CIGRE Study Committes A3
High Voltage Equipment

UHV equipment specifications
Circuit breakers and interrupting phnomena
Vacuum switchgear at transmission voltages
DC interruption and DC switchgears
Controlled switching

Hiroki Ito
Chairman, CIGRE Study Committee A3
Mitsubishi Electric Corporation

What is CIGRE?

Founded in 1921, CIGRE, the Council on Large Electric Systems, is an international Non-profit Association for promoting collaboration with experts from around the world by sharing knowledge and joining forces to improve electric power systems of today and tomorrow.

- ➢ Perform studies on topical issues of the electric power system, such as Supergrid, Microgrid and lifetime management of aged assets, and disseminate new technology and improve energy efficiency.
- ➢ Review the state-of-the-art of technical specifications for power systems & equipment and provide technical background based on the collected information for IEC to assist international standardizations.
- ➢ Maintain its values by delivering unbiased information based on field experience

CIGRE Technical Committee 16 Study Committees

A: Equipment

A1 Rotating electrical machines

E. Figueiredo (Brazil)

A2 Transformers

C. Rajotte (Canada)

A3 High voltage equipment

H. Ito (Japan)

Disseminate new technology and
Promote international standardization

Technical committee

Chairman: Mark Waldron (UK)
Secretary: Yves Maugain (France)

B: Sub-system

B1 Insulated cables

P. Argaut (France)

B2 Overhead lines

K. Papailiou (Switzerland)

B3 Substations

T. Krieg (Australia)

B4 HVDC and Power electronics

B. Anderson (United Kingdom)

B5 Protection and Automation

I. Patriota de Siqueira (Brazil)

Perform studies on topical issues of electric power system and Facilitate the exchange of information

C: System

C1 System development & economics

P. Southwell (Australia)

C2 System operation & control

J. Vanzetta (Germany)

C3 System environmental performance

F. Parada (Portugal)

C4 System technical performance

P. Pourbeik (USA)

C5 Electricity markets & regulations

O. Fosso (Norway)

C6 Distribution systems & dispersed generation

N. Hatziagyriou (Greece)

D: Common technology

D 1 Materials and emerging test technique

J. Kindersberger (Germany)

D 2 Information systems and telecommunication

C. Samitier (Spain)

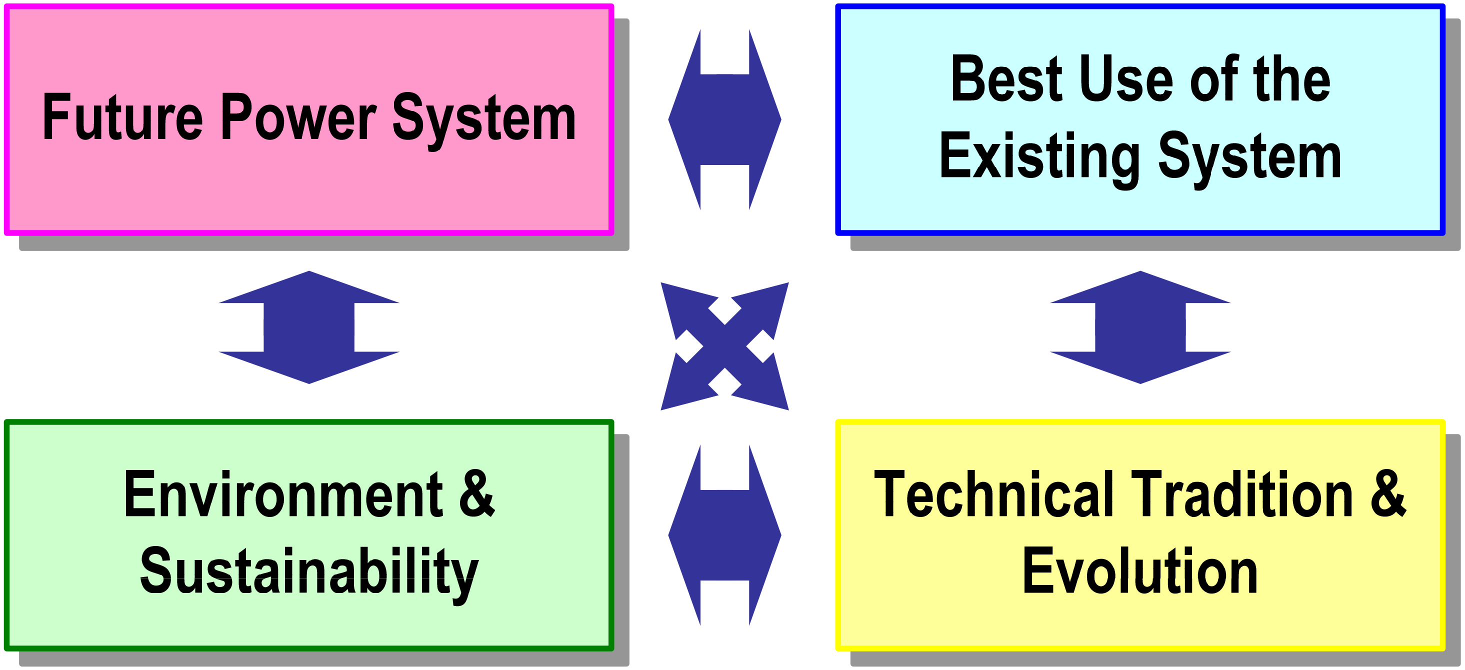
CIGRE Technical Committee Strategic Directions (SD)

SD1: Prepare the “strong and smart” power system of the future

SD2: Make the best use of the existing equipment and system

SD3: Answer the environment concerns

SD4: Develop knowledge and information



Future Power System

Best Use of the Existing System

Environment & Sustainability

Technical Tradition & Evolution

What is Study Committee A3

Study Committee A3 is responsible for the theory, design and application of substation equipment applied to AC and DC systems from distribution through transmission voltages which are not specifically covered under the scope of other study committees. A3 covers all switching devices, surge arresters, capacitors, instrument transformers, insulators, bushings, fault current limiters and monitoring techniques.


72.5kV 31.5kA 2500A VCB


145kV 31.5kA 3150A CO_2 GCB


1100kV Series-capacitor bank


800kV DC Bypass Disconnector


1200kV AC MOSA


800kV DC MOSA


550kV LT-GCB


Internal arc failure


12kV, 800A Superconducting Fault Current Limiter

- Requirements under changing networks and standardisation
- Design and development of substation equipment
- New and improved testing and simulation techniques
- Reliability assessment and lifetime management

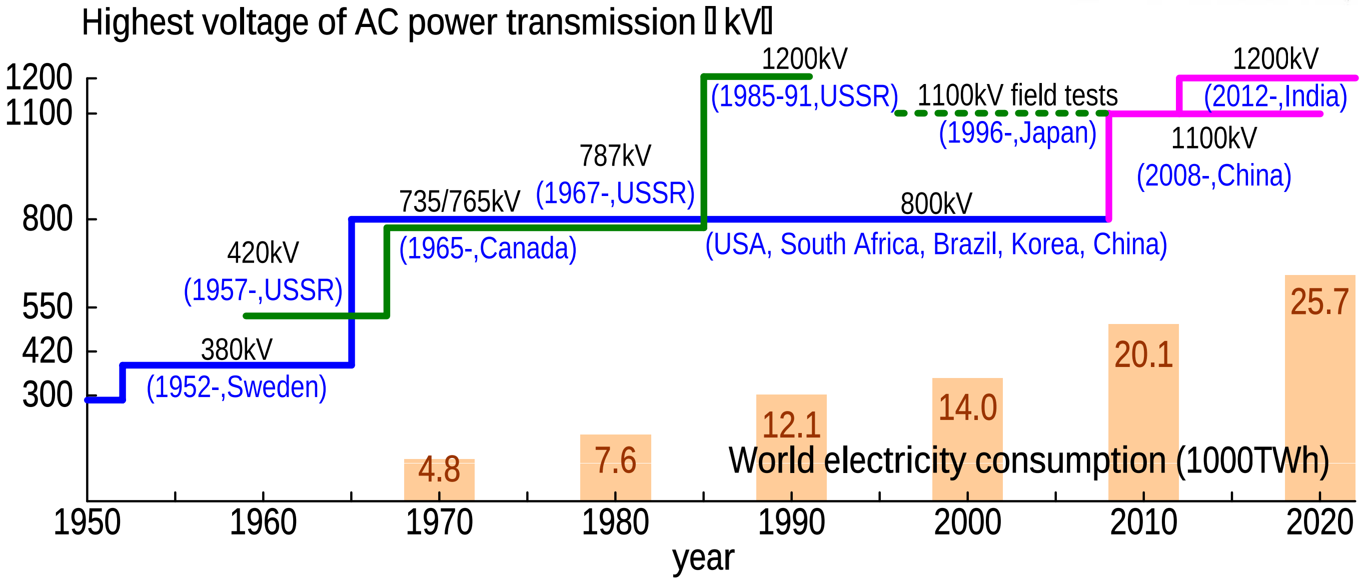
Population, Electricity Supply and Forecast

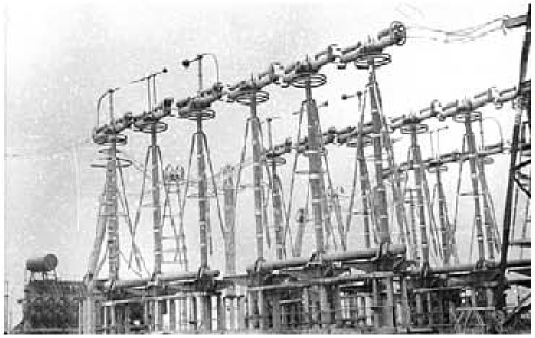
IEA/OECD data	Population (100 milion)			Electricity supply（1000kWh）		
	2008	2012	2020	2008	2013	2020
China	13.4	13.5	13.9	3.5	4.2	6.6
India	11.9	12.3	13.9	0.8	1.0	1.6
Germany	0.8	0.8	0.8	0.6	0.6	0.6
Japan	1.3	1.3	1.2	1.1	1.1	1.0
USA	3.1	3.1	3.4	4.3	4.7	5.3
World	40	69.5	76.5	20.3	20.3	25.7

World population is assumed to rise from 4 billion in 2008 to 8 billion in 2020, 8.6 billion in 2035. Global primary energy demand increases more than 30% in the period to 2020. Over 80% of the electricity demand growth arises in non-OECD countries expecting $37 trillion of investment in the world’s energy supply infrastructure.

Electricity of 1000 TWh is consumed per 0.1 billion population in the US and Japan. China and India are foreseen to continue their investments on energy supply infrastructure.

WG A3.22/28: Requirements for UHV equipment


Highest voltage of AC power transmission（kV）


Russia 1200kV GCB


Japan 1100kV testing field


China 1100kV projects


India 1200kV testing field

A3 provided IEC technical background of UHV specifications for their standardisation works

TB362: Technical requirements for substation equipment exceeding 800 kV
TB456: Background of technical specifications for substation equipment exceeding 800 kV
TB570: Switching phenomena of UHV & EHV equipment

Major results on UHV investigations

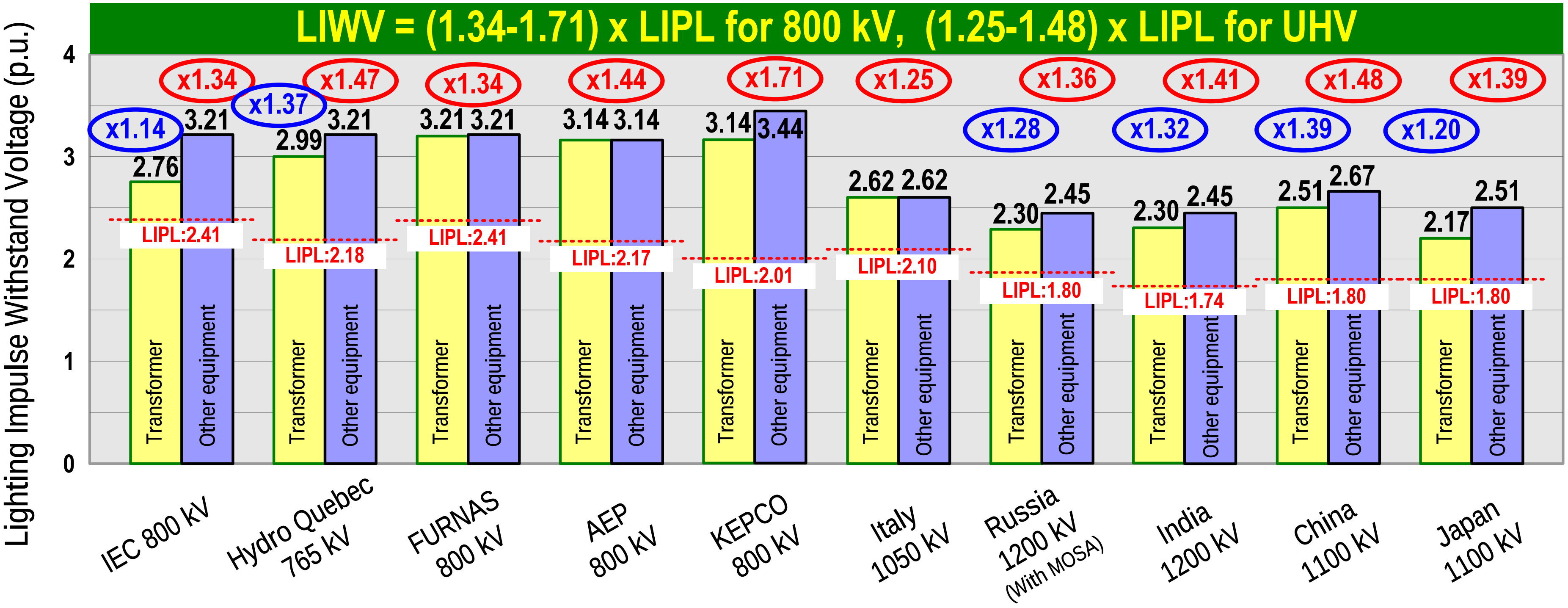
CIGRE UHV project provided excellent opportunities for optimising both the size & cost of UHV equipment.

The CIGRE UHV project has been completed in coordination by several SCs such as WG B3.22/29 on-site testing procedures (TB 400, TB562), WG C4.306 on UHV insulation coordination (TB 542) and AG D1.03 on Very Fast Transient Phenomena (TB 519) beside WG A3.22 and A3.28 on Substation equipment specifications (TB362, TB456, TB570).

UHV transmission can be achieved by optimization of the insulation coordination by application of higher performance MOSA with lower voltage protection levels that can lead to much smaller towers & substations for realizing reliable / economical UHV systems & equipment.

WG A3.28 studied switching phenomena of UHV & EHV equipment in order to support the UHV standardisation works in IEC SC 17A.

Insulation level: LIWV and LIPL



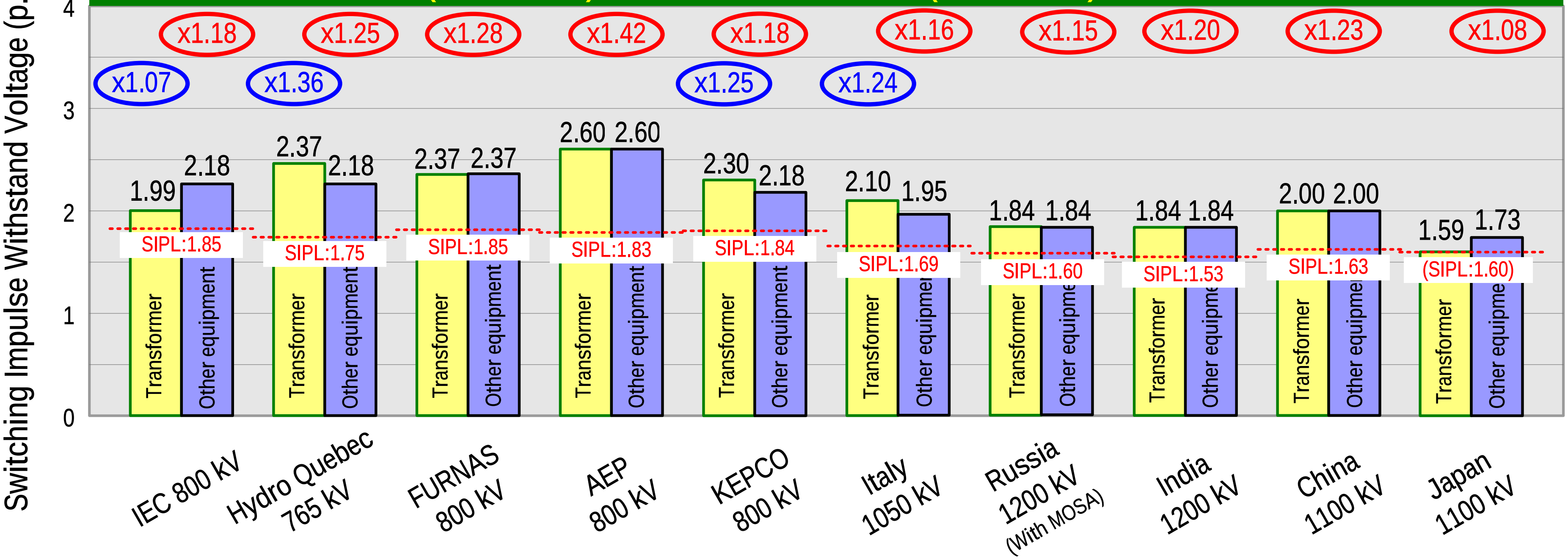
LIWV for UHV=(1.25~1.48) x LIPL is reduced as compared with LIWV for 800 kV=(1.34~1.71) x LIPL providing LIPL with the residual voltage of MOSA at 20 kA.

Typical MOSA arrangement at line entrance, both ends of busbar and transformer terminal

LIWV requirements for UHV transformers in Italy, Russia, India and China are comparable. LIWV requirements for other UHV equipment are fairly close.

