CIGRE Study Committees A3
High Voltage Equipment

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

Hiroki Ito
Chairman, CIGRE Study Committee A3
Mitsubishi Electric Corporation

CIGRE session during ELECRAMA, Bangalore on 9th January 2014
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
- D1 Materials and emerging test technique
  - J. Kindersberger (Germany)
- D2 Information systems and telecommunication
  - C. Samitier (Spain)

Technical committee
Chairman: Mark Waldron (UK)
Secretary: Yves Maugain (France)
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
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.

- 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

<table>
<thead>
<tr>
<th>IEA/OECD data</th>
<th>Population (100 milion)</th>
<th>Electricity supply [1000kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>13.4</td>
<td>13.5</td>
</tr>
<tr>
<td>India</td>
<td>11.9</td>
<td>12.3</td>
</tr>
<tr>
<td>Germany</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Japan</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>USA</td>
<td>3.1</td>
<td>3.1</td>
</tr>
<tr>
<td>World</td>
<td>40</td>
<td>69.5</td>
</tr>
</tbody>
</table>

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.
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 = (1.34-1.71) x LIPL for 800 kV, (1.25-1.48) x LIPL for UHV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Voltage (p.u.) | IEC 800 kV | Hydro Quebec 765 kV | FURNAS 800 kV | AEP 800 kV | KEPCO 800 kV | Italy 1050 kV | Russia 1200 kV (With MOSA) | India 1200 kV | China 1100 kV | Japan 1100 kV |
| LIWL | 3.14 | 3.21 | 3.21 | 3.14 | 3.14 | 3.14 | 2.62 | 2.31 | 2.51 | 2.51 |

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**

<table>
<thead>
<tr>
<th></th>
<th>IEC 800 kV</th>
<th>Hydro Quebec 765 kV</th>
<th>FURNAS 800 kV</th>
<th>AEP 800 kV</th>
<th>KEPCO 800 kV</th>
<th>Italy 1050 kV</th>
<th>Russia 1200 kV (With MOSA)</th>
<th>India 1200 kV</th>
<th>China 1100 kV</th>
<th>Japan 1100 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIWV</td>
<td>1.18</td>
<td>1.25</td>
<td>1.28</td>
<td>1.42</td>
<td>1.18</td>
<td>1.16</td>
<td>1.15</td>
<td>1.20</td>
<td>1.23</td>
<td>1.08</td>
</tr>
<tr>
<td>SIWV</td>
<td>1.07</td>
<td>1.36</td>
<td>1.25</td>
<td>1.24</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**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

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

Switching impulse withstand voltage is more important for air clearance in UHV and EHV equipment.
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 bushing: 15m

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 

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

<table>
<thead>
<tr>
<th>Highest voltage (kV)</th>
<th>Conductors</th>
<th>DC time constants (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Size (mm²)</td>
<td>Bundle number</td>
</tr>
<tr>
<td>800 Canada</td>
<td>686</td>
<td>4</td>
</tr>
<tr>
<td>800 USA</td>
<td>572</td>
<td>6</td>
</tr>
<tr>
<td>800 South Africa</td>
<td>428</td>
<td>6</td>
</tr>
<tr>
<td>800 Brazil</td>
<td>603</td>
<td>4</td>
</tr>
<tr>
<td>800 Korea</td>
<td>480</td>
<td>6</td>
</tr>
<tr>
<td>800 China</td>
<td>400</td>
<td>6</td>
</tr>
<tr>
<td>1200 Russia</td>
<td>400</td>
<td>8</td>
</tr>
<tr>
<td>1050 Italy</td>
<td>520</td>
<td>8</td>
</tr>
<tr>
<td>1100 Japan</td>
<td>810</td>
<td>8</td>
</tr>
<tr>
<td>1100 China</td>
<td>500</td>
<td>8</td>
</tr>
<tr>
<td>1200 India</td>
<td>774</td>
<td>8</td>
</tr>
</tbody>
</table>

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.
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% |

