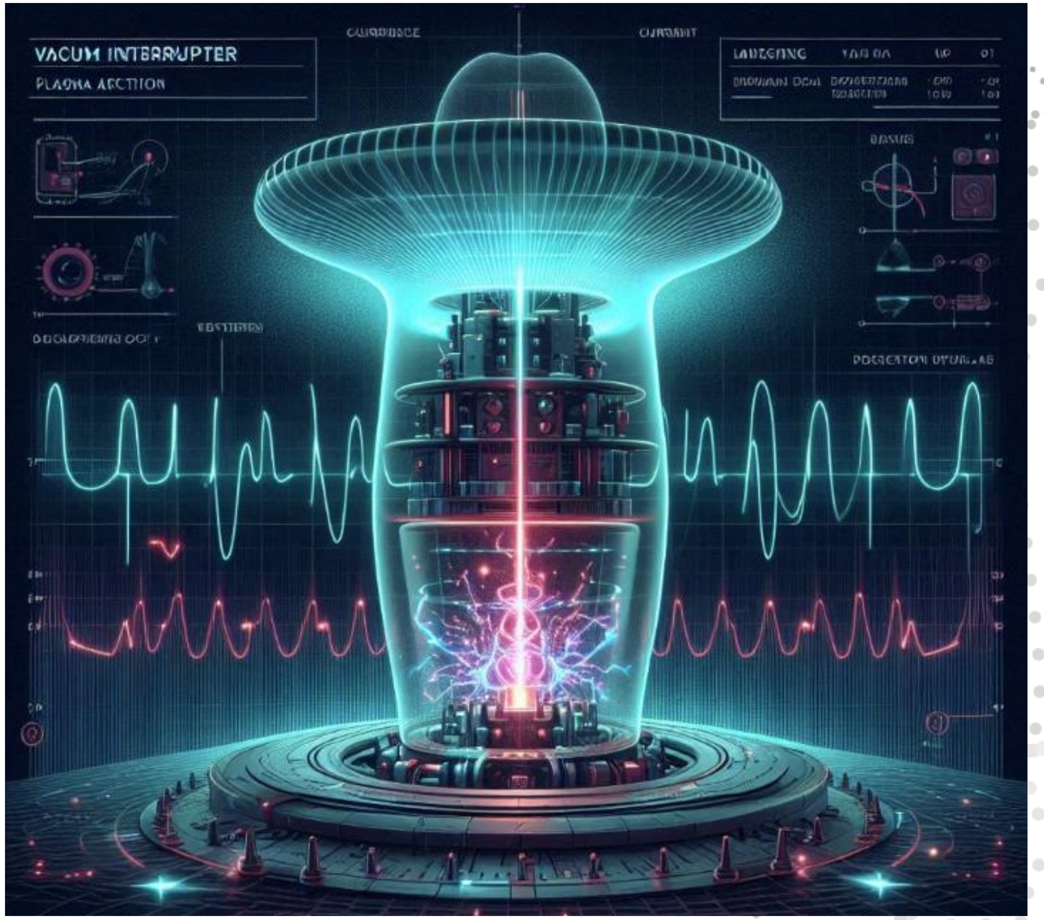

9th ITG International Vacuum Electronics Workshop 2024
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Physikzentrum Bad Honnef, Germany

MAY 30-08-2024

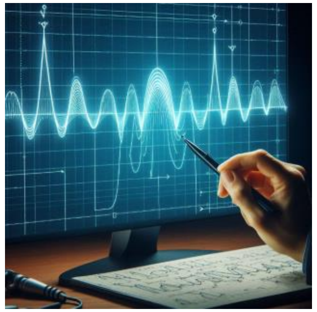
Low- and very low- frequency short-circuit current interruption with vacuum

Dr. Dietmar Gentsch – ABB / Senior Principal Engineer – Research and Development

Dr. Erik D. Taylor – S&C , **Dipl.-Ing. Andreas Lawall** – Siemens, **Dr. Sergey Gortschakow** – INP Greifswald

Introduction:

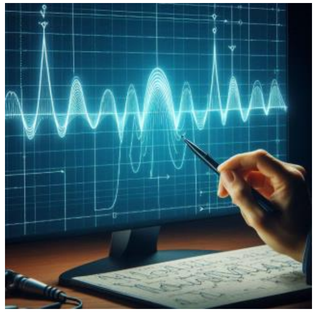
Vacuum Interrupter Family: - Rated Voltage 1.2 … 40.5kV – Short Circuit Current Interruption up to 63kA




Introduction

Basics: Vacuum Interrupters in Electrical Power Systems

- Vacuum interrupters (VIs) play a critical role in electrical power systems, particularly at standard frequencies of **50/60 Hz**:
  - However, their applications extend beyond these frequencies.
  - Rail electrical power systems, operating at **16-2/3 Hz** and **25 Hz**, have also successfully utilized VIs for many years.
  - As the world transitions toward green energy sources, applications such as wind turbines, pumped storage, DC to AC converters in solar parks, and shipboard systems introduce new challenges. These systems can generate temporary fault conditions with **very low frequencies**, leading to prolonged arcing times and high transferred charge.
  - Consequently, interrupting current at the precise moment of **current zero (CZ)** becomes increasingly difficult.



Introduction

Basics: Vacuum Interrupters in Electrical Power Systems

In this study, we explore the performance boundaries of VI interruption across a range of frequencies, specifically **0.5-2 Hz**.

- Our analysis is based on tests conducted at both **16-2/3 Hz** and **50 Hz**.
- Additionally, we examine contact erosion rates under varying current levels, including multiple short-circuit operations at **10-40 kA rms** (at 50 Hz) and several hundred amperes (at 0.5-5 Hz).

Furthermore, we investigate test sequences from the generator circuit breaker standard, including **delayed CZ** and **very high direct current (DC) offset** tests.

- These tests provide insights into VI behavior under conditions effectively equivalent to lower frequencies.

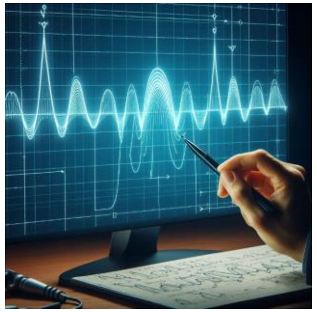
Finally, experimental observations at **2.4 Hz** and **1250-1500 A rms** shed light on the impact of multiple switching operations on contact performance, metal vapor deposition on ceramics, and heat accumulation within the VI.

- Our study encompasses three different contact systems and sizes.

Understanding the intricacies of VI behavior across various frequencies is crucial for designing reliable and efficient electrical systems.

Introduction

Vacuum Interrupters in Low-Frequency Applications



- **Introduction**
  - Basic principle and current interruption for electrical power applications at 50/60 Hz
- **Vacuum interrupter in the loop of low frequency interruption**
  - Basic circuit and interruption under low frequency current load
  - Study, research and interruption at 0.5 … 5Hz
  - Erosion of contact material under these condition, focused on Butt- and TMF- contact systems
  - Considering contact materials CuCr 25 … 50 wt.-% Cr with there specific erosion rate at 4kA; up to 10kA and above 10kA short circuit current
- **Discussion/Summary**

SF_6 – Free

Introduction

Vacuum Interrupters in Low-Frequency Applications

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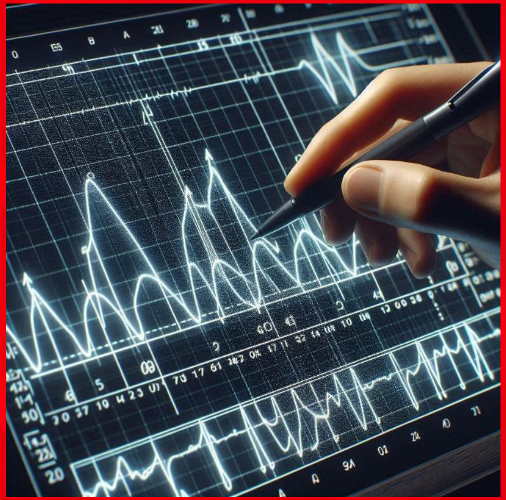

Introduction

Vacuum Interrupters in Low-Frequency Applications

Arc erosion

While several interruption operation

- **Introduction**
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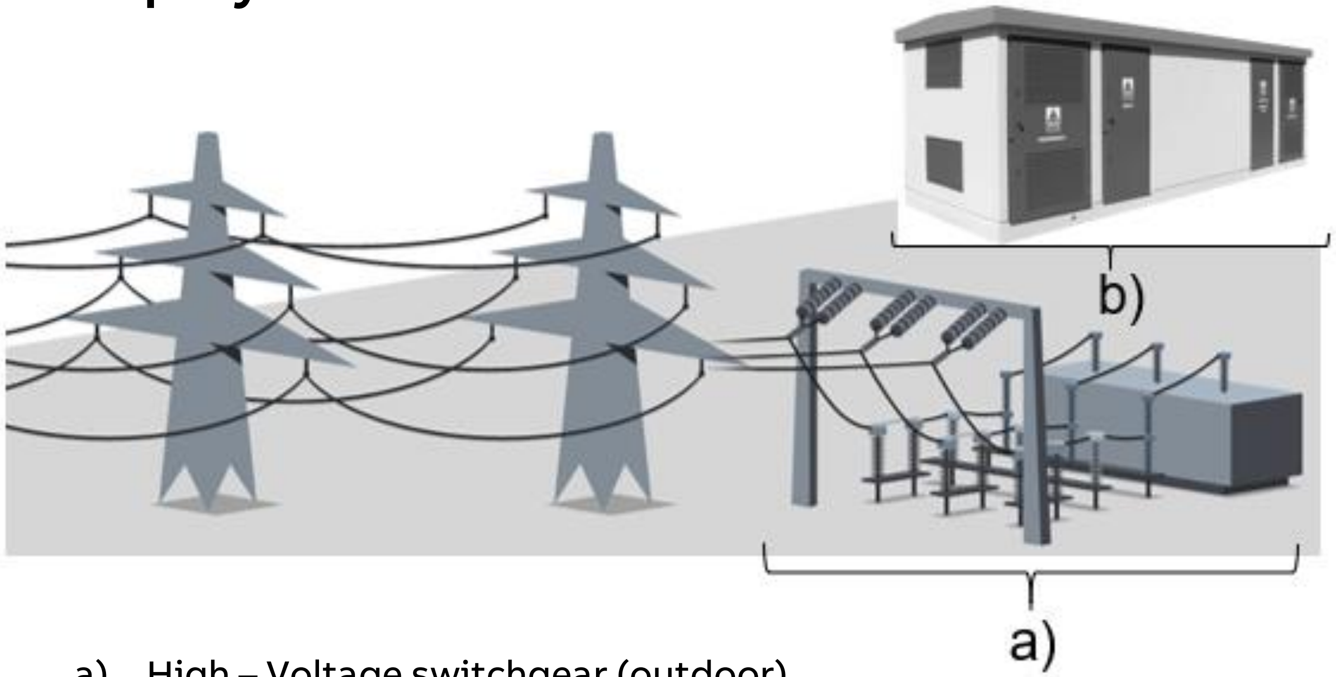
SF_6 – Free

