Influence of Depth of Cathode Arc-remelted Layer on Vacuum Insulation

Zhiyuan Liu, Shimin Li, Yingsan Geng and Jianhua Wang

Presenter: Zhiyuan Liu
State Key Laboratory of Electrical Insulation and Power Equipment,
Xi’an Jiaotong University
MeVarc 2017, Jerusalem, Israel
Mar 22, 2017
CONTENTS

1. Introduction

2. Experimental Setup

3. Experimental Results
   A. The arc-remelted layer forming experiment
   B. Lightning impulse breakdown voltage test
   C. Field emission current measurement and $\beta$
   D. Cross section electron microscope analysis
   E. arc-remelted layer depth and the breakdown voltage

4. Discussion
1. Introduction

Where do we come from? Answer: Xi’an, China
1. Introduction

What is our field? Power Engineering

- Substations
- Transmission Lines
- Circuits
- Circuit breakers
- Failures
- Distributions Transmissions Generations
- Customers
- Industries
- Living life
- Traffics
- Generations
- Transmissions
- Distributions
- Customers
1. Introduction

A 126kV single break vacuum circuit breaker
Xi’an Jiaotong University, Xi’an, China

Vacuum gaps for possible breakdowns in vacuum interrupters
1. Introduction

- Current conditioning is an effective way using vacuum arcs to improve vacuum interrupter’s insulation, by producing a remelted layer on the electrode’s surface.

- The objective of this paper is to determine the influence of the depth of cathode arc-remelted layer on vacuum gap’s insulation.

*Melted layer produced by current conditioning*
2. Experimental Setup

◆ System Setup:

- **Vacuum Interrupter A**: No Arcing Process
- **Vacuum Interrupters B, C, D**: Current Arcing Time
  - B: 10ms
  - C: 46ms
  - D: 73ms
- **Standard 1.2/50μs Lightning Impulse Voltage Test**
- **Field Emission Current Measurement**
- **Cross Section Electron Microscope Analysis**
- **Finish**

The arc remelted layer forming experiment
3. Experimental Results

The arc remelted layer forming experiment

Experiment Setup

Vacuum Interrupter A
No Arcing Process

Vacuum Interrupters B, C, D
Current Arcing Time B: 10ms, C: 46ms, D: 73ms

Standard 1.2/50μs Lightning Impulse Voltage Test

Field Emission Current Measurement

Cross Section Electron Microscope Analysis

Finish
3. Experimental Results

◆ A: The melted layer forming experiment

the experiment circuit

\[ I_{\text{DC}} = 250 \text{ A} \]
\[ B_{\text{AMF}} = 60 \text{ mT} \]

the time sequence of the experiment

Plane electrode-cathode; Rod electrode-anode
3. Experimental Results

◆ A: The melted layer forming experiment

Electrode material:
- plane: CuCr25
- rod: CuCr25

Parameters:
- \( \Phi_{\text{plane}} = 48 \text{ mm}, \)
- \( \Phi_{\text{rod}} = 4 \text{ mm}, \)
- \( d = 1 \text{ mm}. \)

When forming the arc-remelted layer, the rod was the anode.

During the lightning impulse voltage test, the rod was the cathode.

Note: the arc-remelted layer, with different depths, was formed on the rod electrode.
3. Experimental Results

◆ A: The melted layer forming experiment

- In the first 26 ms, the arc voltage fluctuated and it corresponded that the vacuum arc rotated randomly on the cathode.

- After that, the arc voltage kept stable, around 20 V. The vacuum arc was opposite to the rod anode.

- So, the arcing time of vacuum interrupters B, C, D were 10 ms, 46 ms, 73ms, respectively.
3. Experimental Results

**Experiment Setup**

- Vacuum Interrupter A
  - No Arcing Process
  - Standard 1.2/50μs Lightning Impulse Voltage Test
  - Field Emission Current Measurement
  - Cross Section Electron Microscope Analysis
  - Finish

- Vacuum Interrupters B, C, D
  - Current Arcing Time
    - B: 10ms, C: 46ms, D: 73ms
3. Experimental Results

◆ B: Lightning impulse breakdown voltage test

![Graph showing breakdown voltage (kV) vs. number of voltage application]

- **Breakdown voltage (kV)**
- **Number of voltage application**

- **Withstand voltage**
- **Breakdown voltage**

- **Plane electrode-anode**;
- **Rod electrode-cathode**

\[ \Delta U: \sim 4 \text{kV} \]
B: Lightning impulse breakdown voltage test

The scattering of breakdown voltage and the fitting conditioning curve of vacuum interrupter

Vacuum Interrupter A

Vacuum Interrupter B

Vacuum Interrupter C

Vacuum Interrupter D

The scattering of breakdown voltage and the fitting conditioning curve of vacuum interrupter

Zhiyuan Liu- Influence of Depth of Cathode Arc-remelted Layer on Vacuum Insulation
3. Experimental Results

◆ B: Lightning impulse breakdown voltage test

- The breakdown voltage probability distribution of vacuum interrupters A, B, C, D fitted Weibull distribution.

- With arcing times of 10, 46, and 73 ms, $U_{50}$ was higher than that of the no arcing case. The arcing improved the breakdown voltage.

