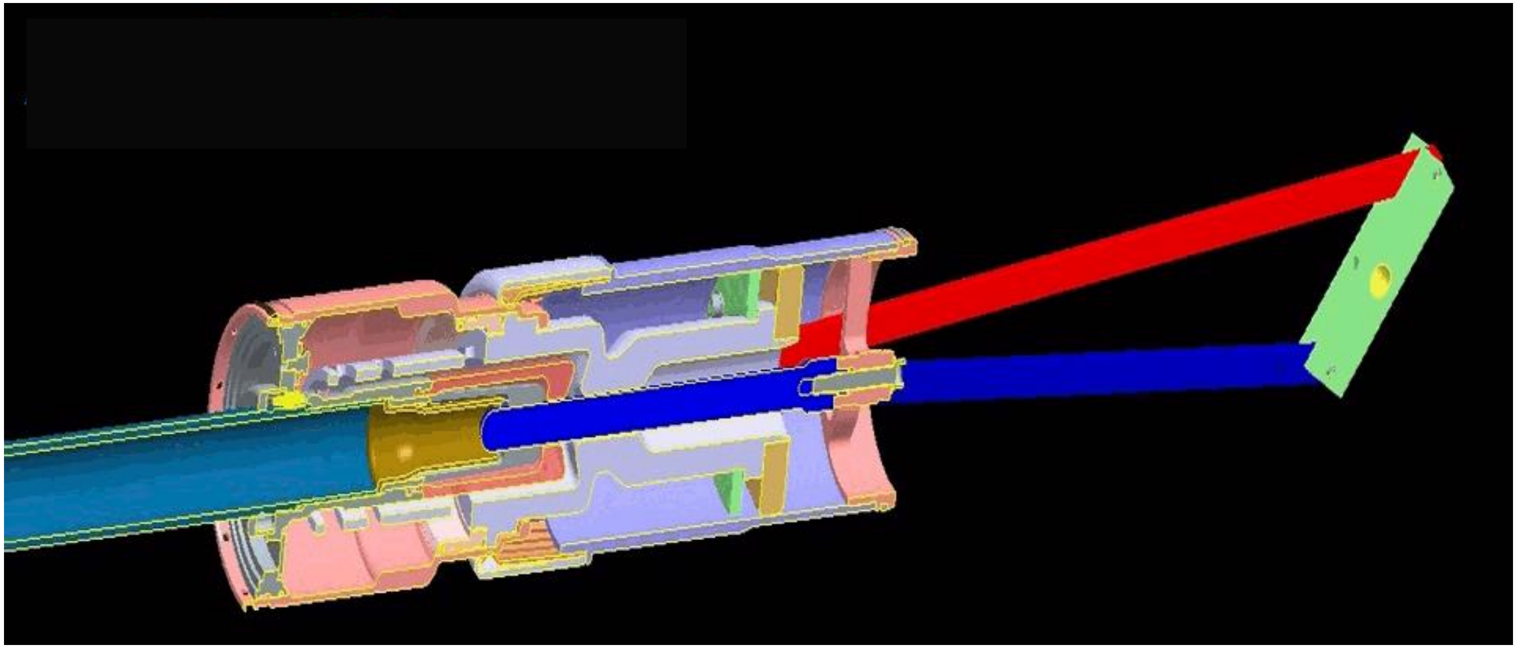
If they have the same speed, the relative speed is multiplied by two.

The necessary tripping speed is obtained with a lower operation energy.

Arc Extinction Principles

Self Blast Circuit Breaker

Self-blast chamber with double motion of contacts



[redacted]

As the speed of the moving parts is divided by two, kinetic energy of each moving part is divided by four.

Even if the total moving mass is doubled, the total kinetic energy is divided by two (compared to a solution with single motion of contacts).

Arc Extinction Principles

Self Blast Circuit Breaker

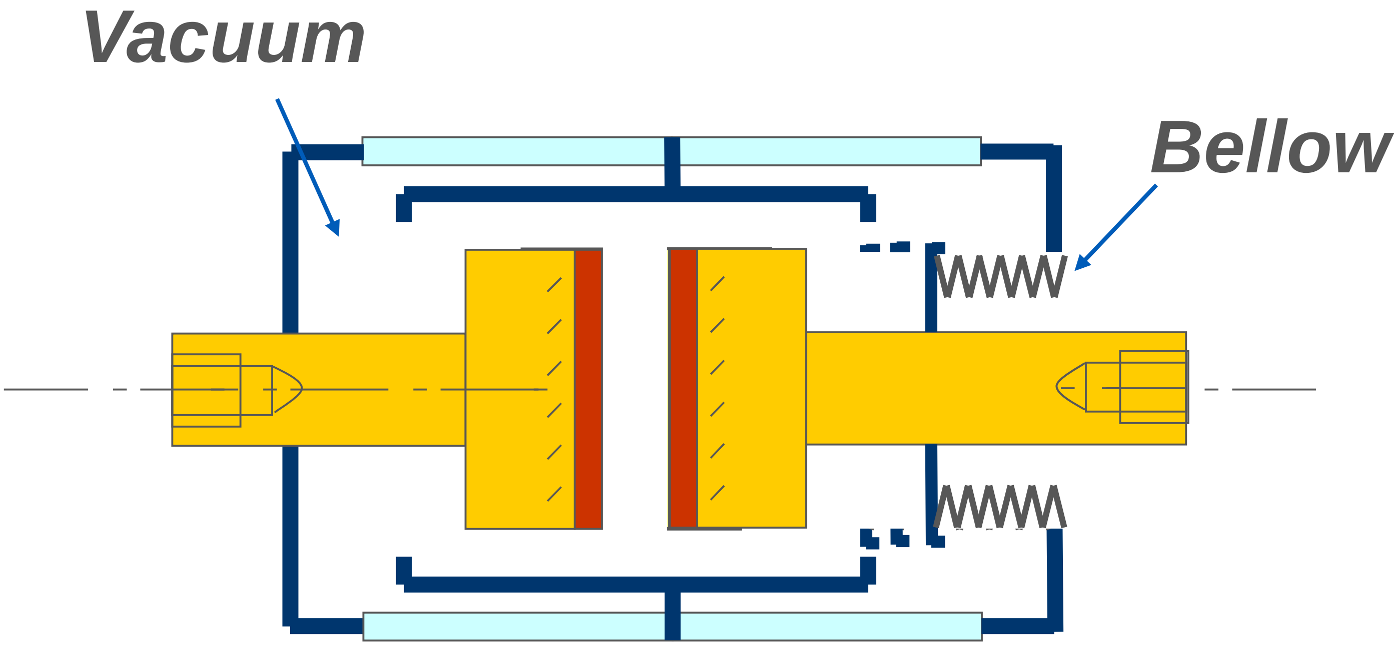
The self blast technique has allowed

- to divide by approximately **9** the energy used for gas compression,
- to use low energy spring operating mechanisms for the operation of high voltage circuit breakers.

Self blast type of circuit breakers have progressively replaced puffer types, from 72.5 kV up to 800 kV.

Arc Extinction Principles

Vacuum interrupter



Introduced in 1926 (CalTech-USA)

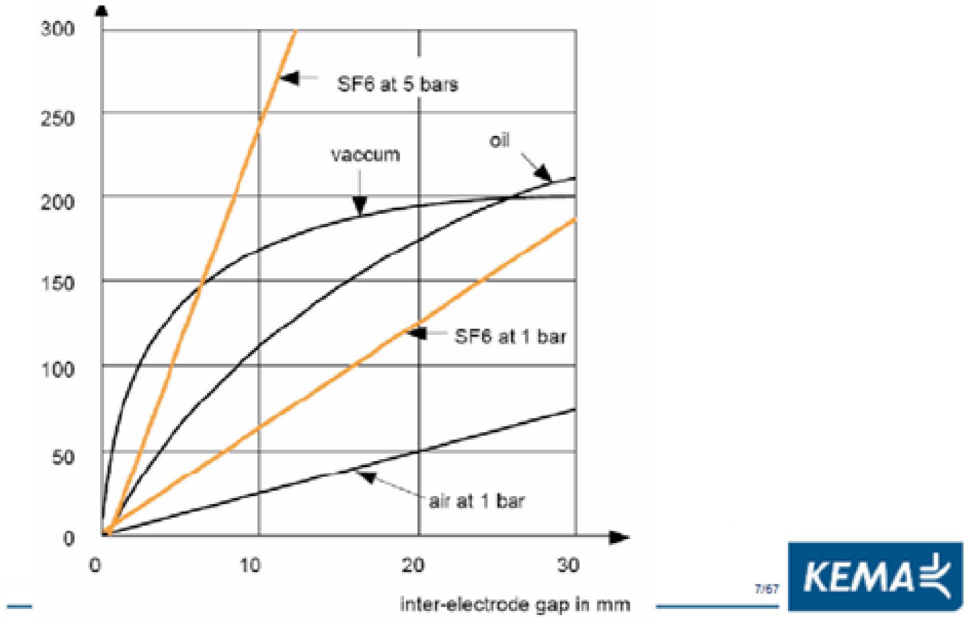
Arc rotation due to a magnetic field

Vacuum circuit-breakers up to 84 kV (since end of 1950’s)

Arc Extinction Principles

Comparison SF_6 vs Vacuum

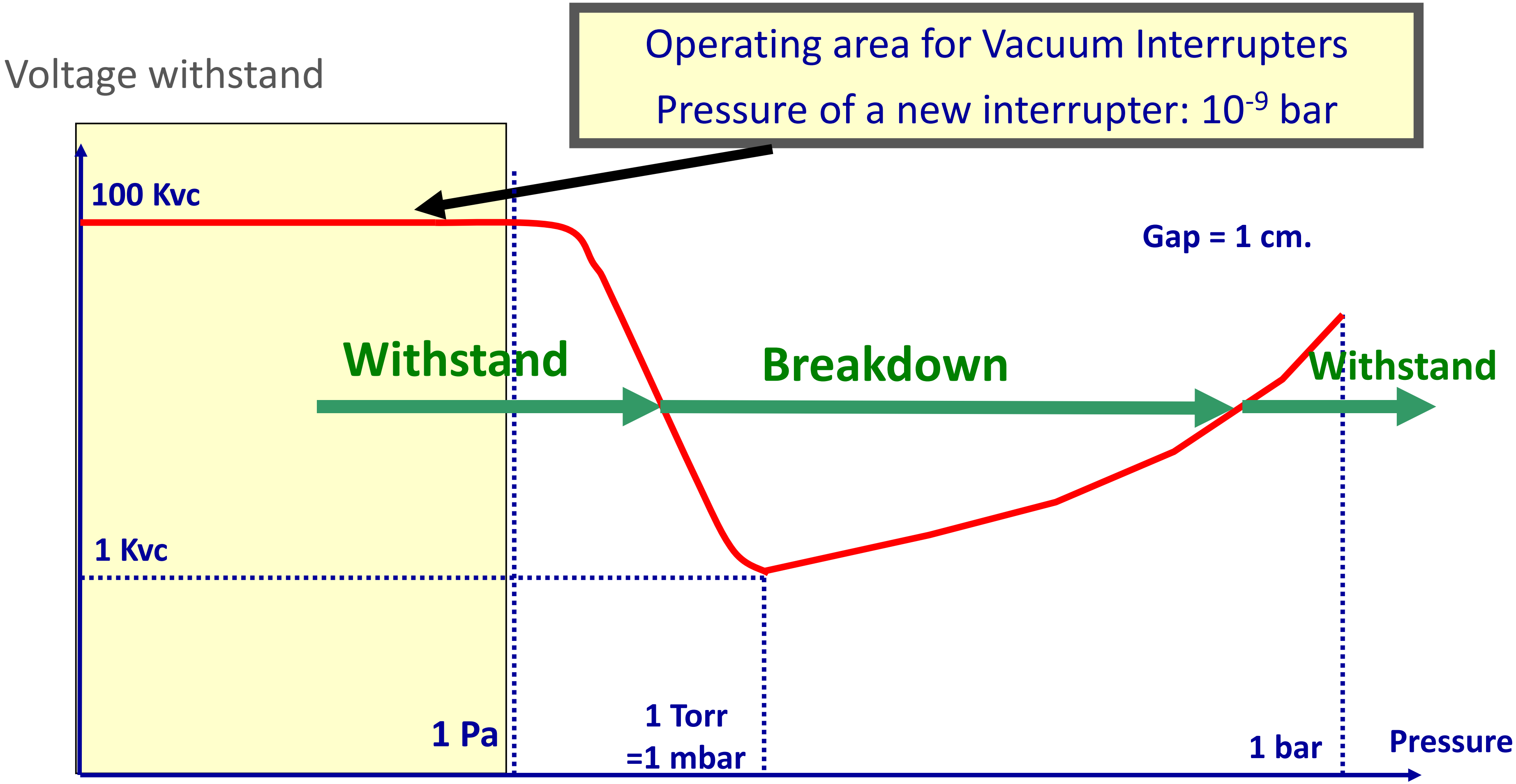
Voltage withstand as function of distance between electrodes



For longer distances between electrodes, a higher voltage withstand is obtained with SF_6. Vacuum is mainly used for MV circuit breakers.

Arc Extinction Principles

Vacuum interrupter



Operating area for Vacuum Interrupters

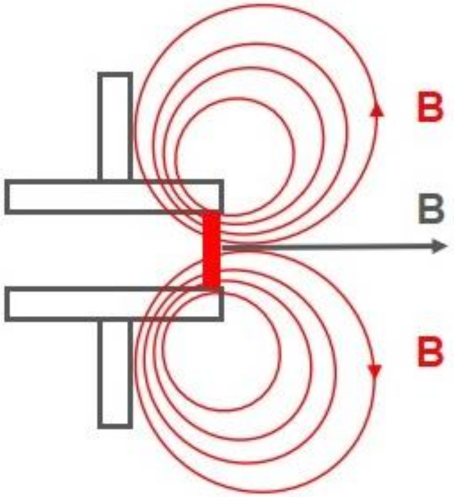
Pressure of a new interrupter: 10^{-9} bar

Paschen Curve

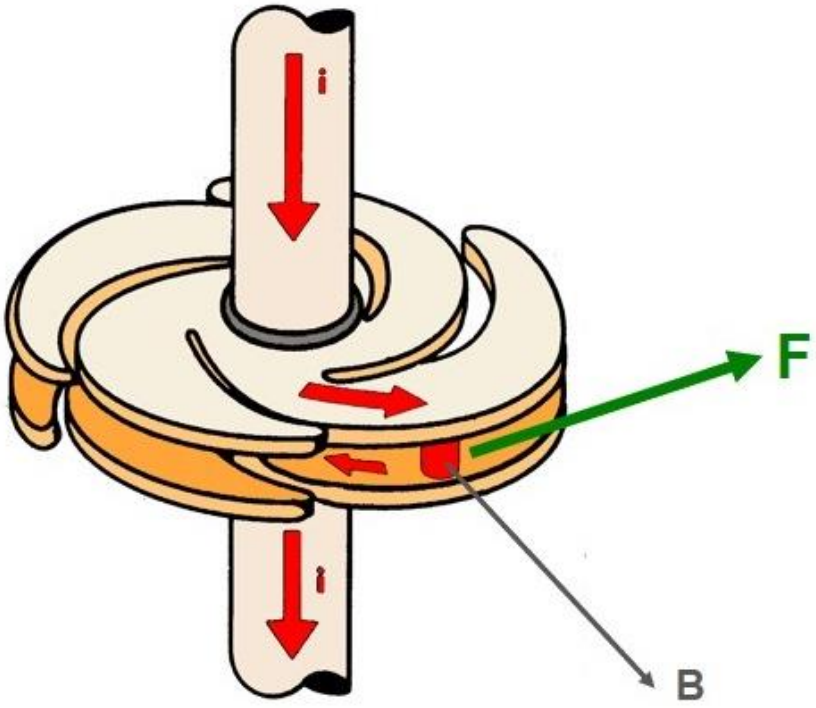
1 Pa (Pascal) = 10^{-5} bar

Arc Extinction Principles

Vacuum interrupter

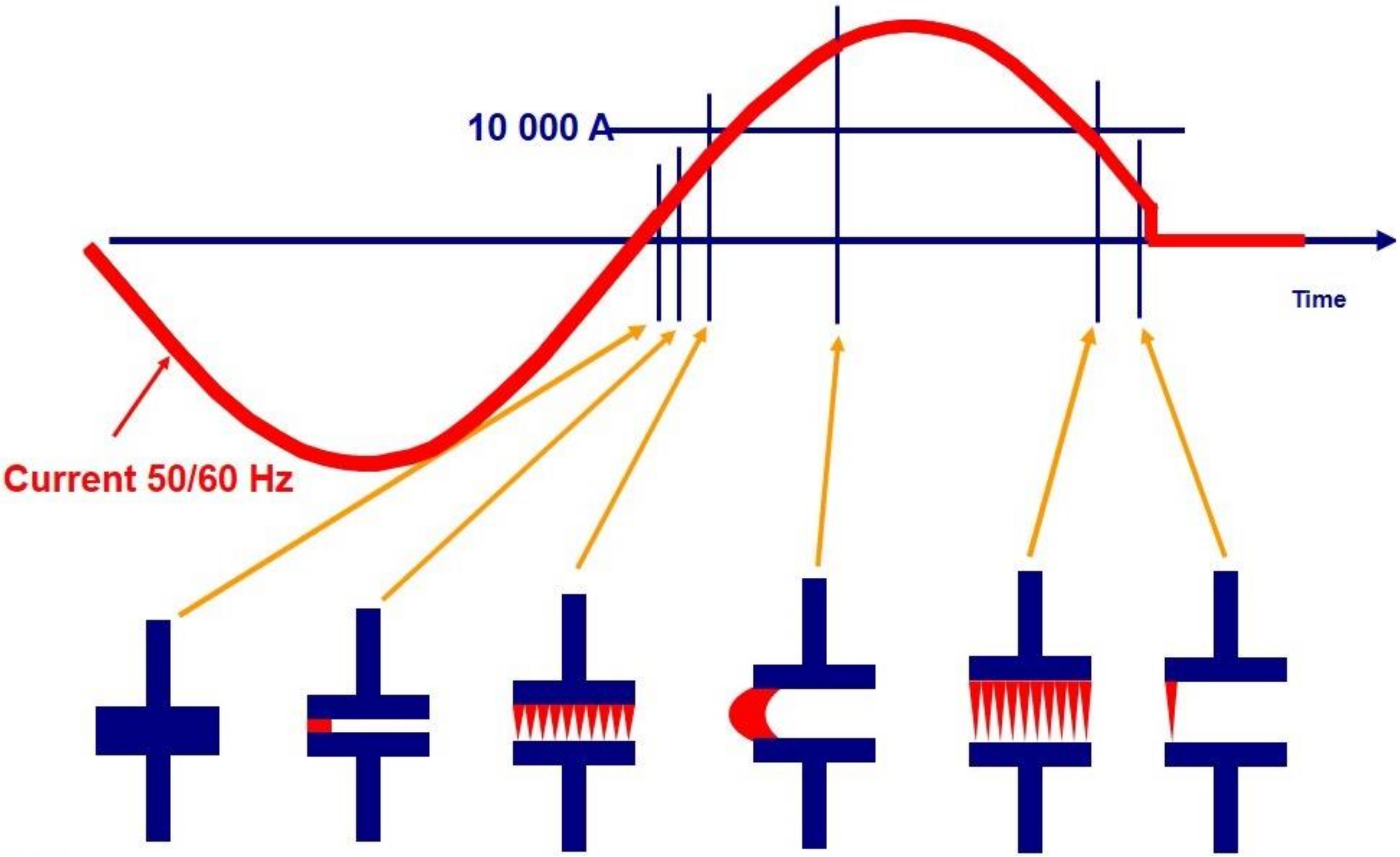


RMF



Arc Extinction Principles

Vacuum interrupter



Content

Switching Duties

Several mandatory switching duties are specified by international standards for high-voltage circuit breakers:

- Making and breaking of terminal fault currents
- Switching of capacitive currents

Except for special applications: e.g. circuit-breakers applied to switch shunt reactors

Depending on the application other switching duties may be required

- Breaking of short-line faults
- Making and breaking in out-of-phase conditions
- Inductive load switching (shunt reactor and motor)
- Breaking of transformer limited fault (TLF) currents

for information on TLF see Annex 3

Switching Duties
Making of short-circuit current

A circuit breaker must have a short-circuit making current capability.