Introduction

Exemplary Substation



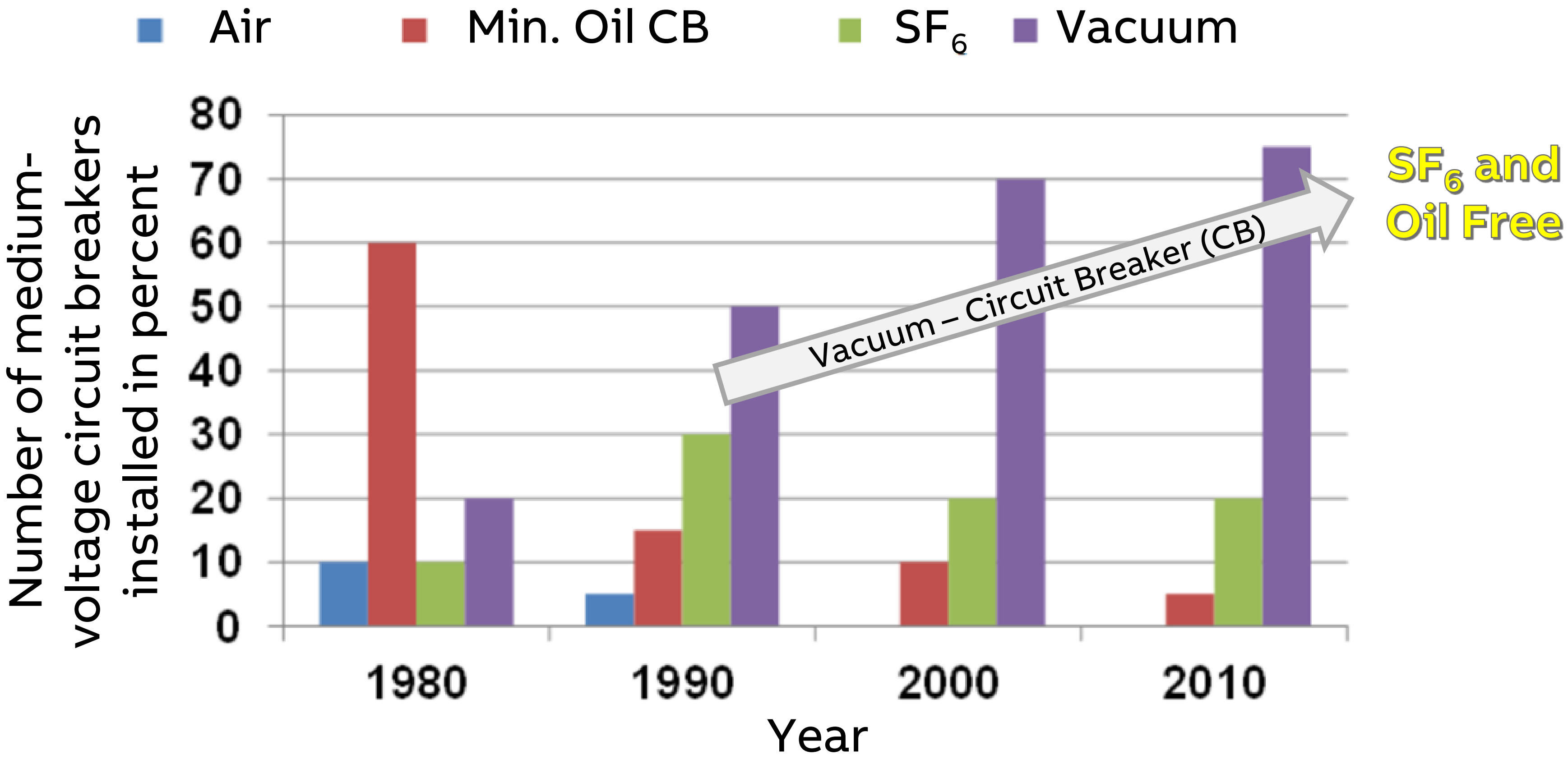
a) High – Voltage switchgear (outdoor)

b) Medium – Voltage switchgear

- Circuit breaker (CB) are required in every switchgear
- Different circuit breaker technologies are used in different voltage level

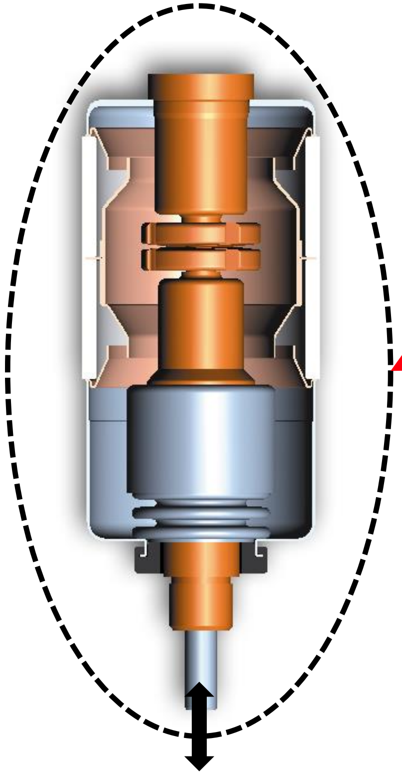
Introduction

Vacuum Circuit breaker type VD4: 12kV, 2000A, 40kA

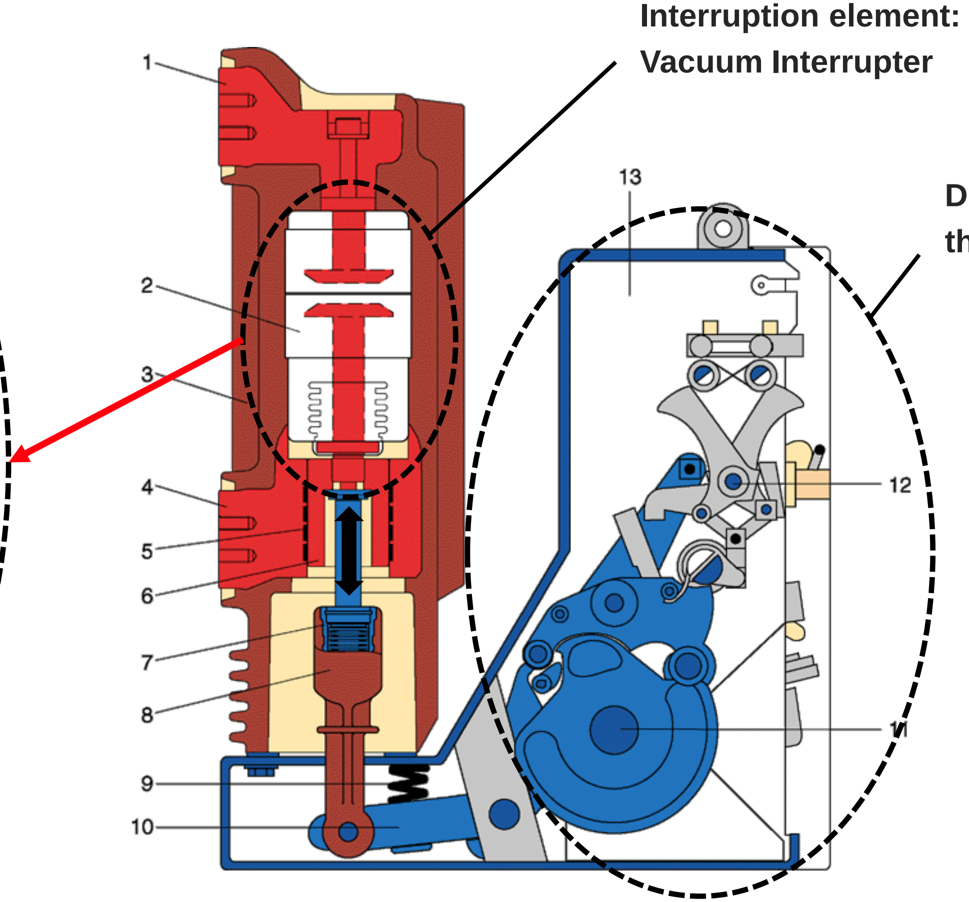


Introduction

- **Design of vacuum interrupter**
- **Principle On- and Off- operation**
- **Advantage and Disadvantages**
- **Application and Tests**
- **Security**



