10th VDE ITG International Vacuum Electronics Workshop (IVEW) 2026 and 16th International Vacuum Electron Sources Conference (IVeSC) 2026

28-08-2026 PHYSIKZENTRUM BAD HONNEF

VACUUM INTERRUPTER – 2026

Low- and very low frequency current interruption in vacuum

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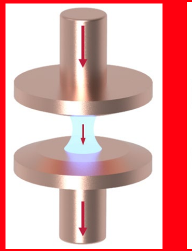
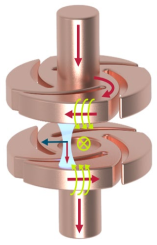
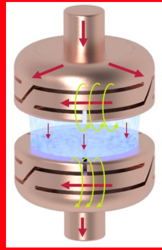
ENGINEERED TO OUTRUN

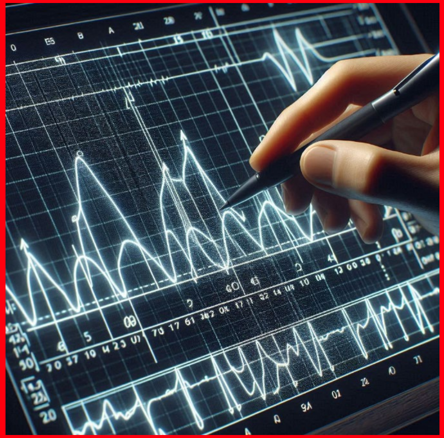
AGENDA

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, simulation and interruption under low frequency current load
  - Study and calculation of charge transfer and energy input, research and interruption at 2 … 4Hz
  - Arcing focused on Butt- / TMF- and AMF- contact systems
  - Dynamics of Arc analysed by means of High-Speed camera technique
- **Discussion / Summary**

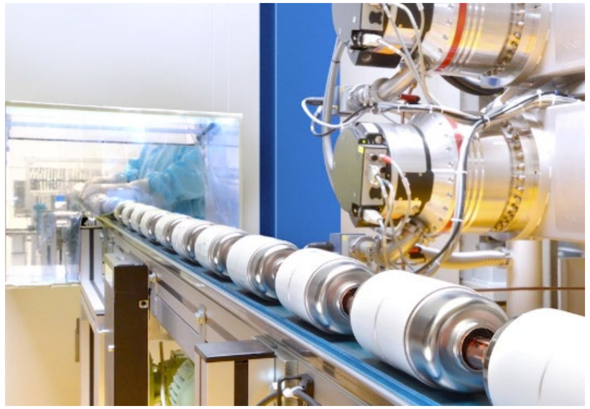
INTRODUCTION:



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

Introduction

Basics: Vacuum Interrupters in Electrical Power Systems



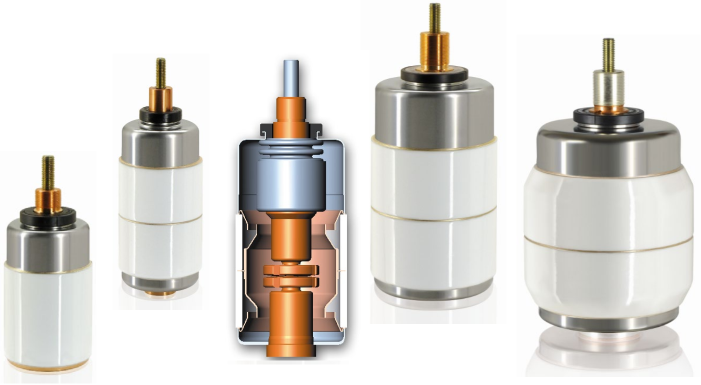
- Vacuum interrupters (VIs) play a critical role in electrical power systems, particularly at standard frequencies of **50/60 Hz**:

  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.

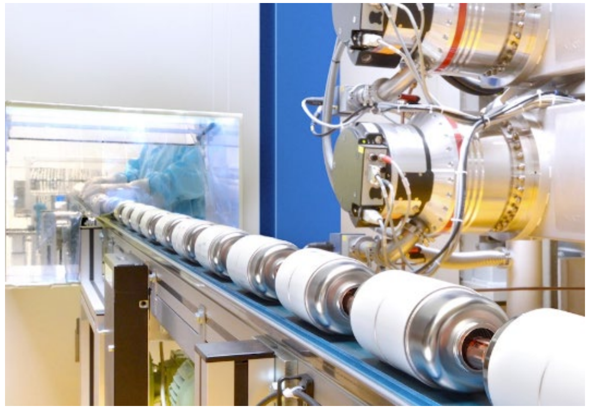
SF_6 – Free



INP FROM IDEA TO PROTOTYPE SIEMENS ABB

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, **2 … 4Hz**.

- Our analysis is based on tests conducted at both **16.7Hz** and **50Hz**
- Additionally, we examine contact erosion rates under varying current levels, including multiple short-circuit operations at **10-40kA** $_{rms}$ (at 50Hz) and several hundred amperes (at 2 … 4Hz)

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 … 4Hz** and **1300 … 2000A** $_{rms}$ shed light on the impact of multiple interrupting 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.