Insulation level: SIWV and SIPL

SIWV = (1.18-1.42) x SIPL for 800 kV, (1.08-1.23) x SIPL for UHV

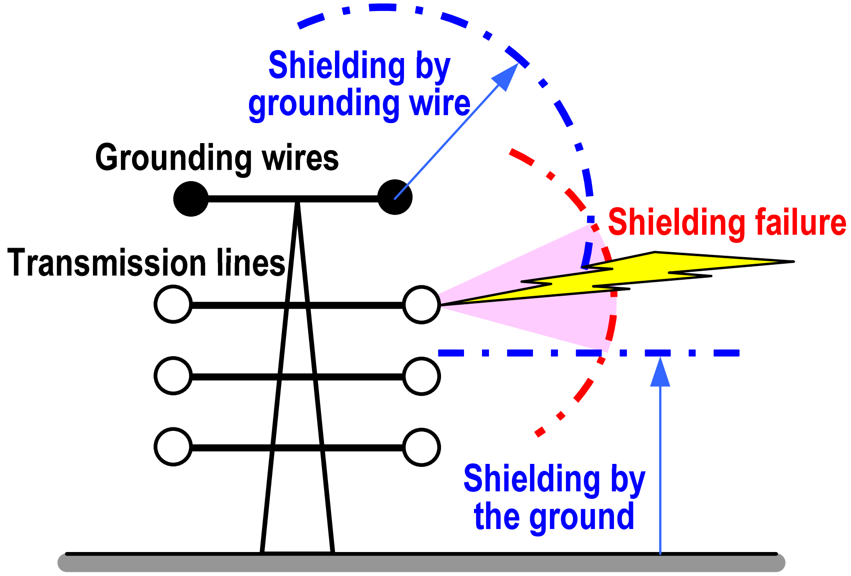


SIWV for UHV=(1.08~1.23) x SIPL is reduced as compared with SIWV for 800 kV=(1.18~1.42) x SIPL providing SIPL with the residual voltage of MOSA at 2 kA.

Mitigation measures such as MOSA with higher performance, CB with opening/closing resistors, DS with switching resistor can effectively suppress the switching surges.

SIWV requirements for 1200 kV in Russia and India have the same values.
SIWV requirements for 1100 kV in China and Japan are slightly different.

Lightning strokes and shielding at tower

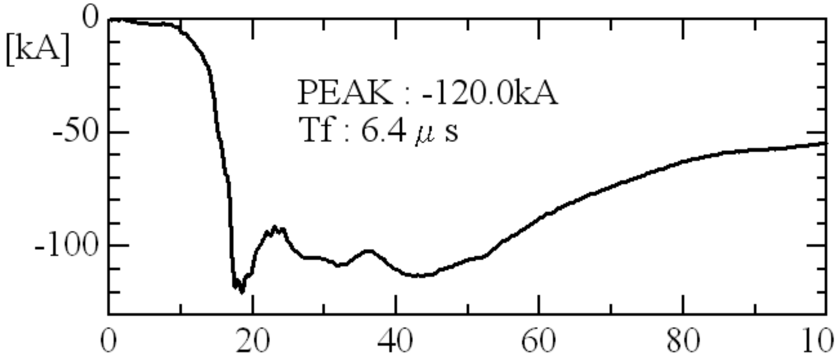


Lightning stroke to Transmission lines

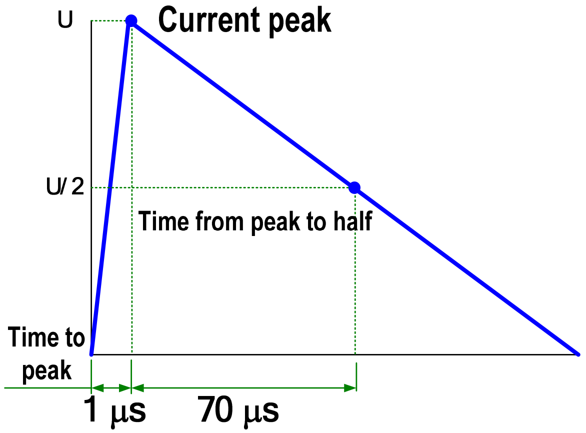
Lightning stroke to Grounding wire

IEEE transactions on power delivery,vol.22,No.1,January 2007

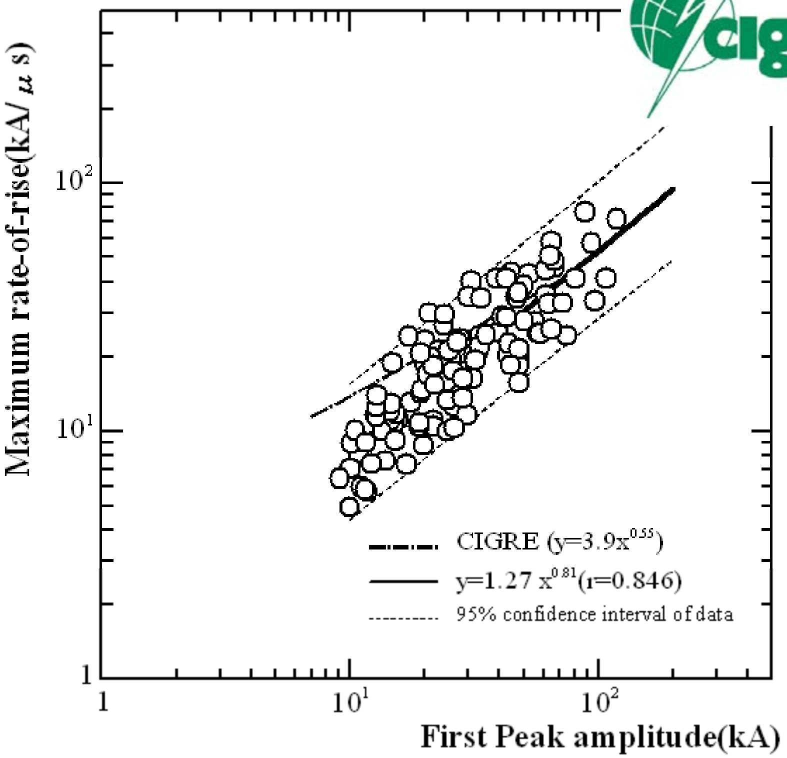
Lightning impulse current survey



Typical measurement of lightning current



Lightning current waveform for UHV



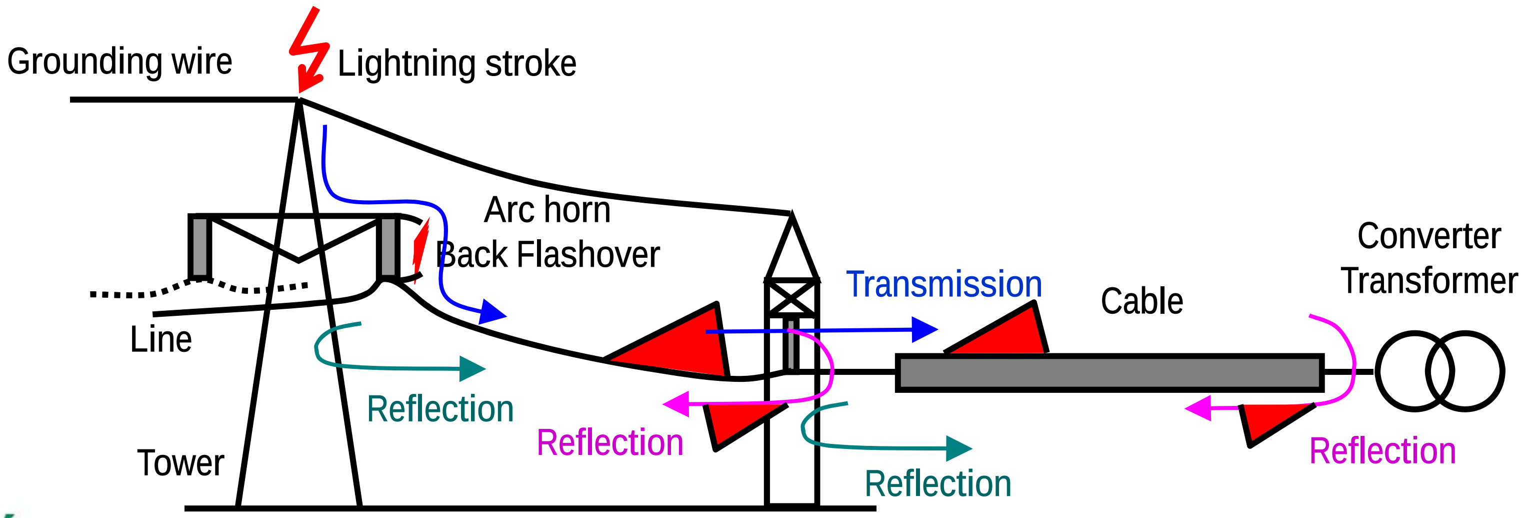
Distribution of lightning currents with di/dt

The maximum lightning current of more than 200 kA is generally used for Lightning surge analysis for systems of 800 kV and above.

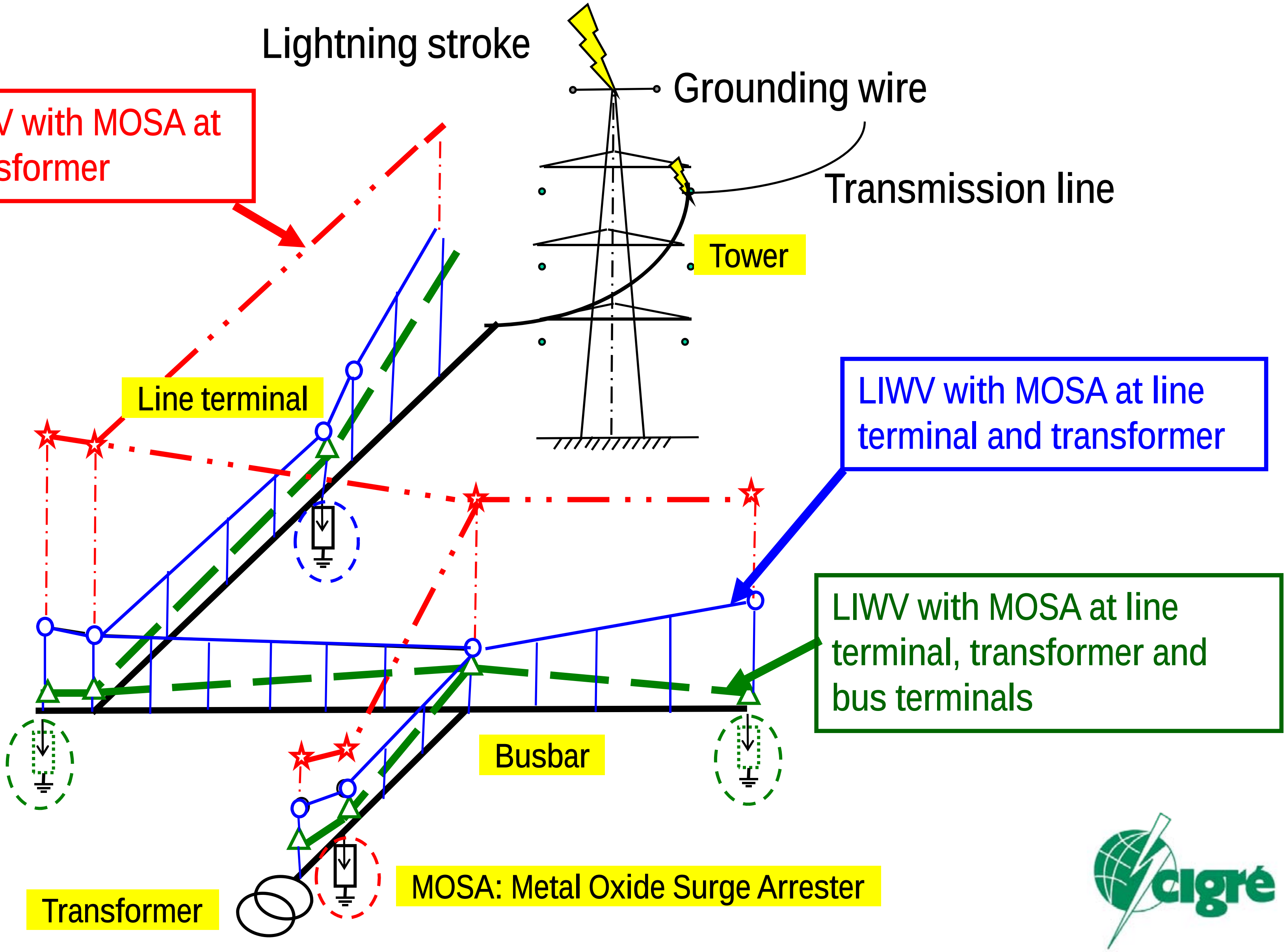
Lightning impulse phenomena

Lightning surge propagated through a transmission line iterates transmissions and reflections at points where line surge impedance changes its value. Superimposed waveforms by the transmissions and reflections may create large lightning impulse surge.

The amplitude of the lightning impulse surge can be evaluated by a surge analysis based on detailed model of transmission system.



LIWV evaluation for different MOSA arrangements



LIWV with MOSA at transformer

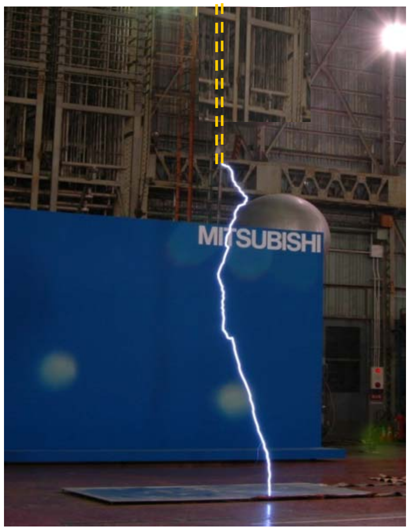
LIWV with MOSA at line terminal and transformer

LIWV with MOSA at line terminal, transformer and bus terminals

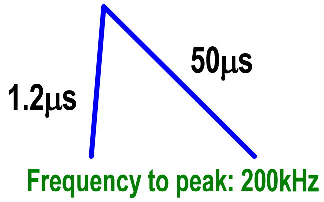
MOSA: Metal Oxide Surge Arrester

Air clearance, Dielectric withstand strength

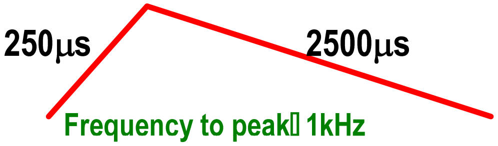
Air Flashover

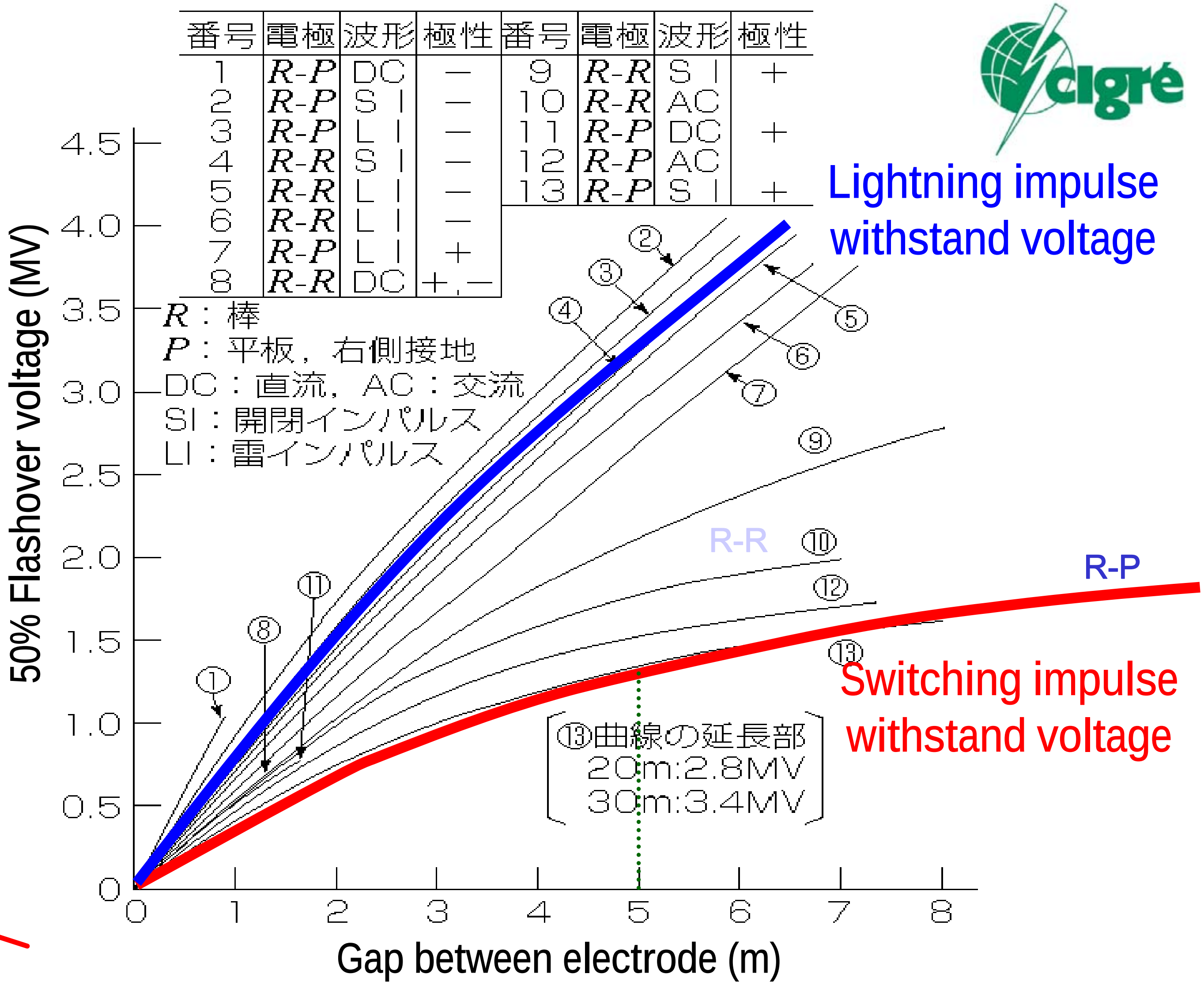


Lightning impulse current



Switching impulse current





番号	電極	波形	極性	番号	電極	波形	極性
1	*R*-*P*	DC	−	9	*R*-*R*	SI	+
2	*R*-*P*	SI	−	10	*R*-*R*	AC	
3	*R*-*P*	LI	−	11	*R*-*P*	DC	+
4	*R*-*R*	SI	−	12	*R*-*P*	AC	
5	*R*-*R*	LI	−	13	*R*-*P*	SI	+
6	*R*-*R*	LI	−				
7	*R*-*P*	LI	+				
8	*R*-*R*	DC	+,−				