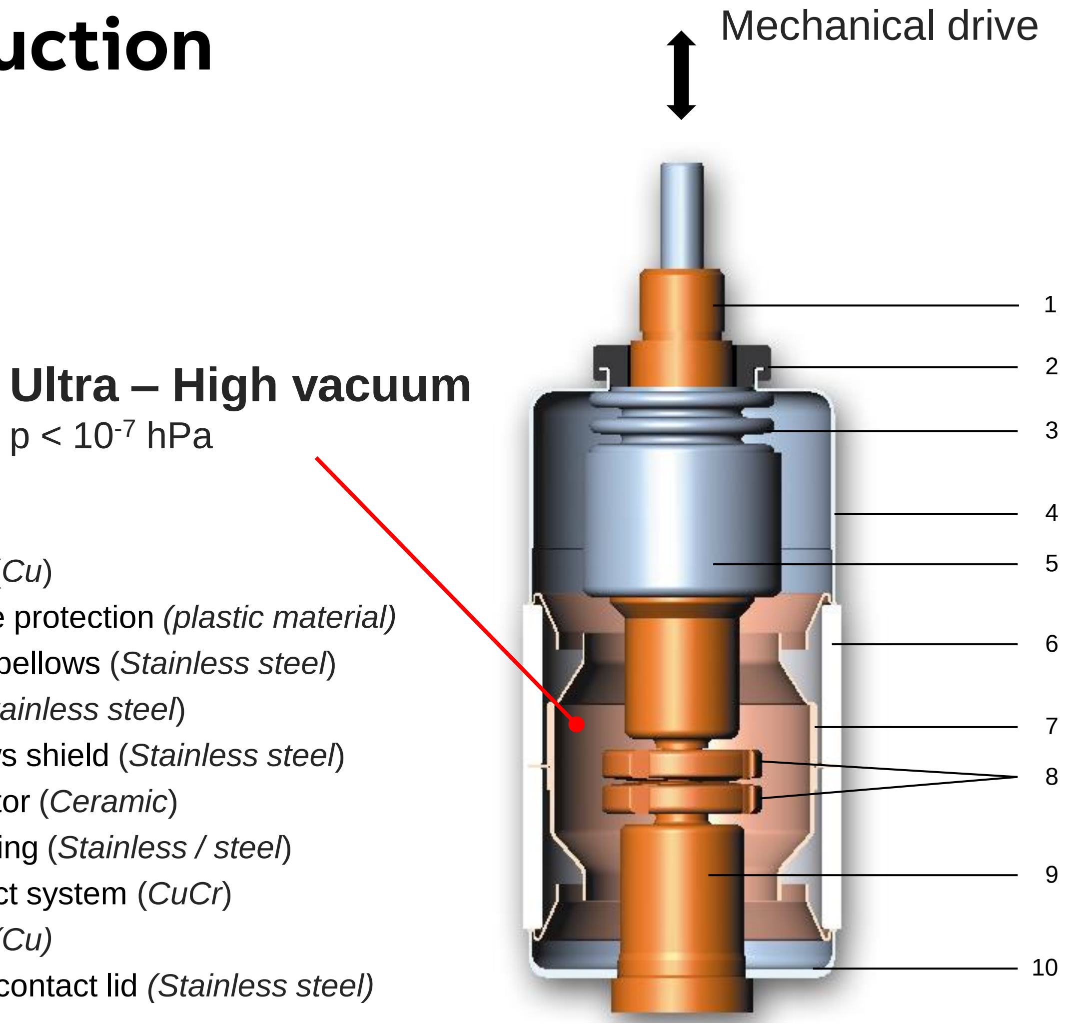
Mechanical drive



Vacuum circuit breaker type VD4: 12kV, 2000A, 40kA

1 Upper contact part
2 Vacuum interrupter
3 Epoxy material
4 Lower contact part
5 Lamella multiband
6 Movable sliding piston
7 Contact spring
8 Push rod insulation
9 Opening spring
10 Transmission lever with curved disc
11 Drive wheel
12 Operation mechanism
13 Spring actuator with Load mechanism

Introduction



1 Stem *(Cu)*
2 Torque protection *(plastic material)*
3 Metal bellows (*Stainless steel*)
4 Lid (*Stainless steel*)
5 Bellows shield (*Stainless steel*)
6 Insulator (*Ceramic*)
7 Shielding (*Stainless / steel*)
8 Contact system (*CuCr*)
9 Stem *(Cu)*
10 Fixed contact lid *(Stainless steel)*

Fixed – Contact:

- Stationary contact no movement (8 … 10).

Movable Contact:

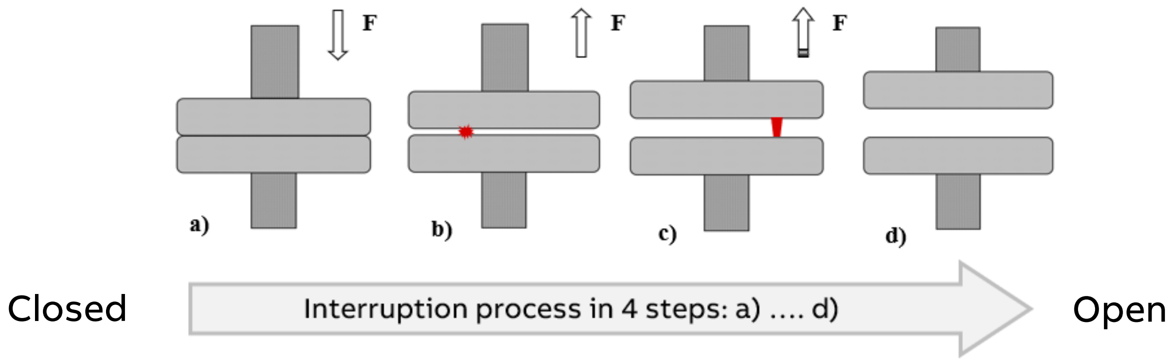
- Connection to the mechanical drive, a bellows (3) allows movement of the contact (8) in vacuum atmosphere.
- The metallic bellows (3) causes the permanent and reliable vacuum sealing to ambient atmosphere.

Vacuum Interrupter insulation:

- For external and internal dielectric insulation ceramic Tubes (6) are used.

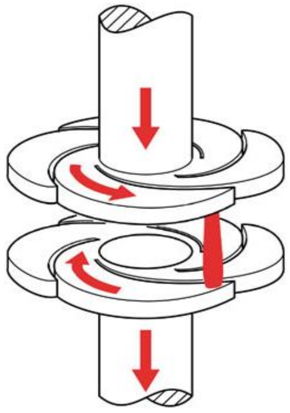
Introduction

Interruption performance vs. contact diameter:

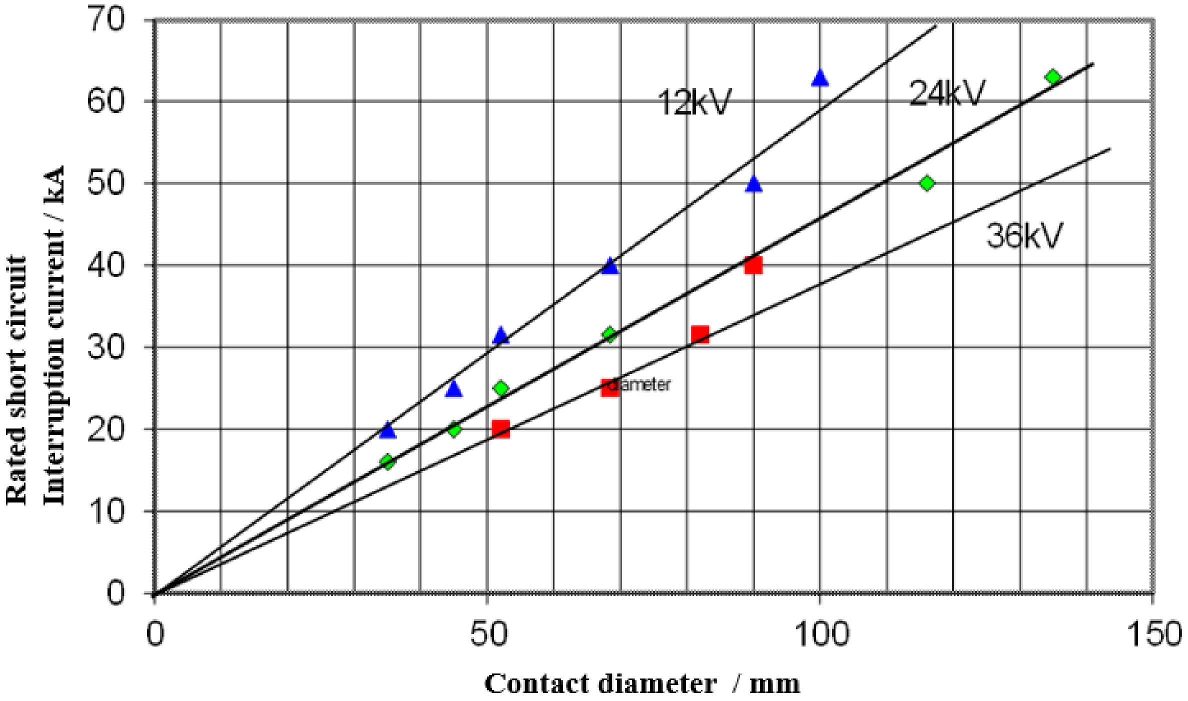


<u>Transverse magnetic field (TMF) contacts</u>:

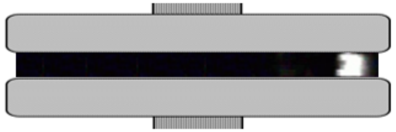
- TMF contact diameter vs. the electrode diameter @ 12kV / 24kV / 36kV
- Roughly linear relationship between breaking current performance and contact piece diameter → (current) $I^2 \sim D^2$ (area)



TMF Spiral contact



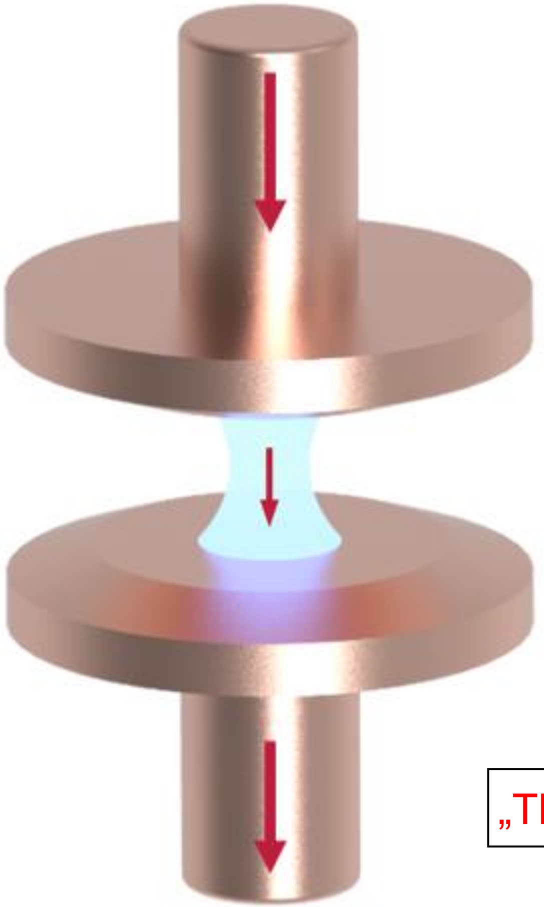
The interruption capacity of an interrupter is reached when the arc energy distributed over the contact surface reaches the physical limit