The capability to make the rated short-circuit current must be demonstrated by performing the following closing operations.

- one with a symmetrical current and the longest pre-arcing time (IEC)
- one with an asymmetrical current with the required peak current (IEC and IEEE).

The peak current is the product of the r.m.s. value of the ac component of its rated short-circuit breaking current by the factor

2.5 for rated frequency 50 Hz

2.6 for rated frequency 60 Hz

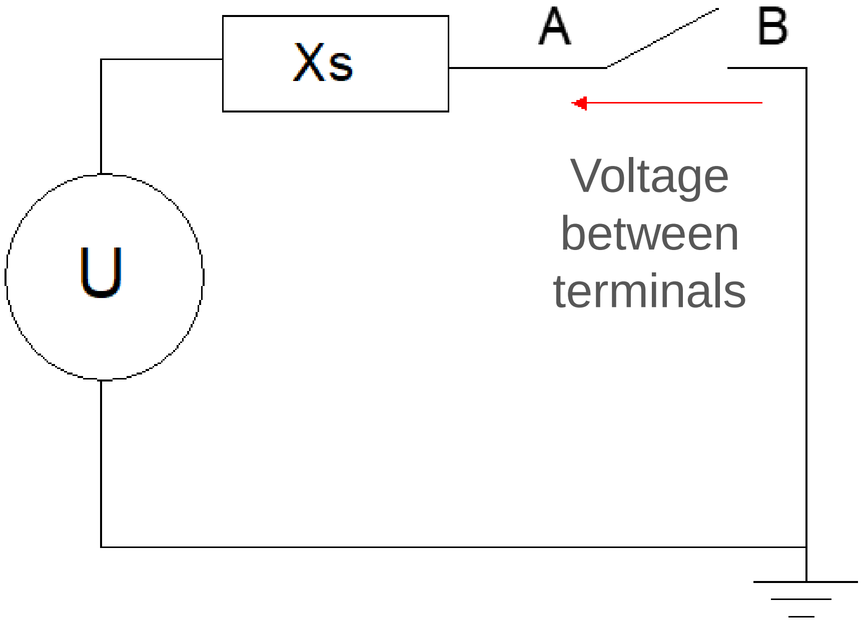
2.7 for special applications of networks with higher time constant

Rating in 5.5.2.3 of IEEE C37.04-201x
Testing in 4.9.5.2 of IEEE C37.09-201x

Switching Duties
Making of short-circuit current

During a making operation of a short-circuit current, when there is voltage between terminals current flows through an arc (pre-arc) before contact touch. The duration of this arc is called pre-arcing time.

When current making is done at zero voltage there is no pre-arcing but current is fully asymmetrical.



Circuit Breaker

Voltage between terminals

Fault

Switching Duties
Making of short-circuit current

Making of an asymmetrical current

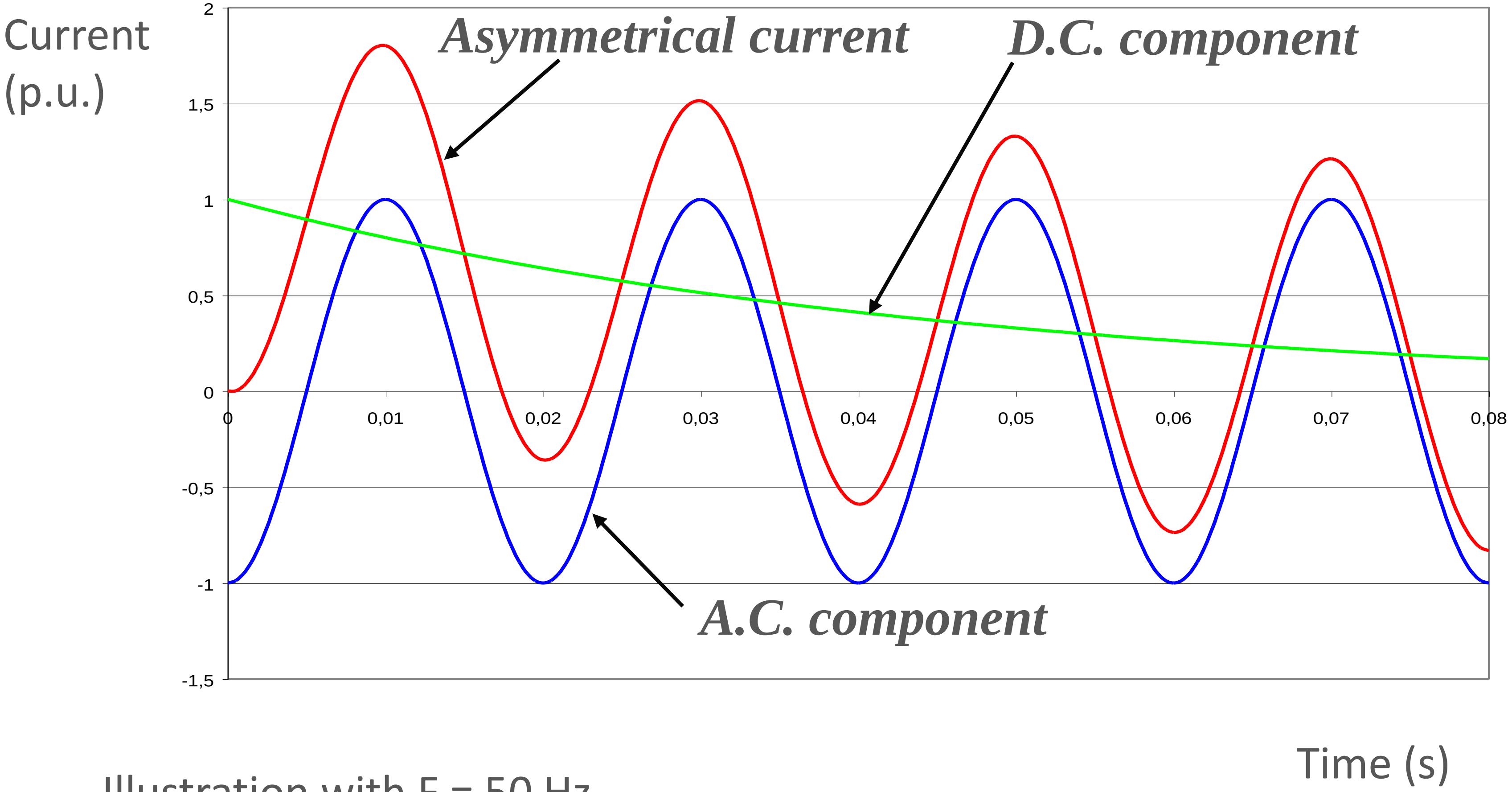


Illustration with F = 50 Hz

Switching Duties
Making of short-circuit currents

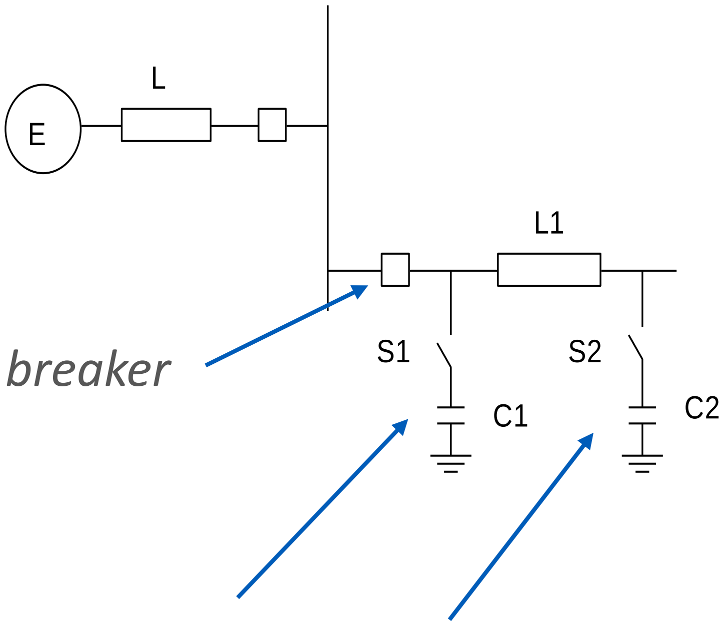
During making operations, the circuit breaker must do its complete stroke:

- it must withstand the electromechanical forces generated by current flow,
- the operating mechanism must have sufficient energy.

Parts, contacts in particular, must not be damaged or distorted and must keep their mechanical characteristics.

Switching Duties
Energization of Capacitor Banks

Energization of back-to-back capacitor banks



Circuit breaker

Capacitor banks

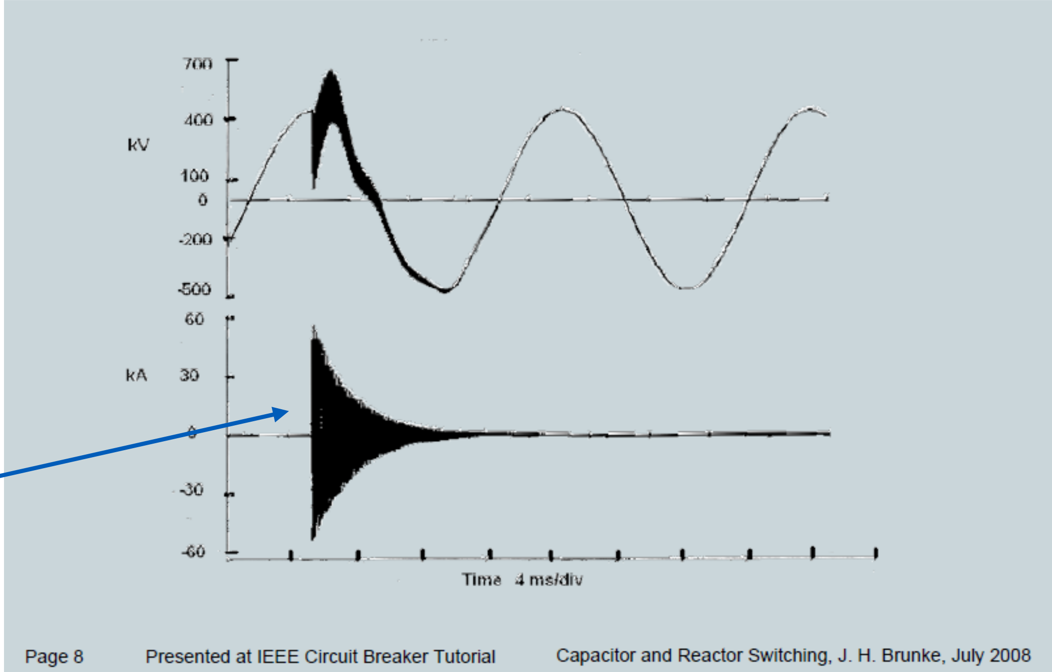
Energization of back-to-back capacitor banks can produce high-frequency inrush currents of high amplitude.

Making of inrush currents leads to contacts wear that increases the risk of restrike during subsequent breaking operations.

Switching Duties
Energization of Capacitor Banks

Energization of back-to-back capacitor banks

500 kV Back to Back Energization



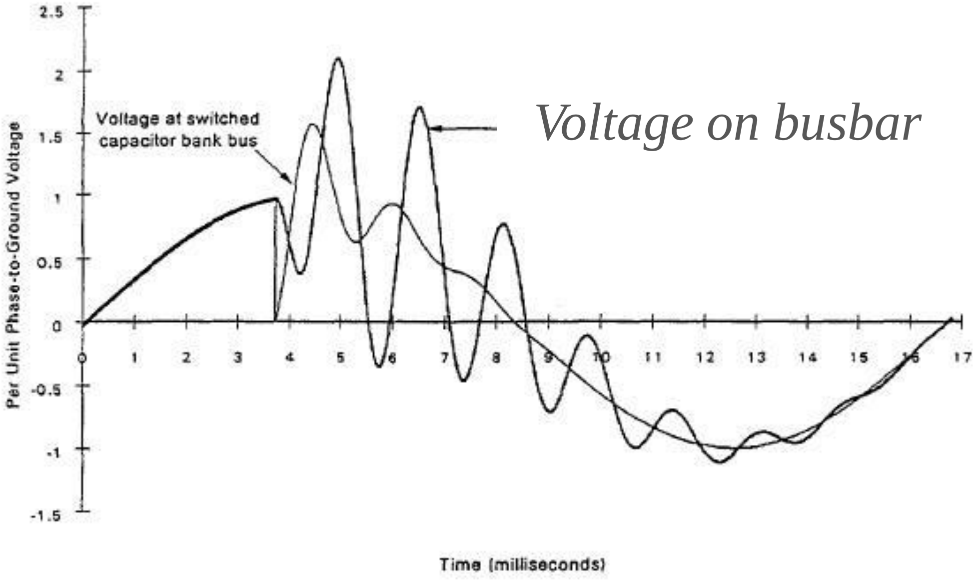
Page 8 Presented at IEEE Circuit Breaker Tutorial Capacitor and Reactor Switching, J. H. Brunke, July 2008

Inrush current

Energization of back-to-back capacitor banks can produce high-frequency inrush currents of high amplitude.

Switching Duties
Energization of Capacitor Banks

Energization of back-to-back capacitor banks can produce overvoltages

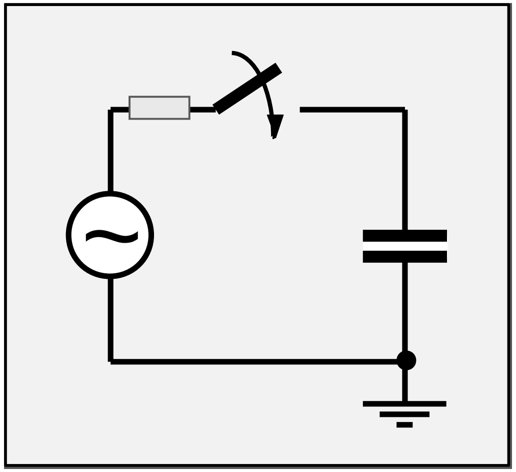


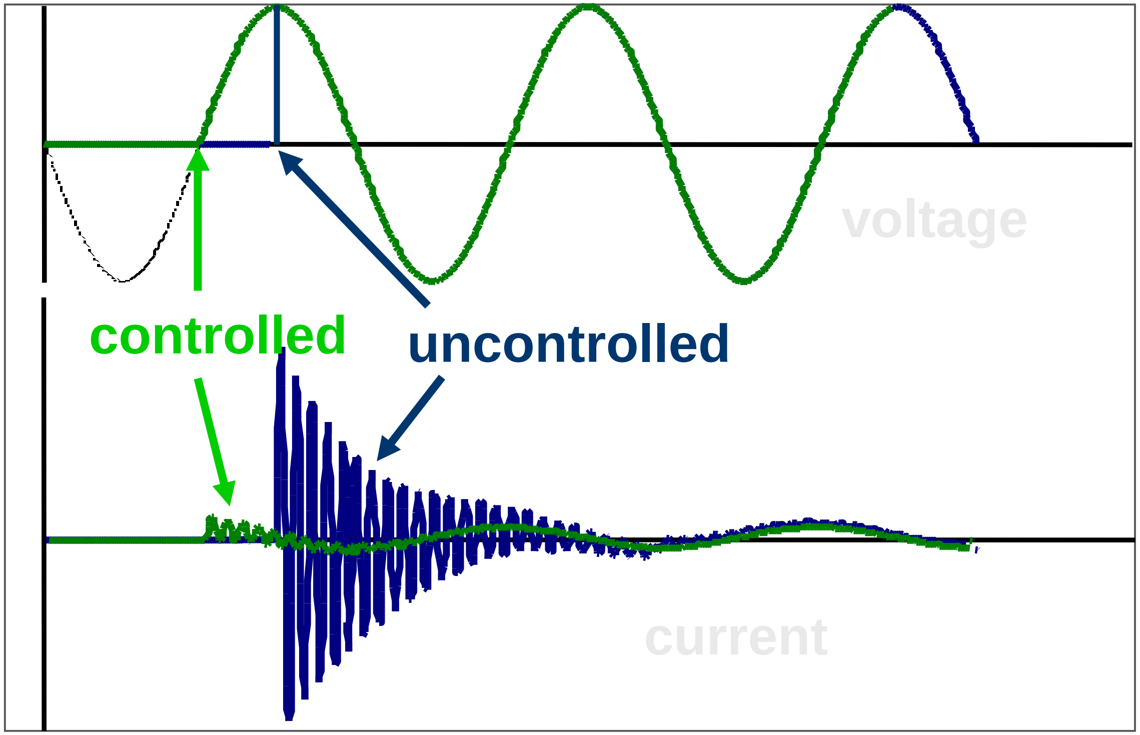
Voltage on busbar

One solution to limit overvoltages and inrush currents: synchronized closing operations (closing at voltage close to zero).