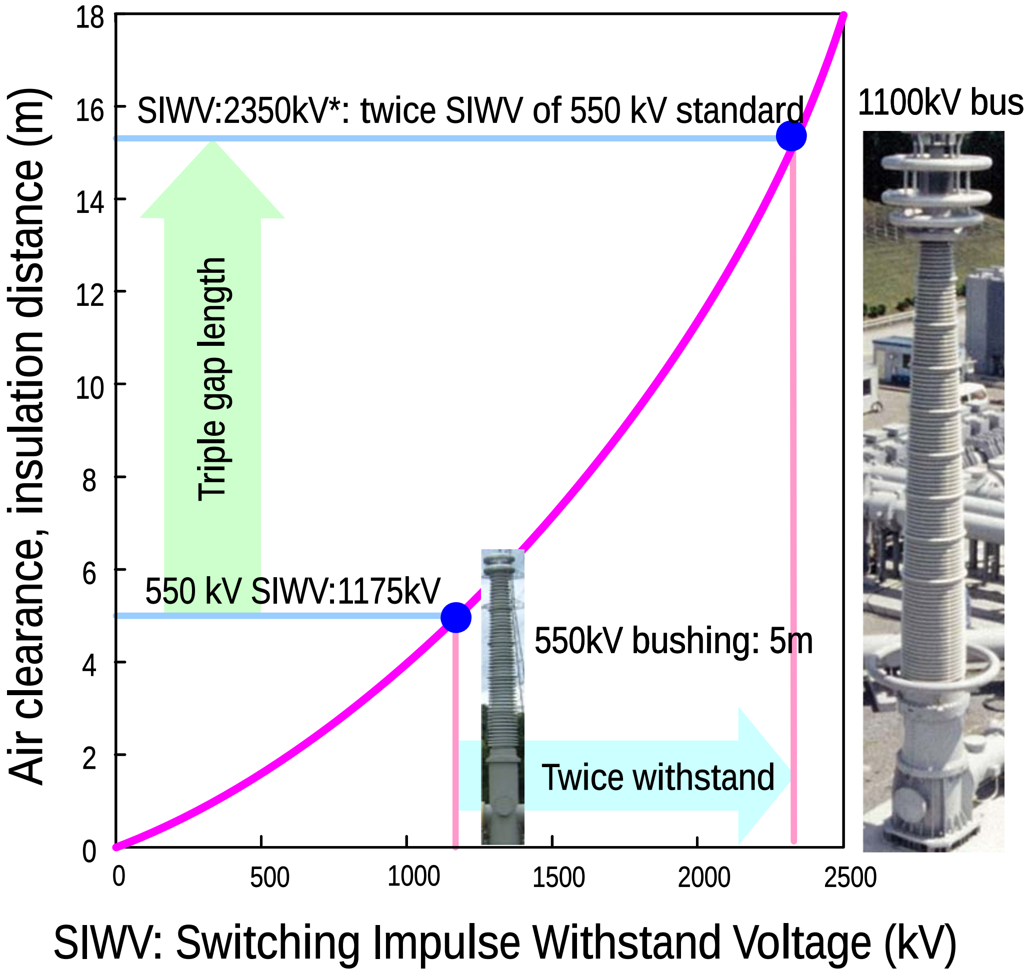
Lightning impulse withstand voltage

Switching impulse withstand voltage

Switching impulse withstand voltage is more important for air clearance in UHV and EHV equipment

Technical limitation for AC transmission

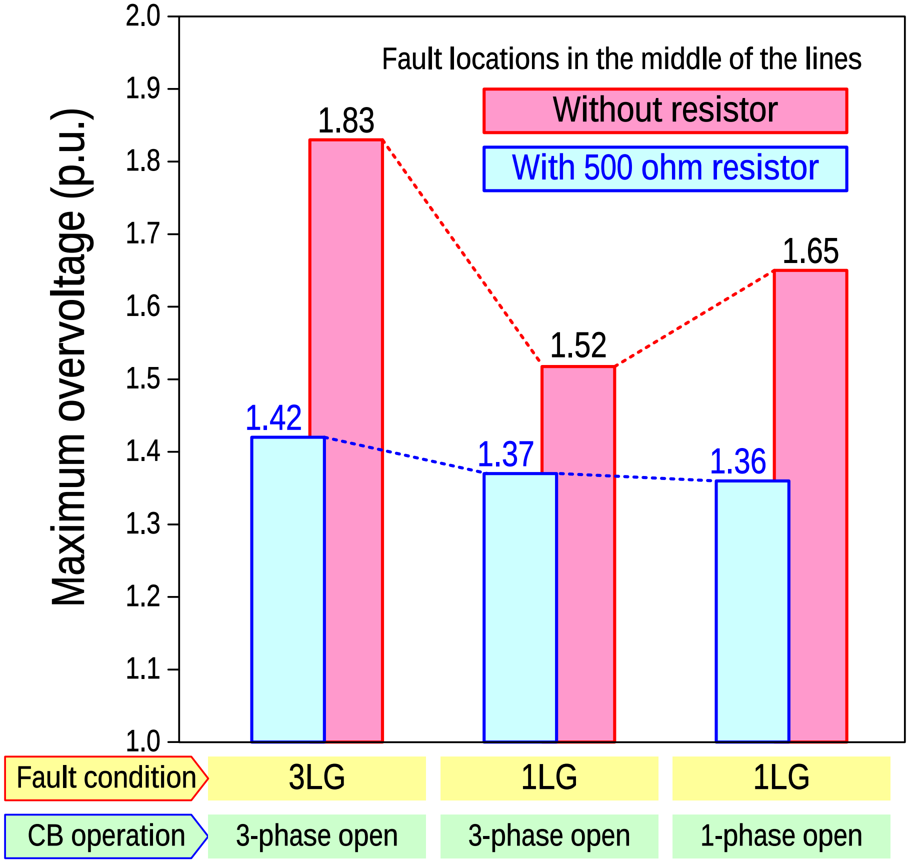
The loss of large-capacity and long-distance AC transmission have been reduced by uprating of transmission voltage but may attain its technical limitation around 1100/1200 kV AC transmission.



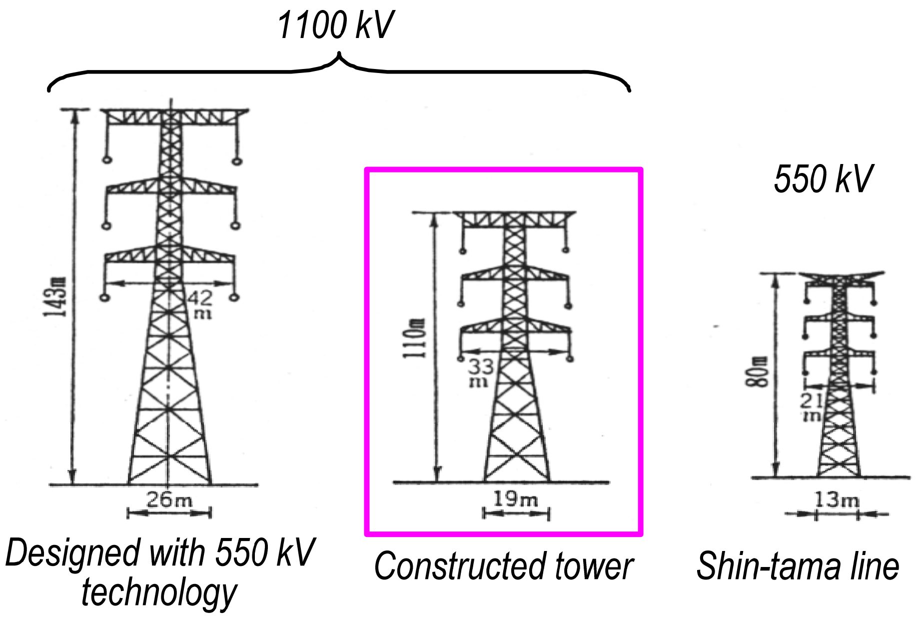
*1100kV SIWV is reduced to 1800 kV using several mitigations besides optimal MOSA arrangement so actual height is about 12 m

The yield of bushing longer than 15m is significantly reduced so it is difficult to produce it at economical price.
1100kV Bushing…15 m correspond to 4 story building, 1650kV Bushing…25 m correspond to 7 story building, 2200kV Bushing…46 m corresponds to 13 story building

GCB with closing/opening resistors



1LG: Single-phase line fault to ground
3LG: Three-phase line faults to ground



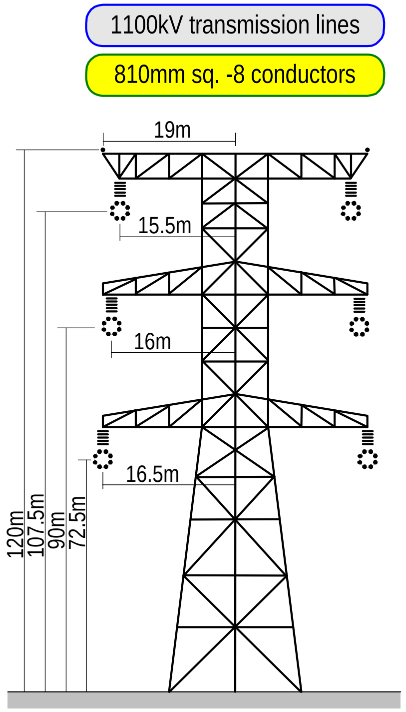
1100kV tower design compaction

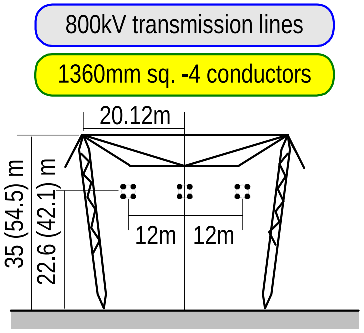
Slow-Front Overvoltage level depends on the fault-type and tends to be larger in an order of 1LG < 2LG < 3LG, even though the probability of 2LG & 3LG faults is comparatively. In the event of a successive fault occurring in a healthy line followed by a fault clearing in another line there could be serious consequence for the system without opening resistors.

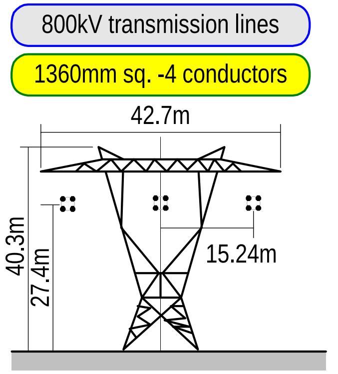
DC time constants in fault currents

Calculations predict a large DC time constants in fault current in UHV transmission systems due to usage of multi-bundles conductor and the existence of large capacity power transformers.

Highest voltage (kV)	Conductors		DC time constants (ms)
	Size (mm^2)	Bundle number	
800 Canada	686	4	75
800 USA	572	6	89
800 South Africa	428	6	67
800 Brazil	603	4	88
800 Korea	480	6	80
800 China	400	6	75
1200 Russia	400	8	91
1050 Italy	520	8	100
1100 Japan	810	8	150
1100 China	500	8	120
1200 India	774	8	100

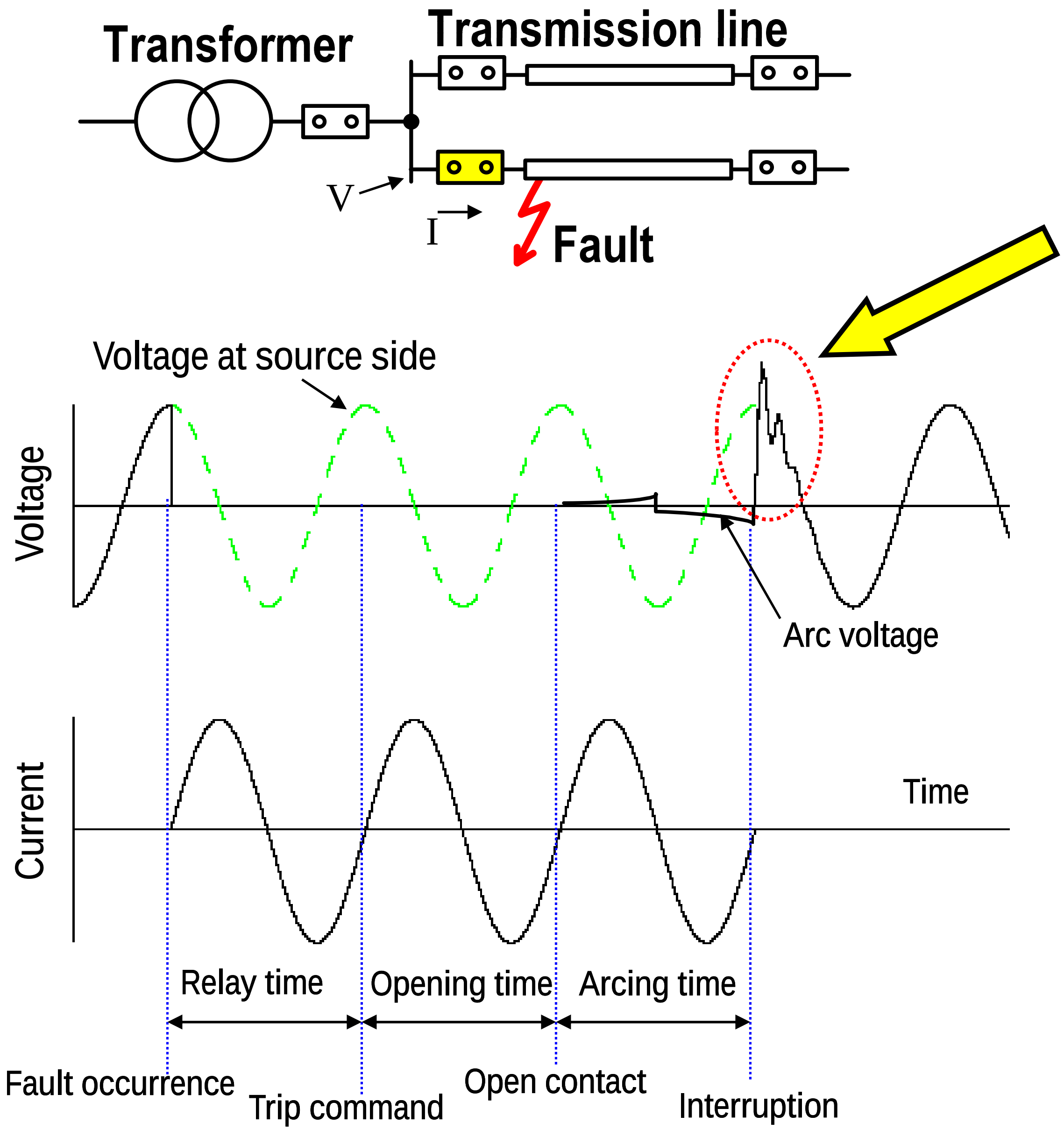






Influences of the high DC component on test-duty T100a does not show any significant difference when the constant exceeds around 120 ms. Therefore, it was recommended to use a time constant of 120 ms for rated voltages higher than 800 kV.

TRV: Transient Recovery Voltage

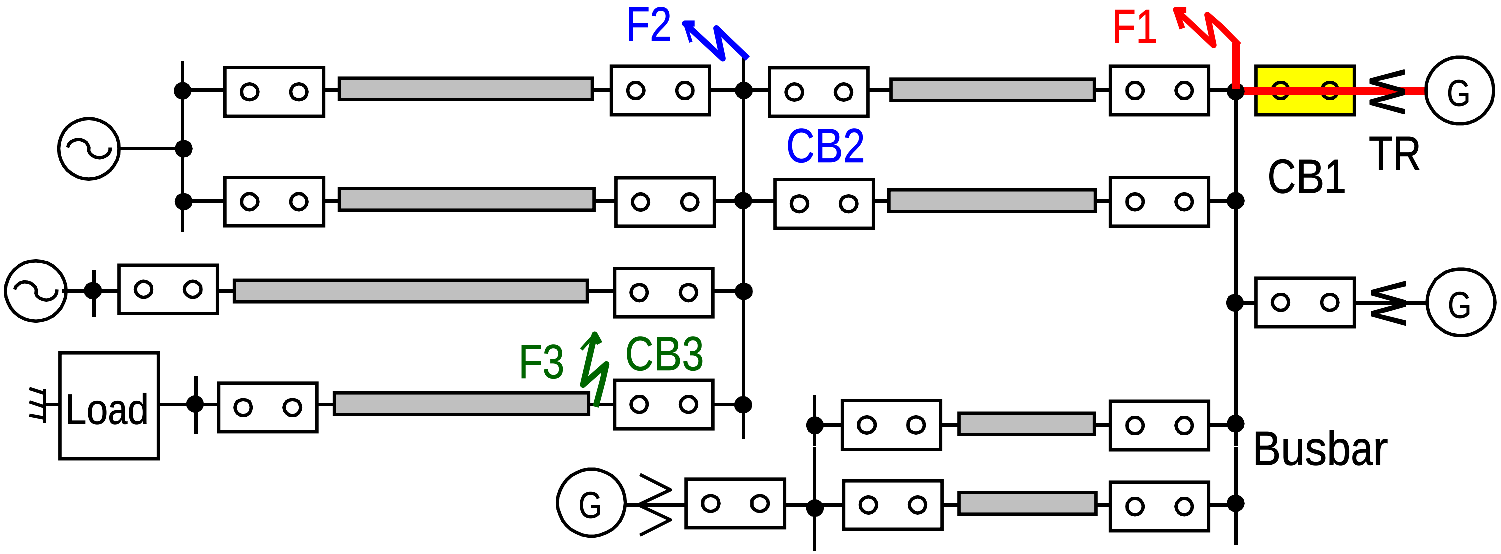


The voltage at line side will recover to the source voltage after a fault clearing, which causes oscillation around the value of the source voltage.

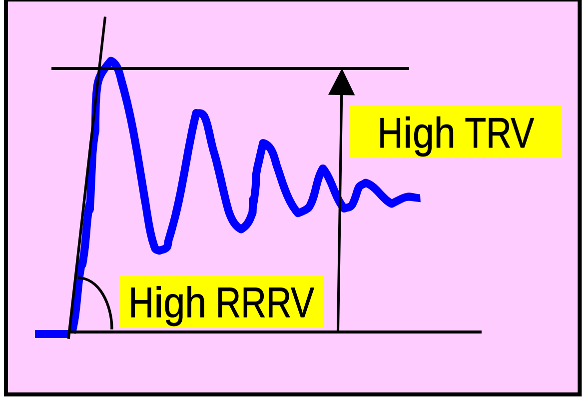
This voltage oscillation immediately after interruption is called as TRV.

The frequency and the amplitude of TRV changes depends on the network configuration, source capacity and a fault location.