Introduction

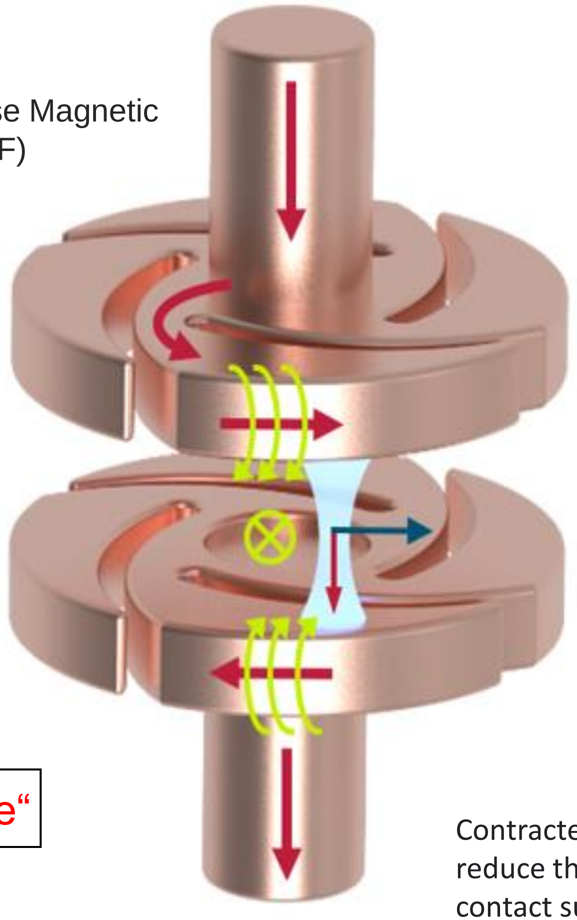
Boundary condition: Short-Circuit Current: **> 10kA**

Schematic representation of different modes of the vacuum arc



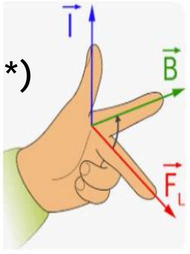
Transverse Magnetic Field (TMF)

„TMF – Mode“

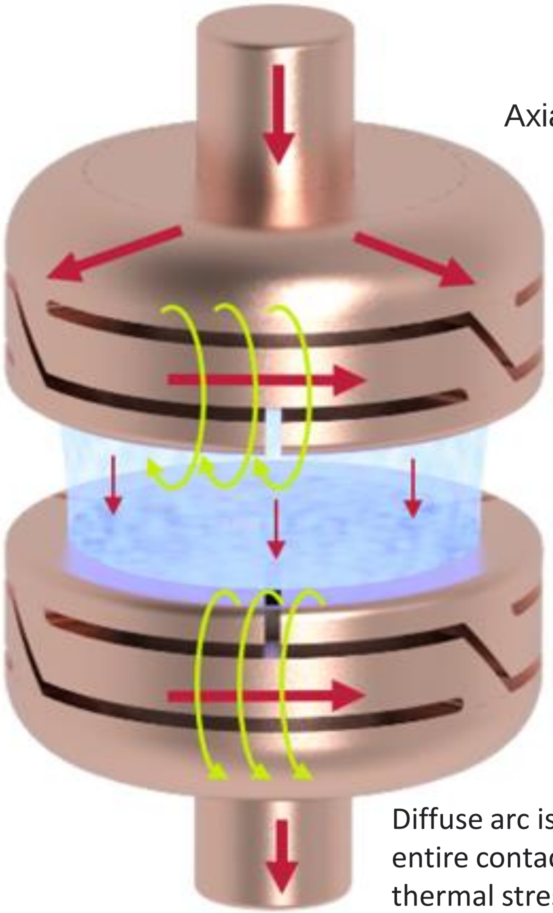


Contracted arc rotates to reduce thermal stress on contact surfaces

*)



Axial Magnet Feld (AMF)



„AMF – Mode“

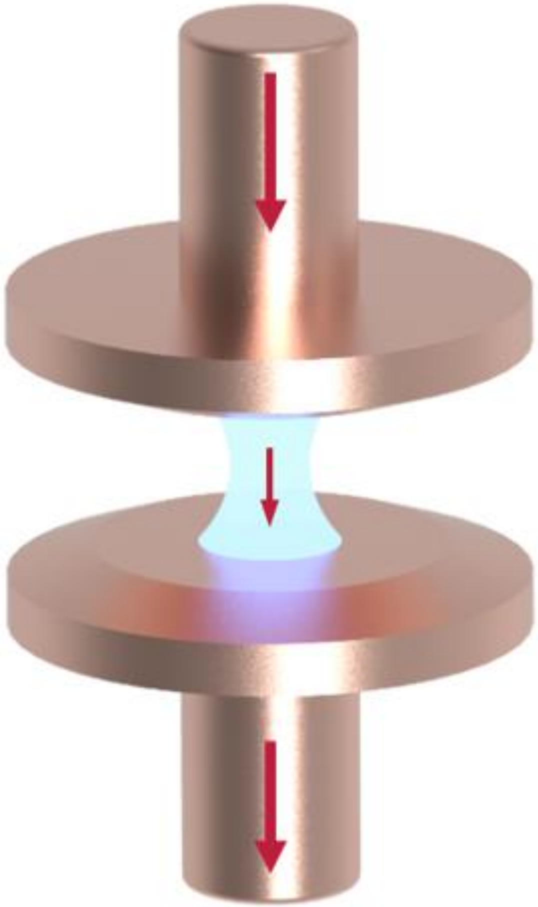
Diffuse arc is evenly distributed over the entire contact surface to reduce thermal stress

*) Fig. source: Wikipedia „three finger rule “

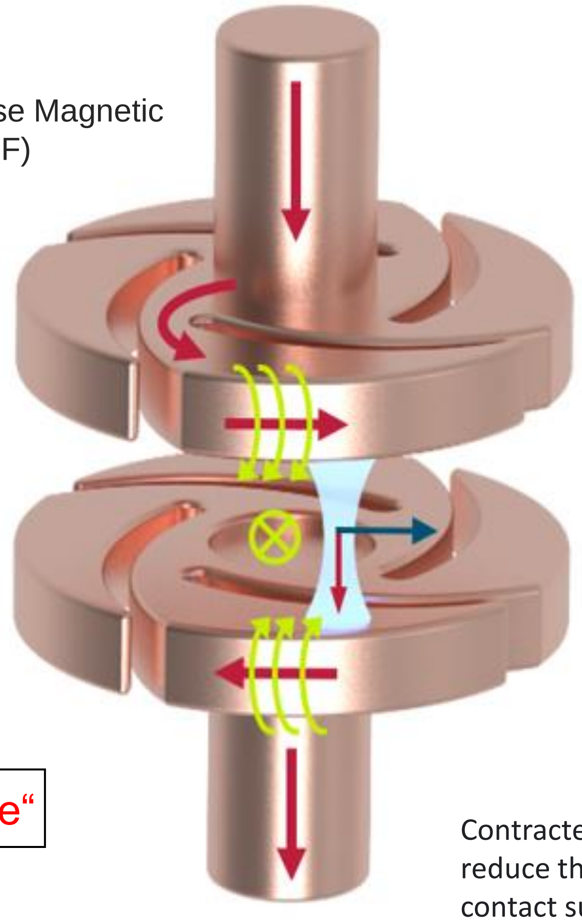
Introduction

Boxed: **Boundary condition**: Short-Circuit Current: **> 10kA**

Schematic representation of different modes of the vacuum arc

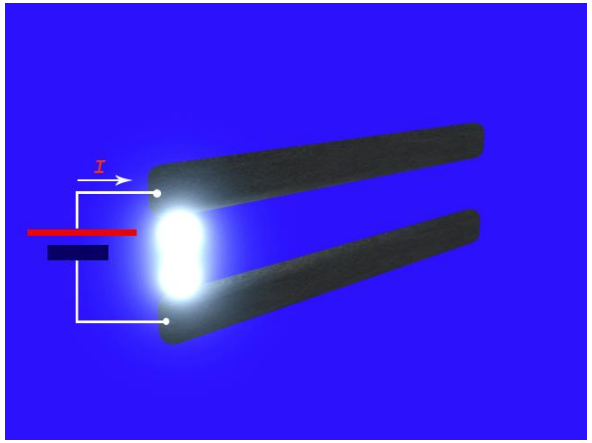


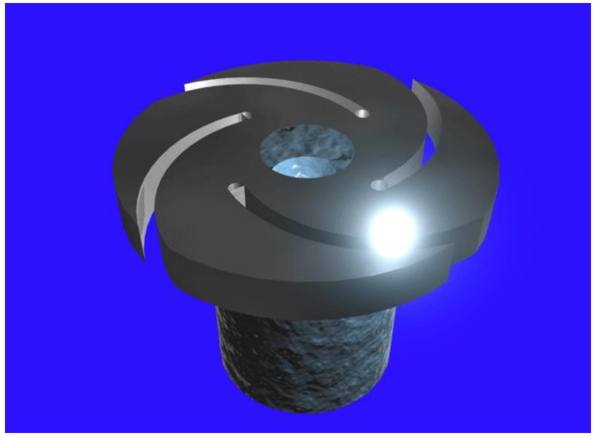
Transverse Magnetic Field (TMF)



„TMF – Mode“

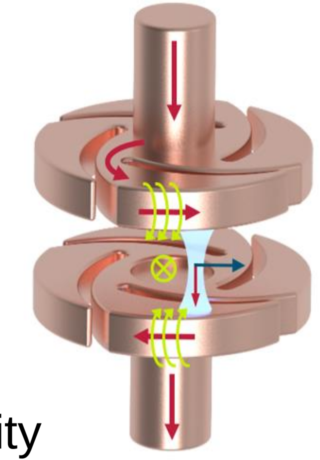
Contracted arc rotates to reduce thermal stress on contact surfaces



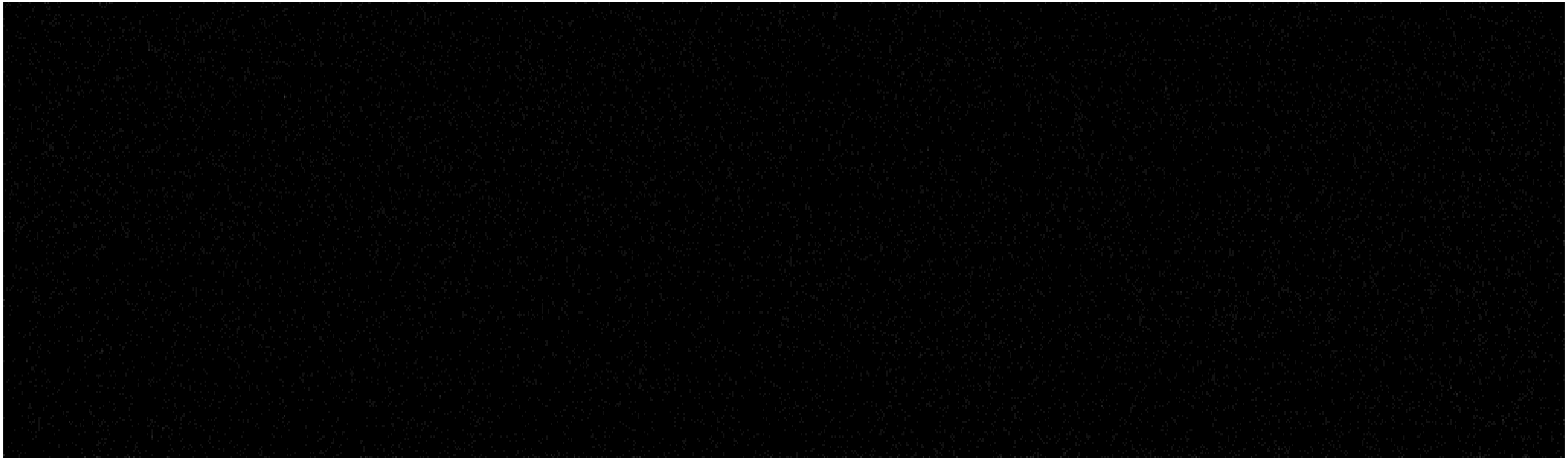


Introduction

Vacuum arc under short circuit current condition; TMF contact principle



CuCr35+: 31,5 $kA_{(rms)}$ & 44 mm final contact gap distance @ 35Hz frequency / 2m/s opening velocity