Series reactors can also be used to limit inrush currents.

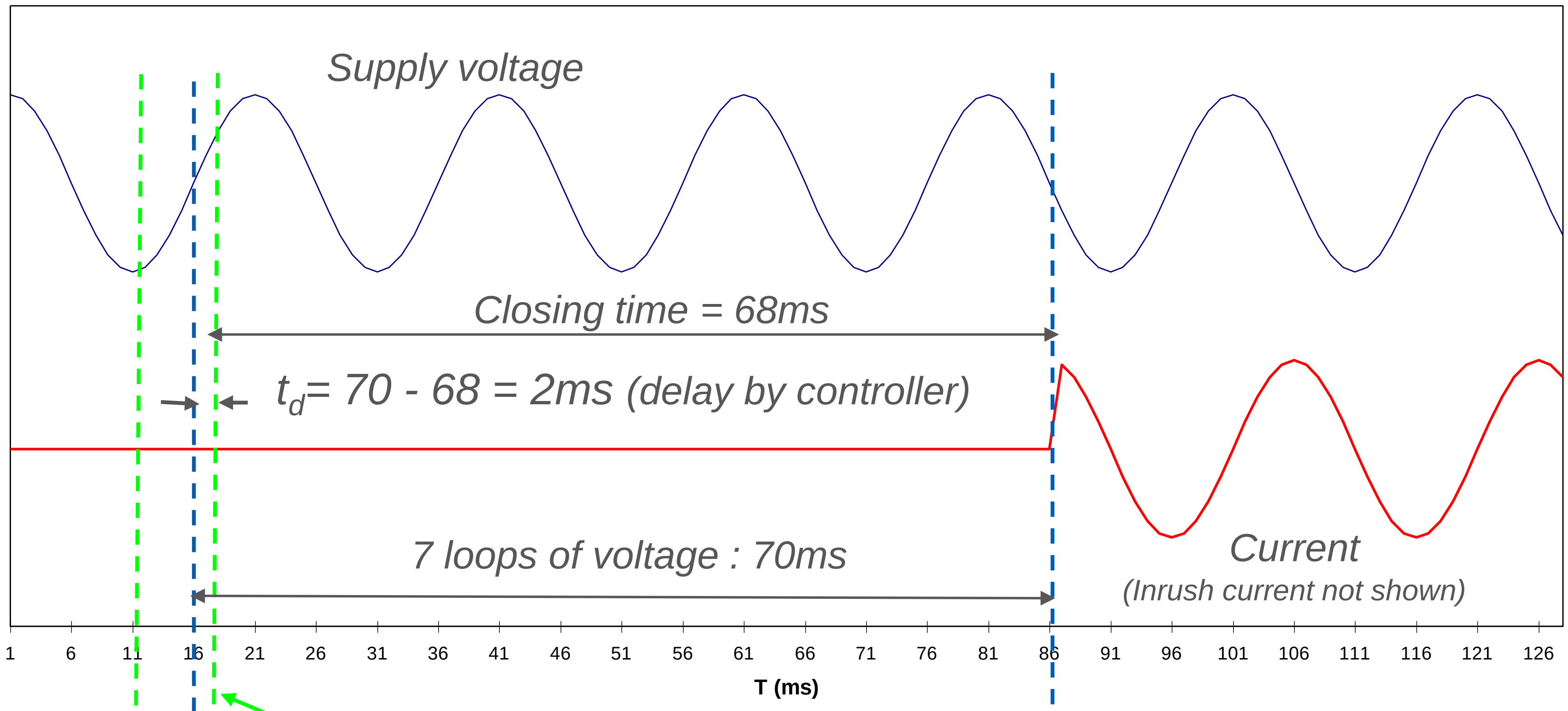
Switching Duties
Energization of Capacitor Banks – Controlled Closing





Switching Duties
Energization of Capacitor Banks – Controlled Closing

Example of synchronized closing at zero voltage to energize a capacitor bank



Order transmitted by controller

Detection of voltage passage through zero

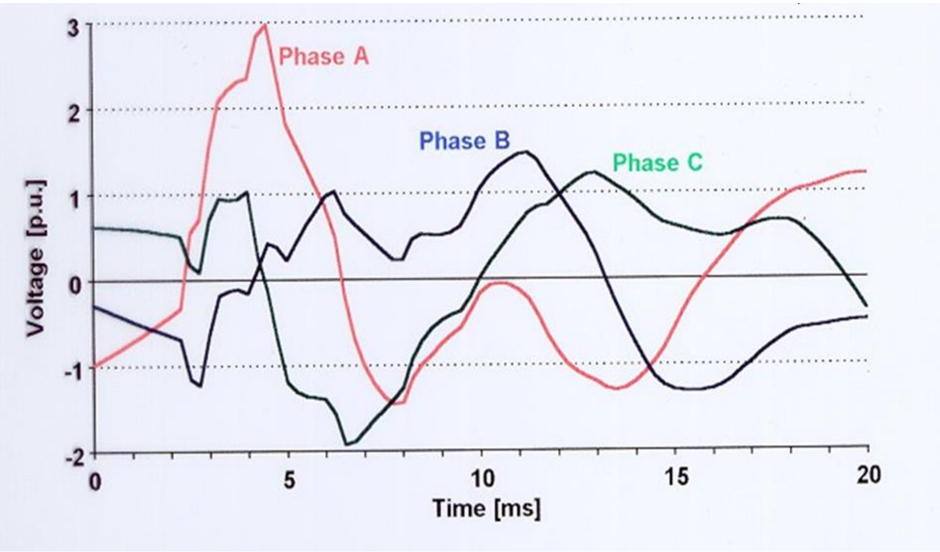
Order given to circuit-breaker

Example of application at 50Hz

Switching Duties
Energization & Re-energization of Lines

- Circuit breakers must close circuits without generating excessive overvoltages on the system. It is particularly important in EHV (Extra-high-voltages) where overvoltages must not exceed 1.6 or 1.8, value resulting from insulation coordination study (see IEC 60071-1).
- When an overhead line is switched onto an energized network, a voltage wave is imposed on the line. The imposed wave is reflected at the far end of the line and when the line is open at the far end, the reflected wave results in doubling of the amplitude.

The voltage can theoretically be up to 3 p.u. when the line has a trapped charge before being energized and the circuit-breaker closes when the polarity of the network voltage is opposite to the voltage on the line. It can happen during reclosing of a line.



Switching Duties
Energization & Re-energization of Lines

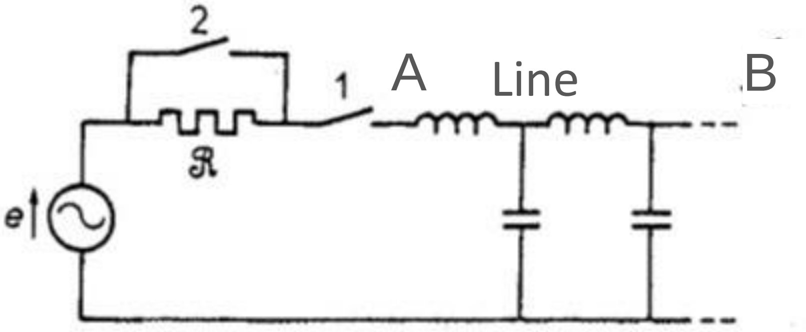
- In order to limit overvoltages during energization and re-energization of long lines, two techniques are mainly used:
  - Closing resistors
  - Synchronized closing
    - Same principle as seen for energization of capacitor banks.
    - Closing is done at zero voltage between terminals of the circuit breaker.

Switching Duties
Energization of Lines – Closing Resistors

Principle of Closing Operation with Resistor

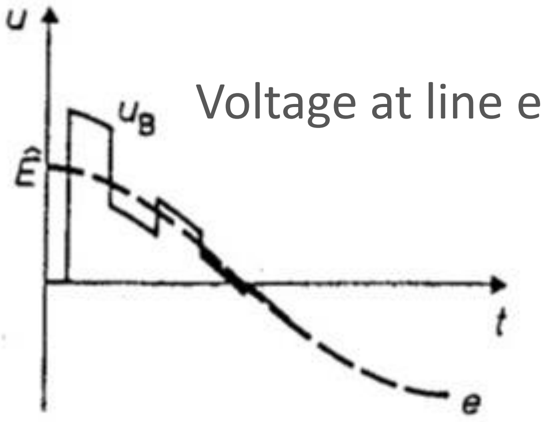
Phase 1 : switch 1 is closed, resistor is inserted

Phase 2 : switch 2 is closed, resistor is by-passed



The optimum value of the resistance is usually of the same order of magnitude as that of the surge impedance of the line (450 Ω).

The insertion time should be 6 ms to 8 ms in order to be effective



Voltage at line end B

Switching Duties
Energization of Lines – Closing Resistors

Principle of closing operation with resistor

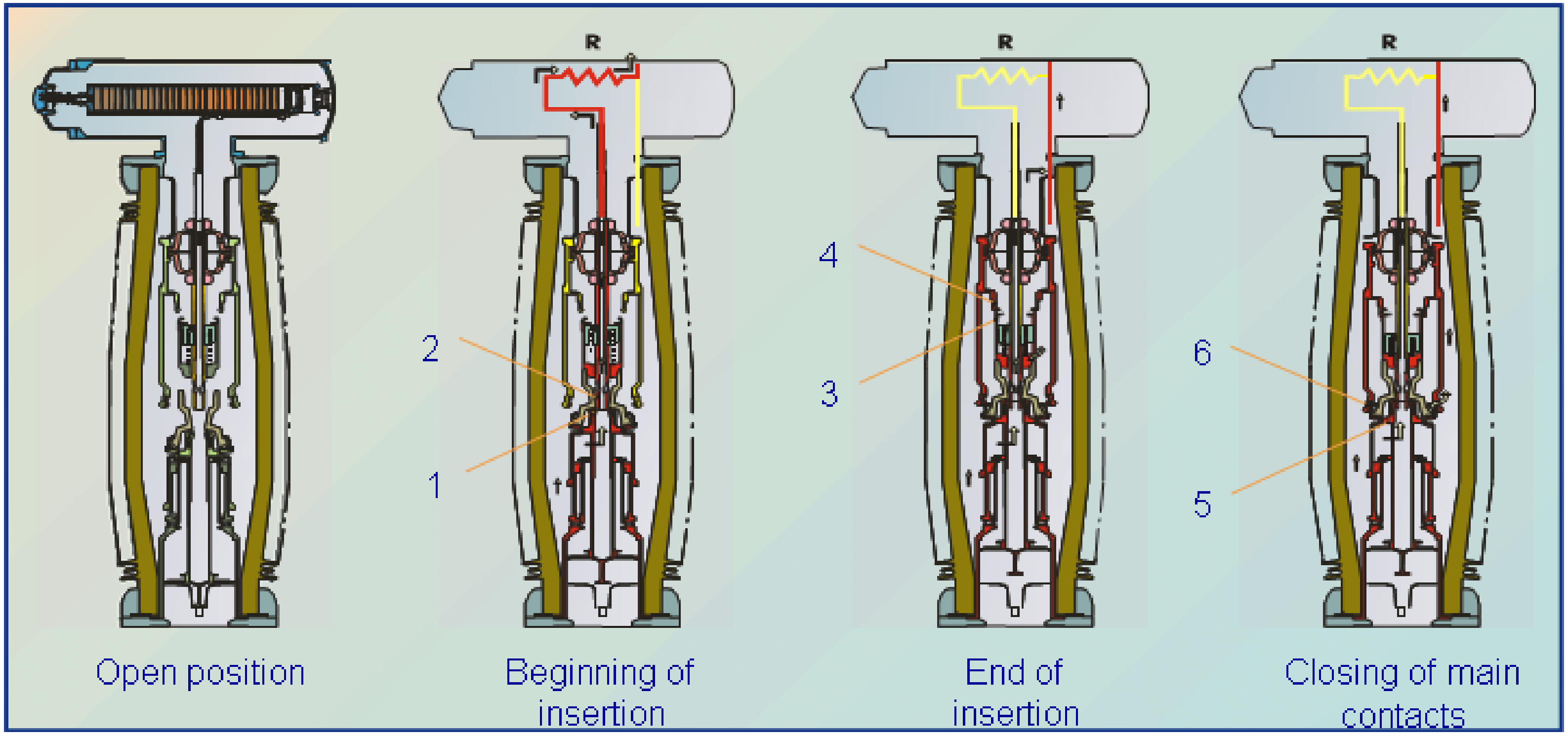


Illustration in case of a live tank circuit breaker

Switching Duties
Energization & Re-energization of Lines

Comparison of switching technologies

Switching Duties
Normal Conditions

Switching (making and breaking) operations in normal conditions (without fault) covered in standards:

- Capacitive current switching (line and cable charging currents, capacitor banks) is covered in IEEE C37.04b (ratings) and IEEE C37.09 (testing). Also in IEEE C37.100.2 currently developed.
- Shunt reactor switching in IEC 62271-110 and Guide IEEE C37.015.
- Load current switching in IEEE C37.09 for circuit breakers with rated voltages lower than 52 kV.

Switching Duties
Switching of capacitive current

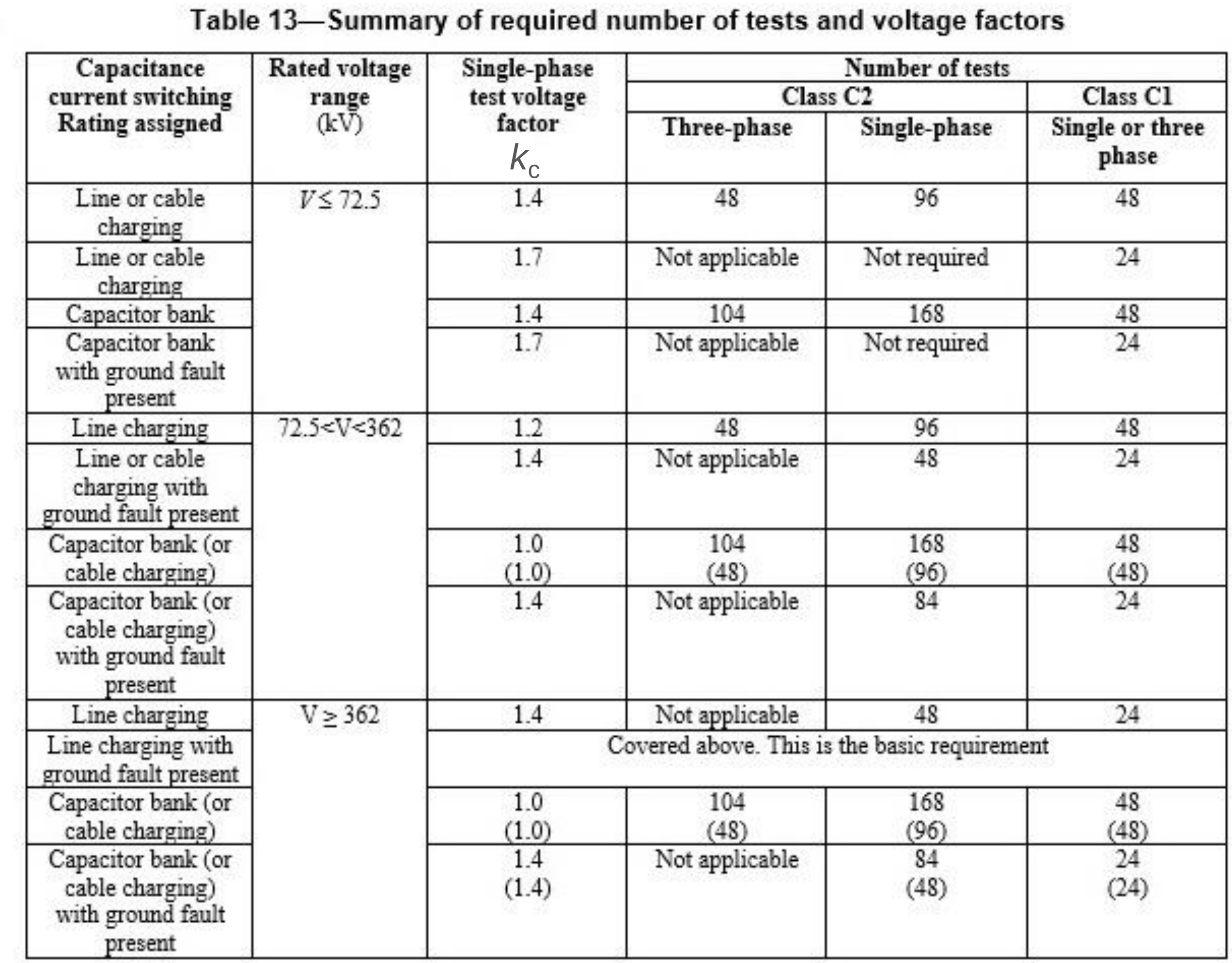


Table 13—Summary of required number of tests and voltage factors

Capacitance current switching Rating assigned	Rated voltage range (kV)	Single-phase test voltage factor k_c	Number of tests		
			Class C2		Class C1
			Three-phase	Single-phase	Single or three phase
Line or cable charging	$V \leq 72.5$	1.4	48	96	48
Line or cable charging		1.7	Not applicable	Not required	24
Capacitor bank		1.4	104	168	48
Capacitor bank with ground fault present		1.7	Not applicable	Not required	24
Line charging	72.5<V<362	1.2	48	96	48
Line or cable charging with ground fault present		1.4	Not applicable	48	24
Capacitor bank (or cable charging)		1.0 (1.0)	104 (48)	168 (96)	48 (48)
Capacitor bank (or cable charging) with ground fault present		1.4	Not applicable	84	24
Line charging	$V \geq 362$	1.4	Not applicable	48	24
Line charging with ground fault present		Covered above. This is the basic requirement			
Capacitor bank (or cable charging)		1.0 (1.0)	104 (48)	168 (96)	48 (48)
Capacitor bank (or cable charging) with ground fault present		1.4 (1.4)	Not applicable	84 (48)	24 (24)

Table from IEEE C37.09

Class C1: with a low probability of restrike

Class C2: with a very low probability of restrike

Class C2 vs C1: higher number of tests, more tests with minimum arcing time, preconditioning with 3 interruptions at 60% of rated short-circuit breaking current