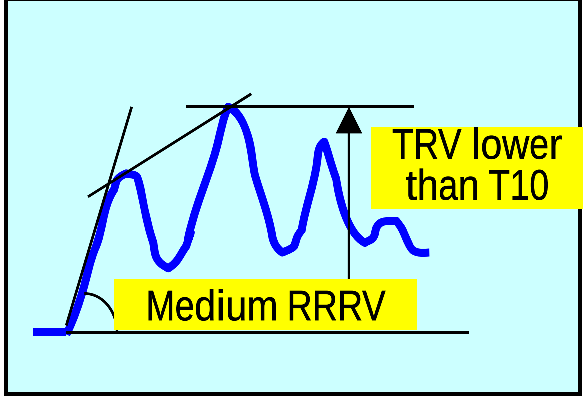
TRV for Breaker terminal faults



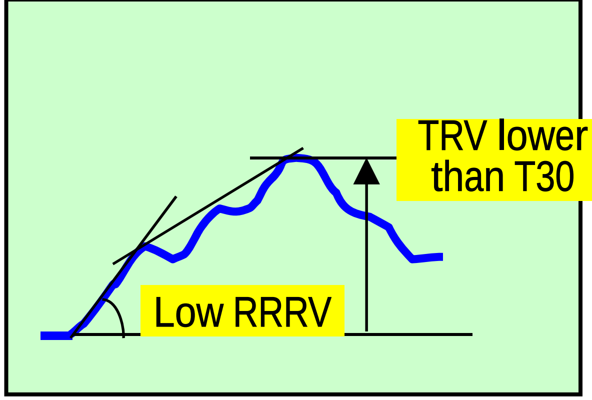
Fault F1	CB1
T10 duty	I=10%



Fault F2	CB2
T30, T60 duties	I=30, 60%



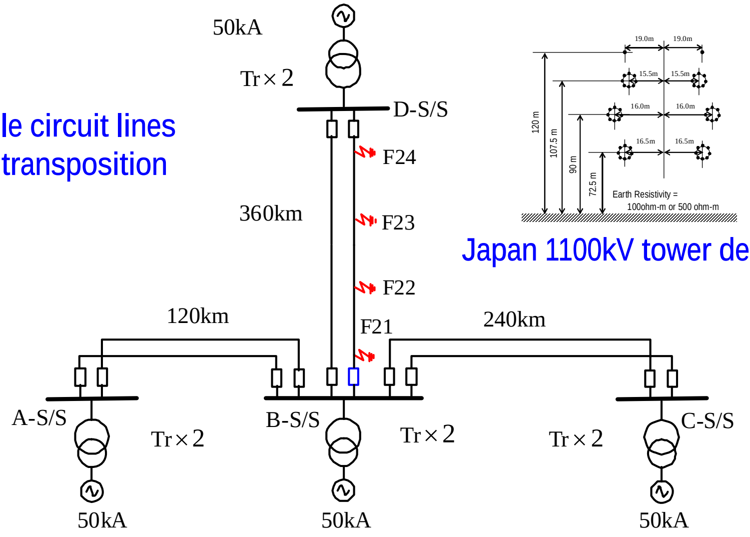
Fault F3	CB3
T100s, a duties	I=100%



UHV TRV simulations

CIGRE Radial network model

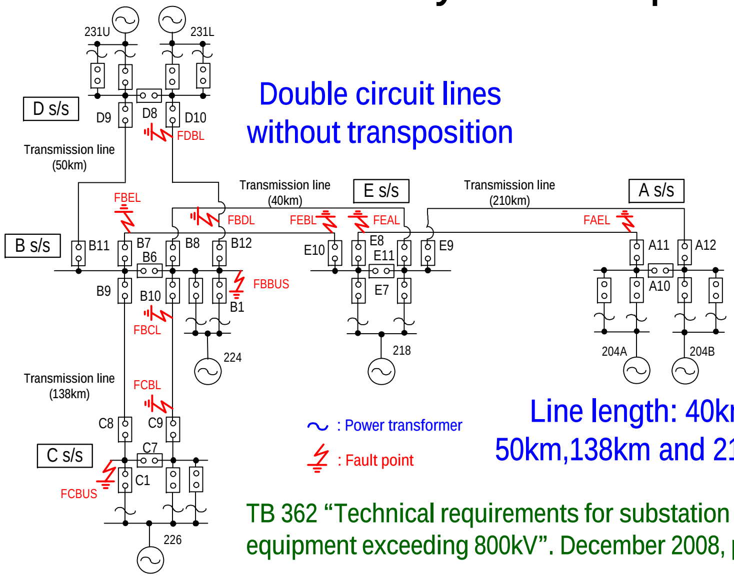
Double circuit lines with transposition



Japan 1100kV tower design

1100 kV system in Japan

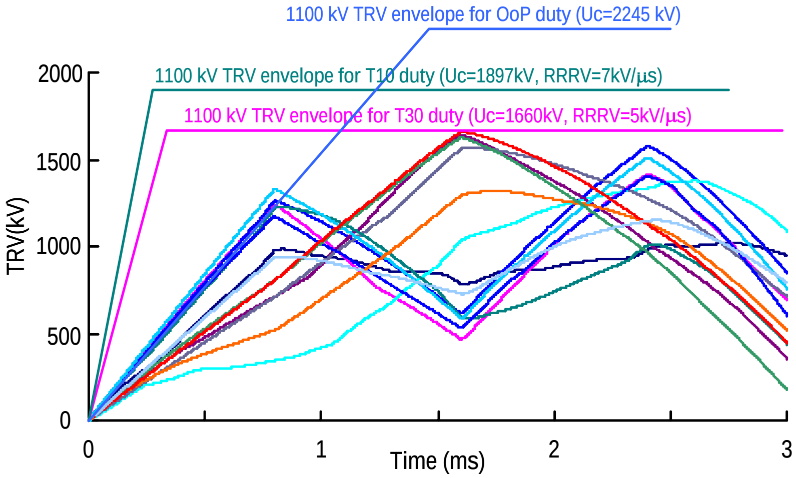
Double circuit lines without transposition



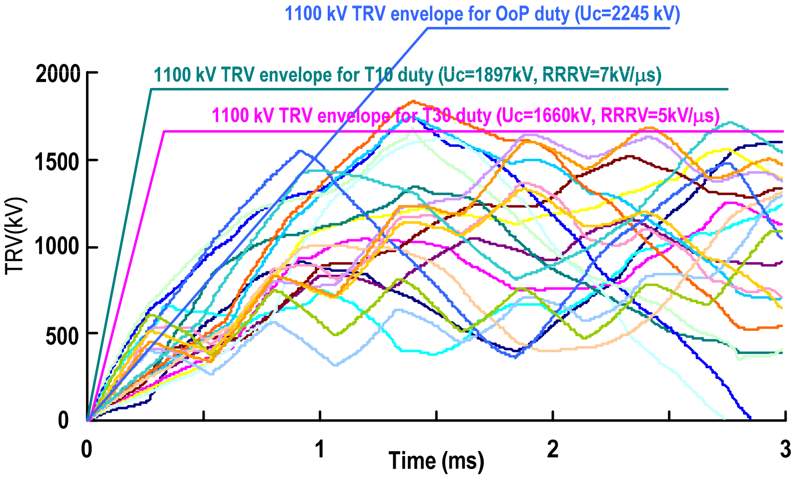
Line length: 40km, 50km,138km and 210km

TB 362 "Technical requirements for substation equipment exceeding 800kV". December 2008, pp.94-95

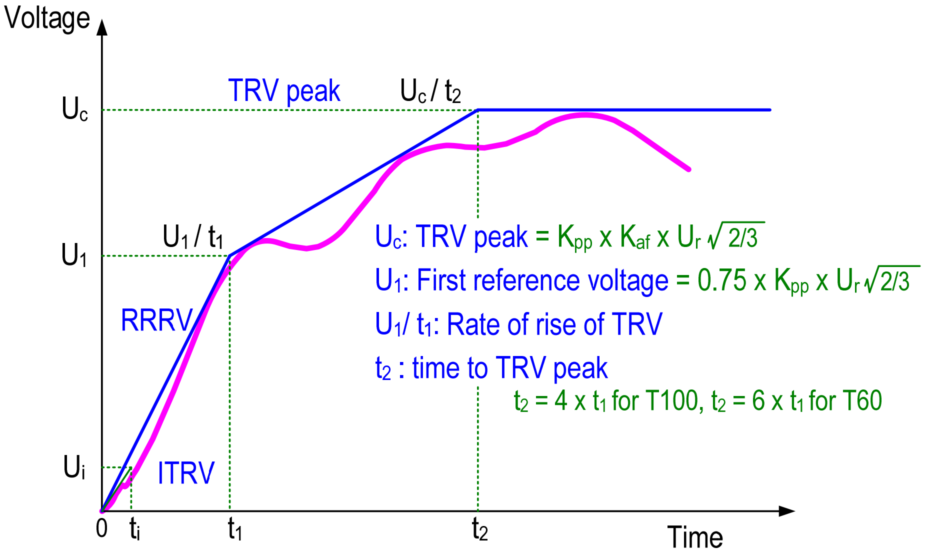
TRV calculated in 1100 kV radial network model



TRV calculated in 1100 kV network in Japan



UHV TRV requirements



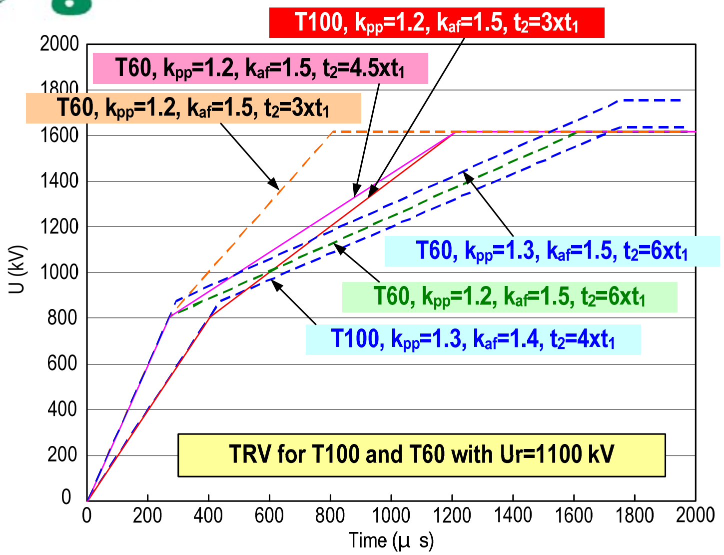
U_c: TRV peak = K_{pp} x K_{af} x $U_r \sqrt{2/3}$

U_1: First reference voltage = 0.75 x K_{pp} x $U_r \sqrt{2/3}$

U_1 / t_1: Rate of rise of TRV

t_2 : time to TRV peak

t_2 = 4 x t_1 for T100, t_2 = 6 x t_1 for T60



UHV	First-pole-to-clear factor	Amplitude factor	1100 kV	1200 kV	Rate of Rise of TRV	Time to TRV peak	Time to TRV peak
DUTY	K_{pp}	K_{af}	TRV peak (kV)	TRV peak (kV)	RRRV (kV/μs)	t_2	t_3
T100	1.2 (1.3)	1.5 (1.4)	1617	1764	2	3.0*t_1 (4*t_1)	
T60	1.2 (1.3)	1.5	1617	1764	3	4.5*t_1 (6*t_1)	
T30	1.2 (1.3)	1.54	1660	1811	5		t_3 (t_3)
T10	1.2 (1.3)	1.76	1897	2076	7		t_3 (t_3)
TLF	1.2 (1.5)	0.9*1.7	1649	1799	(*)		(*)
Out-of-phase	2.0	1.25	2245	2450		1.38*t_1 (2*t_1)	

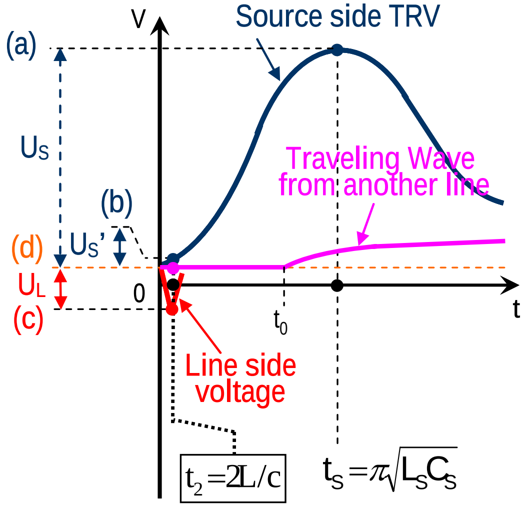
Values ( ) are standards for 800 kV and below. t_1 and t_3 are based on K_{pp}=1.2

(*) : RRRV= U_c / t_3 with t_3 =6 * U_r / I $^{0.21}$ shown in the ANSI C37.06.1-2000 for transformers up to 550 kV

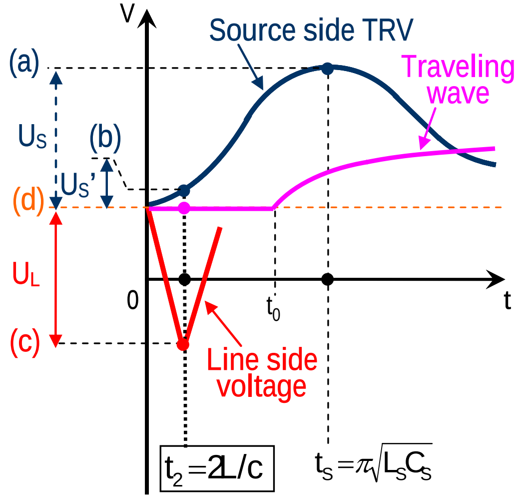
For UHV transformers, RRRV and t_3 are determined by the transformer impedance and its equivalent surge capacitance (specified as 9 nF)

Influence of fault locations on TRV for LLF conditions

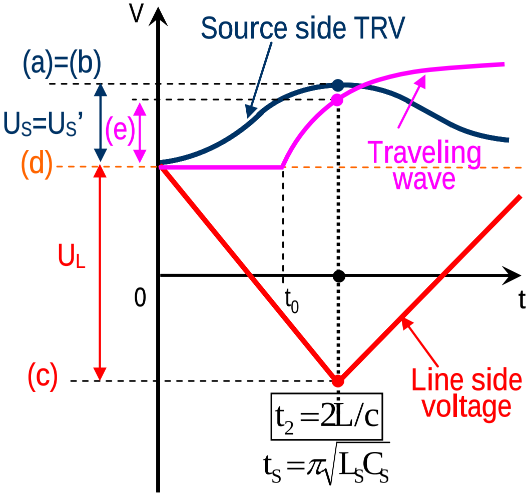
Shorter Distance to the fault point Longer



(i) Short distance

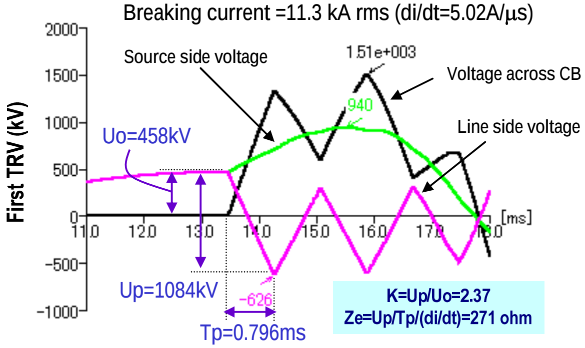


(ii) Middle distance

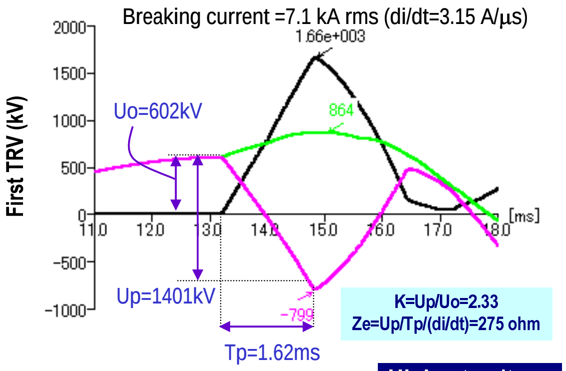


(iii) Long distance

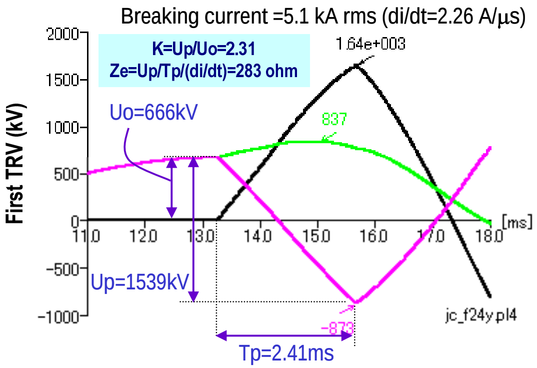
TRV of first-pole-to-clear for 120 km LLF