- High TRV
- High RRRV
- TRV lower than T10
- Medium RRRV
- TRV lower than T30
- Low RRRV
UHV TRV simulations

CIGRE Radial network model

Double circuit lines with transposition

Japan 1100kV tower design

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

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

CIGRE 1100 kV system in Japan

Double circuit lines without transposition

TRV calculated in 1100 kV network in Japan

TRV calculated in 1100 kV radial network model

1100 kV TRV envelope for T30 duty (Uc=1660kV, RRRV=9kV/μs)

1100 kV TRV envelope for T30 duty (Uc=1660kV, RRRV=9kV/μs)

TRV envelope for T10 duty (Uc=1897kV, RRRV=7kV/μs)

TRV envelope for OoP duty (Uc=2245 kV)

TRV envelope for OoP duty (Uc=2245 kV)

TRV envelope for OoP duty (Uc=2245 kV)
### UHV TRV requirements

**U**: TRV peak \( = K_{pp} \times K_{af} \times U_{r} \sqrt{2/3} \)

**U**: First reference voltage \( = 0.75 \times K_{pp} \times U_{r} \sqrt{2/3} \)

**U**/ t2: Rate of rise of TRV

**t2**: time to TRV peak

\( t_2 = 4 \times t_1 \) for T100, \( t_2 = 6 \times t_1 \) for T60

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<table>
<thead>
<tr>
<th>UHV</th>
<th>DUTY</th>
<th>Kpp</th>
<th>Kaf</th>
<th>1100 kV TRV peak (kV)</th>
<th>1200 kV TRV peak (kV)</th>
<th>Rate of Rise of TRV</th>
<th>Time to TRV peak t2</th>
<th>Time to TRV peak t3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T100</td>
<td>1.2 (1.3)</td>
<td>1.5 (1.4)</td>
<td>1617</td>
<td>1764</td>
<td>2</td>
<td>3.0<em>t1 (4</em>t1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T60</td>
<td>1.2 (1.3)</td>
<td>1.5</td>
<td>1617</td>
<td>1764</td>
<td>3</td>
<td>4.5<em>t1 (6</em>t1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T30</td>
<td>1.2 (1.3)</td>
<td>1.54</td>
<td>1660</td>
<td>1811</td>
<td>5</td>
<td>t3 (t)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T10</td>
<td>1.2 (1.3)</td>
<td>1.76</td>
<td>1897</td>
<td>2076</td>
<td>7</td>
<td>t3 (t)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TLF</td>
<td>1.2 (1.5)</td>
<td>0.9*1.7</td>
<td>1649</td>
<td>1799</td>
<td>(*)</td>
<td>(*)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Out-of-phase</td>
<td>2.0</td>
<td>1.25</td>
<td>2245</td>
<td>2450</td>
<td>1.38<em>t1 (2</em>t1)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

\((*)\): \( \text{RRRV} = U_c / t_3 \) with \( t_3 = 6 \times U_r / I^{0.21} \) 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

Breaking current =11.3 kA rms (di/dt=5.02 A/μs)
Breaking current =7.1 kA rms (di/dt=3.15 A/μs)
Breaking current =5.1 kA rms (di/dt=2.26 A/μs)