Introduction

Vacuum Interrupters in Low-Frequency Applications

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- **Discussion / Summary**

Vacuum interrupter in the loop of low frequency interruption

Basic circuit and interruption under low frequency current load

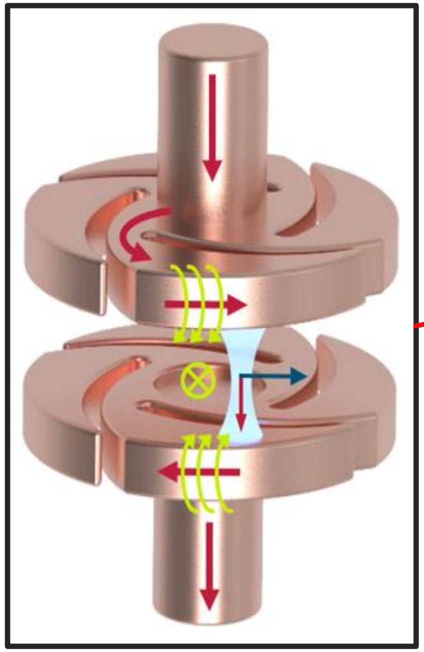
<u>Examples of compact vacuum interrupter</u>:

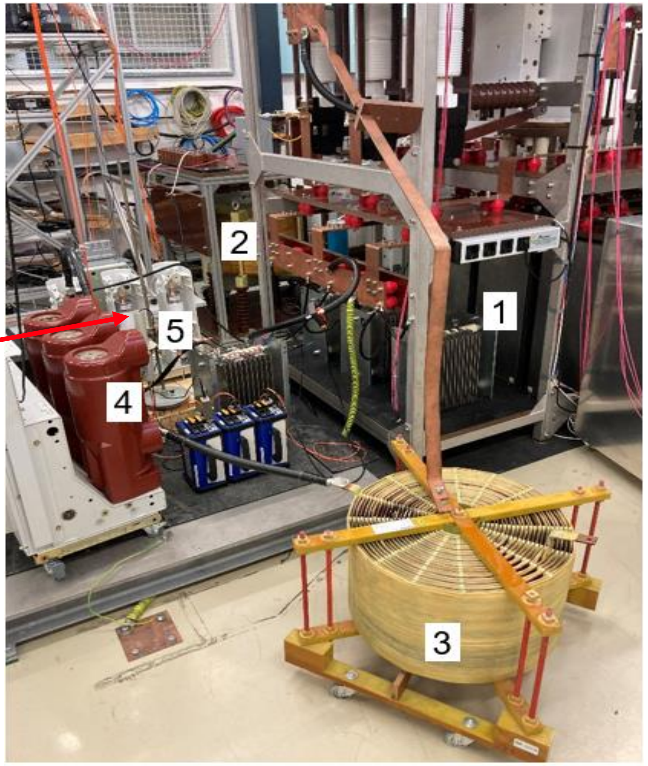
VG6 - (24 kV – 31.5 kA – 2500 A) 217 mm / (36 kV – 31.5 kA – 3150 A) 238 mm, **left side type: ABB**,

VSA12 – 0 – 40 (12 kV – 40 kA – 3150 A) 193 mm, **right side type: SIEMENS** used for the calculation of the interruption performance boundaries

Vacuum interrupter in the loop of low frequency interruption

Basic circuit and interruption under low frequency current load





Experimental setup synthetic circuit:

1 – high current generator
2 – high voltage generator
3 – main coil
4 – disconnecting switch (VCB type VD4)
5 – interruption device under test

Conventional Weil – Dobke synthetic circuit

Introduction

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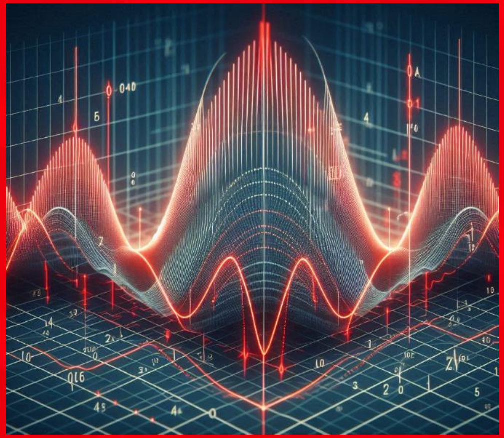
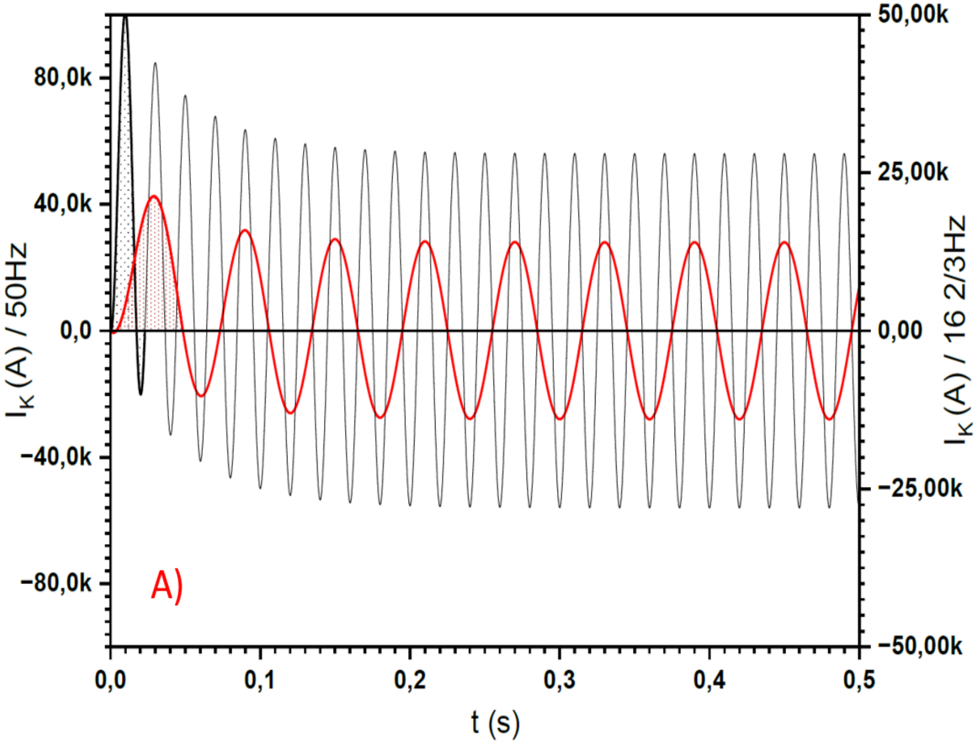


Vacuum interrupter in the loop of low frequency interruption

Basic circuit and interruption under low frequency current load



Single phase short circuit current injection; DC time constant (τ = L/R) to 45 ms reference at frequency 50/60Hz at 40 kA rms with T/2= 10 ms compared to low frequency direct current interruption at:

A) 16.7 Hz at 10 kA rms – T/2= 30 ms

Integral I x dt dotted points at each curve, note different vertical scales

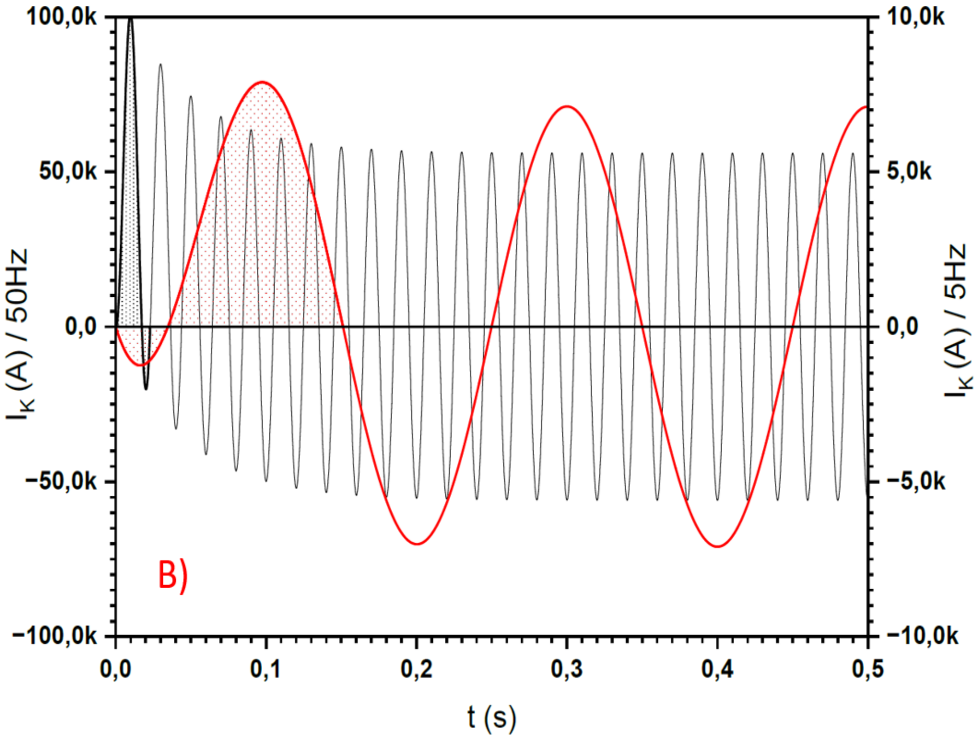
$$C = \int I \cdot \partial t$$

Where C is the transferred charge in As, I is the instantaneous current in A, and t is the time in s. The integral is performed over the arcing period