Switching Duties
Short-circuit Interruption

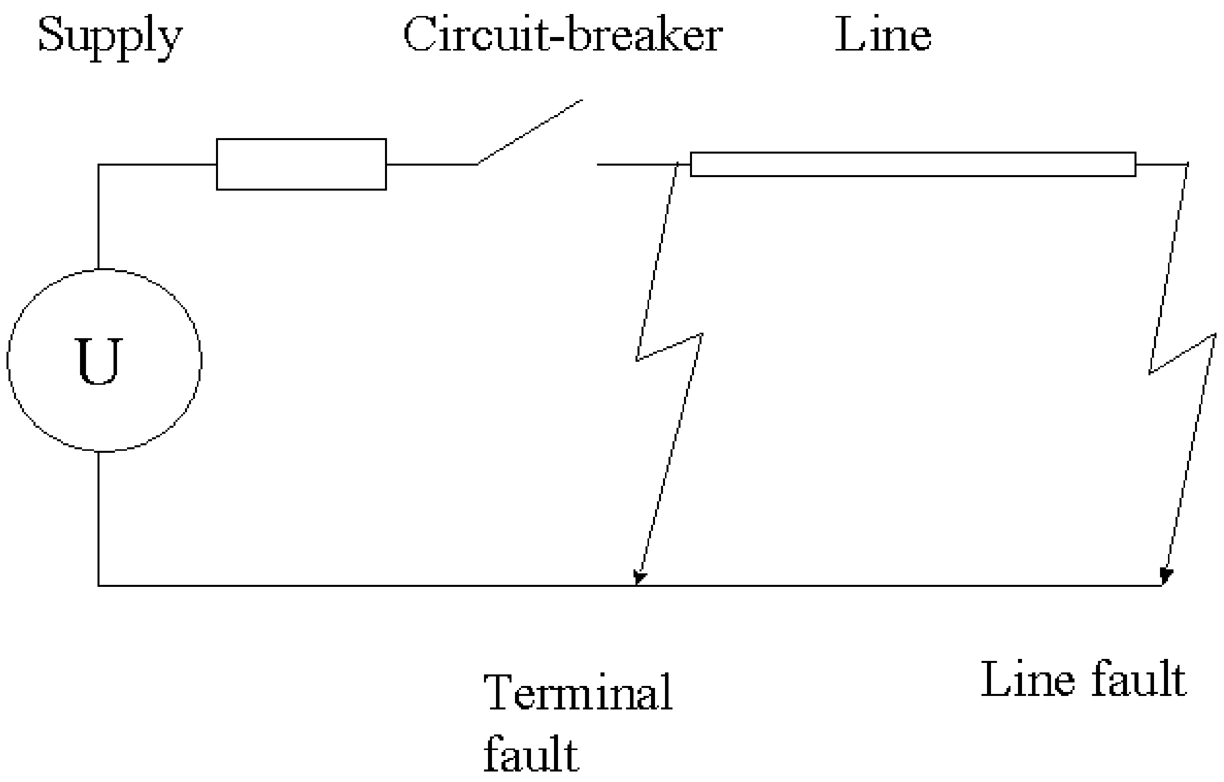
In the next slides the following fault current interruptions are considered

- terminal fault
- short-line fault
- out-of-phase

Transformer limited faults (TLF) are covered in IEEE C37.06.1 currently developed.

Other types of faults possible in applications with associated TRVs are presented in Application Guide IEEE C37.011.

Switching Duties
Terminal Fault Current Interruption



A terminal fault is a short-circuit that occurs at the terminal of a circuit breaker.

Switching Duties
Terminal Fault Current Interruption

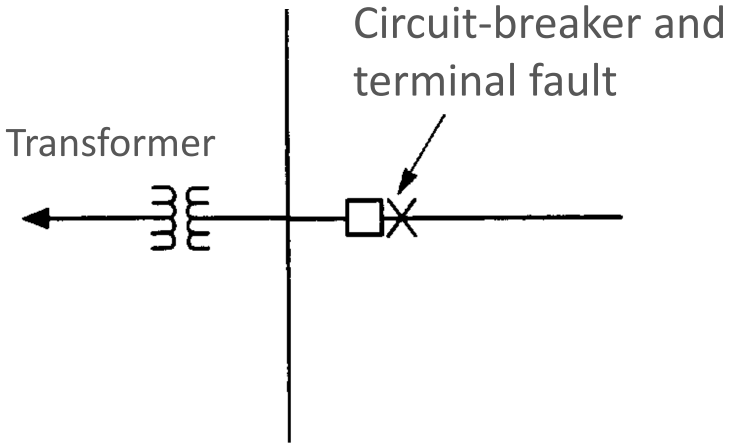
Distribution of faults: single-phase, two-phase, three-phase

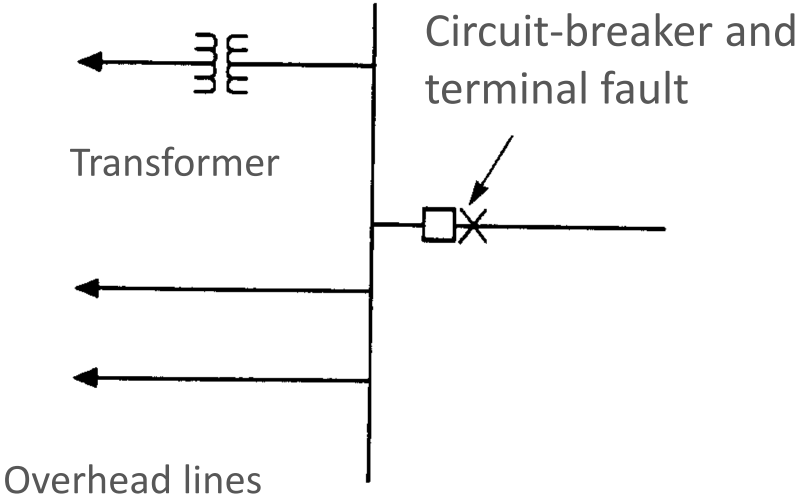
	% Single-Phase	% 2-Phase	% 3-Phase
Ur < 100 kV	64	26	10
100 kV < Ur < 200 kV	65	29	6
200 kV < Ur < 300 kV	74	20	6
300 kV < Ur < 500 kV	83	14	3
Ur = 550 kV	90	10	0
Ur = 800 kV	93	6	1

Source IEC WG29 doc 17A/573/CD 2000-02

Faults are mainly single-phase.

Switching Duties
Terminal Fault Interruption





Current : 10% and 30% rated short-circuit breaking current

TRV with one frequency of oscillation

TRV with two parameters

Current : 60% and 100% rated short-circuit breaking current

TRV with superposition of several voltage waves

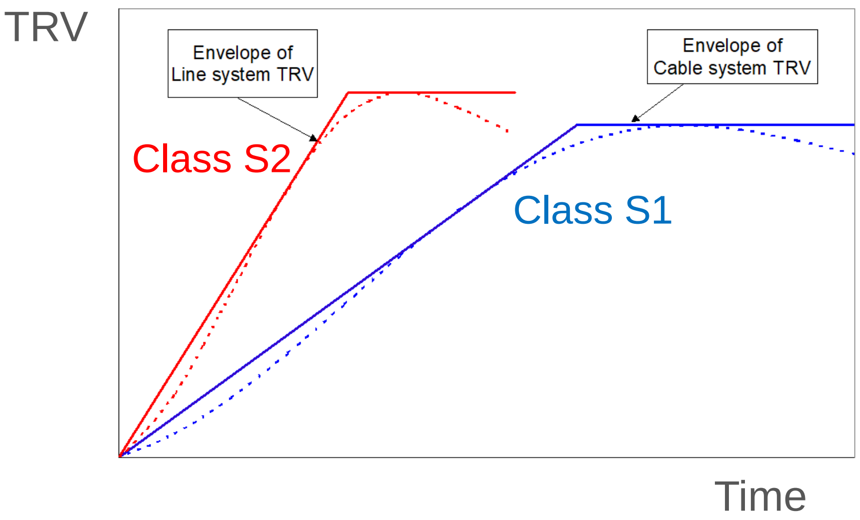
TRV with four parameters

Switching Duties
Terminal Fault Current Interruption

Classes of circuit breakers for rated voltages < 100 kV

- In order to cover all types of networks (distribution, industrial and sub-transmission) and for standardization purposes, two types of systems are introduced: cable systems and line systems

At full short-circuit current, the rate of rise of recovery voltage in line systems is approximately twice the value for cable systems



- Circuit breakers to be used in cable systems are of class S1.
- Circuit breakers to be used in line systems are of class S2.

S1 and S2 characterize a terminal fault TRV withstand capability

Switching Duties
Terminal Fault Interruption - Current

The rated short-circuit current is defined by two components

A.C. Component

Rated values of the a.c. are chosen from the following list derived from the Renard series R10 :

12.5 – 16 – 20 – 25 – 31.5 – 40 – 50 – 63 – 80 – 100 kA

D.C. Component

$$100 \times e^{-(\frac{Top + Tr)}{\tau}} \qquad \text{(in \%)}$$

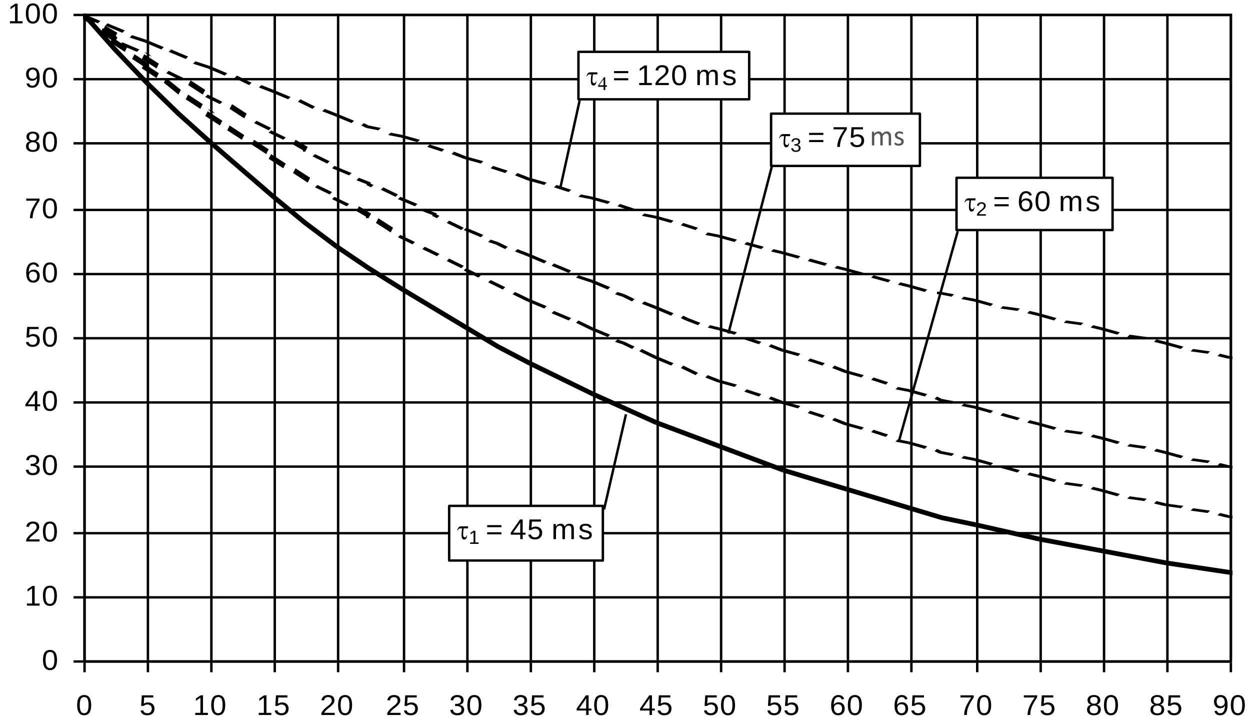
T_{op} minimum duration of opening time (ms)

T_r relay time in ms: 1000/(2 f_r) with f_r = power frequency

τ standard time constant (45 ms)

Switching Duties
Terminal Fault Interruption - Current

Network time constant (L/R)



Standard value of time constant L/R = 45 ms

Special cases : 120 ms (≤ 52kV), 75 ms (≥ 550kV) & 60ms (> 52kV & ≤ 420kV)

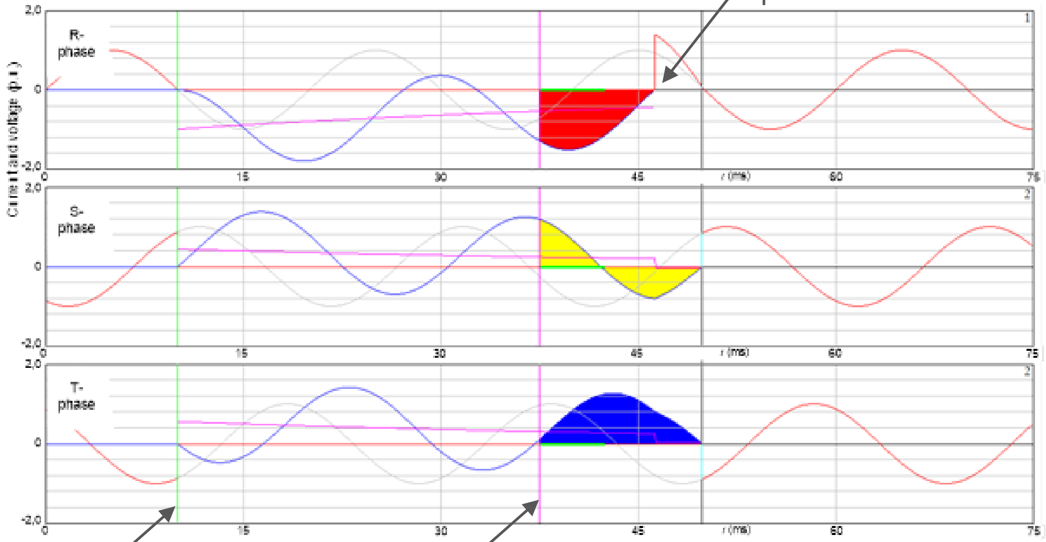
Switching Duties
Terminal Fault Interruption - Current

A test circuit having the standard DC time constant (45 ms) would give the correct conditions for current interruption: peak and duration of the last major loop of current, slope of current (di/dt) and TRV.

However, as the DC time constant of the test circuit is usually different from 45 ms, the correct conditions are obtained by specifying calculated values of the last major loop of current before interruption (peak and duration).

Example of a three-phase fault interruption where the peak value and the duration of the last major loop of current before interruption is specified for the first-pole-to-clear (red phase).

Current trace in blue (and voltage trace in red)



Interruption by first-pole-to-clear

Current initiation

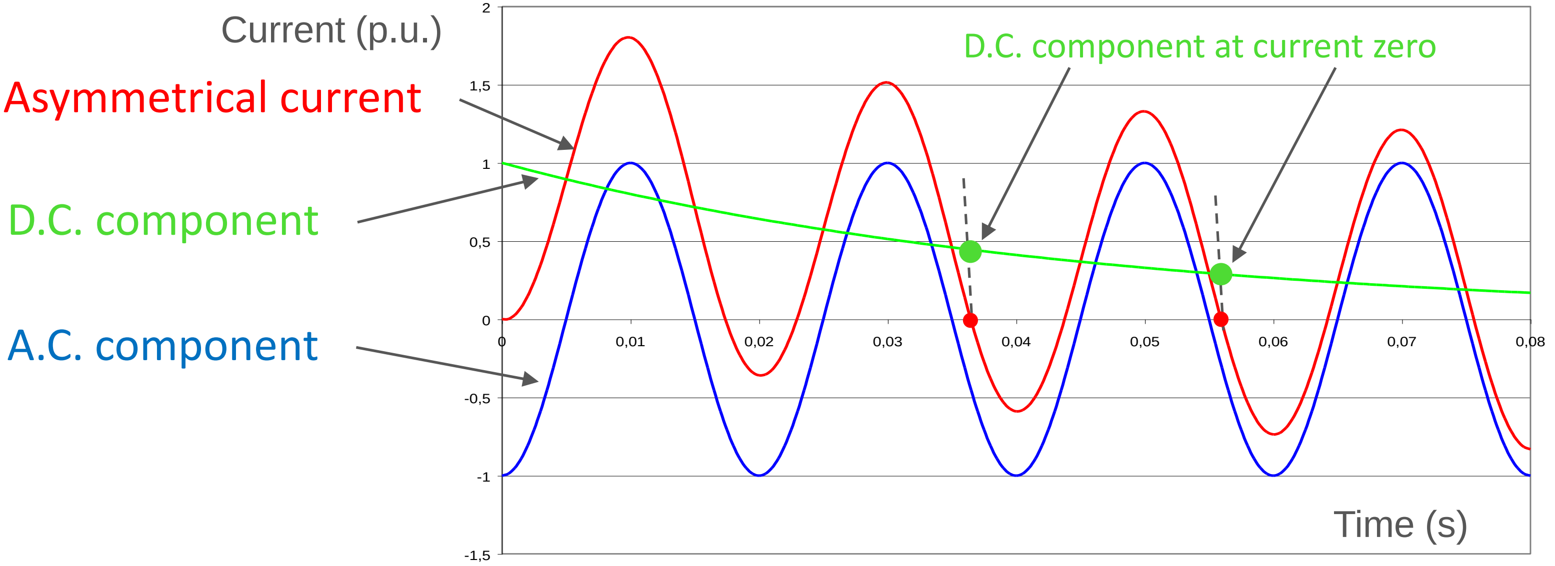
Arcing contacts separation

Switching Duties
Terminal Fault Interruption – Current – T100a

Testing T100a (asymmetrical current)

It is the amplitude and duration of the last major current loop that must be met in order to have the correct conditions for current interruption (DC component and di/dt at current zero, TRV).

The amplitude and duration of the last major current loop before interruption are given in the draft revision of IEEE C37.09 and in IEC 62271-100 as function of the minimum clearing time of the circuit breaker.