Source side TRV
Line side TRV
Traveling Wave

Source side voltage
Voltage across CB
Line side voltage

1st T

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

<table>
<thead>
<tr>
<th>GAS/MIXTURE*</th>
<th>$z_o = 65,\Omega$</th>
<th>$z_o = 225,\Omega$</th>
<th>$z_o = 450,\Omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$i_c (\text{kA})$</td>
<td>$\text{SF}_6 = 100$</td>
<td>$i_c (\text{kA})$</td>
</tr>
<tr>
<td>$\text{SF}_6$</td>
<td>21.0</td>
<td>100</td>
<td>26.3</td>
</tr>
<tr>
<td>$\text{SF}_6/N_2$ (75/25)</td>
<td>17.8</td>
<td>85</td>
<td>20.4</td>
</tr>
<tr>
<td>CH$_4$/CCLF$_2$CF$_3$ (50/50)</td>
<td>17.8</td>
<td>85</td>
<td>20.2</td>
</tr>
<tr>
<td>CF$_2$CF$_2$/SF$_6$ (75/25)</td>
<td>17.0</td>
<td>81</td>
<td>20.0</td>
</tr>
<tr>
<td>CF$_3$SO$_2$/SF$_6$ (30/70)</td>
<td>16.5</td>
<td>79</td>
<td>18.3</td>
</tr>
<tr>
<td>$\text{SF}_6$/He (75/25)</td>
<td>15.4</td>
<td>73</td>
<td>20.4</td>
</tr>
<tr>
<td>SF$_6$/N$_2$ (50/50)</td>
<td>14.9</td>
<td>71</td>
<td>17.2</td>
</tr>
<tr>
<td>CF$_2$CF$_2$</td>
<td>14.8</td>
<td>70</td>
<td>17.8</td>
</tr>
<tr>
<td>$\text{SF}_6$/He (50/50)</td>
<td>14.7</td>
<td>70</td>
<td>19.7</td>
</tr>
<tr>
<td>CCLF$_2$/CF$_3$/SF$_6$ (70/30)</td>
<td>14.0</td>
<td>67</td>
<td>17.6</td>
</tr>
<tr>
<td>CHCIF$_2$/SF$_6$ (75/25)</td>
<td>13.8</td>
<td>66</td>
<td>14.7</td>
</tr>
<tr>
<td>CBF$_3$/SF$_6$ (75/25)</td>
<td>11.6</td>
<td>55</td>
<td>14.5</td>
</tr>
<tr>
<td>CF$_3$SO$_2$/SF$_6$ (75/25)</td>
<td>11.4</td>
<td>54</td>
<td>13.8</td>
</tr>
<tr>
<td>CF$_4$</td>
<td>11.1</td>
<td>53</td>
<td>14.6</td>
</tr>
<tr>
<td>CBF$_3$</td>
<td>11.1</td>
<td>53</td>
<td>16.8</td>
</tr>
<tr>
<td>CCLF$_2$CF$_3$</td>
<td>10.8</td>
<td>51</td>
<td>15.4</td>
</tr>
</tbody>
</table>

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.

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
Superior SF₆ dielectric / interrupting performance

**Dielectric performance: 3 times better**

- **SF₆**
  - Smaller diameter in arc (Less energy dispassion)
  - Rapid switching: conductor to insulator (Faster resistance change)

Less breaks for interrupter
Compact equipment & substation

**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 SF₆ relative to one kilogram of CO₂)

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

Air insulated substation (AIS)

180 m
30 m
20 m
75 m
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)
The increased application of spring operating mechanisms improved CB reliability.
### WG A3.06: CB Reliability surveys: components

<table>
<thead>
<tr>
<th>Components</th>
<th>Major Failure /100units/year</th>
<th>Minor Failure /100units/year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st Survey</td>
<td>2nd Survey</td>
</tr>
<tr>
<td>Main Circuit</td>
<td>0.76 (48%)</td>
<td>0.14 (21%)</td>
</tr>
<tr>
<td>Control Circuit</td>
<td>0.30 (19%)</td>
<td>0.19 (29%)</td>
</tr>
<tr>
<td>Operating Mech.</td>
<td>0.52 (33%)</td>
<td>0.29 (43%)</td>
</tr>
<tr>
<td>Others</td>
<td>0.05 (7%)</td>
<td></td>
</tr>
<tr>
<td>World data</td>
<td>1.58</td>
<td>0.67</td>
</tr>
</tbody>
</table>

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
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

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
71 kV for 36 kV
47 kV 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

