Characterization of the breakdown voltage of vacuum interrupters by different procedures

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Outline

- Introduction and rationale
- Experimental setup
- Experimental result collected with AwBD procedure on VIs (repeatability check)
- Deconditioning effect at different gap lengths for VI
- Comparison between AwBD and Up-Down (UD) methods
Introduction and rationale

Vacuum interrupters have standard requirements to withstand voltage pulses

The Basic Insulation Level (BIL) is precisely codified (e.g. peak voltage and shape of the voltage waveform)

The Lighting Impulse Voltage Waveform (LIVW) has a front time and a time to half-value of 1.2/50 μs

The electrical stress in this experiments is much higher than in the actual application

Different procedures for the LIVW application can be adopted to characterize the hold off voltage of a device under a statistical approach

In this work 2 procedures have been investigated and the results have been compared
- Up and Down (UD) → widely adopted
- Always Breakdown (AwBD) → faster procedure to collect statistical results

The collected results have been adopted to tune and validate the Voltage Holding Predictive Model (VHPM) [2], a numerical tool developed at Consorzio RFX aimed at improving the design of high-vacuum complex electrostatic devices (see N.Marconato presentation).

BIL lighting impulse voltage

![Graph showing the relationship between voltage (kV) and time (µs). The voltage decreases exponentially over time.]
Experimental setup

Marx Generator: $12 \times 200\text{kV} = 2.4\text{ MV}$ \quad \left(\eta = \frac{V_{\text{peak}}}{V_{\text{charge}}} = 0.86\right)

- Output capacitor
- Voltage divider
- Cable to VI
- Ground plane
- Vacuum interrupter
- Cable to GND
Experimental results collected with AwBD procedure on FS VIs

- Ceramic insulator
- Arcing chamber
- Arc shield

<table>
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<th>AwBD procedure P-N</th>
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Experimental results collected with AwBD procedure on FS VIs: chronological sequence

1. FS_01_4mm negative polarity
2. FS_01_4mm positive polarity
3. FS_01_10mm positive polarity
4. FS_01_10mm negative polarity
5. FS_02_4mm negative polarity
6. FS_02_4mm positive polarity
7. FS_02_10mm positive polarity
8. FS_02_10mm negative polarity
9. FS_03_4mm negative polarity
10. FS_03_4mm positive polarity
11. FS_03_10mm positive polarity
12. FS_03_10mm negative polarity
13. FS_03_15mm negative polarity
14. FS_02_15mm negative polarity
15. FS_02_15mm positive polarity
16. FS_03_15mm positive polarity
17. FS_01_15mm negative polarity
18. FS_01_15mm positive polarity
Experimental results collected with AwBD procedure on FS Vis: 4mm gap

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**Experimental data: VCB-36kV Gap=4mm neg**

- **Vset 138kV (40kVx4x\(\eta\))**

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**Breakdown Probability 4mm neg**

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**Experimental data: VCB-36kV Gap=4mm pos**

- **Vset 138kV (40kVx4x\(\eta\))**

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**Breakdown Probability 4mm pos**

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**Vset** 260kV (75kVx4x\(\eta\))

**Vset** 170kV (50kVx4x\(\eta\))

**Vset** 138kV (40kVx4x\(\eta\))
Experimental results collected with AwBD procedure on FS Vis: 10mm gap

Experimental data: VCB-36kV Gap=10mm neg

Experimental data: VCB-36kV Gap=10mm pos

Breakdown Probability 10mm neg

Breakdown Probability 10mm pos

HV holding degradation!
Experimental results collected with AwBD procedure on FS Vis: 15mm gap

- Experimental data: VCB-36kV Gap=15mm neg
  - HV holding degradation!

- Experimental data: VCB-36kV Gap=15mm pos
  - HV holding degradation!

- Breakdown Probability 15mm neg

- Breakdown Probability 15mm pos
Experimental results collected with AwBD procedure on FS Vis: remarks

**Marx generator:**
- Stages n° = 12
- Vmax\_stage = 200 kV
- Vmax\_generator = 2400 kV

→ Only 4 stages were used for the tests
With 4mm gap all the VIs behave almost in the same way and there is a slightly conditioning during the pulses

With 10mm gap VI_01 and VI_02 behave almost in the same way for the whole tests while VI_03 at a given time suddenly deconditions

With 15mm gap the VIs behave in a different way and starting from good performances (VI_01 and VI_02) degraded pulse after pulse

For 4mm gap V50% is about 110kV for all the VIs and polarities

For 10mm gap V50% is about 220kV for all the VIs and polarities

For 15mm gap V50% is scattered (from 140kV to 200kV) and different both among the VIs and polarities
Deconditioning effect at different gap lengths for FS VI

1. VI_01_4mm N AwBD
2. VI_01_4mm P AwBD
3. VI_01_10mm P AwBD
4. VI_01_10mm N AwBD

Reconditioning attempt!

5. VI_04_4mm N UD
6. VI_04_4mm P UD
7. VI_04_4mm N UD (tested again)
8. VI_04_10mm P UD
9. VI_04_10mm N UD
10. VI_01_4mm P UD (tested again)

Test of a new VI with UD method
Reconditioning effect at different gap lengths for FS VI: 4mm
Deconditioning effect at different gap lengths for FS VI: 10mm

Experimental data: 36kV-01 10mm pos

Vs = 80 kV

Vs = 60 kV

Vs = 50 kV

Experimental data: 36kV-01 10mm neg

Vs = 80 kV

Vs = 60 kV

Vs = 50 kV

Breakdown Probability 10mm 01 pos

Breakdown probability: 36kV-01 10mm neg
Remarks

1. VI 01_02_03 did not show any de-conditioning effect for 4mm gap length, even if during previous tests with 15mm gap de-conditioning was evident. The overall VH performances are better for both polarities w.r.t. new VIs.

2. VI 01_02_03 showed an evident de-conditioning effect for 10mm gap length for both polarities. Thousands pulses are not enough to produce any reconditioning effect.

3. VI_01_10mm N AwBD showed that breakdown voltage might be related to set voltage, lower set voltage -> lower average breakdown voltage. Voltage derivative (time) might be not negligible in breakdown voltage occurrence.

Possible explanation: micro-tips on the sides of electrodes might have been generated during 15mm gap tests due to high arc energy, with short gap their effect is masked since E between the plates is much greater than that involving electrodes side.
Comparison among procedures: 4mm summary

Breakdown probability: 36kV 4mm neg

Breakdown probability: 36kV 4mm pos
Comparison among procedures: 10mm summary

Breakdown Probability 10mm neg

Breakdown Probability 10mm pos
Conclusions and remarks

1. Tests on the breakdown behavior of commercial vacuum interrupters.

2. AwBD (always breakdown) procedure gave repeatable results over different polarities and particularly for the 4mm contact gap. The AwBD also give similar results for 10mm gap, but with wider scatter (possible due to conditioning / higher breakdown energy).

3. De-conditioning events could be recovered from for the 4mm gap (with the lower arc energy), but very limited re-condition at larger gaps. Possible effect from the applied voltage / voltage rise time / delay between breakdown and voltage collapse needs to be studied.

4. Good general agreement between the AwBD and the up-and-down methods. The AwBD allows for much quicker data acquisition, so it gives significant practical advantages.

5. Data is the basis for further future comparisons to breakdown models.