40kA – 50Hz – I x dt: 938C+73C = 1011C /// 10kA – 16 2/3Hz – I x dt: 1153C

Vacuum interrupter in the loop of low frequency interruption

Basic circuit and interruption under low frequency current load



Single phase short circuit current injection; DC time constant (τ = L/R) to 45 ms reference at frequency 50/60Hz at 40 kA rms with T/2= 10 ms compared to low frequency direct current interruption at:

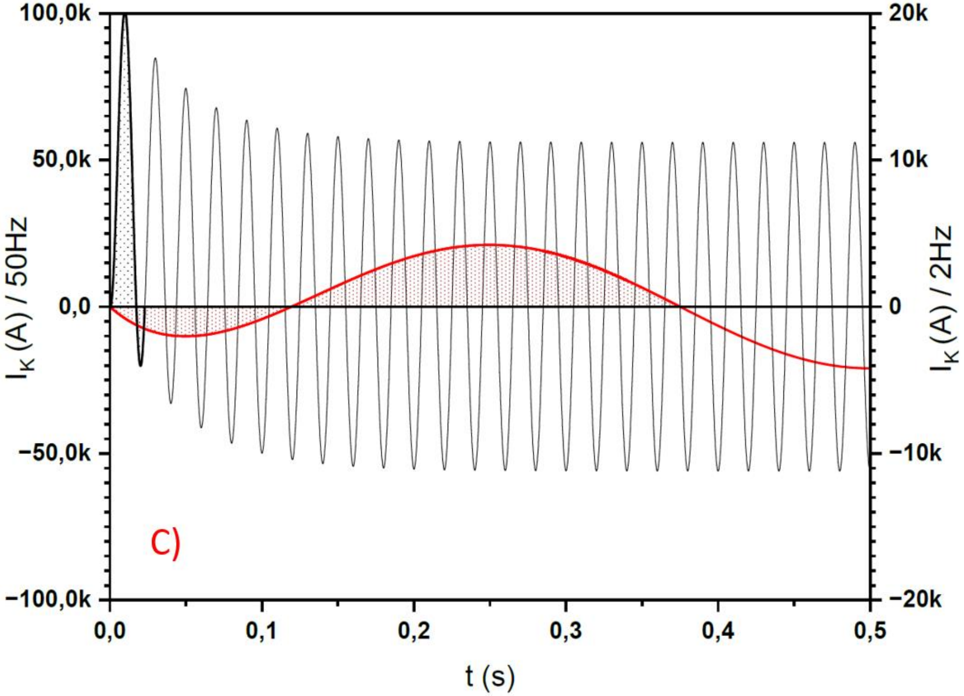
B) 5 Hz at 5 kA rms – T/2= 100 ms

Integral I x dt dotted points at each curve, note different vertical scales

40kA – 50Hz – I x dt: 938C+73C = 1011C /// 5kA – 5Hz – I x dt: 563C + 29C = 592C

Vacuum interrupter in the loop of low frequency interruption

Basic circuit and interruption under low frequency current load



Single phase short circuit current injection; DC time constant (τ = L/R) to 45 ms reference at frequency 50/60 Hz at 40 kA rms with T/2= 10 ms compared to low frequency direct current interruption at:

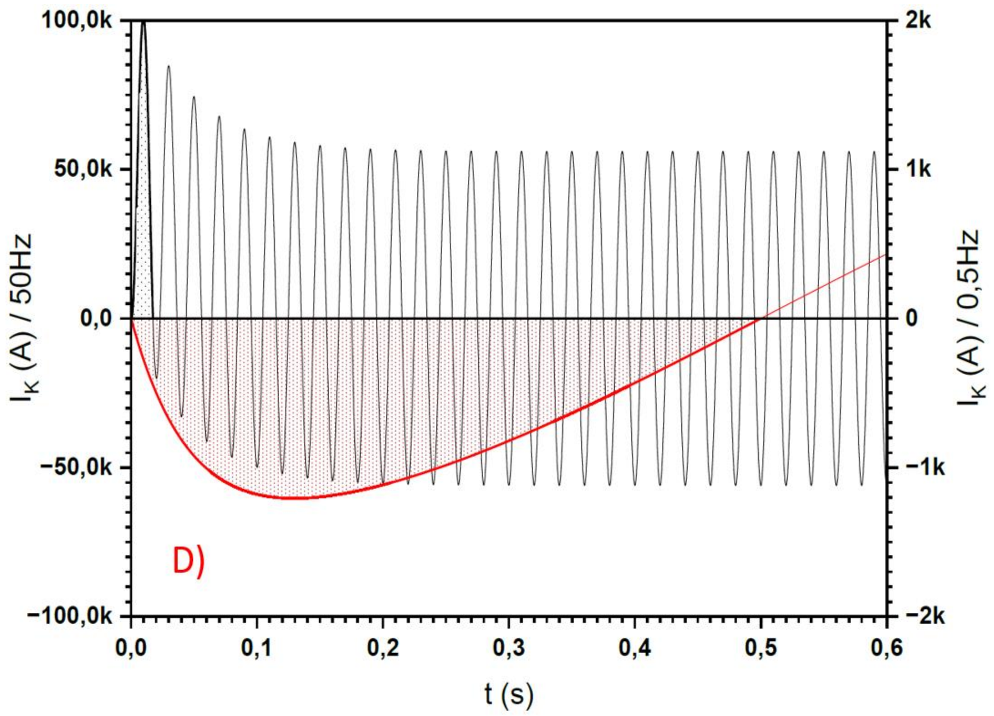
C) 2 Hz at 3 kA rms – T/2= 250 ms

Integral I x dt dotted points at each curve, note different vertical scales

40kA – 50Hz – I x dt: 938C+73C = 1011C /// 3kA – 2Hz – I x dt: 681C + 158C = 839C

Vacuum interrupter in the loop of low frequency interruption

Basic circuit and interruption under low frequency current load



Single phase short circuit current injection; DC time constant (τ = L/R) to 45 ms reference at frequency 50/60 Hz at 40 kA rms with T/2= 10 ms compared to low frequency direct current interruption at:

D) 0.5 Hz at 1 kA rms – T/2= 1000 ms, symmetric

Integral I x dt dotted points at each curve, note different vertical scales

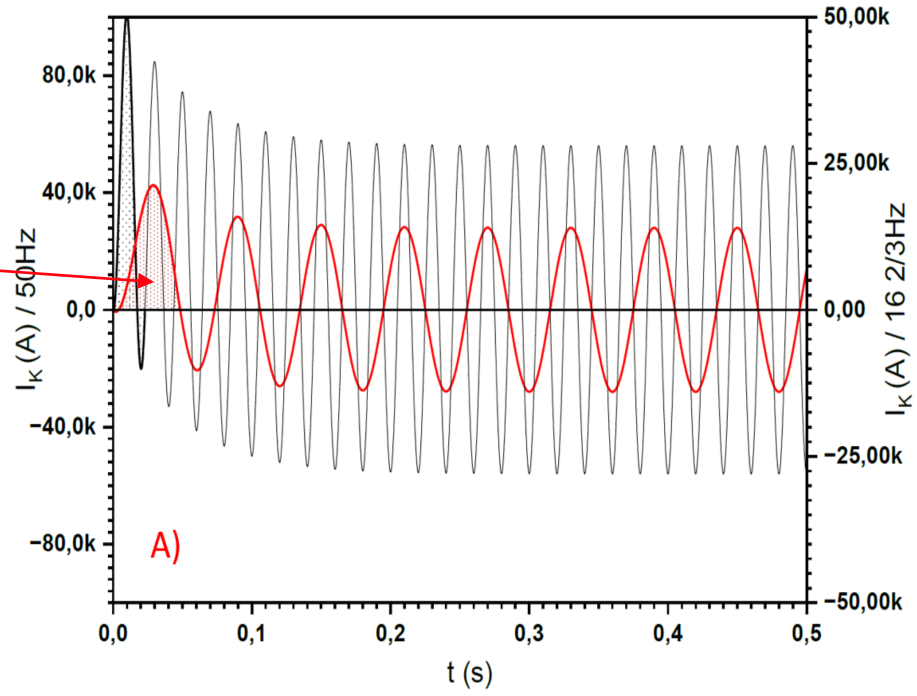
40kA – 50Hz – I x dt: 938C+73C = 1011C /// 1kA – 0.5Hz – I x dt: 389C

Vacuum interrupter in the loop of low frequency interruption

Basic circuit and interruption under low frequency current load

Charge transfer compare oscillogram at different frequency, according: Circuit (τ = L/R) to 45ms

Frequency	Current	Max. arcing time (T/2)	I x dt (As) major loop	I x dt (As) minor loop
50/60Hz	$40kA_{rms}$	10…8ms	938	73
16.7Hz	$10kA_{rms}$	30ms	1153	--
5Hz	$5kA_{rms}$	100ms	563	29
2Hz	$3kA_{rms}$	250ms	681	158
0.5Hz	$1kA_{rms}$	1000ms	383	--

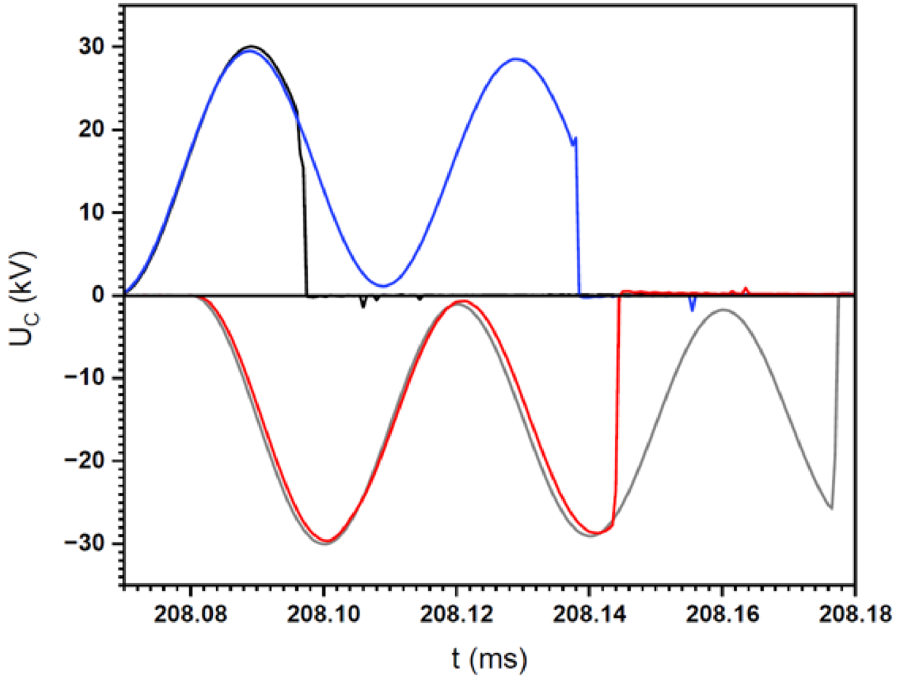


Vacuum interrupter in the loop of low frequency interruption

Basic circuit and interruption under low frequency current load

Surface of **Butt** contact **diameter 24 mm W-Cu 30 wt. %** and electrical life operation at **1250 A rms**/**2.4Hz**, arc times covered three ranges: “short” ($2-4\ ms$), “middle” ($100-103\ ms$), and “long” ($206-208\ ms$)), **total number of operation 36**

