Technology Past, Present & Future for Medium Voltage Vacuum Switchgear
Contents

◆ Application and Composition

◆ Characteristics of Vacuum

◆ Vacuum Interrupter (VI)
  - VI Configuration
  - Insulation in Vacuum
  - Arc Control Technology
  - Reliability and Quality Control

◆ Vacuum Circuit Breaker (VCB)
  - VCB Configuration
  - Mechanical Characteristics
  - Special Application

◆ Solid Insulated Switchgear (SIS)
  - Introduction of Insulation material

◆ Toward The Future
Medium Voltage; up to 84kV Vacuum Switchgear Application

Power plant system
- VEMV CB
- B.LOMACB

Power distribution system
- 網路設備設置
- 25kV電源
- 供電用真空開關

Transportation system

Factory system
- 通用設備
- 電動機控制
- VHFV CB

Buildings system
- 受電用スイッチギヤ
- VMU8SWGR
- VHRV CB

General supply system
- JIS
- キャビネット
- 電力箱

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Medium Voltage Vacuum Switchgear Composition

- 7.2kV Metal-Clad Switchgear
- 7.2kV JIS standard power distribution switchgear
- Air insulated SWGR
- Gas, Solid insulated SWGR
- Vacuum Interrupters
- Vacuum Circuit Breakers
- Protection, Control, Monitoring system
- Multi-function relay for switchgear
- Multi-function motor protection relay
- Sensor technology
- Digital Technology
- Computer Technology
- Local monitor
- Thermal relay

- 24kV Spot network system
- 66/84kV Compact Cubicle type Gas Insulated Switchgear
- 36kV Solid Insulated Switchgear
- 22-77kV Cubicle type Gas Insulated Switchgear
- 36kV Solid Insulated switchgear
- 36kV-63kA Nuclear and thermal power station
- 3.6-24kV VCB
- 36kV VCB
- 36kV For electric railway
- 36kV VCB

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To extinguish arc – to interrupt current

Ex. flame of a candle….to extinguish flame

- Blast
- Extend
- Pour liquid (water..)
- Choke off
To extinguish arc – to interrupt current

Current flow

Conductor Arc Conductor

Ambient liquid, gas, ...

Oil Air SF6 Vacuum

OCB • Oil Circuit Breaker
ACB • Air Circuit Breaker
ABB • Air Blast Circuit Breaker
GCB • Gas Circuit Breaker (SF6)
VCB • Vacuum Circuit Breaker
• Environmentally friendly

  SF6 was placed on the list of greenhouse gases under the Kyoto Protocol in 1997.

• Low flammability

• High insulation capability
Characteristics in Vacuum (Paschen’s Curve)

Pressure of actual products is $10^{-5}\text{Pa}$ order.

Breakdown Voltage vs. Pressure

Atmospheric Pressure

Breakdown Voltage (kV)

Pressure (Pa)
Characteristics in Vacuum

<table>
<thead>
<tr>
<th>Pressure (Pa)</th>
<th>Molecular</th>
<th>Mean free path (N₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10³ Pa</td>
<td>3X10¹⁷/cm³</td>
<td>10⁻⁵ m</td>
</tr>
<tr>
<td>10⁻¹ Pa</td>
<td>3X10¹³/cm³</td>
<td>10⁻¹ m</td>
</tr>
<tr>
<td>10⁻⁵ Pa</td>
<td>3X10⁹ /cm³</td>
<td>10³ m</td>
</tr>
</tbody>
</table>
Vacuum Insulation Capability

Withstand Voltage Characteristic by Insulation Media

Impulse Withstand Voltage (kV) vs. Distance (mm)

- Vacuum
- Air
- Abs. 0.1MPa SF₆

Normal contact Stroke in vacuum

Insulation Comparison:
- Air
- SF₆
- Vacuum
Current Interruption in a Vacuum interrupter
(The Case of Axial Magnetic Field Electrodes)
Current Interruption

Characteristics of Recovery Voltage by Insulation Media

Transient recovery voltage between contacts

Voltage Wave

Recovery voltage [kV]

Time after zero current [μs]

Vacuum

SF₆

N₂

H₂

Current Interruption

Contact Separation

Zero Current
Transition of Circuit Breakers

Transition of production

Reference: 遮断器 & 断路器のメンテナンス入門 オーム社
History of Vacuum Circuit Breakers

1965
Vacuum Switch
(7.2kV 100A 50MVA)

1966
Vacuum Circuit Breaker
(7.2kV 600A 150MVA)
Progress on Interrupting Capacity
(24kV-25kA Rating)
Technical Progress on Vacuum Interrupters

- High Voltage application
- High Current Interruption

- Compact Design at Same Rating

Insulation in Vacuum

Arc Control
Dielectric Breakdown Mechanism in Vacuum

Hypotheses have been proposed;

The field emission is generated from the micro-protrusion on the cathode surface

Field Emission Hypothesis

Clump is a contamination of micro-particle on the electrode surface.