Minimum clearing time = relay time + opening time + minimum arcing time

Switching Duties
Terminal Fault Interruption – Current – T100a

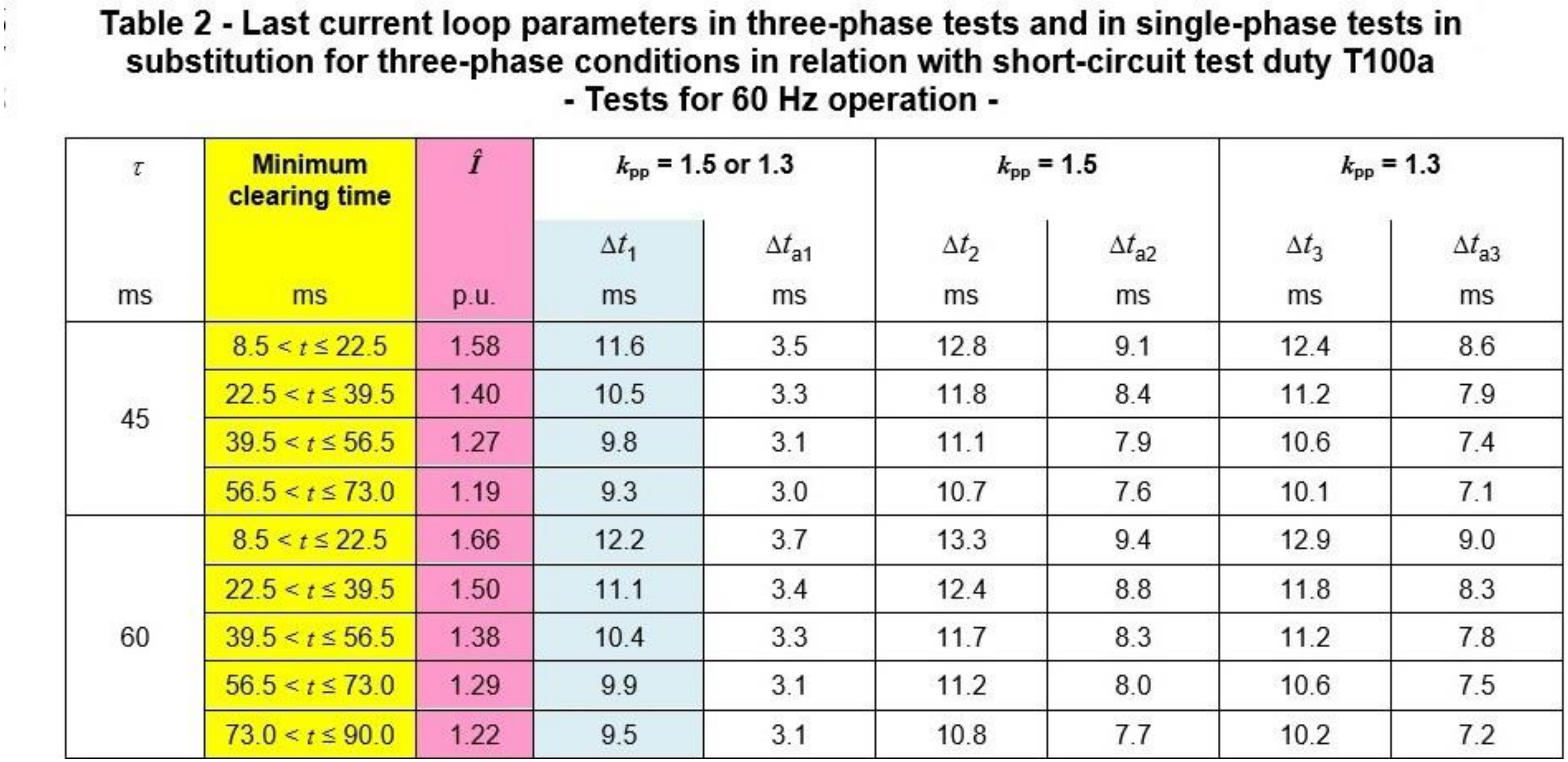


Table 2 - Last current loop parameters in three-phase tests and in single-phase tests in substitution for three-phase conditions in relation with short-circuit test duty T100a
- Tests for 60 Hz operation -

τ	Minimum clearing time	$\hat{I}$	k_{pp} = 1.5 or 1.3		k_{pp} = 1.5		k_{pp} = 1.3	
			Δt_1	Δt_{a1}	Δt_2	Δt_{a2}	Δt_3	Δt_{a3}
ms	ms	p.u.	ms	ms	ms	ms	ms	ms
45	$8.5 < t \leq 22.5$	1.58	11.6	3.5	12.8	9.1	12.4	8.6
	$22.5 < t \leq 39.5$	1.40	10.5	3.3	11.8	8.4	11.2	7.9
	$39.5 < t \leq 56.5$	1.27	9.8	3.1	11.1	7.9	10.6	7.4
	$56.5 < t \leq 73.0$	1.19	9.3	3.0	10.7	7.6	10.1	7.1
60	$8.5 < t \leq 22.5$	1.66	12.2	3.7	13.3	9.4	12.9	9.0
	$22.5 < t \leq 39.5$	1.50	11.1	3.4	12.4	8.8	11.8	8.3
	$39.5 < t \leq 56.5$	1.38	10.4	3.3	11.7	8.3	11.2	7.8
	$56.5 < t \leq 73.0$	1.29	9.9	3.1	11.2	8.0	10.6	7.5
	$73.0 < t \leq 90.0$	1.22	9.5	3.1	10.8	7.7	10.2	7.2

Duration of the last major current loop before interruption by the first-pole-to-clear

Peak value in p.u. of the peak value of the symmetrical short-circuit current

Minimum clearing time = relay time + opening time + minimum arcing time

Switching Duties
Terminal Fault Interruption – Current – T100a

IEEE WG C37.09 has revised the test requirements for T100a in order to have the correct conditions for current interruption (DC component and di/dt at current zero, TRV).

The draft is in the final stage of revision (Recirculation 2).

Additional explanations are given in Annex 2 of this presentation.

The new test procedure for T100a is the same as in the new amendment 2 to IEC 62271-100.

For synthetic tests, reference is made to IEC 62271-101. It has recently been amended to include this revised test procedure.

Switching Duties
Terminal Fault Test Duties

Test duties are required at 10% (T10), 30% (T30), 60% (T60) and 100% (T100) of rated short-circuit breaking current

T10 : in the case of few or no line connected on the supply side

It covers also the case of faults far away on a line (long line faults where current is also limited by the impedance of the line).

T30 : as for T10 but more transformer(s) connected on the supply side.

It covers also the case of long line faults, but at a shorter distance than in the case of T10.

T60 : with a higher number of lines on the supply side of the circuit-breaker.

Switching Duties
Terminal Fault Test Duties

T100 : with all lines and sources connected on the supply side.

Breaking capability must be demonstrated by tests with symmetrical current (T100s) and asymmetrical current (T100a).

Five test duties are required, each with 3 interruptions demonstrating the full interrupting window (minimum, medium and maximum arcing times).

The rated operating sequence (OCO - CO) is performed, except in the case of T100a where 3 O are performed.

Three-phase tests are required. Single-phase tests can be performed also in substitution for three-phase tests (demonstrating the full interrupting window with the specified TRV).

Short-circuit making and breaking tests are performed at minimum pressure for insulation and/or interruption.

Test duties are specified in 4.9.4 of IEEE C37.09-201x

Switching Duties
Terminal Fault – Single-Phase Fault Tests

In addition to the three-phase terminal fault tests, single-phase fault tests can be required:

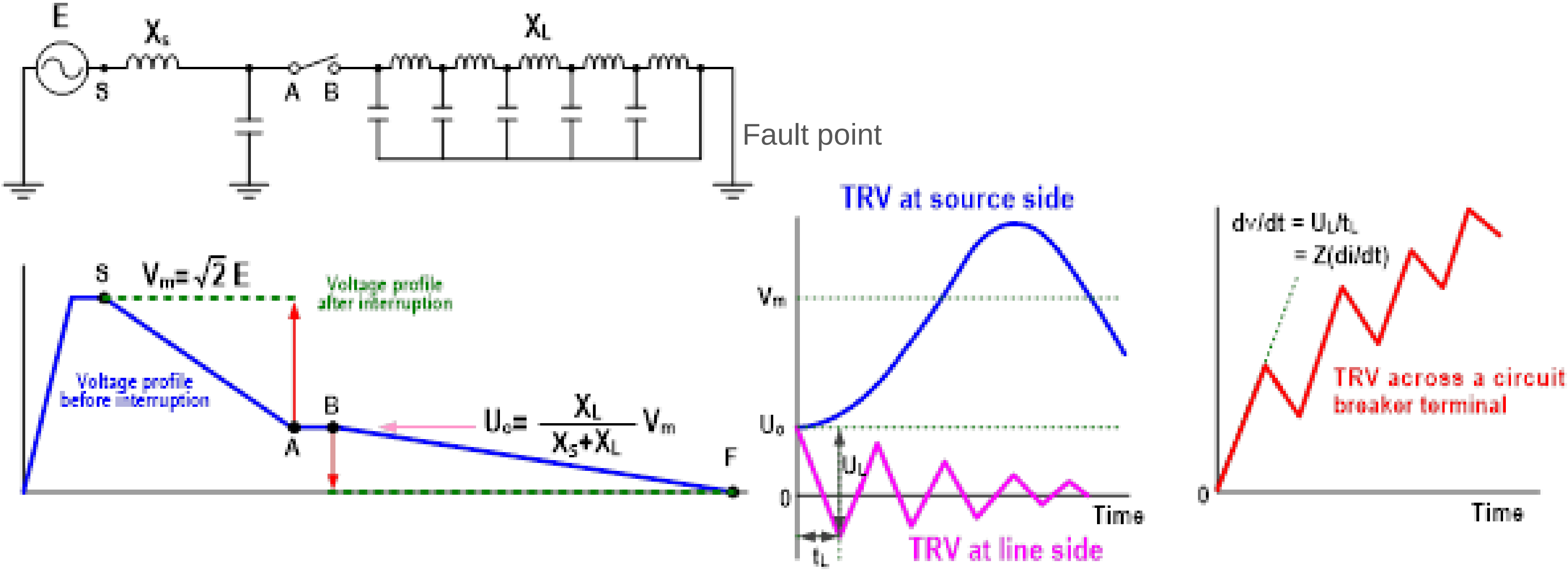
- For circuit breaker with k_{pp} = 1.5 that are tested three-phase, in order to prove their capability to interrupt single-phase faults in effectively grounded neutral systems.
  - In IEC 62271-100 one test is required with rated short-circuit breaking current, a symmetrical current and a long arcing time.
  - In IEEE C37.09 two tests are required with the rated short-circuit breaking current, one with a symmetrical current and a second one with an asymmetrical current.
  - Draft revision of IEEE C37.09: the single phase test duties are not required if test duties T100s and T100a are performed by single-phase tests in substitution for three-phase tests.

Tests are specified in 4.9.4.5 of IEEE C37.09-201x

Switching Duties
Short Line Fault Current Interruption

Short-line faults (SLF) occur on a line, hundreds of meters up to a few kilometers from the circuit breaker.

SLF is characterized by a steep rate-of-rise of recovery voltage (RRRV or du/dt).



Equivalent circuit and TRV waveforms

Source: CIGRE

Switching Duties
Short Line Fault Current Interruption

SLF interrupting capability is required for circuit breakers directly connected to overhead lines.

Standards require to perform only single-phase tests.

In practical terms, single-phase tests cover also three-phase faults as the dominant TRV parameter (RRRV) is highest during a single-phase to ground fault.

Z single-phase fault = 450 Ω
Z three-phase fault (first-pole-to-clear) = 405 Ω

Two test duties are required in IEEE C37.09:

- L90 at 90% of rated short-circuit current
- L75 at 75% of rated short-circuit current

These SLF test conditions are the more severe for circuit breakers.

SLF interruption is a typical case of thermal interruption as success depends on the energy balance in the arc during tens of micro-seconds around current passage through zero.

Tests are specified in 4.9.4.6 of IEEE C37.09-201x
See also 4.2.4 of IEEE C37.011-2011

Switching Duties
Short Line Fault Current Interruption

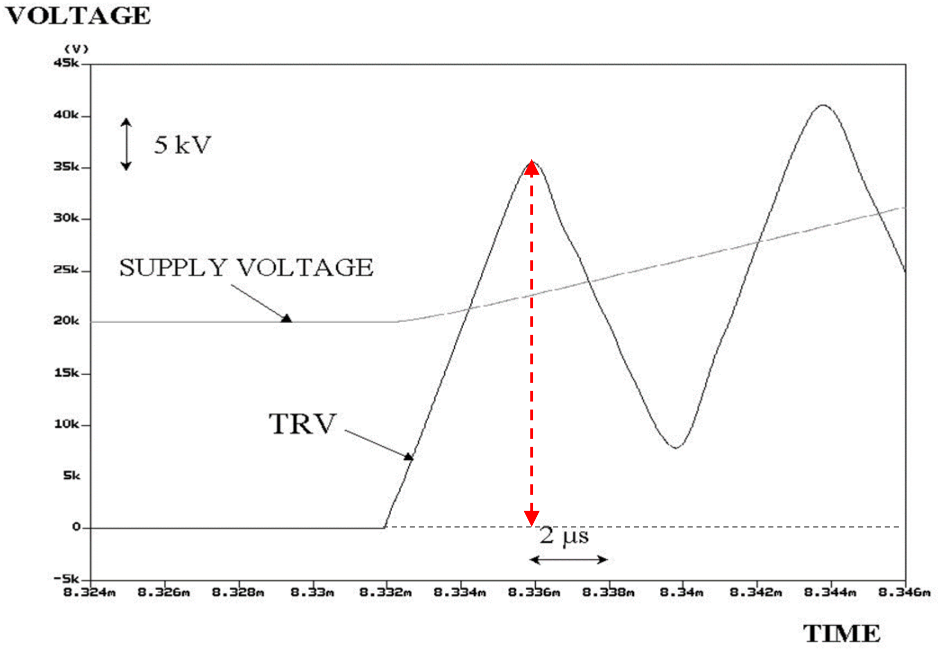
Example SLF L90 at 90% of 40 kA 60 Hz under 245 kV

First TRV peak is 35 kV

3 kV on supply side

32 kV on line side

TRV slope is 9.5 kV/µs



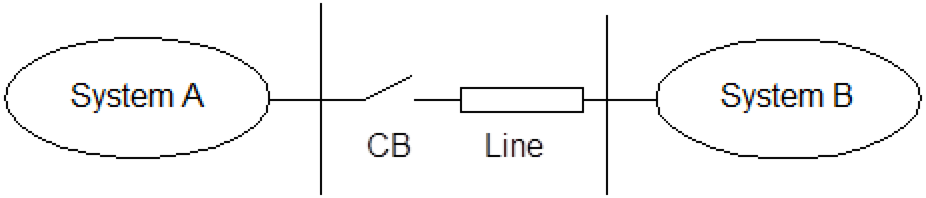
TRV slope is 4.7 times higher than that of terminal fault T100 (2 kV/µs).

The slope of TRV for SLF is the highest for high short-circuit current interruption

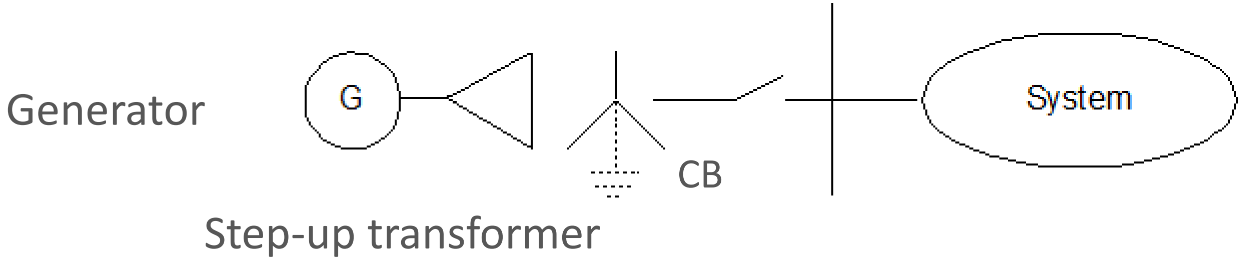
Switching Duties
Out-of-Phase Fault Interruption

Two operating conditions can lead to out-of-phase switching

A) Instability of a system in service, due to overloading, load rejection, or other major disturbances



B) Erroneous switching operation during synchronizing.



IEC: Since the out-of-phase switching duty is required only for certain circuit breaker applications, the specification of a rated out-of-phase making and breaking current is not mandatory.

Switching Duties
Out-of-Phase Fault Current Interruption

The standard out-of-phase factors

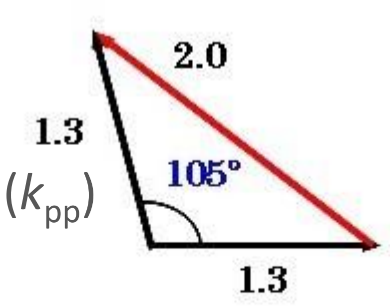
2.0 for circuit breakers in systems with effectively grounded neutral

2.5 for circuit breakers in systems with non-effectively grounded neutral

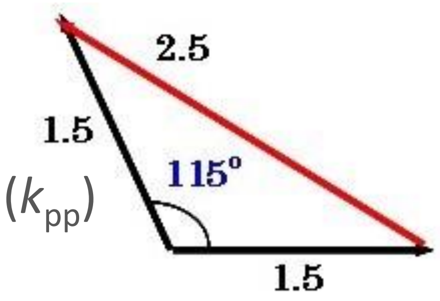
cover respectively an out-of-phase angle of

105° for circuit breakers in systems with effectively grounded neutral

115° for circuit breakers in systems with non-effectively grounded neutral



Effectively grounded systems



Non-effectively grounded systems

Out-of-phase switching current tests are specified in 4.13 of IEEE C37.09-201x

Switching Duties

Influence of Switching Duties on Interrupting Chamber and/or Mechanism for Self Blast Circuit Breakers

Switching Duty	Influence on
Capacitive current breaking	Opening speed and energy, dielectric withstand
Inrush current making (back-to-back capacitor banks)	Controlled switching, closing speed, closing time stability
T10 and T30	Compression volume, stroke, opening distance, and dielectric withstand (together with BIL required)
T60, T100s, T100a breaking operations	Thermal volume, nozzle diameter, gas volume in chamber, gas exhaust, dielectric withstand with hot gases, mechanical endurance, mechanical withstand
T100s making operations	Closing energy, arcing contacts geometry, mechanical withstand
L75, L90	Thermal volume, nozzle diameter, gas exhaust
OP2	Closing speed for making operation, dielectric withstand
Inductive load current breaking	Controlled switching, opening time stability, dielectric withstand with short arcing times

Switching Duties

- For more information on current switching and TRV
  - Short presentation on TRV in Annex 1
  - Transient Recovery Voltage for High-Voltage Circuit Breaker – Part 1

    http://www.ewh.ieee.org/soc/pes/switchgear/presentations/2013-1_Thu_Dufournet.pdf
  - Transient Recovery Voltage for High-Voltage Circuit Breaker – Part 2

    http://www.ewh.ieee.org/soc/pes/switchgear/presentations/2013-2_Thu_Dufournet.pdf
  - IEEE C37.011 (2011) Guide for the Application of TRV for High-Voltage Circuit Breakers

Content

1. AC High-Voltage Circuit Breaker
2. SF_6 and Alternatives
3. Rated Characteristics
4. Operating Mechanism
5. Arcing Phenomena in HV Circuit Breakers
6. Arc Extinction Principles
7. Switching Duties
8. **Standards Related to High-Voltage Circuit Breakers**
9. Annexes
    - Annex 1 on TRV
    - Annex 2 on New Test Procedure T100a
    - Annex 3 on Transformer Limited Faults

Standards Related to HV Circuit Breakers

Standards are important as they

- Facilitate exchanges in the world by suppressing technical barriers
- Ensure the quality of goods and services
- Contribute to safety, protection of environment
- Guarantee interoperability of systems.