TRV of first-pole-to-clear for 240 km LLF

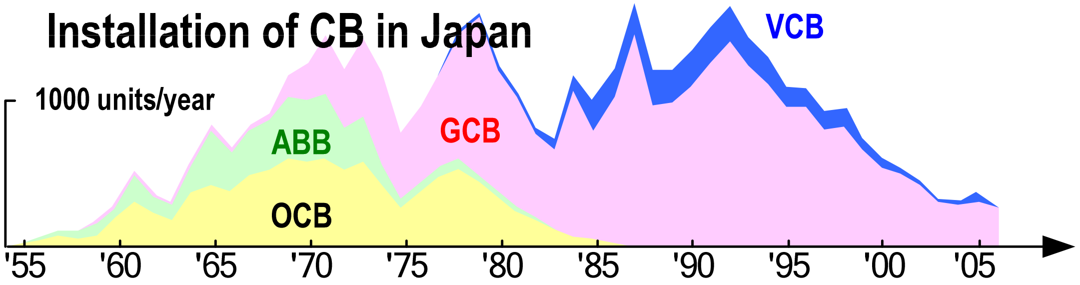


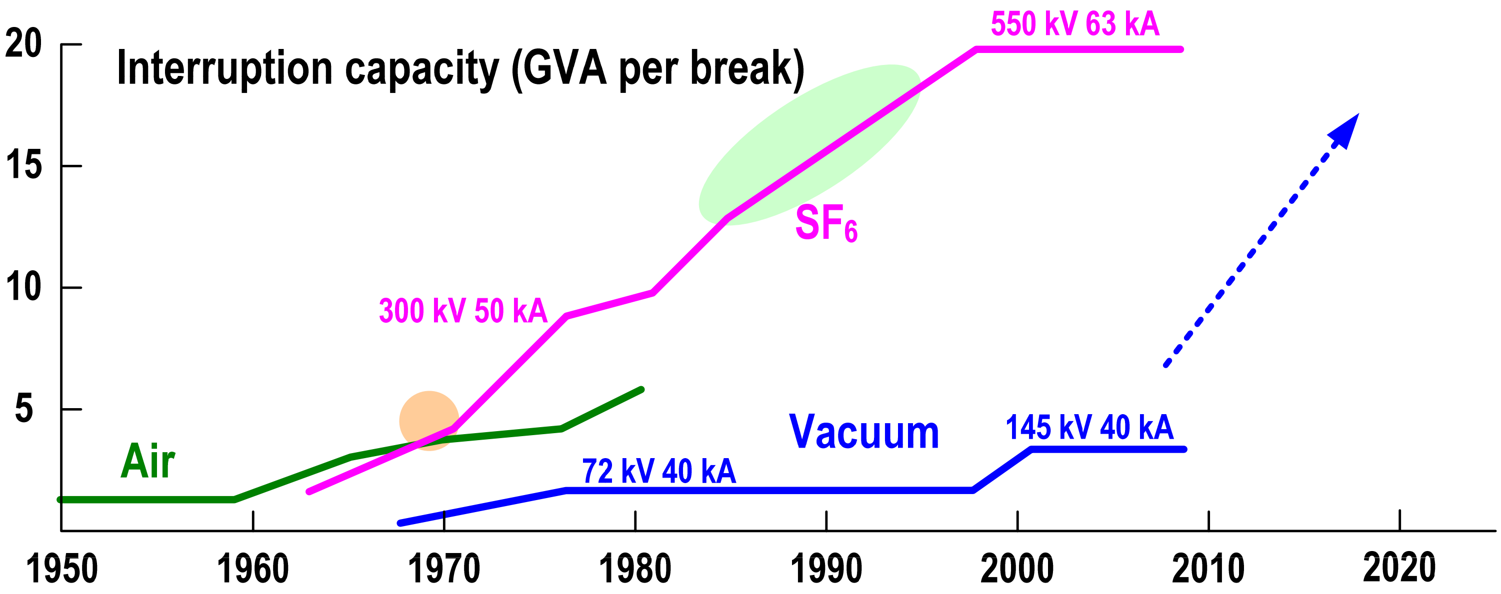
TRV of first-pole-to-clear for 360 km LLF



Highest voltage (kV)	Maximum TRV peak (kV)	Time to TRV peak t_2 (μs)	Distance to fault point (km)
1100	1727	1842	276
800	1270	1596	239
550	885	1095	164

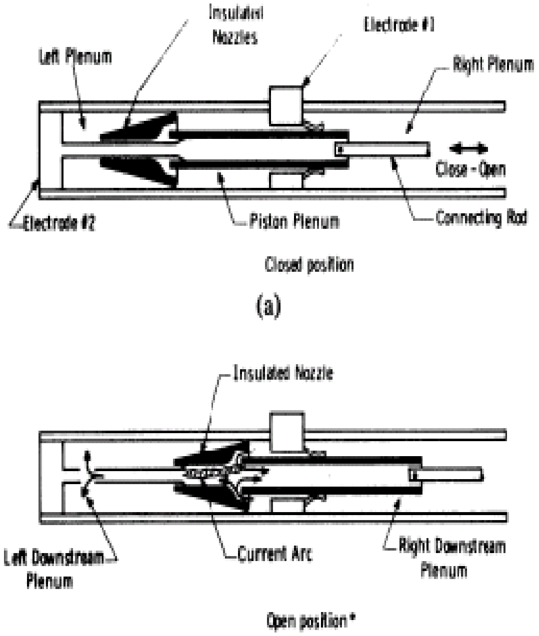
WG 13.01 Circuit breaker, Interrupting phenomena



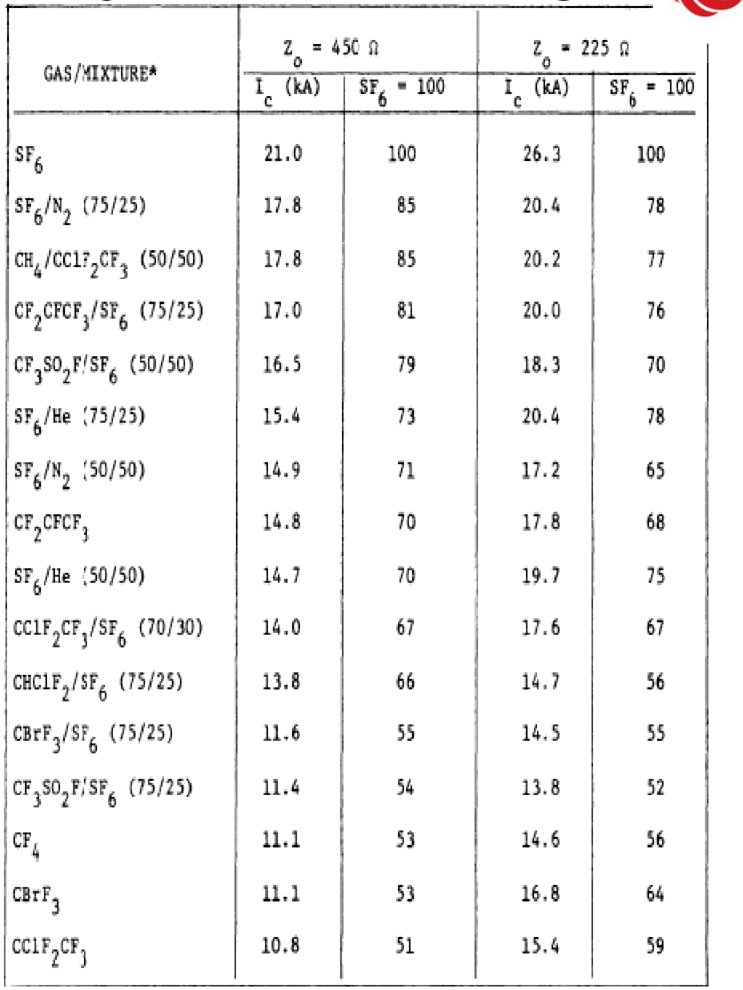


Transition from Air Blast Breakers (ABB) to GCB occurred in late 1960s.
Higher voltage and larger capacity GCB developments were accelerated in 80’s & 90’s.
Development slowed down in the middle of the 1990’s.
Technical breakthrough on HV-VCB is required.

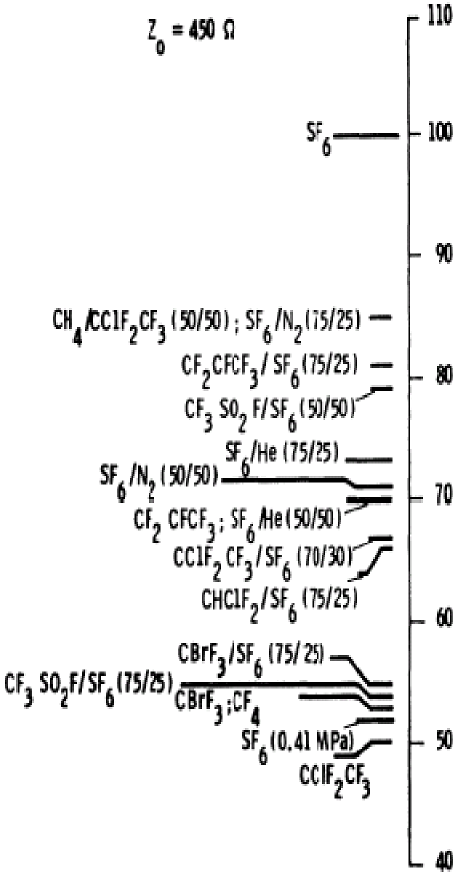
Interrupting capability of different gases



Puffer-type circuit breaker used for evaluation (stroke: 12.7 cm, speed: 4.76 m/s, nozzle throat: 27mm)
A. Lee, IEEE PS-8, No.4, 1980



GAS/MIXTURE*	Z_o = 450 Ω		Z_o = 225 Ω	
	I_c (kA)	SF_6 = 100	I_c (kA)	SF_6 = 100
SF_6	21.0	100	26.3	100
SF_6/N_2 (75/25)	17.8	85	20.4	78
$CH_4/CClF_2CF_3$ (50/50)	17.8	85	20.2	77
CF_2CFCF_3/SF_6 (75/25)	17.0	81	20.0	76
CF_3SO_2F/SF_6 (50/50)	16.5	79	18.3	70
SF_6/He (75/25)	15.4	73	20.4	78
SF_6/N_2 (50/50)	14.9	71	17.2	65
CF_2CFCF_3	14.8	70	17.8	68
SF_6/He (50/50)	14.7	70	19.7	75
$CClF_2CF_3/SF_6$ (70/30)	14.0	67	17.6	67
$CHClF_2/SF_6$ (75/25)	13.8	66	14.7	56
$CBrF_3/SF_6$ (75/25)	11.6	55	14.5	55
CF_3SO_2F/SF_6 (75/25)	11.4	54	13.8	52
CF_4	11.1	53	14.6	56
$CBrF_3$	11.1	53	16.8	64
$CClF_2CF_3$	10.8	51	15.4	59

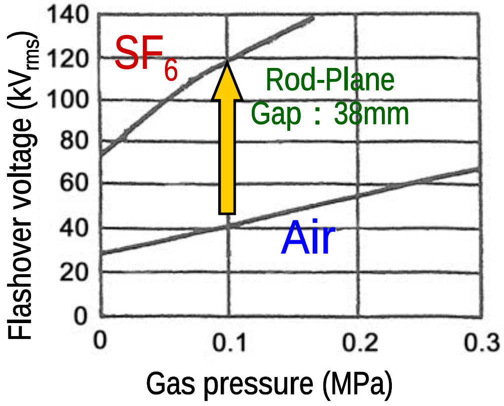


SF6 is the best interrupting media. there are no alternative interrupting media comparable to SF6 covering the complete high voltage and breaking current ranges as needed by today's power systems with the same reliability and compactness as modern GCB.

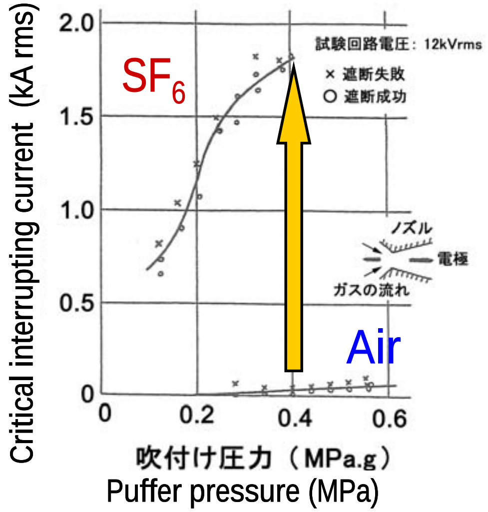
Interrupting capability with other gases such as CO2, N2 and air is much inferior which leads to larger interrupters (often multi-breaks) with a higher gas pressure that requires the use of a larger driving energy of the operating mechanism, resulting in a higher environmental impact.

Superior SF_6 dielectric / interrupting performance

Dielectric performance: 3 times better



Interrupting performance: 100 times better



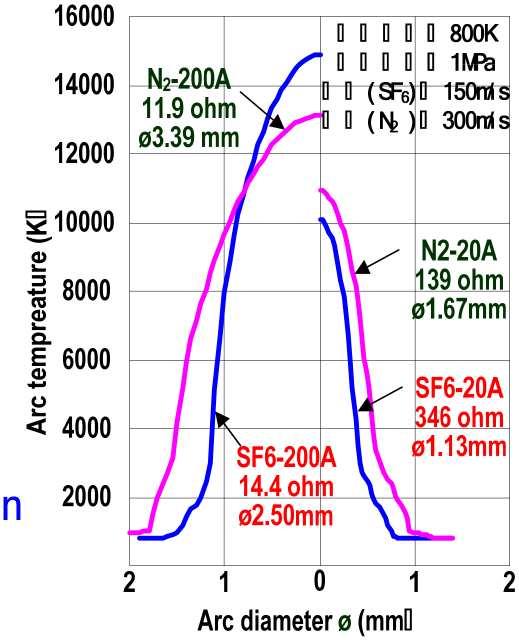
Environmental impact

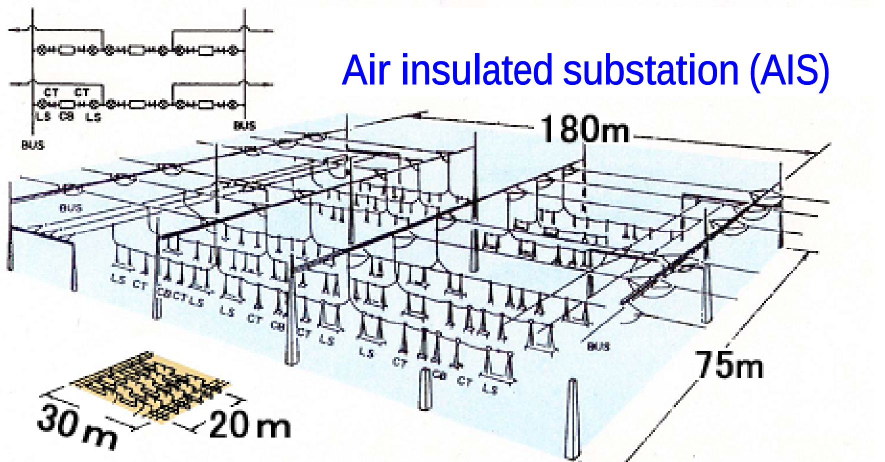
Global Warming Potential value of 22800 (calculated in terms of the 100-year warming potential of one kilogram of SF_6 relative to one kilogram of CO_2)

SF_6

- Smaller diameter in arc (Less energy dispassion)
- Rapid switching: conductor to insulator (Faster resistance change)

Less breaks for interrupter
Compact equipment & substation

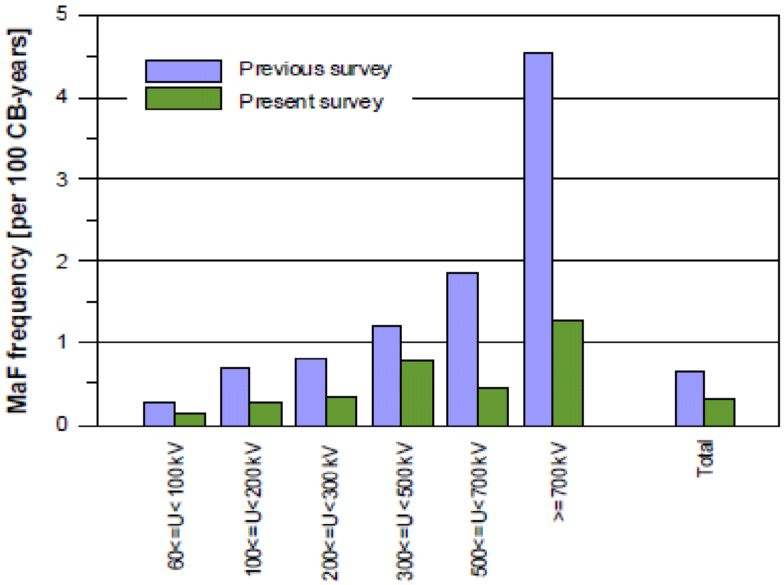




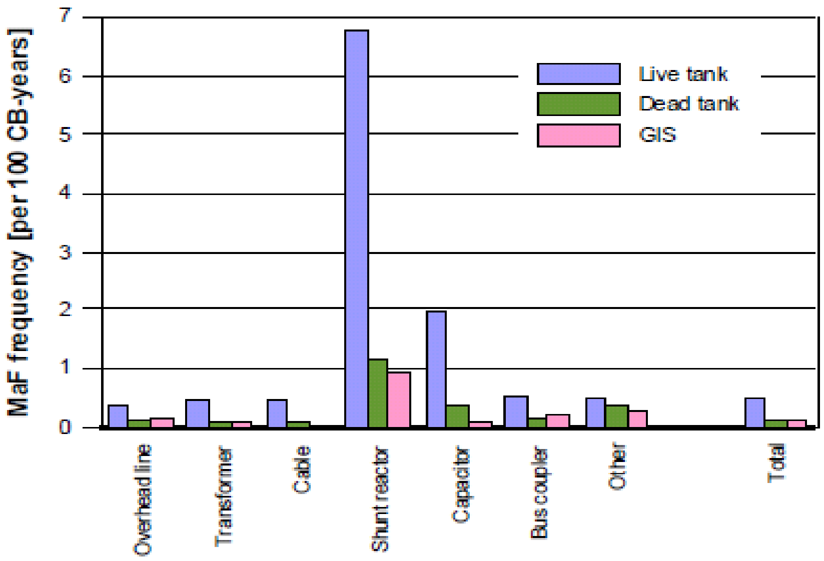
Gas insulated substation (GIS)
5% installation area, 1% volume as compared with AIS

WG A3.06: Circuit Breaker Reliability surveys

Part 1: Summary and general matters (TB 509)
Part 2: SF_6 gas circuit breakers (TB 510)
Part 3: Disconnectors and Earthing switches (TB 511)
Part 4: Instrument transformers (TB 512)
Part 5: Gas insulated switchgears (TB 513)
Part 6: GIS practices (TB 514)



CB Major failure frequency for different voltage levels



CB Major failure frequency for different kinds of service

WG A3.06: CB Reliability surveys : rating voltages

Reliability surveys	1st survey	2nd survey	3rd survey
Period	1974 - 1977	1988 - 1991	2004 - 2007
Objective	All types of CB (In service after 1964)	Single pressure SF6 CB (In service after 1978)	Single pressure SF6 CB (No limitation)
Voltage class	63 kV and above	63 kV and above	60 kV and above
Participation (world)	120 utilities from 22 countries	132 utilities from 22 countries	83 utilities from 26 countries
Number of CB-year	77,892 CB-year	70,708 CB-year	281,090 CB-year

Ratings	Major Failure, /100 unit year			Minor Failure, /100 units year		
	1st Survey	2nd Survey	3rd Survey	1st Survey	2nd Survey	3rd Survey
	1974 - 1977	1988 - 1991	2004 - 2007	1974 - 1977	1988 - 1991	2004 - 2007
60 - 99 kV	0.41	0.28	0.13	1.65	2.23	---
100 - 199 kV	1.63	0.68	0.28	4.18	4.75	---
200 - 299 kV	2.59	0.81	0.35	6.39	6.97	---
300 - 399 kV	4.55	1.21	0.78	16.35	7.76	---
500 kV & above	10.46	1.97	0.48	4.93	8.18	---
World data	**1.58**	**0.67**	**0.30**	**3.55**	**4.66**	**2.37**

The increased application of spring operating mechanisms improved CB reliability.