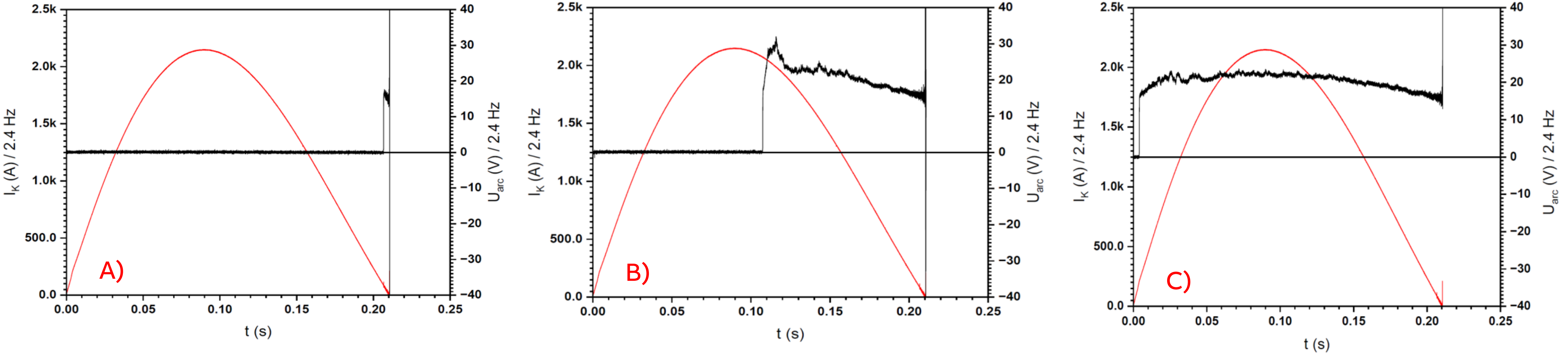
4 breakdowns on Cu-W contacts after different times and after peak of TRV;



Weil – Dobke circuit used; Late breakdown U_C = 34kV

Vacuum interrupter in the loop of low frequency interruption

Basic circuit and interruption under low frequency current load



Section of one **TMF** contact with **diameter 67 mm Cu-Cr 40 wt. %** and electrical life operation at **1500 A rms/2.4Hz**, arc times covered three ranges: A) “short” ($2 - 4\ ms$), B) “middle” ($100 - 103\ ms$), and C) “long” ($206 - 208\ ms$), **total number of <u>operation 26</u>**

Vacuum interrupter in the loop of low frequency interruption

Basic circuit and interruption under low frequency current load

Tests on the 67 mm diameter TMF spiral contacts

VI – No. 1 TMF spiral contact 67 mm (Cu-Cr 40 wt. %)			
Number of operations	**t_{arc}**	**polarity**	**U_c *(kV peak)***
15	"Short"	+	None
2	"Short"	+	21
2	"Middle"	+	None
2	"Long"	+	None
3	"Short"	-	None
2	"Middle"	-	None
8	"Long"	-	None

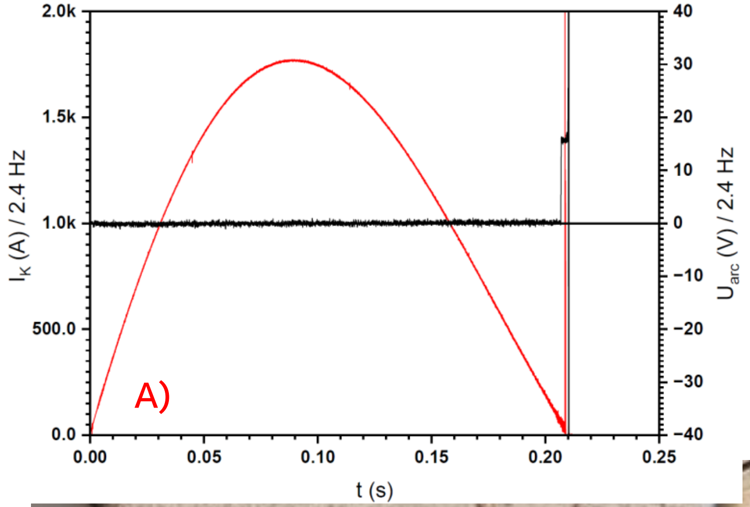
VI – No. 2 TMF spiral contact 67 mm (Cu-Cr 40 wt. %)			
Number of operations	**t_{arc}**	**polarity**	**U_c *(kV peak)***
2	"Long"	+	None
5	"Long"	+	18 – 27
3	"Long"	+	30
4	"Long"	-	None
10	"Long"	-	5 – 27
2	"Long"	-	None

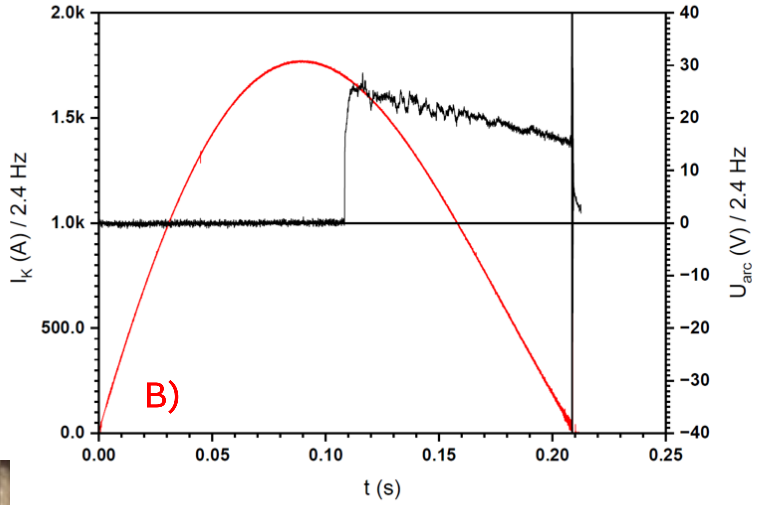
No breakdowns were observed in any tests

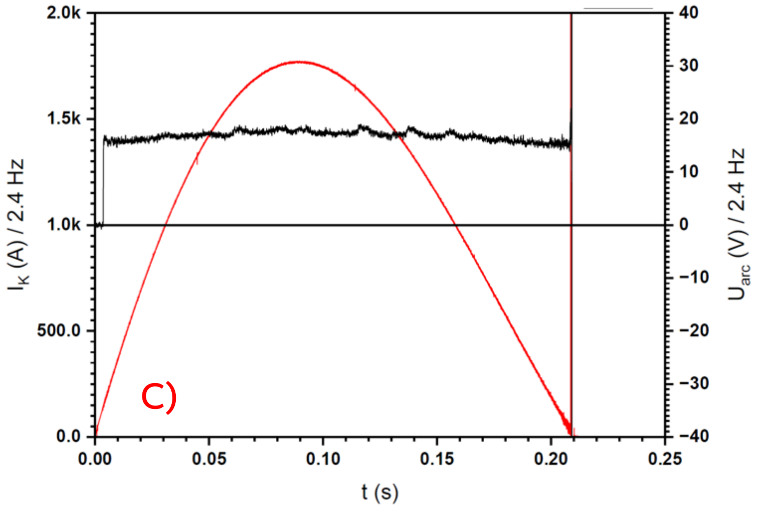
Both VI passed $U_d = 65\ kV\ rms$ and $U_p = 125\ kV + 10\% = 137 kV$

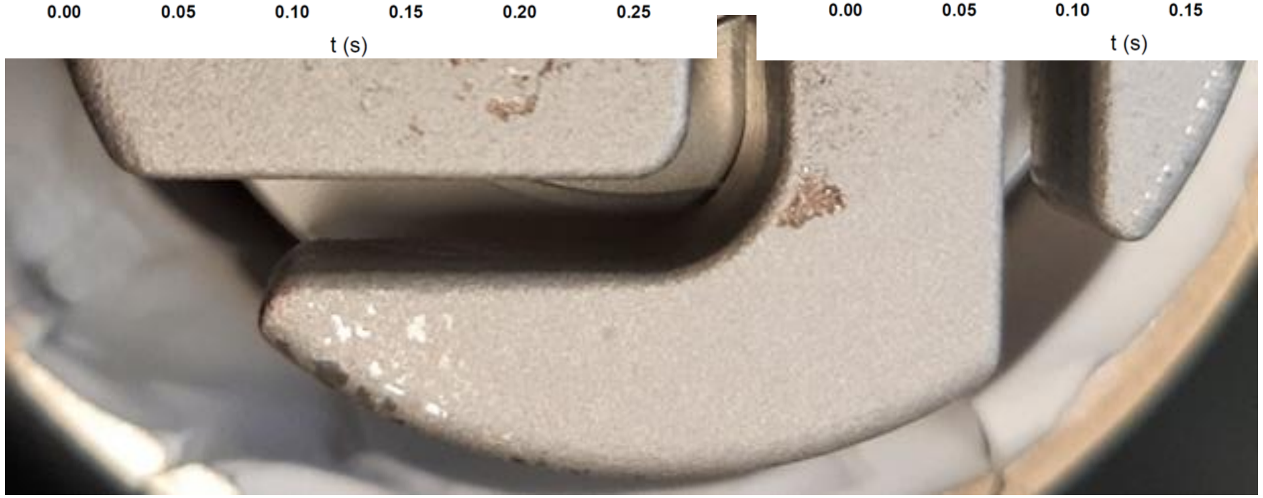
Vacuum interrupter in the loop of low frequency interruption

Basic circuit and interruption under low frequency current load









Section of one **TMF** contact with **diameter 45 mm Cu-Cr 40 wt. %** and electrical life operation at **1250 A rms/2.4Hz**, arc times covered three ranges: A) “short” ($2-4\ ms$), B) “middle” ($100-103\ ms$), and C) “long” ($206-208\ ms$), **total number of operation 33**