How standards are made ?

- by Standards Development Organizations (SDO) such as IEEE, IEC and ISO that offer platforms, rules, governance and methodologies for the development, distribution and maintenance of standards.

Standards Related to HV Circuit Breakers

- IEC is an organization for international standards in electrotechnology.
- IEC standards are used all over the world, in more than 160 countries.
- IEC has a large membership: 60 National Committees (NCs), plus 23 associates
- Technical work is done by 122 Technical committees (TC) covering all aspects of electrotechnology
- TC17 is the high-voltage switchgear committee
- Drafts are prepared by experts in working groups
- Comments and votes on drafts are done by National Committees.
- The committee draft for voting (CDV) and the final draft for international standard (FDIS) are approved when at least 2/3 of votes are positive.

Standards Related to HV Circuit Breakers

Main IEC standards related to high-voltage circuit breakers

IEC 62271-1 – Common specifications for HV switchgear

under revision, new edition 2 in 2017

IEC 62271-100 – High-Voltage circuit breakers

under revision, amendment 2 in 2017

IEC 62271-101 – Synthetic testing

under revision, amendment 1 in 2017

IEC 62271-110 – Inductive load switching

under revision, new edition 4 in 2017

IEC 62271-203 – Gas-insulated metal-enclosed switchgear for rated voltages above 52 kV

Standards Related to HV Circuit Breakers

Main IEC standards (Cont'd)

IEC/IEEE 62271-37-013 – Generator circuit breakers

common development with IEEE, under revision

IEC 62271-300 – Seismic qualification of AC circuit-breakers

IEC 62271-302 – Alternating current circuit-breakers with intentionally non-simultaneous pole operation

IEC 62271-306 – Guide for the application of IEC 62271-100, 62271-1 and other related circuit-breaker standards.

under revision, new edition in 2017

IEC 62271-4 – Use and handling of SF_6 in high-voltage switchgear and controlgear

IEC 60376 – Specification of technical grade sulfur hexafluoride (SF_6) for use in electrical equipment

Standards Related to HV Circuit Breakers

IEEE Standards

- Mainly used in North-America;
- Prepared by committees e.g. IEEE Switchgear Committee;
- The IEEE Standard Association oversees the standard development process.
- The responsibility for the development of standards for HV circuit breaker lies with the High Voltage Circuit Breaker (HVCB) Subcommittee of PES (Power & Energy Society) Switchgear Committee.
- Work is done by experts in working groups
- Documents have the status of standard, recommended practice or guide.
- Only standards contain mandatory requirements.

Standards Related to HV Circuit Breakers

Main IEEE standards

IEEE C37.100.1 – Common requirements for Power Switchgear

under revision, new edition in 2017

IEEE C37.04 – Ratings and Requirements for AC HV Circuit Breakers

under revision, combined with IEEE C37.06

IEEE C37.06 – Preferred Ratings

IEEE C37.06.1 – Recommended Practice for Preferred Ratings for HV AC Circuit Breakers – Designated Definite Purpose for Fast TRV Rise Times

under development

IEEE C37.09 – Test Procedure

under revision, new edition in 2018

Standards Related to HV Circuit Breakers

Main IEEE standards (Cont'd)

IEEE C37.010 – Application Guide for AC HV Circuit Breakers

under revision, published in April 2017

IEEE C37.011 – Guide for the Application of Transient Recovery Voltage for AC High-Voltage Circuit Breakers

IEEE C37.012 – Guide for the Application of Capacitance Current Switching for AC High-Voltage Circuit Breakers

under revision, work starting on amendment 012a

IEEE C37.015 – Guide for the Application of Shunt Reactor Switching

under revision

IEC/IEEE 62271-37-013 – AC Generator Circuit Breaker

common development with IEC

Standards Related to HV Circuit Breakers
Harmonization of IEC & IEEE Standards

Harmonization of IEC & IEEE standards for HV circuit breakers

- Work done from 1995 to 2010
- Common ratings & test requirements for making and breaking capabilities.
- Done for shunt reactor switching, capacitive current switching, TRVs

Dual logo standards

- First IEC-IEEE agreement signed in 2002
- Dual logo standard IEC-IEEE 62271-111 for reclosers

Joint development of standards (starting in 2008)

Sound pressure measurements	IEC/IEEE 62271-37-082
Generator circuit breakers	IEC/IEEE 62271-37-013

Standards Related to HV Circuit Breakers Future Work

Some suggestions for the present and future revisions of standards for high-voltage circuit breakers

- Remove significant differences that exist in ratings and testing for dielectric withstand capabilities
  - Between requirements of IEEE C37.100.1 (that includes IEC values and IEC test procedure) and C37.04 & C37.09
- Transfer test requirements presently in IEEE C37.04 but should be in IEEE C37.09;
- Avoid keeping alternate Tables or additional lines in Tables with historical values (that can be found in past edition of standards);
- Be bold, as some of us were when working on the harmonization of TRVs between IEC and IEEE. Together with will, work, expertise and leadership, it is needed to write better standards for the future.

Thanks for your attention
Questions ?

Content

1. AC High-Voltage Circuit Breaker
2. SF_6 and Alternatives
3. Rated Characteristics
4. Operating Mechanism
5. Arcing Phenomena in HV Circuit Breakers
6. Arc Extinction Principles
7. Switching Duties
8. Standards Related to High-Voltage Circuit Breakers
9. **Annexes**
    - Annex 1 on TRV
    - Annex 2 on New Test Procedure T100a
    - Annex 3 on Transformer Limited Faults

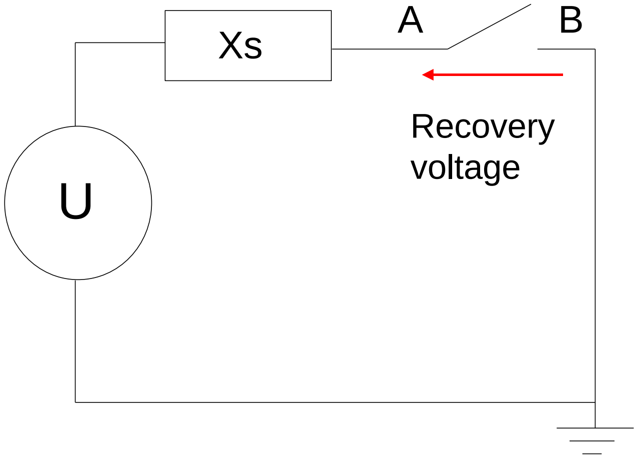
Content

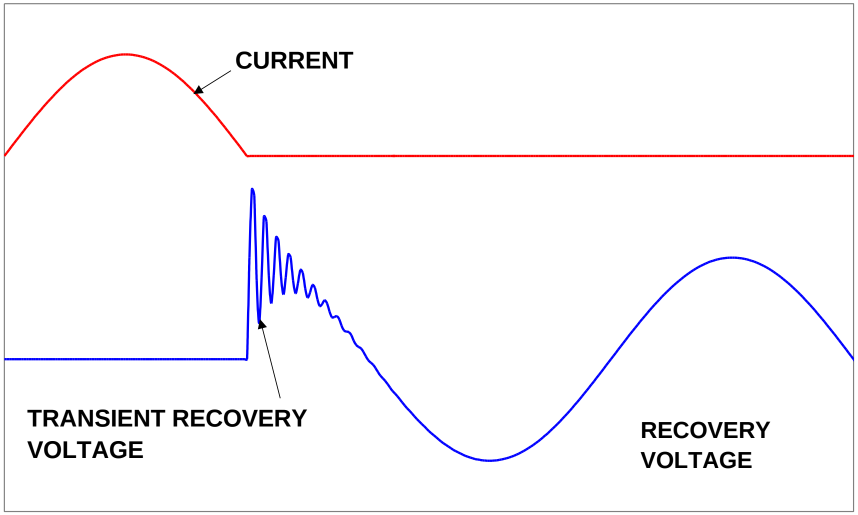
Transient Recovery Voltage

The recovery voltage is the voltage which appears across the terminals of a pole of circuit breaker after current interruption.

In an inductive circuit

- A transient recovery voltage (TRV) is applied during several hundreds of microseconds.
- It is followed by a recovery voltage at power frequency (50Hz or 60Hz).





Transient Recovery Voltage

The nature of the TRV is dependent on the circuit being interrupted, whether primarily resistive, capacitive or inductive, (or some combination).

When interrupting a fault at the circuit breaker terminal (terminal fault) in an inductive circuit, the supply voltage at current zero is maximum.

The circuit breaker interrupts at current zero (at a time when the power input is minimum), the voltage on the supply side terminal meets the supply voltage in a transient process called the TRV.

TRV frequency is

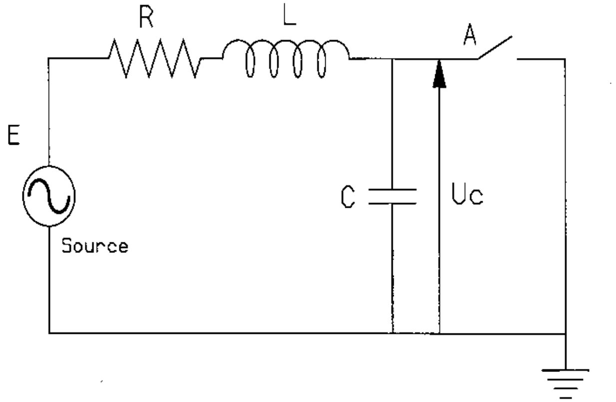
$$\frac{1}{2\pi\sqrt{LC}}$$

with

L = short-circuit inductance

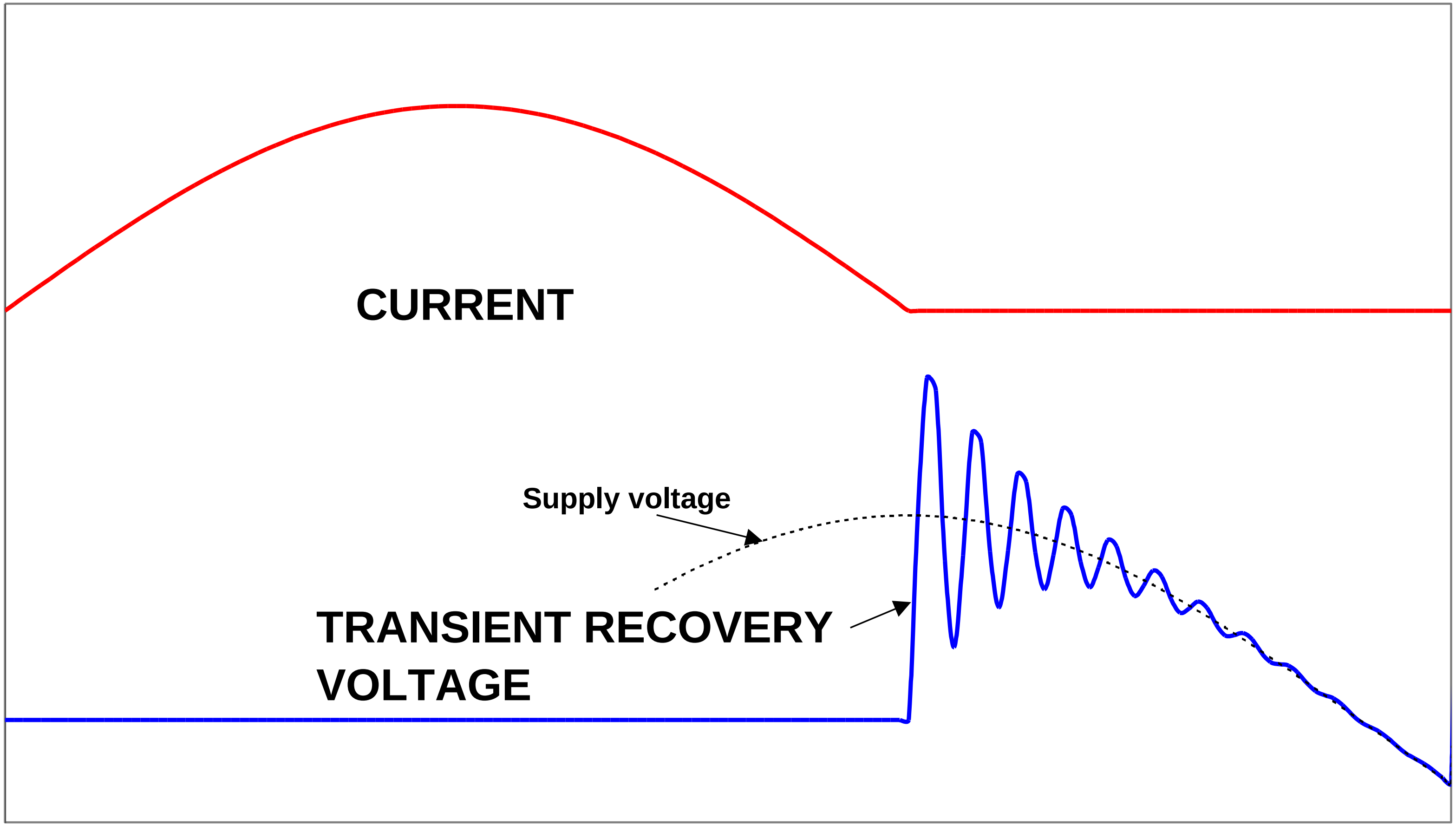
C = capacitance on source-side

$R \ll L\omega$



Transient Recovery Voltage

TRV during inductive current interruption



Transient Recovery Voltage

The TRV is a decisive parameter that limits the interrupting capability of a circuit breaker.

The interrupting capability of a circuit breaker was found to be strongly dependent on TRV in the 1950’s.

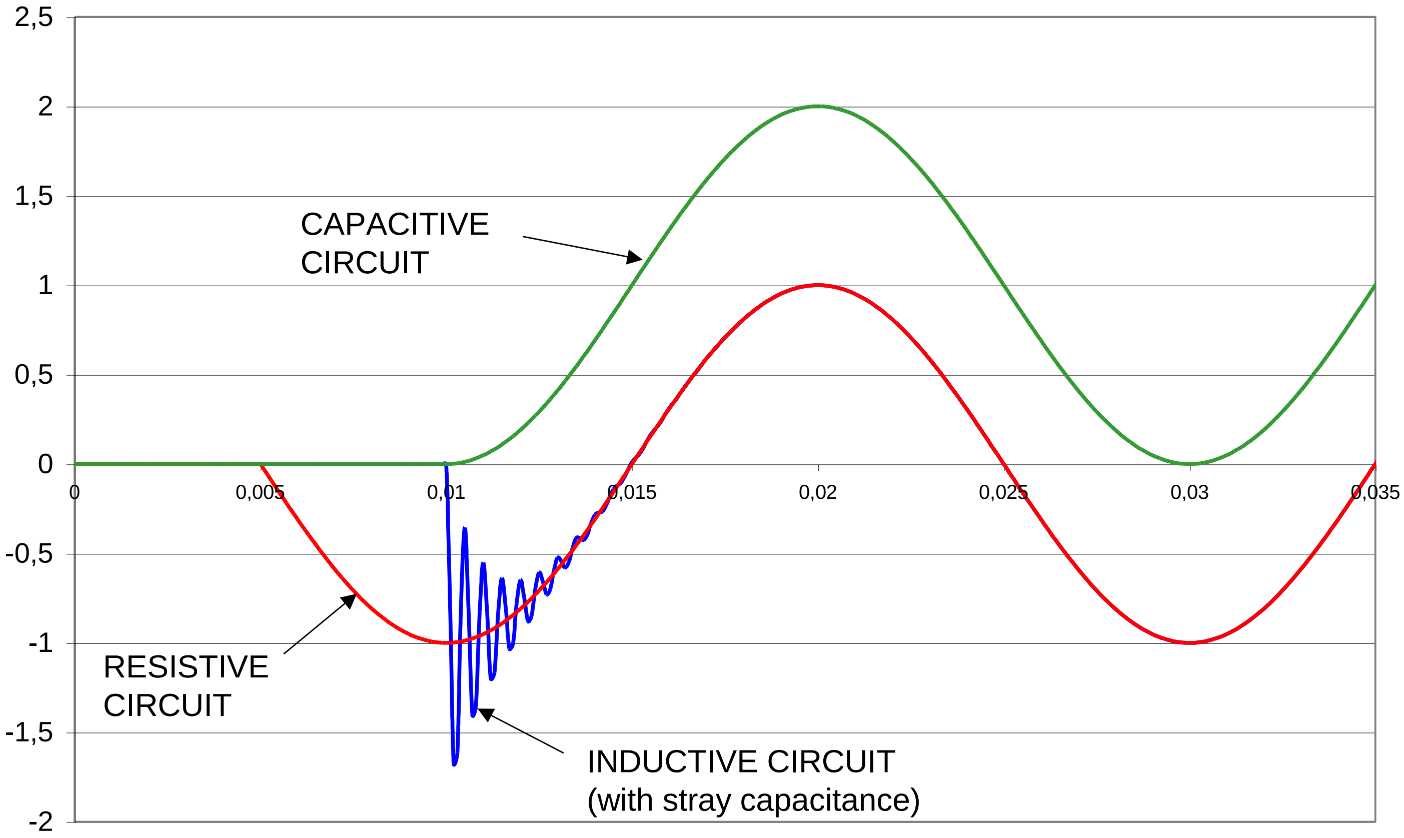
When developing interrupting chambers, manufacturers must verify and prove the TRV withstand specified in the standards for different test duties.