WG A3.06: CB Reliability surveys : components

Components	Major Failure /100units year			Minor Failure /100units year		
	1st Survey	2nd Survey	3rd Survey	1st Survey	2nd Survey	3rd Survey
	1974 - 1977	1988 - 1991	2004 - 2007	1974 - 1977	1988 - 1991	2004 - 2007
Main Circuit	0.76 (48%)	0.14 (21%)	0.06 (20%)	0.92 (26%)	1.44 (31%)	---
Control Circuit	0.30 (19%)	0.19 (29%)	0.09 (30%)	0.57 (16%)	0.92 (20%)	---
Operating Mech.	0.52 (33%)	0.29 (43%)	0.15 (50%)	2.06 (58%)	2.05 (44%)	---
Others		0.05 (7%)			0.05 (5%)	---
World data	**1.58**	**0.67**	**0.30**	**3.55**	**4.66**	**2.37**

Half of the Major / Minor failures are responsible for operating mechanisms.

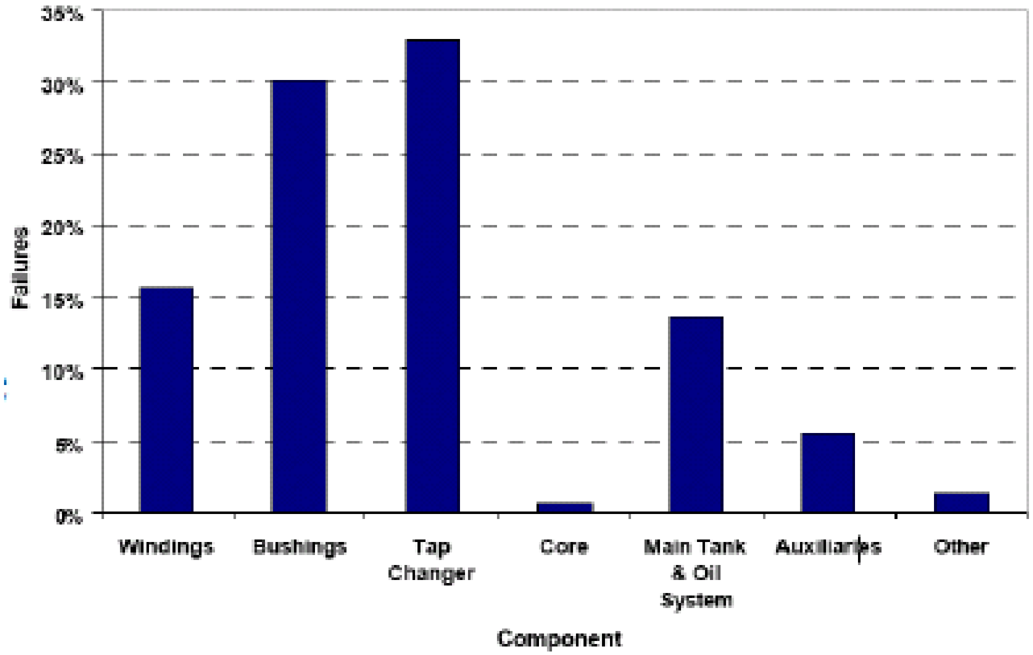
SF6 circuit breakers:	0.30 *(0.67)* MaF / 100 CB-years
Disconnectors and earthing switches:	0.21 MaF / 100 DE-years
Instrument transformers:	0.053 MaF / 100 IT-years (1-phase units)
Gas insulated switchgear:	0.37 *(0.53)* MaF / 100 GIS CB-bay-years

WG A2.37: Transformer Reliability

Review all existing national surveys.

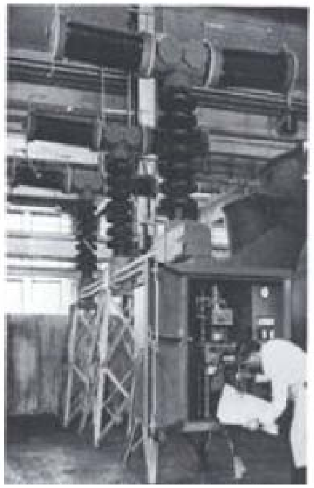
Preliminary results, based on a transformer population with more than 150.000 unit-years and 685 major failures in 48 utilities, indicate a failure rate of 0.44%.

Winding related failures appear to be the largest contributor of major failures, and a significant decrease in tap changer related failures.



WG A3.27: Application of vacuum switchgear at transmission voltage


245 kV load switch (USA)


132 kV 16 kA VCB (UK)


72.5 kV 31.5 kA VCB (France)


72 kV VCB (China)


72 kV 31.5 kA VCB (Japan)


145 kV & 72 kV VI (Germany)

HV-VCB technical merits

Frequent switching capability, Less maintenance work, SF_6 free

HV-VCB challenges at transmission level despite of excellent experience at distribution

Limited experience on long term reliability

Scatter of dielectric performance especially for capacitive current switching

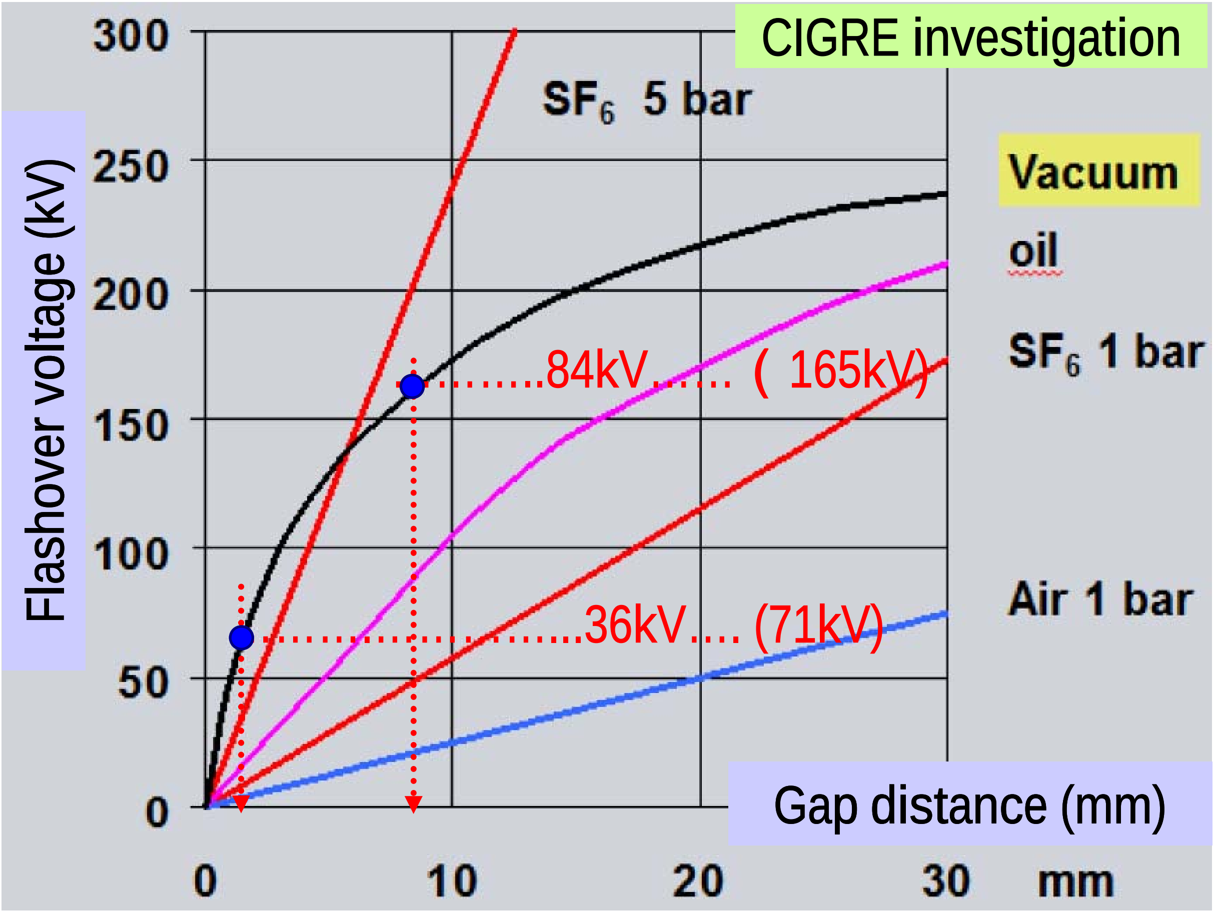
Limited current carrying capability, limited unit voltage

Difficulty of higher voltage vacuum interrupter

Recovery voltage of small capacitive current interruption
Voltage factor = 1.7

Transmission
165 kV for 84 kV
141 kV for 145 kV

Distribution
71kV for 36 kV
47kV for 24 kV



Dielectric withstand voltage in SF6 linearly increases with gap distance but that in Vacuum tends to saturate, which makes difficult to increase a unit voltage per break.

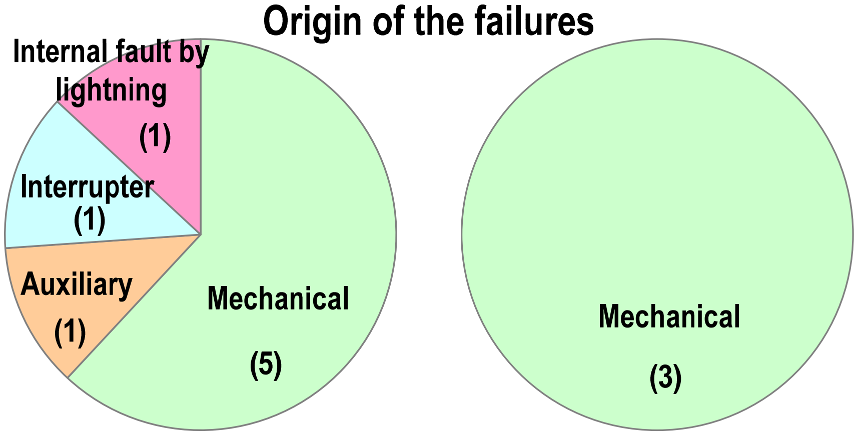
Comparison of HV applications and Failure rates of HV-VCB and GCB

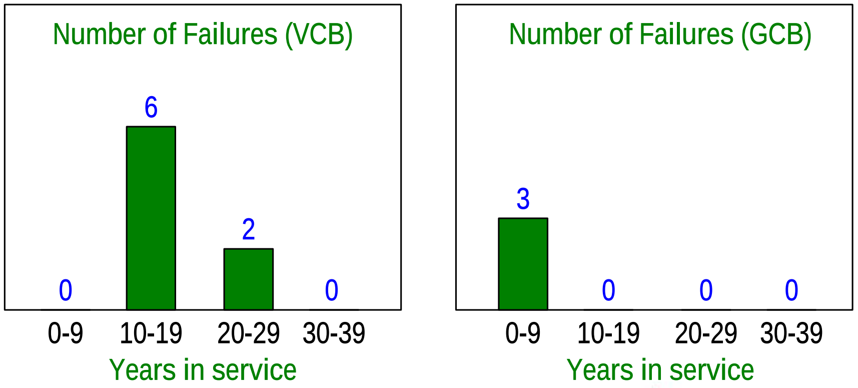
	VCB	GCB
Rating	84 / 72 kV	84 / 72 kV
	12.5-31.5 kA	12.5-31.5 kA
	600-2000 A	600-3000 A
CB-year	24907 unit-year	12953 unit-year
Failure Rate	0.032	0.023

Total Installations	**2583**	**1454**
Main Transformer	263	99
Distribution Transformer	814	199
Line Protection	1287	863
Shunt capacitor	117	30
Shunt reactor	0	15
Neutral point	3	147

VCB **GCB**

Origin of the failures





Motivations for VCB developments & installations in Japan

Advantages of VCB

Utilities

- Less maintenance work
- Frequent switching capability

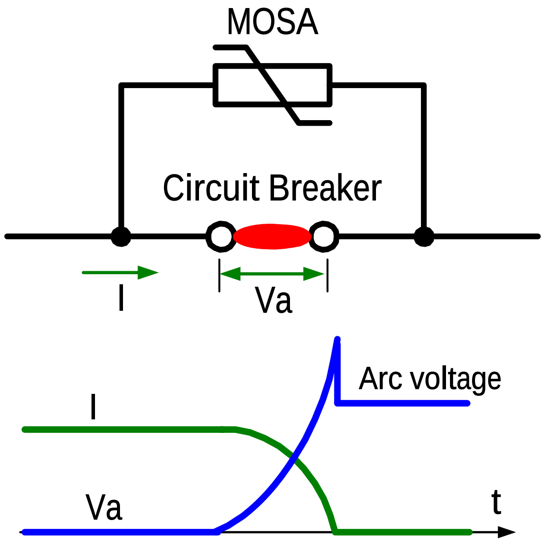
Industrial system

- Non-flammability
- Low operating energy

A large number of VCBs have been put in service at transmission voltages since 1970's and installed to special switching requirements in the 1980's and 1990's .
Apparently, the reduction of SF6 gas usage seems not to be a primary factor of utilities' policy and decision for VCB installations since it was 1997 when COP3 conference was defined as SF6 gas to be one of the global warming gas.

JWG A3/B4.34 DC current interruption

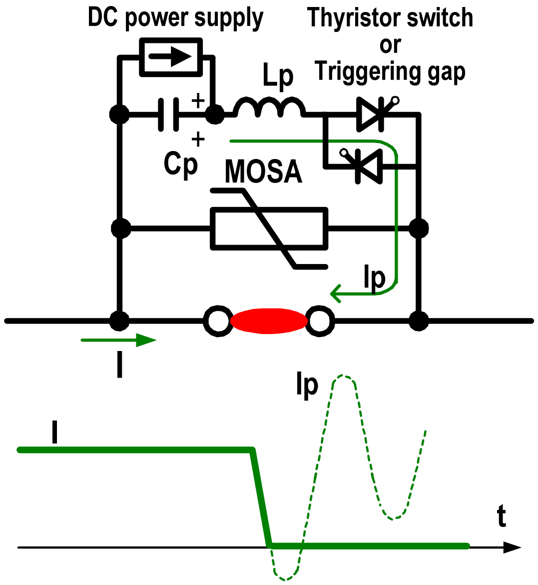
Current limiting scheme



The scheme is applied to several 100 V class DC-NFB & 2000 V class air-blast type high speed switch used for railway system.

The arc generated voltage across the circuit breaker contacts limits the DC current.

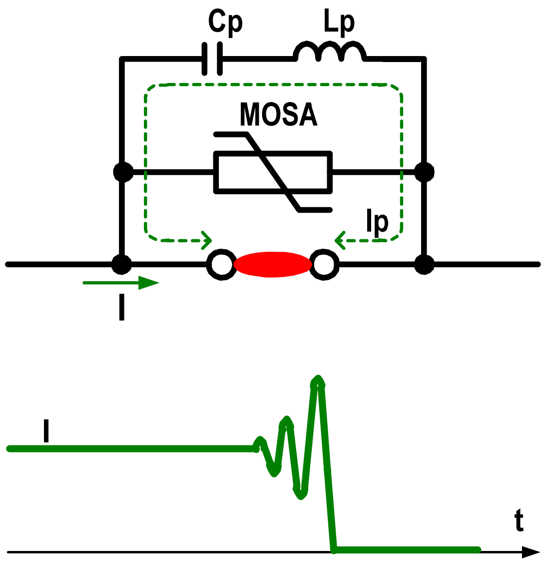
Forced current zero formation



The scheme can potentially applicable to interrupt HVDC current even though a large capacity capacitor bank is required.

The pre-charged capacitor imposes an reverse current on faulted DC current and creates the current zero within a few milliseconds.

Resonant current zero formation



The scheme is applied to MRTB which interrupt the DC current in the neutral line of HVDC transmission.

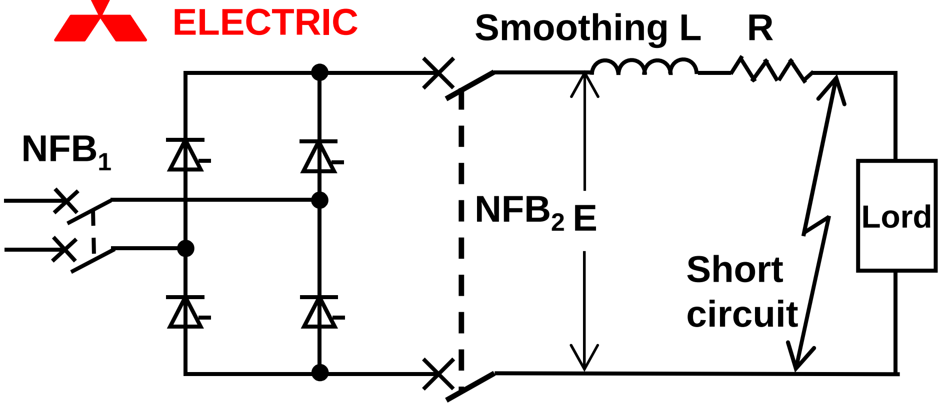
The parallel capacitor and reactor across the circuit breaker generates the current oscillation, which eventually leads to the current zero.