- The $U_{50}$ of the arcing times of 10, 46, and 73 ms were 73.3, 75.5, and 77.9 kV, respectively. They were quite close to each other, so the different arcing times had little influence on the breakdown voltage.
3. Experimental Results

Experiment Setup

Vacuum Interrupter A

No Arcing Process

Vacuum Interrupters B, C, D

Current Arcing Time
B: 10ms, C: 46ms, D: 73ms

Standard 1.2/50μs Lightning Impulse Voltage Test

Field Emission Current Measurement

Cross Section Electron Microscope Analysis

Finish
3. Experimental Results

Experiment Setup

- **Vacuum Interrupter A**
- **Vacuum Interrupters B, C, D**

No Arcing Process

- **Current Arcing Time**
  - B: 10ms, C: 46ms
  - D: 73ms

- **Standard 1.2/50µs Lightning Impulse Voltage Test**

- **Field Emission Current Measurement**

- **Cross Section Electron Microscope Analysis**

- **Finish**
3. Experimental Results

**D: Cross section electron microscope analysis**

- **VI A**
  - Arcing time: 0 ms
  - No arc-remelted layer, rough surface
  - Average depth: 0 μm

- **VI B**
  - Arcing time: 10 ms
  - A thin arc-remelted layer with smooth surface
  - Average depth: 5 μm

- **VI C**
  - Arcing time: 46 ms
  - Arc-remelted layer: 10-50 μm
  - Average depth: 35 μm

- **VI D**
  - Arcing time: 73 ms
  - Arc-remelted layer: 50-80 μm
  - Average depth: 65 μm

Zhiyuan Liu - Influence of Depth of Cathode Arc-remelted Layer on Vacuum Insulation
3. Experimental Results

◆ **D: Cross section electron microscope analysis**

- The average depths of the arc-remelted layers 0, 5, 35, and 65 μm corresponded to arcing times of 0, 10, 46, and 73 ms, respectively.
- The average depth of arc-remelted layer was proportional to the arcing time.

![Graph showing the relationship between arcing time and average depth of arc-remelted layer.](image)
3. Experimental Results

◆ E: Relationship between arc-remelted layer depth and the breakdown voltage

- Having an arc-remelted layer apparently improved vacuum insulation significantly.
- The various depth of the arc-remelted layer seem have close vacuum insulation level.

<table>
<thead>
<tr>
<th>Vacuum interrupter</th>
<th>Average depth of arc-remelted layer / μm</th>
<th>50% breakdown voltage / kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>55.6</td>
</tr>
<tr>
<td>B</td>
<td>5</td>
<td>73.3</td>
</tr>
<tr>
<td>C</td>
<td>35</td>
<td>75.5</td>
</tr>
<tr>
<td>D</td>
<td>65</td>
<td>77.9</td>
</tr>
</tbody>
</table>
4. Discussion

- Observation: Arcing times of 0, 10, 46 and 73 ms corresponded to
  1) the average arc-remelted layer depths of 0, 5, 35 and 65 μm, respectively.
  2) The 50% breakdown voltages of 55.6, 73.3, 75.5, and 77.9 kV

- It is not surprising that an arc-remelted layer significantly increase the breakdown voltage.

- However, the arc-remelted layers seem have virtually no influence on the vacuum insulation level, why?

- Is the vacuum insulation level decided by the electrode surface conditions, not the arc-remelted layer depth?
4. Discussion

◆ C: Field emission current measurement

The field emission current measurement circuit

Gap spacing : 1.0 mm
Rs : 2kΩ
BD voltage of TVS: 15 V
Maximum leakage current before BD of TVS: 1 µA

The field emission current I and the applied voltage V fit Fowler-Nordheim equation

\[
\ln \left( \frac{I}{V^2} \right) = \ln \left[ \frac{1.54 \times 10^{-6}}{\Phi d^2} \left( \frac{A_e \beta^2 10^{4.52 \Phi^{-0.5}}}{\Phi d^2} \right) \right] - \frac{2.84 \times 10^9 d \Phi^{1.5}}{\beta} \cdot \frac{1}{V}
\]

CuCr25, \( \Phi: 4.6 \text{ eV} \)
4. Discussion

◆ Electric field enhancement factor

<table>
<thead>
<tr>
<th>Vacuum interrupter</th>
<th>Peak value of voltage /kV</th>
<th>Electric field enhancement factors β</th>
<th>Breakdown</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>39.9</td>
<td>270</td>
<td>No.1</td>
</tr>
<tr>
<td>B</td>
<td>42.7</td>
<td>340</td>
<td>--</td>
</tr>
<tr>
<td>C</td>
<td>39.9</td>
<td>273</td>
<td>No.1</td>
</tr>
<tr>
<td>D</td>
<td>39.9</td>
<td>275</td>
<td>No.1</td>
</tr>
</tbody>
</table>

The field emission current measurement were carried out before the first breakdown. Therefore, sample B is out of consideration.

- β values of sample A, C and D were nearly the same, around 273 at the same applied voltage.
- Remember: The 50% breakdown voltages of sample C and D with arcing (75.5 kV and 77.9 kV) were much higher that that of sample A (55.6 kV) without arcing.
The similar β values suggest the similar contact surface conditions.

However, similar surface conditions lead to different breakdown voltage?
4. Discussion

◆ Electric field enhancement factor?

Fowler-Nordheim equation

\[
\ln \frac{I}{V^2} = \ln \left[ \frac{1.54 \times 10^{-6} A e^2 \beta^2 10^{4.52 \Phi^{-0.5}}}{\Phi d^2} \right] - \frac{2.84 \times 10^9 d \Phi^{1.5}}{\beta} \cdot \frac{1}{V}
\]

CuCr25, work function: 4.6 eV

Same value for the cases with and without the arc-remelted layers

- How to deal with the work function with and without the arc-remelted layers to reflect the difference on the arc-remelted layers?

- Different \( \beta \) values should distinguish the contact surface with and without the arc-remelted layers…
Thanks for your attention!