Users must specify TRVs in accordance with their applications.

Type tests in high-power laboratories must be performed in accordance with international standards, in particular with rated values of TRVs.

Transient Recovery Voltage

TRV and recovery voltage in resistive, inductive and capacitive circuits



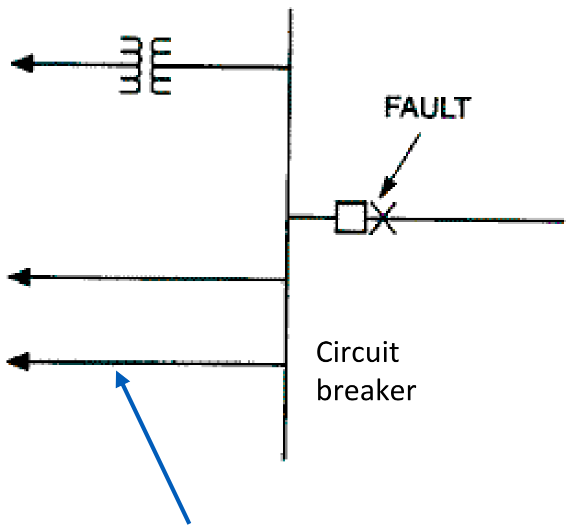
Transient Recovery Voltage

- TRVs can be oscillatory, triangular, or exponential and can occur as a combination of these forms
  - Oscillatory and/or exponential TRV in case of terminal fault
  - Triangular TRV in case of short-line-fault
- In general, a network can be reduced to a simple parallel RLC circuit for TRV calculations.

  This representation is valid for a short-time period until voltage reflections return from remote buses (see IEEE C37.011-2011).

Transient Recovery Voltage

Real network

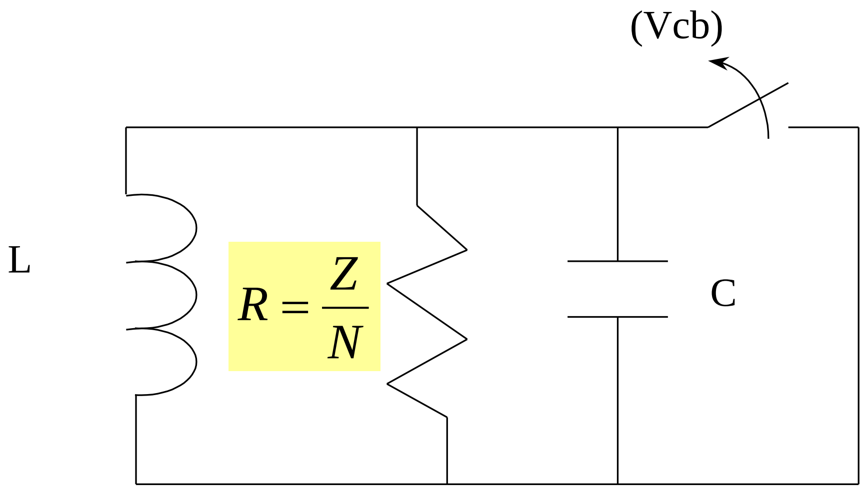


N lines, each with surge impedance

$$Z = \sqrt{\frac{l}{c}}$$

l and *c* = inductance and capacitance per unit length

Equivalent circuit



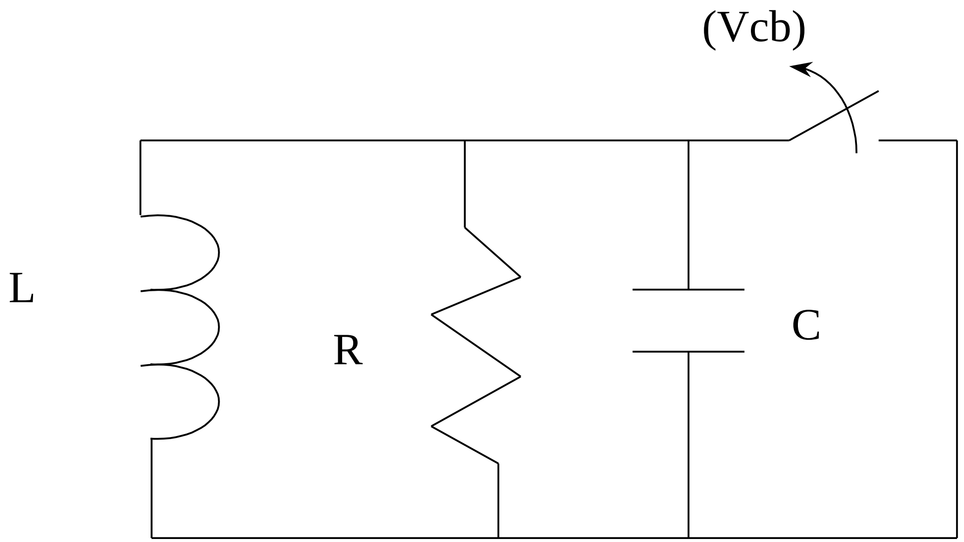
$$R = \frac{Z}{N}$$

L: source inductance, lines excepted

C: source capacitance, lines excepted

Note: in cases where C can be neglected, the initial slope of the TRV is equal to (*Z*/N) x (di/dt) where di/dt is the slope of current before interruption.

Transient Recovery Voltage



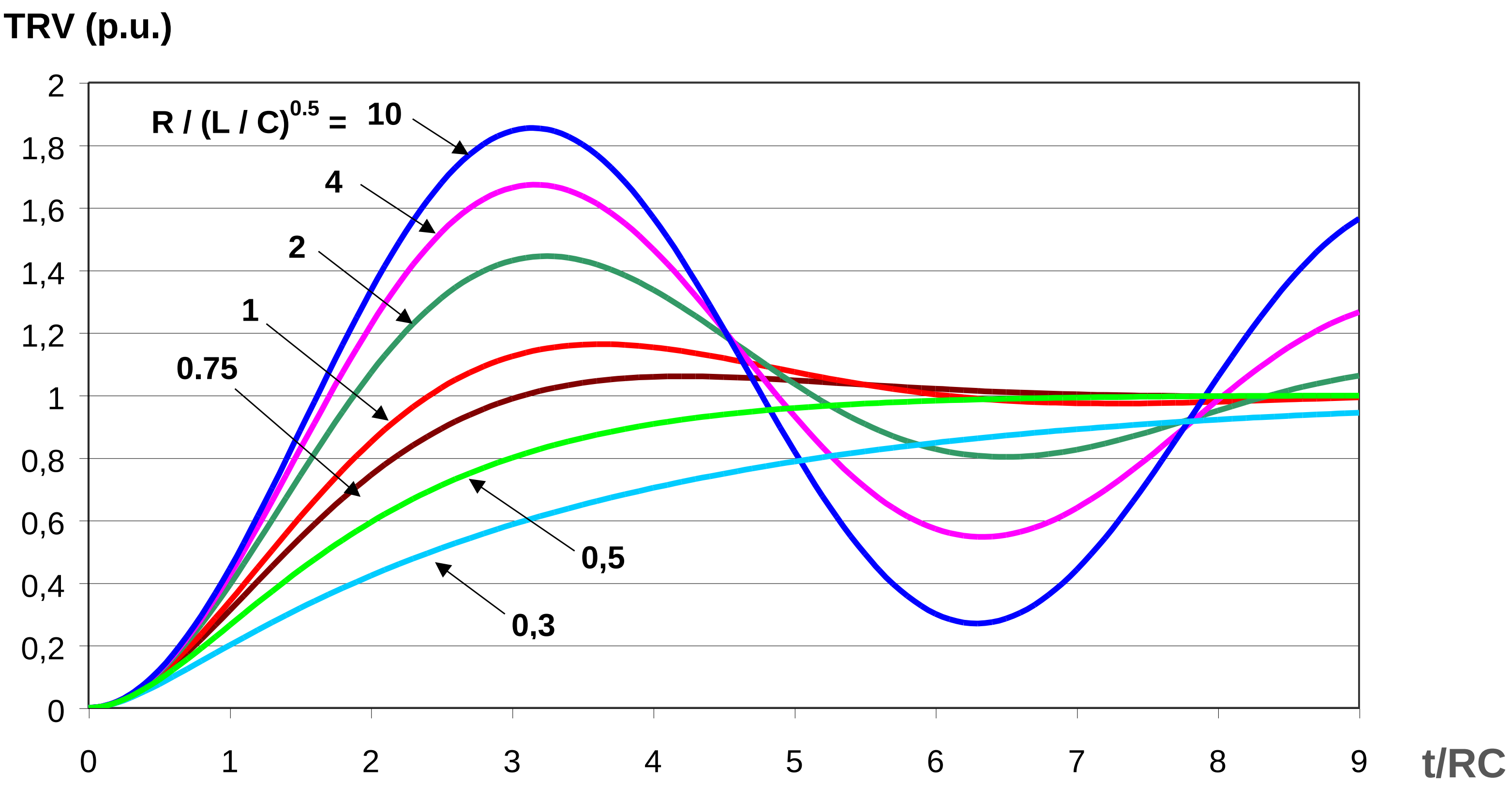
- The TRV in the parallel RLC circuit is oscillatory (under-damped) if

$$R \rangle \frac{1}{2}\sqrt{L/C}$$

- The TRV in the parallel RLC circuit is exponential (over-damped) if

$$R \le \frac{1}{2}\sqrt{L/C}$$

Transient Recovery Voltage



Damping of the oscillatory TRV is done by R.

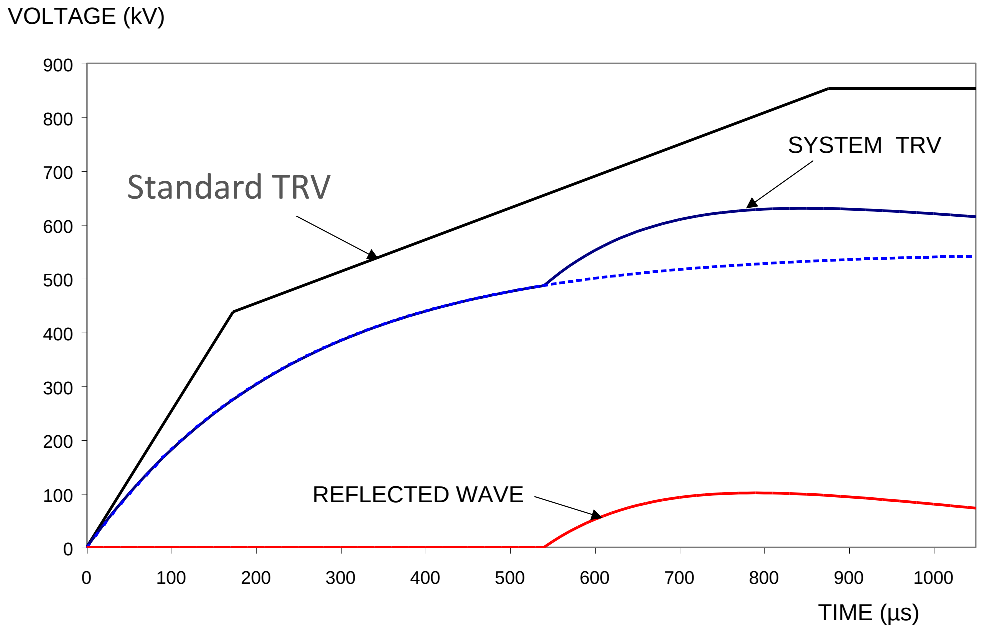
As R is in parallel with L and C (parallel damping) the damping decreases when R increases. The TRV peak increases when R increases.

TRV is damped by a resistance of low value in parallel to a circuit breaker.

Transient Recovery Voltage

Reflection from end of lines

When longer time frames are considered, typically several hundreds of micro-seconds, reflections on lines must be considered.



Voltage waves travel on lines after current interruption.

These traveling waves are reflected and refracted when reaching an open circuit, an earth fault or a discontinuity.

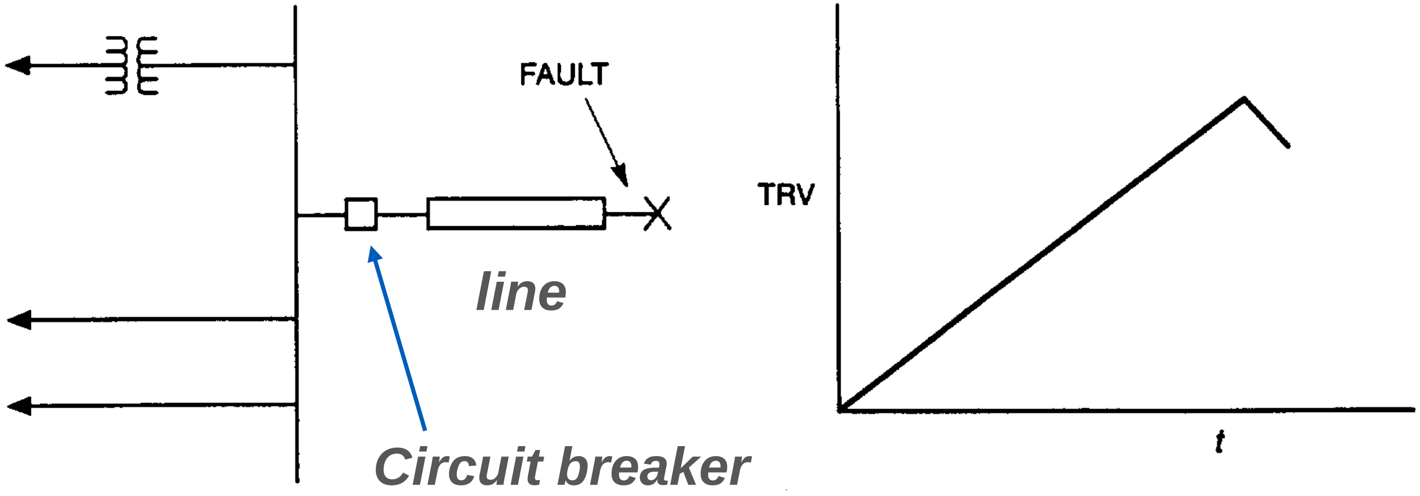
As will be seen in the chapter on Terminal Fault Breaking, the resulting wave shape is covered in Standards by a “Four parameters TRV”.

Transient Recovery Voltage

Triangular-shaped TRVs are associated with short-line faults (SLF).

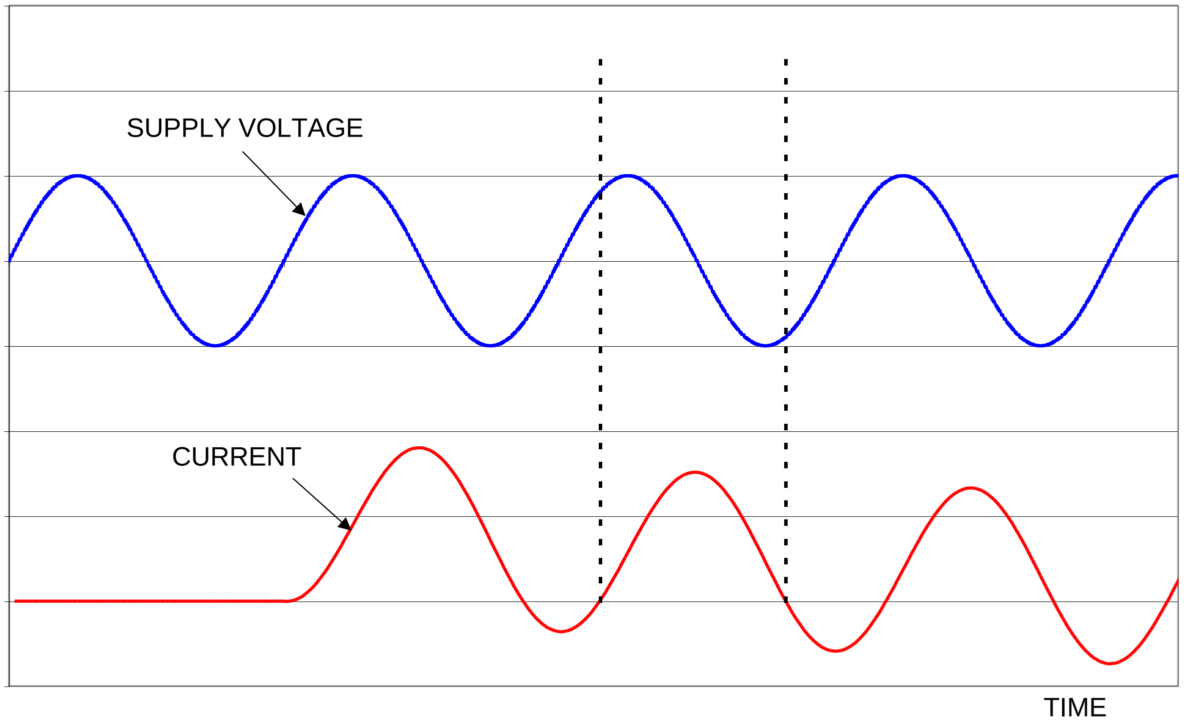
After current interruption, the line-side voltage exhibits a characteristic triangular waveshape.

The rate-of rise of TRV is usually higher than that experienced with exponential or oscillatory TRVs (in case of high short-circuit current), however the TRV peak is generally low.



Transient Recovery Voltage
TRV Modification

When interrupting asymmetrical currents, TRV is less severe (lower RRRV and lower TRV peak) than when interrupting the related symmetrical current because the instantaneous value of the supply voltage at the time of interruption is lower than the peak value.



Transient Recovery Voltage
TRV Modification

TRV modification due to current asymmetry

- Correction factors of the TRV peak and rate of rise of recovery voltage (RRRV) when interrupting asymmetrical currents are given in IEC 62271-101 “Synthetic testing” (2012-10)

- The RRRV is proportional to the slope of current before interruption (di/dt). Factor F_1 gives the correction due to current asymmetry:

$$F_1 = \sqrt{1 - D^2} \pm \frac{D}{X / R}$$

with		
	D	degree of asymmetry at current zero (p.u.)
	$-D$	interruption after a major loop of current
	$+D$	interruption after a minor loop of current
	X / R	short-circuit reactance divided by resistance

- When the time to peak TRV is relatively short (< 500 µs), the correction factor for the TRV peak is also F_1.

Transient Recovery Voltage
TRV Modification

During current interruption, the circuit TRV can be modified by a circuit breaker:

- by arc resistance,
- by the circuit breaker capacitance or opening resistor (if any).