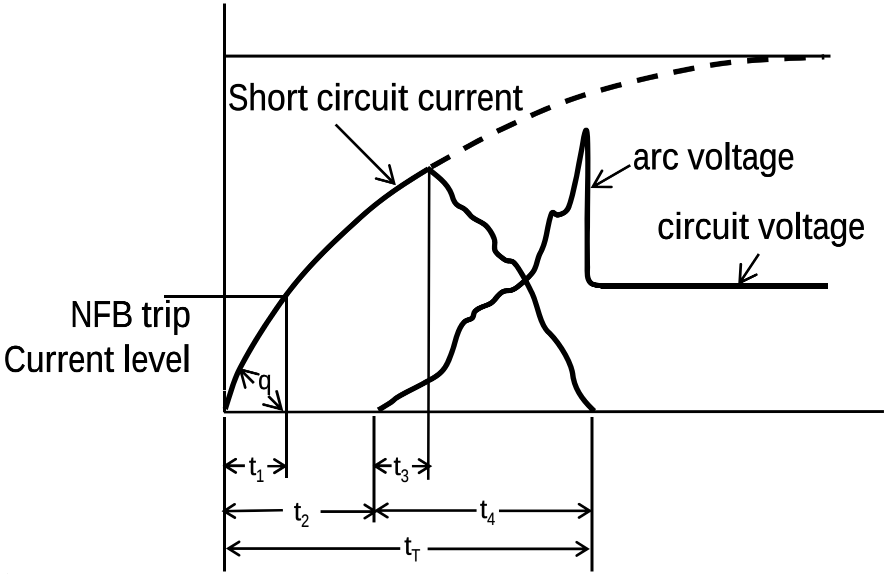
Current limiting scheme: DC-NFB

DC480V15kA-NFB

Rated voltage: DC 480V
Rated interrupting current: DC 15kA
Typical interrupting time: 5ms

MITSUBISHI ELECTRIC



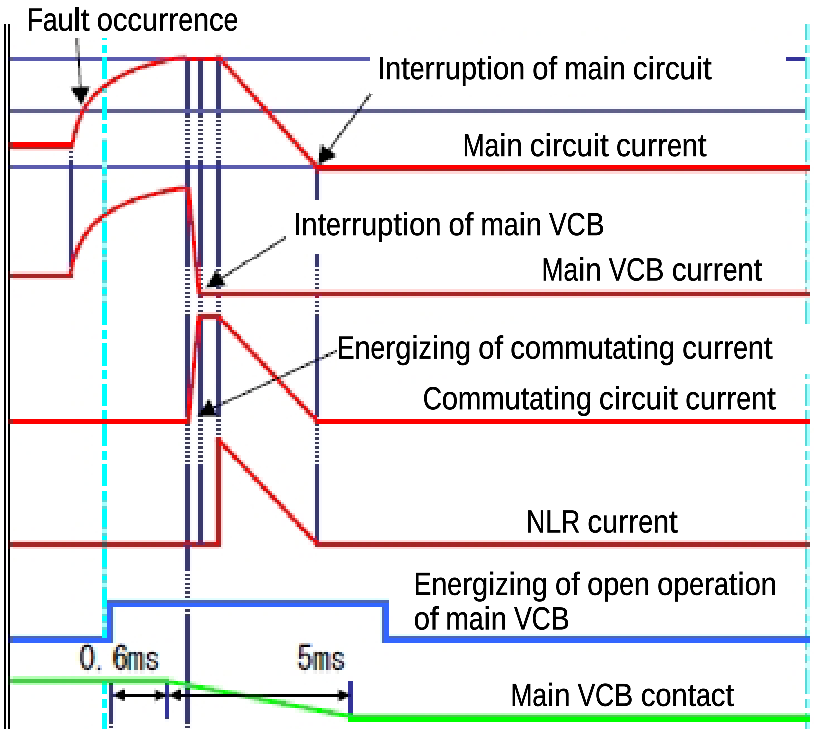


t_1: time to the NFB trip current level
T_2: contact parting time
T_3: time from the instant of contact parting to the instant of current peak
T_4: Arcing time
t_T: total time of interruption
q: rate of rise of current (di/dt)

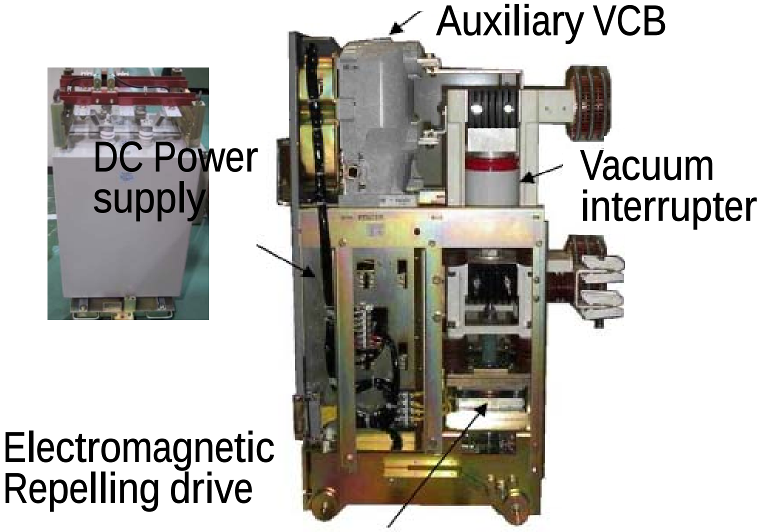
Forced current commutation scheme

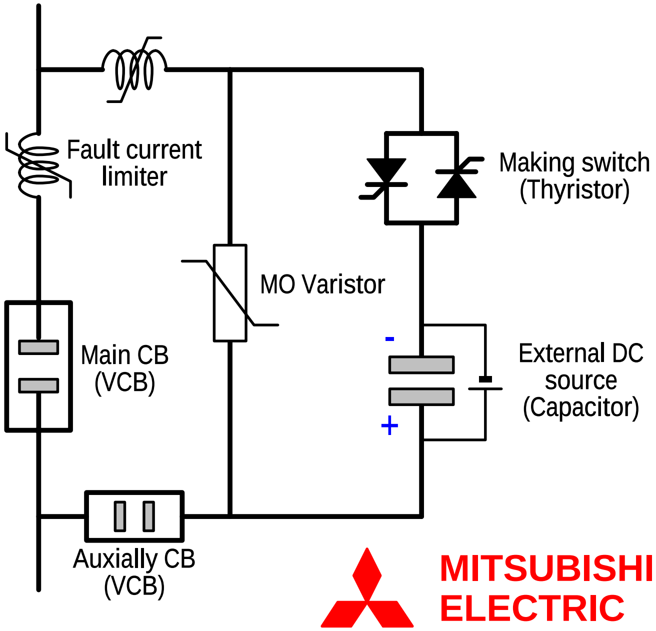
High Speed Vacuum Circuit Breaker (HSVCB) for railway application

Rated voltage: DC 750, 1500 V
Rated nominal current: 3-4 kA
Rated interrupting current: DC 100kA
Interrupter: VCB



In case of fault occurrence, external DC source discharge a reverse current and create a current zero.



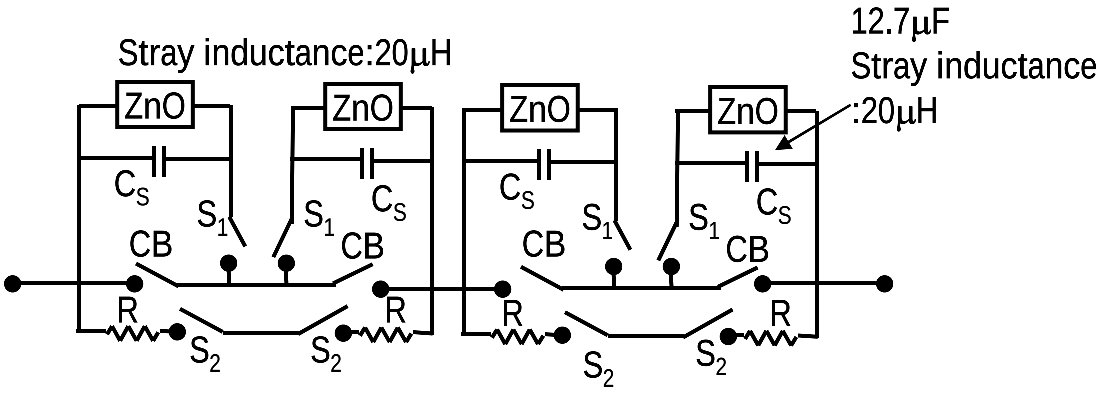


Self current commutation scheme: DCCB

DCCB for DC transmission line

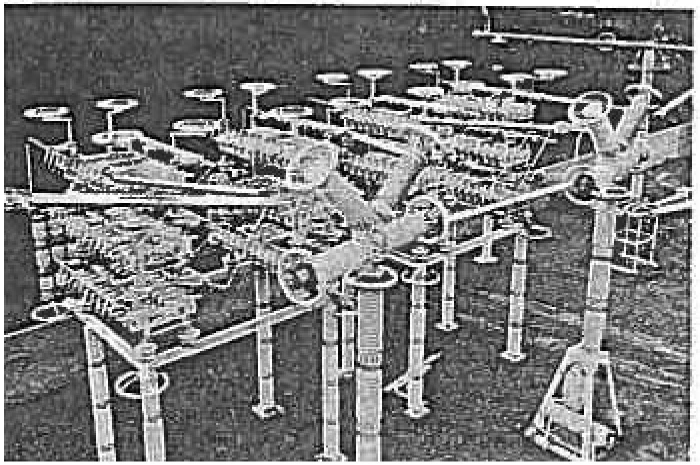
In 1985, Europe and US developed DC 550 kV / 2200 A DCCB with four break SF6 GCB and tested in the field at 400 kV Pacific DC intertie with 1360 km line

Rated voltage: DC 550 kV
Rated interrupting current: DC 2200 A
Interrupter: SF6 puffer type
Typical interrupting time: 25 ms

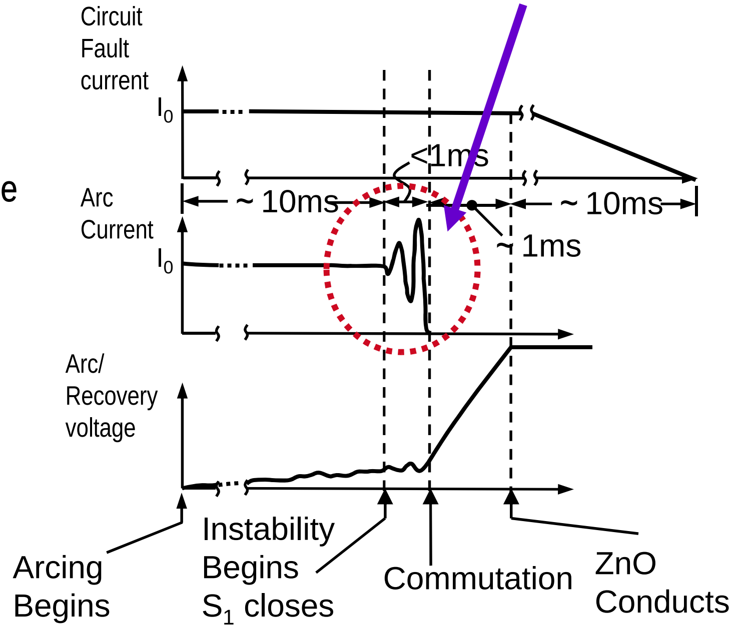


Reference: HVDC CIRCUIT BREAKER DEVELOPMENT AND FIELD TEST, IEEE Trans. Vol. PAS-104, No.10, Oct. 1985

Westinghouse SF6 HV-dc breaker prototype



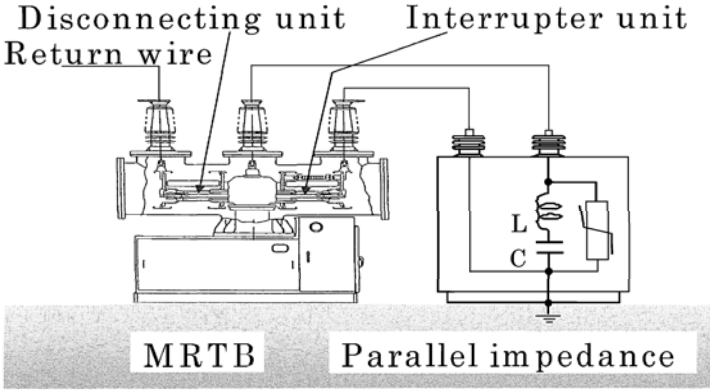
The current oscillation caused by reaction of arc and parallel impedance continues to grow and lead to a current zero



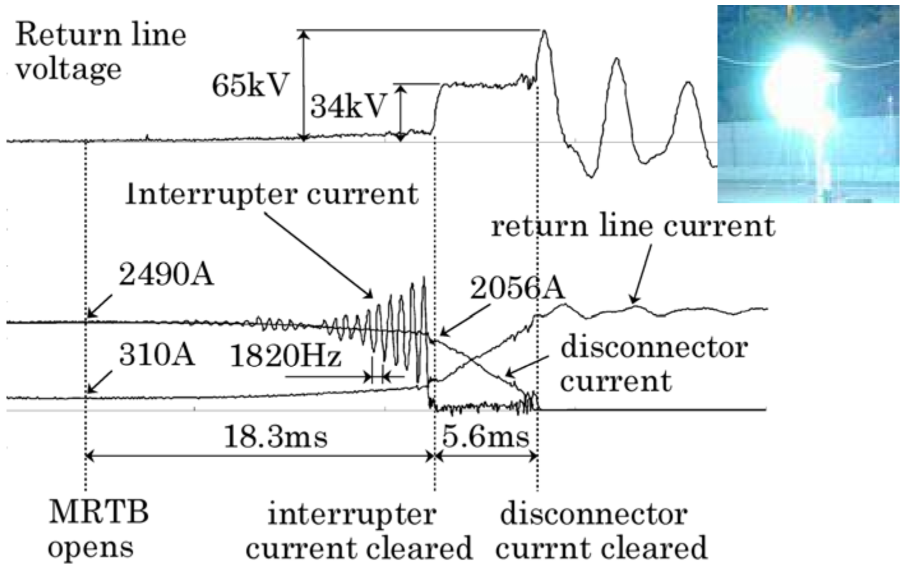
Resonant current commutation scheme

MRTB (Metric return transfer breaker) for the neutral line of HVDC transmission

Rated voltage: DC 250 kV
Rated interrupting current: DC 2800/3500 A
Interrupter: SF6 puffer type
Typical interrupting time: 20-40 ms

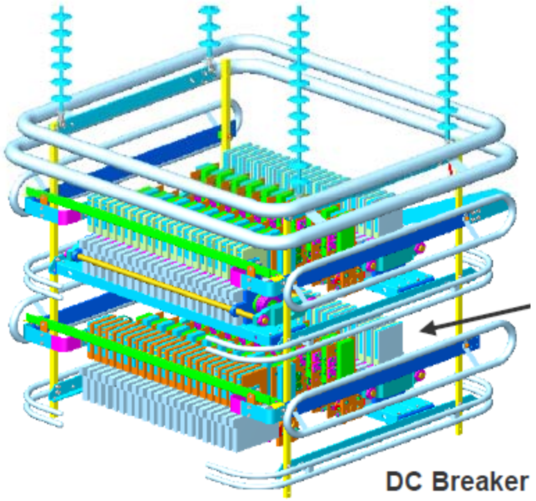


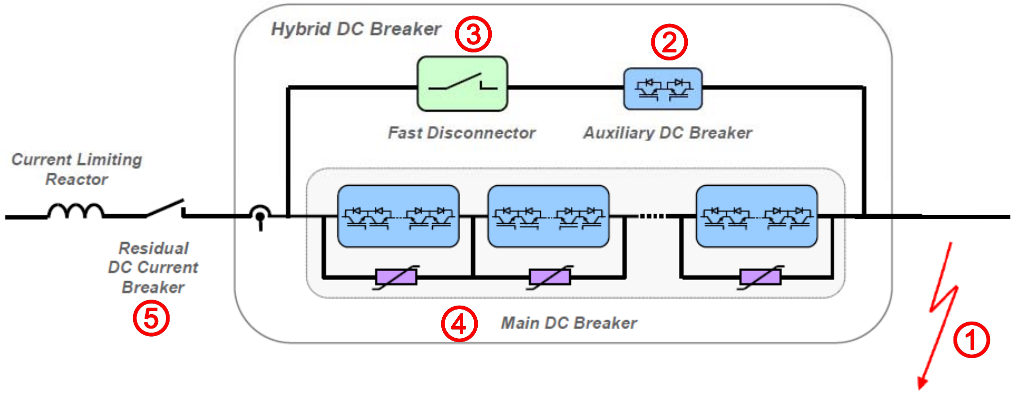
Artificial grounding DC current interruption by MRTB



H. Ito, et al., Instability of DC arc in SF6 circuit breaker", IEEE 96 WM, PE-057-PWRD-0-11-1996

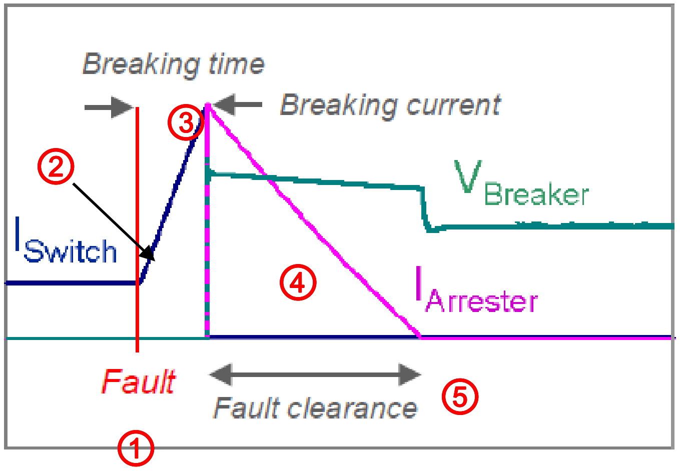
Hybrid type HVDC CB based on power electronic devices





Development target
Rated voltage: DC 320 kV
Rated nominal current: DC 2000 A
Rated interrupting current: DC 9 kA
Interrupter: Power electronics devices
Typical interrupting time: 5 ms

ABB Grid Systems, Technical Paper Nov. 2012



1. Fault occurrence
2. Commutate the current by Auxiliary DC Breaker
3. Disconnect the main circuit by Fast DS
4. Interrupt the current by power electronics DCCB
5. Disconnect the residual current