Vacuum interrupter in the loop of low frequency interruption

Basic circuit and interruption under low frequency current load

Tests on the 45 mm diameter TMF spiral contacts

VI – No. 1 TMF spiral contact 45 mm (Cu-Cr 40 wt. %)			
Number of operations	**t_{arc}**	**polarity**	**U_c *(kV peak)***
8	"Short"	+	None
10	"Middle"	+	None
11	"Long"	+	None
1	"Long"	+	15
1	"Long"	+	27
9	"Long"	+	30

VI – No. 2 TMF spiral contact 45 mm (Cu-Cr 40 wt. %)			
Number of operations	**t_{arc}**	**polarity**	**U_c *(kV peak)***
3	"Long"	+	None
30	"Long"	+	30

VI – No. 3 TMF spiral contact 45 mm (Cu-Cr 40 wt. %)			
Number of operations	**t_{arc}**	**polarity**	**U_c *(kV peak)***
3	"Long"	-	None
1	"Long"	-	15
6	"Long"	-	30

No breakdowns were observed in any tests

All VI´s passed $U_d = 65\ kV\ rms$ **and** $U_p = 125\ kV + 10\% = 137kV$

Introduction

Vacuum Interrupters in Low-Frequency Applications

- **Introduction**
  - Basic principle and current interruption for electrical power applications at 50/60 Hz
- **Vacuum interrupter in the loop of low frequency interruption**
  - Basic circuit and interruption under low frequency current load
  - Study, research and interruption at 0.5 … 5Hz
  - Erosion of contact material under these condition, focused on Butt- and TMF- contact systems
  - Considering contact materials CuCr 25 … 50 wt.-% Cr with there specific erosion rate at 4kA; up to 10kA and above 10kA short circuit current
- **Discussion / Summary**

Vacuum interrupter in the loop of low frequency interruption

Erosion of contact material under these condition, focused on Butt- and TMF- contact systems

1. First, the contact erosion of both contacts should be limited to a maximum of 2.0 … 2.5 mm.
2. Second, the **category I**, **II** and **III** of the contact material melting and loss needs to be evaluated.
3. Third, the vacuum interrupter (VI) should continue to maintain a certain level of dielectric performance and be able to withstand the TRV over the expected lifetime.

Finally, the heating of the contact part should be under 450 °C to prevent softening of the brazing joint between the contact plate and terminal.

The very long arcing times and resulting high transferred charge during arcing make low frequency applications challenging. The transferred charge during a 1 kA rms fault at 0.5 Hz is 383 As, for example.

Wind turbines operating at low wind speeds can produce currents of 2 kA rms at 0.5 Hz, leading to 766 As during current interruption.

For comparison, a railway power fault at 16.7 Hz can have 2700…2800 As of transferred charge when interrupting according to EN 50152 – 1 with u_c = 34 kV.

Vacuum interrupter in the loop of low frequency interruption

Erosion of contact material under these condition, focused on Butt- and TMF- contact systems

Experiments performed and measured the effect of contact erosion on the VI electrical lifetime, specified by the number of allowed interruption operations.

Categories I, II and III combined with the number of operations in each **category** leads to a clear end of life value.

These categories are set by the effect of the current level on the observed contact erosion.

Category I the contact erosion is 5.5 +/-0.5 µg/C (Cu-Cr 25) for currents of 4 kA rms and below, compare Table to come.

Category II higher currents ranging to 10 kA rms, where molten droplets ejected from the contact surface appear combined with the evaporation already observed in **category I**.

Category III adds another erosion mechanism with the formation of a constricted columnar arc for currents above 10 kA rms. In addition to the erosion mechanisms outlined for **category I** and **II**, a new mechanism appears with the splashing of molten metal off the contact surfaces.

Category III: This limits the number of operations to the order of 100 at max. I_k
Based on the good fit to Eq. (2), lower short-circuit currents I_k can be determined from the CSR (contact stroke reduction) equation

Vacuum interrupter in the loop of low frequency interruption

Erosion of contact material under these condition, focused on Butt- and TMF- contact systems

Above 10 kA the erosion switches to **category III**. The erosion can be calculated using the same formula, although the number of operations is typically in the range of 30 - 100 operations.

$$\boldsymbol{TMF-Contact} : \boldsymbol{CSR} = \frac{\boldsymbol{K}}{\boldsymbol{A}} \cdot (\boldsymbol{I_K})^{\mathbf{2}} \cdot \boldsymbol{N} \cdot \boldsymbol{t} \qquad (2)$$

Contact stroke reduction (TMF): **CSR** (mm); factor **K**: set to 6.8 (mm³/s · kA²); short circuit current $\mathbf{I_K}$ (kA); average arcing time at $50/60\ Hz$; $\boldsymbol{t} = 6 \cdot 10^{-3}\ s$; effective contact surface **A** (mm²) and **N** number of short circuit interruption.

- The total erosion between the two contacts is 2 mm.
- Figure following side shows a photograph of 250,000 operations at 2600 A rms current.
- The contact melting after the total transferred charge of $3.58 \cdot 10^6$ As.
- The lightning impulse withstand voltage U_p and the power frequency withstand voltage U_d according to the stipulated standard IEC 62271-1 passed 100 % at U_p = 185 kV and U_d = 95 kV rms.

ABB

Vacuum interrupter in the loop of low frequency interruption

Erosion of contact material under these condition, focused on Butt- and TMF- contact systems

At currents of 3 kA rms, the number of operations at 50/60 Hz is 239,000 for contact diameter 67 mm. Operations at 0.5 Hz with 1 kA rms and a total transferred charge of 383 As would give.

An example: N = 13 g/mm / (5.5 · 10^{-3}s · 3000 A rms x 5.5 · 10^{-6} g/C · 0.6) = 239,000 operation → Total erosion on both contacts to 2 mm. The 60 % of the DC erosion rate corresponds to material lost from the contacts to the shield of the VI.

Quarter section of **TMF** contact with Cu-Cr 35 wt. % Cr with **diameter 67 mm** after **250,000 operations** under current load **2600 A rms/50Hz** after a charge transfer of 2.6 · 10^{6} As in VCB

Arc erosion

While several interruption operation

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Vacuum interrupter in the loop of low frequency interruption

Summary: Erosion of contact material under these condition, focused on Butt- and TMF- contact systems

Material erosion rate while arcing

TMF spiral contact					
Category	**Current**	**Contact erosion +/-0.5 / Cu-Cr 25 wt. %**	**Contact erosion +/-0.5 / Cu-Cr 35 wt. %**	**Contact erosion +/-0.5 / Cu-Cr 45 wt. %**	**Re-condensation to contacts**
I	**> 0…4kA$_{rms}$**	approx. 5.5µg/C	approx. 4.2µg/C	approx. 3.5µg/C	40%
II	**4…10kA$_{rms}$**	approx. 50µg/C	approx. 40µg/C	approx. 32µg/C	40%
III	**> 10kA$_{rms}$**	**CSR (mm) =** $\frac{K}{A} \times (I_K)^2 \times N \times t$			-

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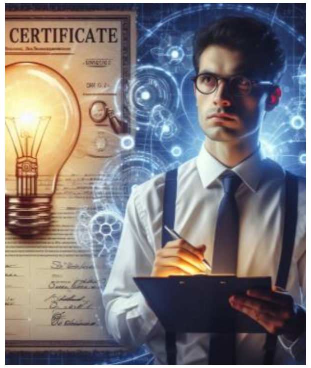
Discussion / Summary

Discussion / Summary: Vacuum Interrupter and Current Interruption at Low Frequencies



The electrical power system landscape is evolving, prompting interest in current interruption below the standard **50/60 Hz** frequency. While rail power systems have long relied on vacuum interrupters (VIs) and vacuum circuit breakers (VCBs) at **25 Hz** and **16.7 Hz**, emerging green energy applications are pushing frequencies even lower.

1. Theoretical view:

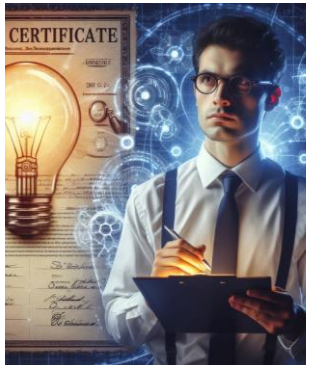
1. Theoretical calculations of evaporation allow straightforward estimate of behavior to lower frequencies compared to interruption tests conducted at 50/60 Hz.
2. For instance, the transferred charge during symmetric current interruption at **40 kA rms** at **50 Hz** is equivalent to that at **3 kA rms** at **2 Hz**.
3. Experiments at **2 Hz** reveal that this will be possible, especially when the arc operates in a naturally diffuse mode: category I < 4kA.

2. Erosion Categories:

1. Three erosion categories (I, II, and III) correlate current load with contact material / erosion rate.
2. Category I focuses on currents below **4 kA** in full diffuse arc mode for specific Cu-Cr ratios.
3. Category II considers currents between **4 kA** and **10 kA**, were molten material splash and droplet spray increase erosion alongside natural material evaporation.

Discussion / Summary

Vacuum Interrupter and Current Interruption at Low Frequencies



3. <u>Design Criteria</u>:
   - **Contact plate and shielding design criteria** are based on full short-circuit current over approximately **100 operations**.
   - **Erosion rates are calculated** using the Contact Stroke Reduction (CSR) equation for short circuit current ratings above **10 kA eff.**
   - **Heating Considerations**:
     - The joint between contacts and terminals must not exceed **450°C** to prevent softening of brazing joints.
     - Shields around the arc allow predictable arc erosion rates at shield element.
4. <u>Interruption Capability</u>:
   1. Laboratory tests demonstrate VI and VCB performance at very low frequencies (**2-15 Hz**) and even down to **0.5 Hz** with corresponding rated breaking currents.
   2. **VI and VCB are well-suited to handle faults with lower frequency** due to their lower short-circuit current requirements.

Understanding these factors ensures reliable VI and VCB operation across diverse frequency ranges.

Discussion / Summary

Vacuum Interrupter and Current Interruption at Low Frequencies

Don´t worry about interruption at
“Low Frequency”

Line manager: Dr. Barbara Panella
ELDS Division Technology Manager / EL,ELDS,DSGBF

Dr. –Ing. Dietmar Gentsch

Electrification - Distribution Solutions (ELDS)
Research and Development
Senior Principal Engineer and ITE Member

ABB AG

Oberhausener Straße 33
40472 Ratingen, Germany
Phone: +49 (0) 2102 121685
Mobile: +49 (0) 175 299 0358

dietmar.gentsch@de.abb.com

abb.com