The TRV during current interruption measured across the terminals of different types of circuit breakers under identical conditions can be different.

To simplify both rating and application, the power system TRV is calculated ignoring the influence of the circuit breaker.

In standards, the circuit breaker is considered to be ideal i.e. without modifying effects on the electrical characteristics of a system,

- circuit breaker impedance is zero before current interruption,
- at current zero its impedance changes from zero to infinity.

Transient Recovery Voltage
First Pole To Clear

- The recovery voltage for the first-pole-to-clear a three-phase fault is the product of the phase-to-ground voltage multiplied by the first-pole-to-clear factor (k_{pp}).
- The value of k_{pp} is dependent upon the sequence impedances from the location of the fault to the various system neutral points (ratio X_0/X_1).

$$\boxed{k_{pp} = \frac{3X_0}{X_1 + 2X_0}}$$

where X_0 is the zero sequence reactance of the system,

X_1 the positive sequence reactance of the system.

For systems with effectively grounded neutrals the ratio X_0/X_1 is taken to be ≤ 3.0. It follows that k_{pp} is 1.3.

For systems with non-effectively grounded neutrals k_{pp} is 1.5.

Transient Recovery Voltage
TRV peak

The peak value of TRV is calculated as follows:

$$\boxed{U_c = k_{af} \times k_{pp} \times \sqrt{2} \times \frac{U_r}{\sqrt{3}}}$$

where

k_{pp}	is the first-pole-to-clear factor
k_{af}	is the amplitude factor
U_{r}	is the rated maximum voltage

In IEC 62271-100 and IEEE C37.04, k_{af} is 1.4 at 100% rated breaking current.

Content

New Test Procedure T100a Introduction

A new test procedure is introduced in IEEE C37.09-201x (also in amendment 2 to IEC 62271-100) in order to have a better correspondence between the test conditions during three-phase tests and single-phase tests made in substitution for three-phase tests (same amplitude of the major loop, arcing times, etc.). The aim is also to have tests with the correct amplitude and duration of the major loop of current before interruption, independently of the time constant of the test circuit.

The new test procedure is based on the fact that the relevant major loop of current with full asymmetry to consider before current interruption for the two main test conditions (interruption of the first pole to clear after a major loop of current with required asymmetry and longest arcing time, and interruption of a last pole to clear after a major extended loop of current with required asymmetry and longest arcing time) depends on the capability of the circuit-breaker to interrupt after a minor loop of current with intermediate asymmetry.

A new definition has been introduced to define the minimum clearing time of a circuit-breaker: it is the sum of the minimum opening time, minimum relay time (0.5 cycle) and the shortest arcing time of a minor loop interruption in the phase with intermediate asymmetry that starts with a minor loop at short-circuit current initiation. It will be explained by the example given in the next slides.

New Test Procedure T100a
Basis

To illustrate the different cases of three-phase fault interruption presented hereafter the following parameters are chosen:

Rated frequency = 50 Hz relay time = 10 ms $k_{pp} = 1.5$ $\tau = 45$ ms

Opening time = 11.5 ms

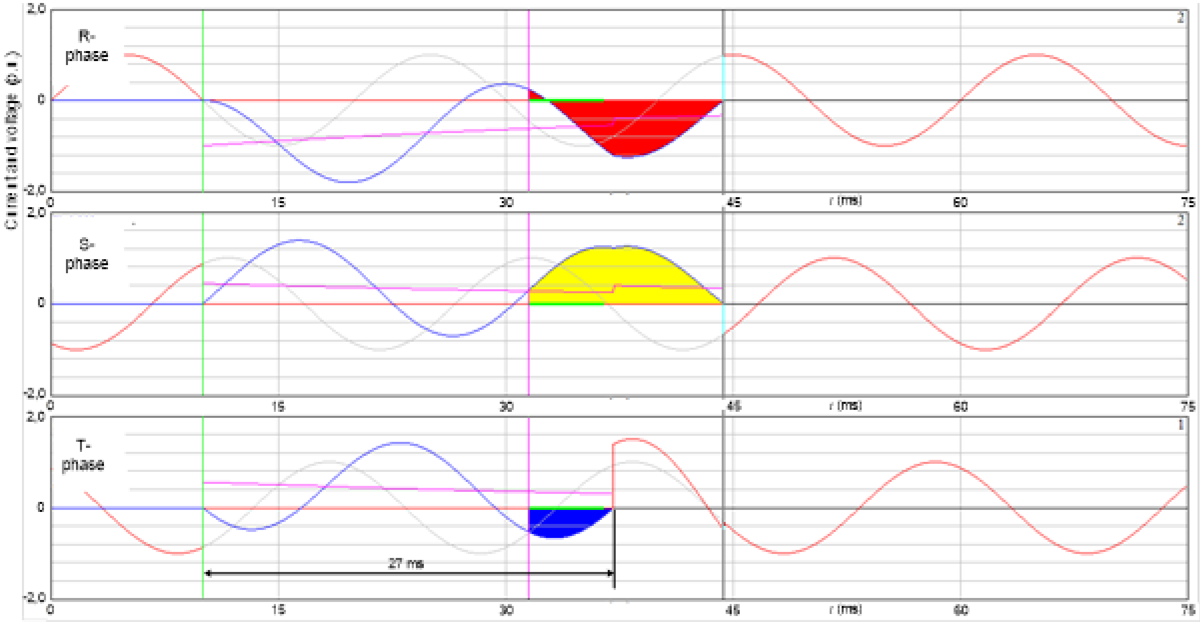
Shortest arcing time interruption after a minor loop (blue phase shown in the next slides) = 5 ms

Minimum clearing time = 10 + 11.5 + 5 = 26.5 ms

The example chosen corresponds to the first line in Table 2 of IEEE C37.09-201x.

New Test Procedure T100a
Basis – Case 1

Figure 1 illustrates a first case of three-phase fault interruption in which a first pole (blue phase) clears after a minor loop of current with intermediate asymmetry. This is possible as the minimum clearing time is lower than the duration of 27 ms between initiation of the short-circuit current and passage through zero of current in the blue phase. This would not be a valid test but it is shown here to illustrate what happens when instant of constant separation is changed.

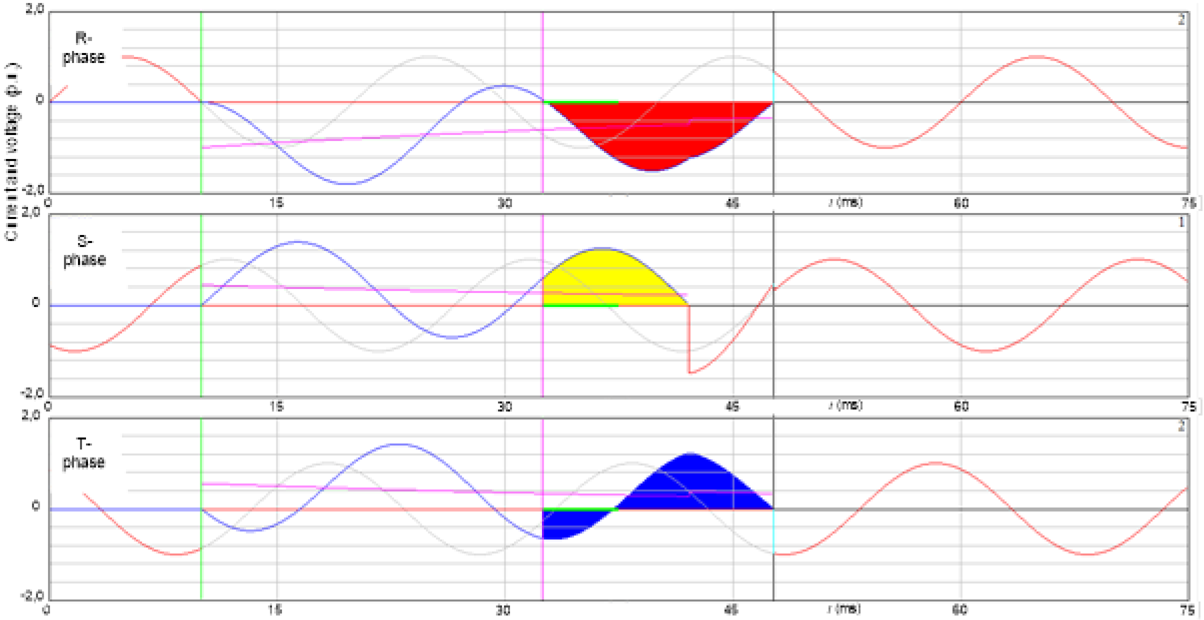


Case 1 - Interruption by a first pole (blue phase) after minor loop of current with intermediate asymmetry

New Test Procedure T100a
Basis – Case 2

If contact separation is delayed by 18° (1 ms at 50 Hz), a first pole interrupts after a symmetrical loop of current (yellow phase) and a last pole clears a major extended loop with required asymmetry and the longest possible arcing time. This is one of the two breaking conditions for which interruption must be proved.

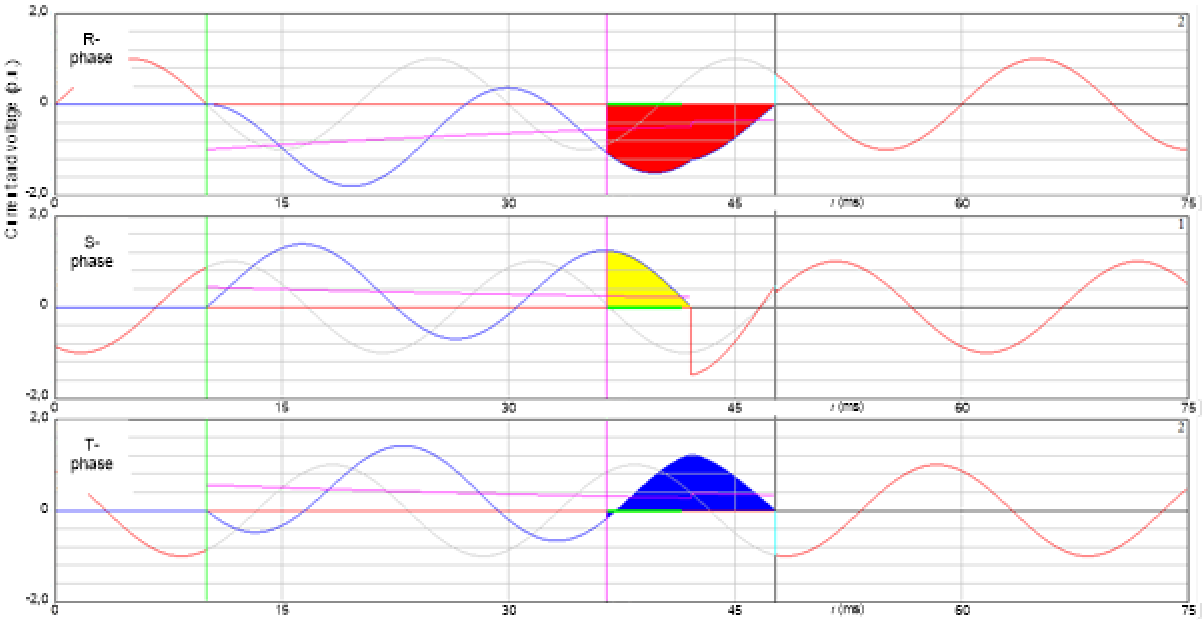
The major extended loop of current in the red phase has an amplitude of 1.52 p.u. and a duration Δ*t*2 of 15 ms, as given in line 1 of Table 2.



Case 2 - Interruption of a last-pole-to-clear after a major extended loop of current with required asymmetry and longest arcing time.

New Test Procedure T100a
Basis – Case 3

If contact separation is delayed by 4 ms, Figure 3 shows that the test condition is less severe as last pole that clears in the red phase with a major extended loop has a shorter arcing time.

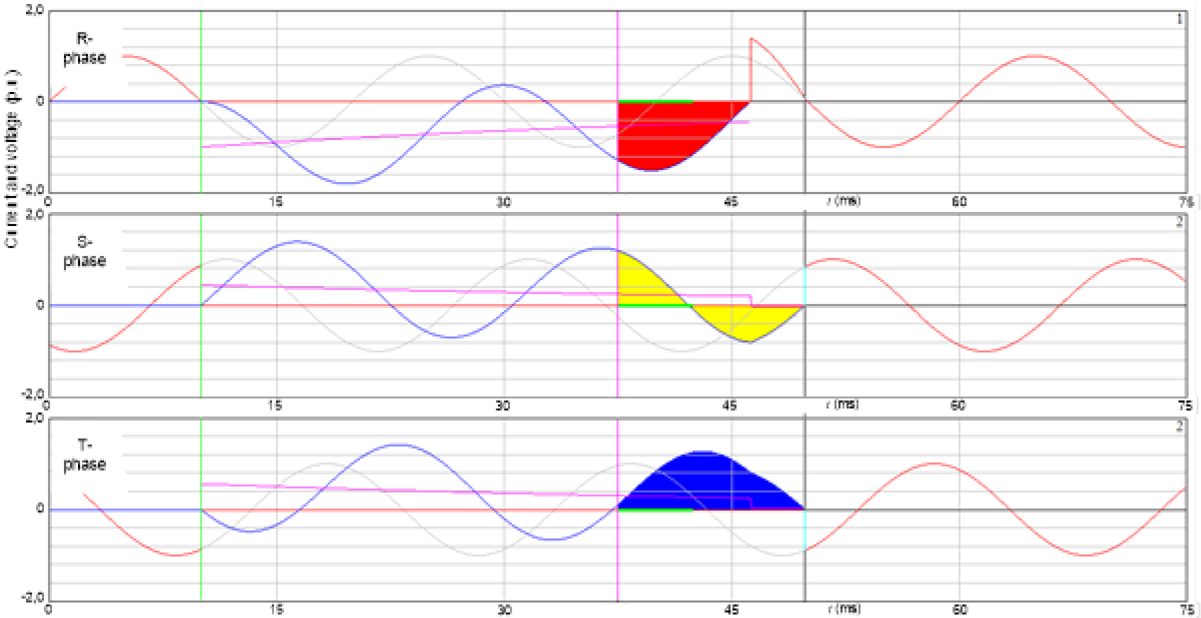


Case 3 - Interruption of a last-pole-to-clear after a major extended loop of current with required asymmetry but not the longest arcing time.

New Test Procedure T100a
Basis – Case 4

If contact separation is further delayed by 1 ms Figure 4 shows that the first pole clears in the red phase after a major loop with required asymmetry and the longest arcing time for a first-pole-to-clear. It is the second breaking condition for which interruption must be proved. It should be noted that the major loop with maximum asymmetry to consider for the first pole to clear is the same as seen in case 2 (for a last-pole-to-clear). It is also function of the minimum clearing time.

The major loop of current in red phase has an amplitude of 1.52 p.u. and a duration Δt_1 of 13.6 ms, as given in line 1 of Table 2.



Case 4 - Interruption by the first pole in the red phase after a major loop of current with required asymmetry and the longest arcing time (for a first-pole-to-clear).

New Test Procedure T100a
Basis

The parameters considered in this example corresponds to the first line of Table 2 i.e. with a minimum clearing time higher than 10 ms and equal or lower than 27 ms.

The other intervals of minimum clearing time given in Table 2 are the intervals between each possible instant of interruption after a minor loop in the blue phase.

New Test Procedure T100a
Test Requirements

Requirements are given in section 4.9 of IEEE C37-09-201x

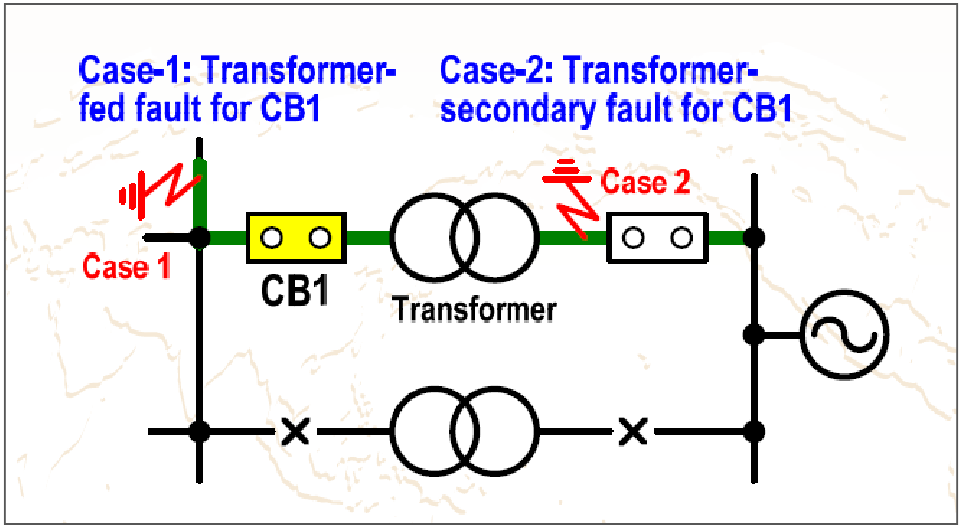
- 4.9.2.3.3 Arcing time for three-phase test duty T100a
- 4.9.2.3.4 Arcing time for additional tests to three-phase tests to cover both conditions for kpp = 1.3 and kpp = 1.5
- 4.9.2.3.5 Arcing time for single-phase tests in substitution for three-phase conditions and short-line fault tests
- 4.9.2.3.7 Arcing time for single-phase tests duty T100a in substitution for three-phase tests
- 4.9.2.3.8 Arcing time for single-phase tests covering both conditions for k_{pp} = 1.3 and kpp = 1.5

Content

Switching Phenomenon
Transformer Limited Fault Interruption

Severe TRV (Transient Recovery Voltage) may occur when a short-circuit current is fed or limited by a transformer without any appreciable capacitance between the transformer and the circuit breaker.

These faults are called Transformer Limited Faults (TLF).



In such case, the rate-of-rise of recovery voltage (RRRV) exceeds the values specified in the standards for terminal faults.

Switching Phenomenon
Transformer Limited Fault Interruption

As explained in IEEE C37.011 (2011) , Guide for the Application of TRV for AC High-Voltage Circuit Breakers), the user has several basic possibilities

1. Specify a fast TRV for TLF with values taken from IEEE C37.06.1 (currently developed),
2. Specify a TRV calculated for the actual application taking into account
   - the natural frequency of the transformer,
   - additional capacitances present between the circuit breaker and the transformer
3. Add a capacitor to reduce the RRRV

Thanks for your attention

Questions ?