CIGRE/IEC Controlled Switching Survey

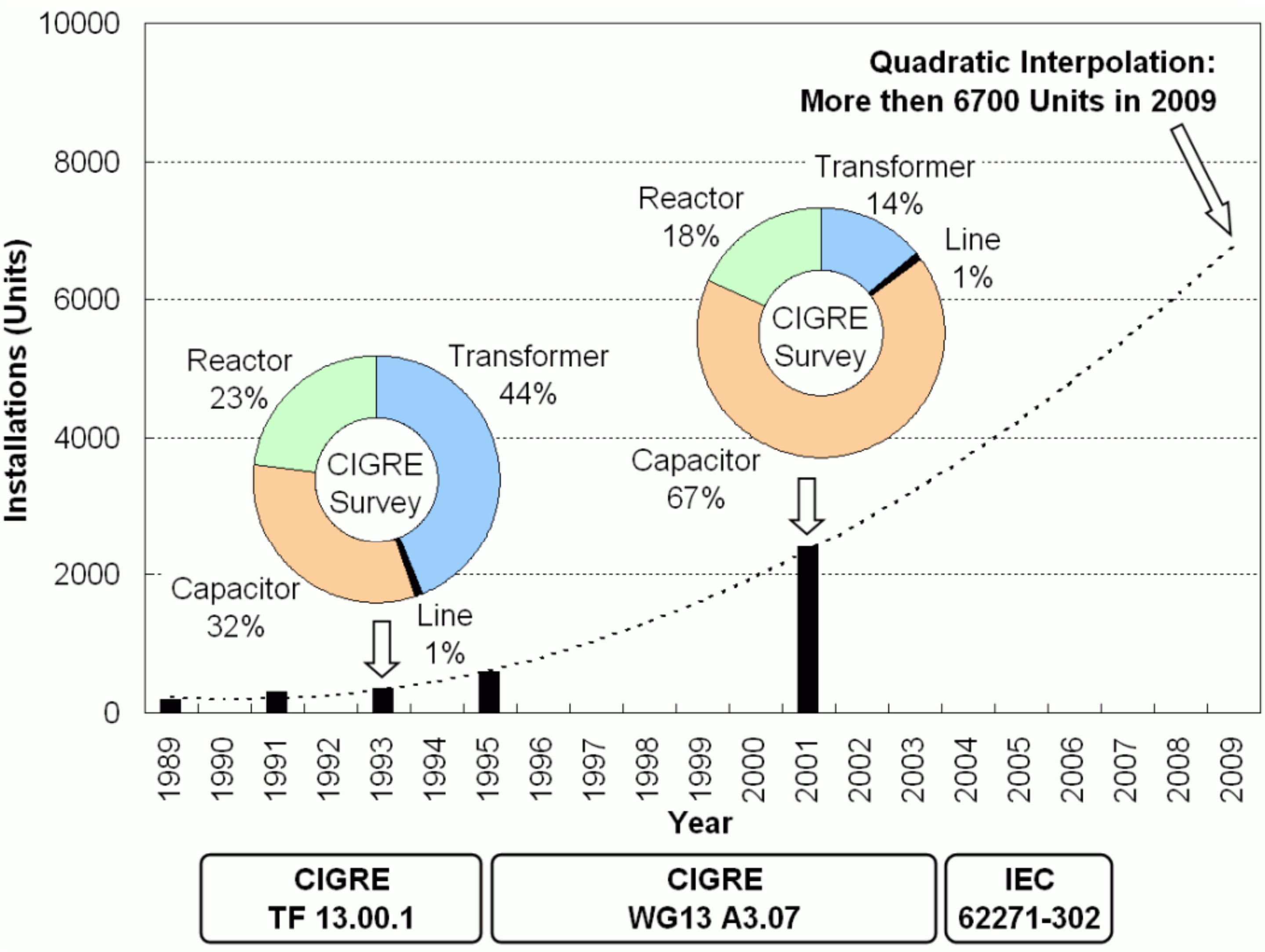
CIGRE TF 13.00.01:Controlled Switching, 1990-1995
Field experience of controlled switching

WG 13/A3.07: Controlled switching of HVAC circuit-breakers, 1996-2003
Application guide for lines, reactors, capacitors, transformers switching
Further applications such as unloaded transformer switching, load and fault interruption and circuit-breaker uprating
Benefits and Economic aspects
Planning, Specifications & Testing of controlled switching

IEC62271-302: High voltage alternating current circuit-breaker with internationally non-simultaneous pole operation, 2004-2006

CIGRE WG A3.35: Guidelines and Best Practices for the Commissioning and Operation of Controlled Switching Projects, 2014-

WG A3.07: Controlled switching su



The number of installations is based on several WG members' reports so it did not cover the worldwide statistics but shows the trend of applications.

CIGRE TF 13.00.01: Controlled Switching

Application	Conventional practice	Controlled switching
No load Transformer	Closing resistor	Voltage peak (low residual flux)
No load line	Closing resistor Surge arrester	Voltage zero across CB
Capacitor	Closing resistor Surge arrester	Voltage zero across CB
	Surge arrester	Maximum arcing time
Rector	Opening resistor Surge arrester	Maximum arcing time to avoid restrike

WG 13.07: Controlled switching

Compensation functions required for a Controller

Conditional compensation :

Variations of operating time depending on ambient temperature, control voltage and mechanical pressure

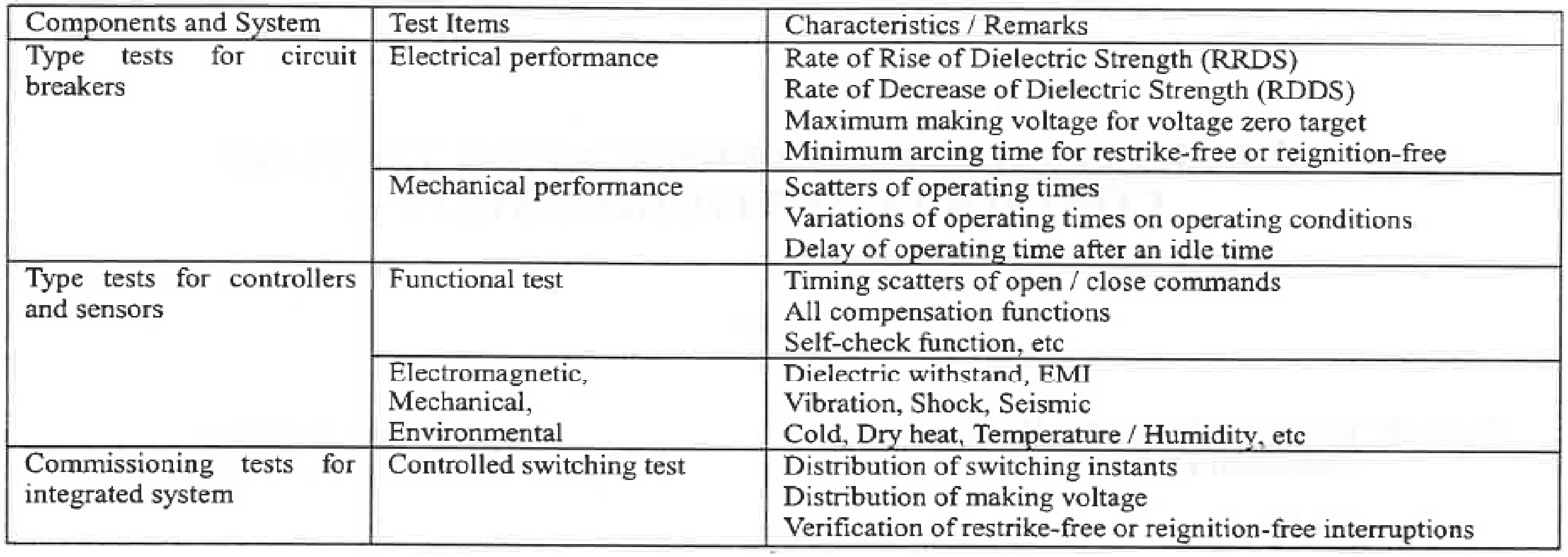
Idle time compensation :

Delay of operating time after an idle time of the breaker for next operation

Adaptive compensation :

Deviation of operating time due to long-term aging during the consecutive operations

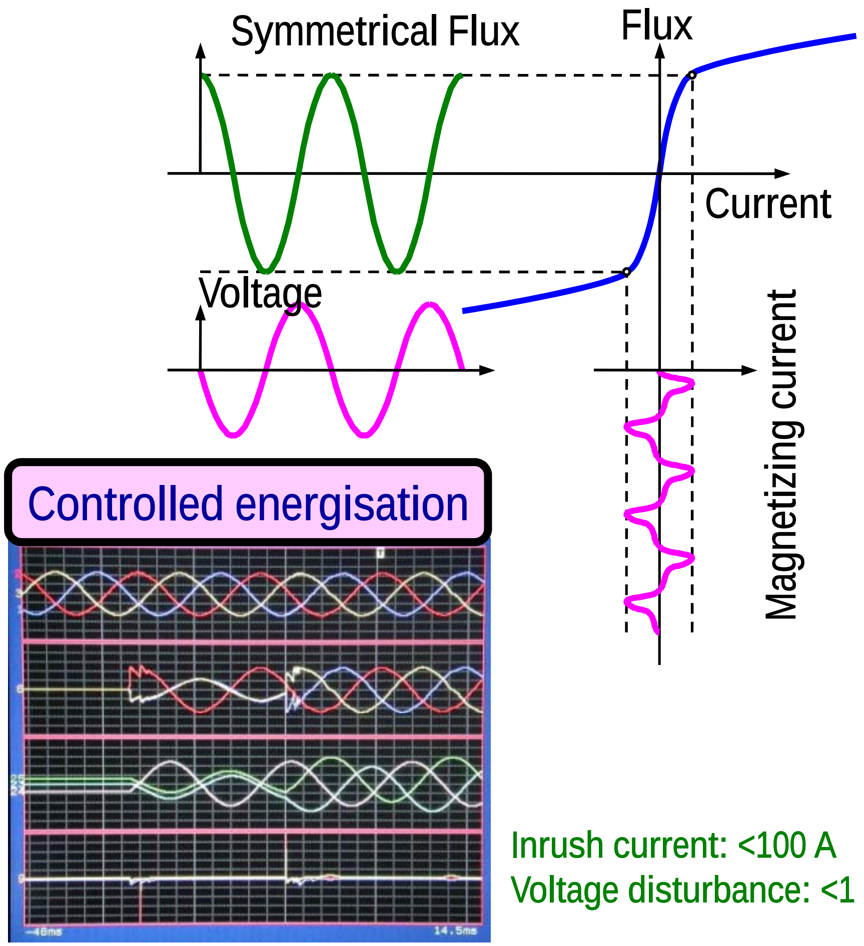
Factory Tests for Circuit Breakers



Components and System	Test Items	Characteristics / Remarks
Type tests for circuit breakers	Electrical performance	Rate of Rise of Dielectric Strength (RRDS) Rate of Decrease of Dielectric Strength (RDDS) Maximum making voltage for voltage zero target Minimum arcing time for restrike-free or reignition-free
	Mechanical performance	Scatters of operating times Variations of operating times on operating conditions Delay of operating time after an idle time
Type tests for controllers and sensors	Functional test	Timing scatters of open / close commands All compensation functions Self-check function, etc
	Electromagnetic, Mechanical, Environmental	Dielectric withstand, EMI Vibration, Shock, Seismic Cold, Dry heat, Temperature / Humidity, etc
Commissioning tests for integrated system	Controlled switching test	Distribution of switching instants Distribution of making voltage Verification of restrike-free or reignition-free interruptions

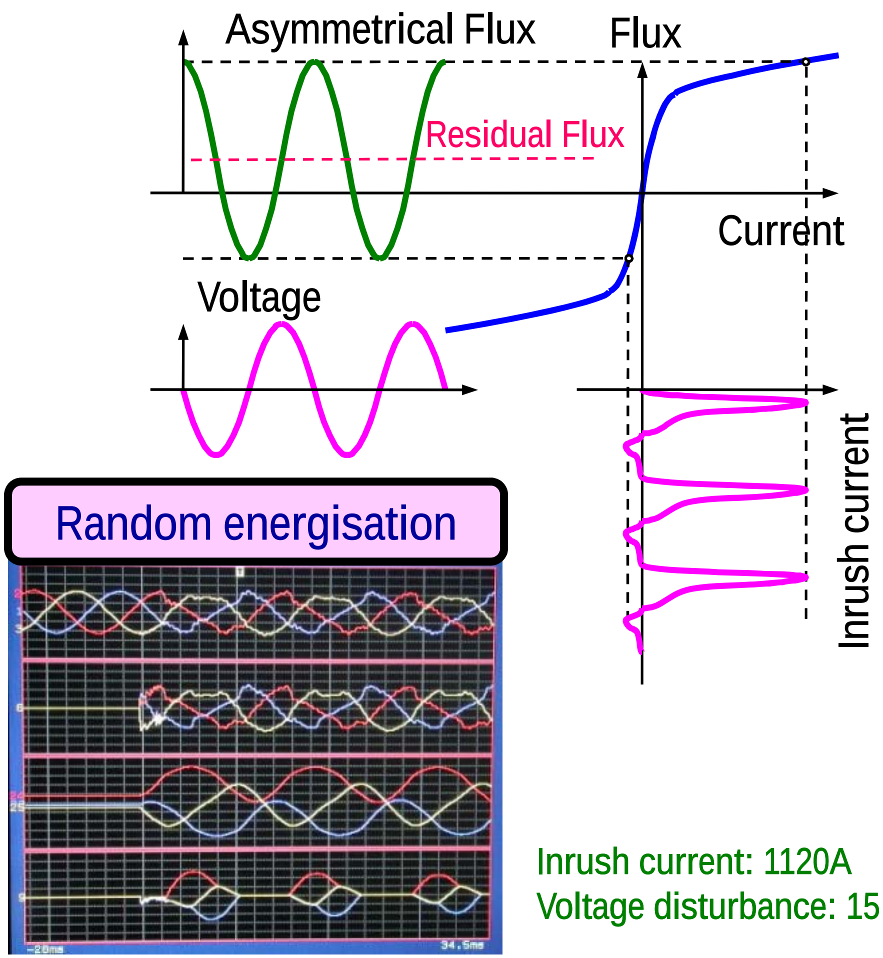
Controlled transformer switching

Transient Inrush Current at energization depends on the switching angle and the residual flux of the core. The higher residual flux causes the core saturation resulting in larger inrush current.



Controlled energisation

Inrush current: <100 A
Voltage disturbance: <1 %



Random energisation

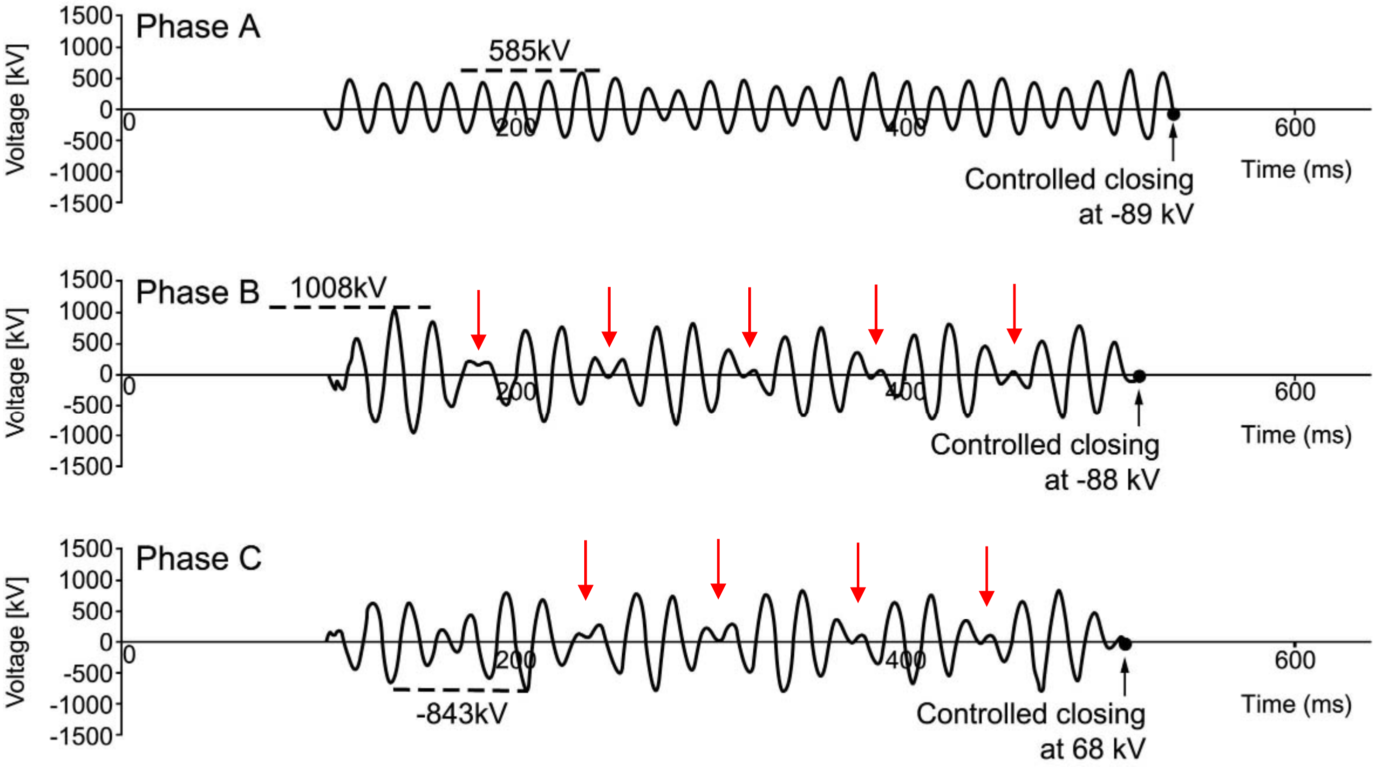
Inrush current: 1120A
Voltage disturbance: 15 %

The optimum targets should be adjusted taking into account the residual flux. The inrush current can be only eliminated by energisation when the prospective normal core flux is identical to the residual flux.

Compensated Line switching

The degree of compensation has significant effect on the line-side voltage. The voltage across the breaker show a prominent beat especially for a high degree of compensation.

The optimum instant is voltage minimum across the breaker, preferably during a period of the minimum voltage beat



CIGRE Controlled Switching Publication

CIGRE TF 13.00.01:Controlled Switching
A state-of-the-art survey, Part 1, ELECTRA NR. 163, pp65-96, 1995
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Study Committee A3, summary

A3 Scope

Design and development of substation equipment
New and improved testing techniques
Maintenance, Refurbishment and Lifetime management
Reliability assessment and Condition monitoring
Requirements presented by changing networks, standardizations

WG investigations

WG A3.06: Reliability of High Voltage Equipment
WG A3.25: MO Surge Arresters for emerging system conditions
WG A3.26: Influence of shunt capacitor banks on circuit breaker fault interruption duties
WG A3.27: Impact of the application of vacuum switchgear at transmission voltages
WG A3.28: Switching phenomena and testing requirements for UHV & EHV equipment
WG A3.29: Deterioration and ageing of substation equipment
WG A3.30: Overstressing of substation equipment
WG A3.31: Accuracy, Calibration & Interfacing of Instrument Transformers with Digital Outputs
JWG A3.32/CIRED: Non-intrusive methods for condition assessment of T&D switchgears
WG A3.33: Experience with equipment for series / shunt compensation
JWG A3/B4.34: DC switchgear
WG A3.35: Commissioning practices of controlled switching projects

Study Committee A3: Equipment

Thank you very much for your attention