#### Rating

<table>
<thead>
<tr>
<th></th>
<th>VCB</th>
<th>GCB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rating</td>
<td>84 / 72 kV</td>
<td>84 / 72 kV</td>
</tr>
<tr>
<td></td>
<td>12.5-31.5 kA</td>
<td>12.5-31.5 kA</td>
</tr>
<tr>
<td></td>
<td>600-2000 A</td>
<td>600-3000 A</td>
</tr>
<tr>
<td>CB-year</td>
<td>24907 unit-year</td>
<td>12953 unit-year</td>
</tr>
<tr>
<td>Failure Rate</td>
<td>0.032</td>
<td>0.023</td>
</tr>
</tbody>
</table>

#### Total Installations

<table>
<thead>
<tr>
<th></th>
<th>VCB</th>
<th>GCB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Transformer</td>
<td>263</td>
<td>99</td>
</tr>
<tr>
<td>Distribution Transformer</td>
<td>814</td>
<td>199</td>
</tr>
<tr>
<td>Line Protection</td>
<td>1287</td>
<td>863</td>
</tr>
<tr>
<td>Shunt capacitor</td>
<td>117</td>
<td>30</td>
</tr>
<tr>
<td>Shunt reactor</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>Neutral point</td>
<td>3</td>
<td>147</td>
</tr>
</tbody>
</table>

#### Frequency of failures

- **VCB**:
  - Internal fault by lightning: 1
  - Interrupter: 1
  - Auxiliary: 1
  - Mechanical: 5

- **GCB**:
  - Mechanical: 3

#### Number of Failures by Years in Service

- **VCB**:
  - 0-9 years: 6
  - 10-19 years: 2
  - 20-29 years: 0
  - 30-39 years: 0

- **GCB**:
  - 0-9 years: 3
  - 10-19 years: 0
  - 20-29 years: 0
  - 30-39 years: 0
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

Short circuit current
arc voltage
circuit voltage

NFB trip
Current level

Smoothing L R

NFB$_1$
NFB$_2$

Lord

$t_1$: 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 (HSVVCB) 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

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**

![Diagram showing MRTB and parallel impedance](image)

- **Return line voltage:** 65kV  
- **Interrupter current:** 2490A  
- **Return line current:** 2056A  
- **Disconnector current:** 310A 1820Hz  
- **MRTB opens:** 18.3ms  
- **Current cleared:** 5.6ms

---

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


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


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

<table>
<thead>
<tr>
<th>Application</th>
<th>Conventional practice</th>
<th>Controlled switching</th>
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</thead>
<tbody>
<tr>
<td>No load Transformer</td>
<td>Closing resistor</td>
<td>Voltage peak (low residual flux)</td>
</tr>
<tr>
<td>No load line</td>
<td>Closing resistor</td>
<td>Voltage zero across CB</td>
</tr>
<tr>
<td></td>
<td>Surge arrester</td>
<td></td>
</tr>
<tr>
<td>Capacitor</td>
<td>Closing resistor</td>
<td>Voltage zero across CB</td>
</tr>
<tr>
<td></td>
<td>Surge arrester</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Surge arrester</td>
<td>Maximum arcing time</td>
</tr>
<tr>
<td>Rector</td>
<td>Opening resistor</td>
<td>Maximum arcing time to avoid restrike</td>
</tr>
<tr>
<td></td>
<td>Surge arrester</td>
<td></td>
</tr>
</tbody>
</table>
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

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

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

WG 13.07: Controlled switching of HVAC circuit-breakers
Guide for application lines, reactors, capacitors, transformers 1st part. ELECTRA 183, April 1999, 2nd Part, ELECTRA 185, August 1999

Planning, specification and testing of controlled switching systems, ELECTRA 197, August 2001
Controlled switching of unloaded power transformers, ELECTRA 212, February 2004
Controlled Switching: non-conventional applications, ELECTRA 214, June 2004

Benefits and Economic aspects, ELECTRA 217, December 2004
Benefits & Economic Aspects, TB262, December 2004

Guidance for further applications including unloaded transformer switching, load and fault interruption and circuit-breaker uprating, TB263, December 2004
Planning, Specifications & Testing of controlled switching systems, TB264, December 2004
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/CIRE: 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
Thank you very much for your attention.