Clump Hypothesis

Clump is accelerated by electrostatic power.

VAPORIZATION
BREAKDOWN

Clump Hypothesis

VAPORIZATION

Clump Hypothesis

CATHODE
-
ANODE
+

Clump Hypothesis

CATHODE
-
ANODE
+

Clump Hypothesis

CATHODE
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ANODE
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Clump Hypothesis

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ANODE
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Clump Hypothesis

CATHODE
-
ANODE
+
10th September, 2009
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**Conditioning Effect – what is conditioning effect?**

Comparison of conditioning effect between machining and electrochemical buffing electrodes

- **Breakdown voltage [kV]**
- **Number of voltage application**

<table>
<thead>
<tr>
<th>Number of voltage application</th>
<th>Breakdown voltage [kV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>200</td>
<td>40</td>
</tr>
<tr>
<td>600</td>
<td>120</td>
</tr>
<tr>
<td>800</td>
<td>160</td>
</tr>
</tbody>
</table>

- **Electrochemical buffing treatment**
  - $R_{a} = 0.04 \mu m$
  - $R_{w} = 0.49 \mu m$
  - $R_{z} = 0.28 \mu m$

- **Machining**
  - $R_{a} = 0.16 \mu m$
  - $R_{w} = 2.41 \mu m$
  - $R_{z} = 1.83 \mu m$

- **Surface roughness**
- **Cross-section after conditioning**
  - Melted layer
  - Base material
  - 25 $\mu m$

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### Breakdown Field Strength in Vacuum

**Effective area $S_{\text{eff}}$**

<table>
<thead>
<tr>
<th>Structure</th>
<th>Effective Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel</td>
<td>$E_b = 380 \cdot S_{\text{eff}}^{-0.23}$</td>
</tr>
<tr>
<td>Copper</td>
<td>$E_b = 580 \cdot S_{\text{eff}}^{-0.25}$</td>
</tr>
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</table>

The diagram illustrates the breakdown field strength ($E_b$) in terms of the effective area ($S_{\text{eff}}$) for stainless steel and copper. The effective area is more than 90% of the maximum field strength.

**Effective area $S_{\text{eff}}$ (cm²)**

- Stainless steel: $E_b = 380 \cdot S_{\text{eff}}^{-0.23}$
- Copper: $E_b = 580 \cdot S_{\text{eff}}^{-0.25}$
Electrical Field Analysis of Vacuum interrupter

Example of electrical field analysis of vacuum interrupter
Size Reduction of 72/84kV Vacuum Interrupter

Vacuum Circuit Breaker for C-GIS

Volume reduction history of vacuum interrupter for 72/84kV C-GIS

<table>
<thead>
<tr>
<th>Volume ratio</th>
<th>1985</th>
<th>1989</th>
<th>1997</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development year</td>
<td>100</td>
<td>65</td>
<td>40</td>
</tr>
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</table>

The volume of C-GIS is reduced to traditional half.
Arcing in Vacuum

Arcing plasma; Ion and electron

Cathode spot (μm in order): Supply plasma by melting cathode electrode

Arcing Characteristic in Vacuum

Arc concentrate in cathode (anode) spot → Heating rising → Metal vapor emitted continuously → Re-ignition

Control arc not to be concentrated increases capability of interruption
Major Electrodes in the world

Magnetic Driven Method

Axial Magnetic Field Method
Magnetic Driven Method

Spiral

Arc

Current Flow in Coil

Force against Arc

Typical Configuration

Side section

A - A
Generate Axial Magnetic Field by current in coil (Parallel flux to arc)
Axial Magnetic Field Electrode

- Electrons and Ions are trapped by magnetic line
- Arc is captured within spaces between contacts
- Arc root spread uniformly
Electrode Designing

Magnetic Field Analysis (ELKTRA)
Eddy Current Consideration in 3D

Example of Analyzed Results
Large Current interruption

13.8kV-100kA Type VGB2 VCB

- Largest Vacuum Interrupting Capability in the World -

VCB Front View

Vacuum Interrupters
Reliability of Vacuum Interrupters

- Quality Control on Vacuum leakage
- Measurements of Vacuum pressure
Quality Control for Vacuum Life

A: Pressure Change caused by Gas Evolution
B: Pressure Change caused by leakage

Critical Pressure

Internal Pressure

Shortage time

Target life

Tolerance

C = A + B

Expected Vacuum Life

Internal Pressure Change

PASS

DEFECT

Measurement of Internal Pressure
Measurement of Vacuum

**Principle**

Apply Magnetic Field and Electrical Field

Increase Path of Electron

Dissociation by Electron in Collision with Particle

Proportional Current to Particle (Vacuum pressure)

- Movement of Electron
- Direction of Electrical Field
- Magnetic Field from Outside
- Electrode
- Arc Shield
- Source for Magnetic Field
- High Voltage DC
- Micrometer