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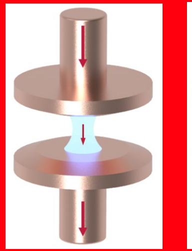
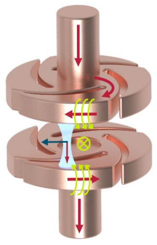
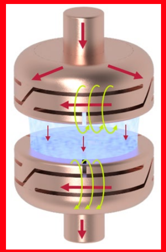
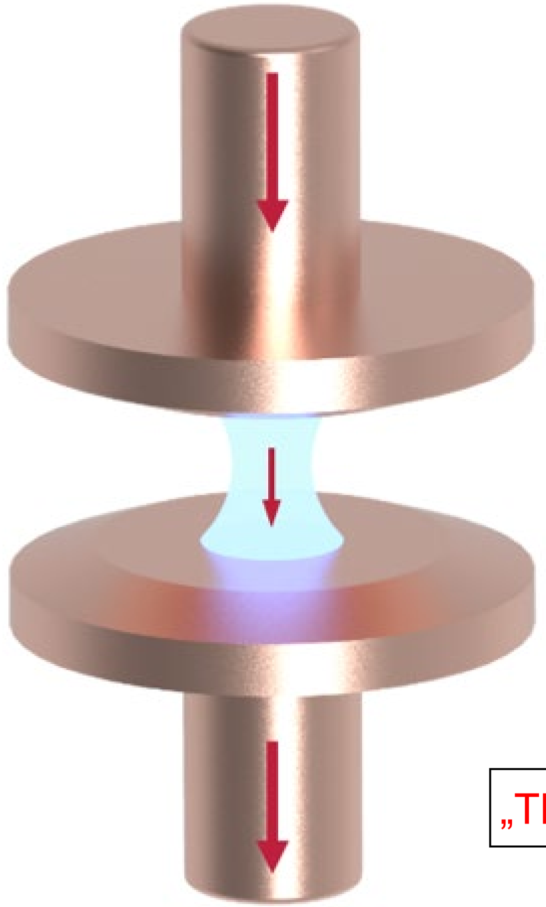




Introduction

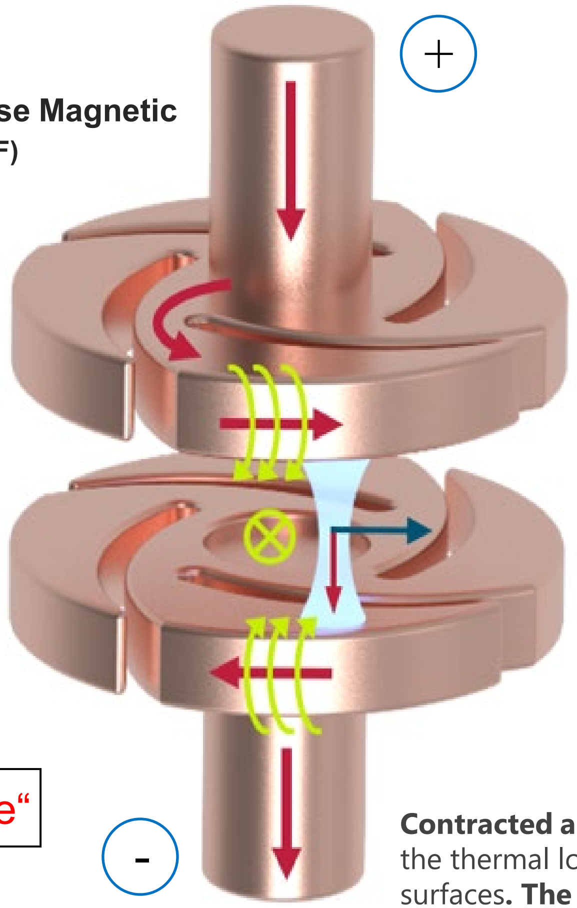
Schematic representation of different modes of the vacuum arc

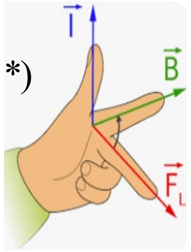
Boundary condition: Short-Circuit Current: **> 10kA**



„TMF – Mode“

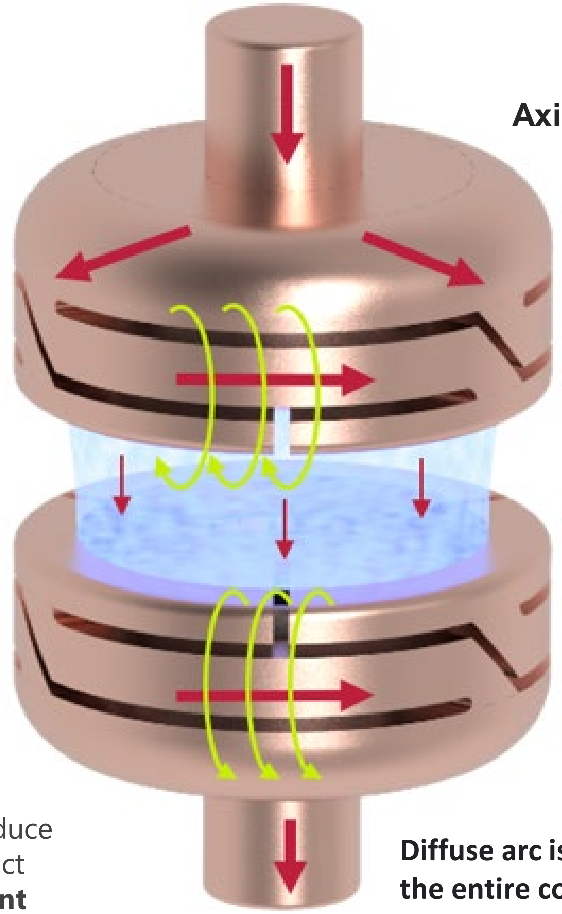
Transverse Magnetic Field (TMF)





Contracted arc rotates to reduce the thermal load on the contact surfaces. **The technical current flow direction is shown**

Axial Magnet Feld (AMF)



„AMF – Mode“

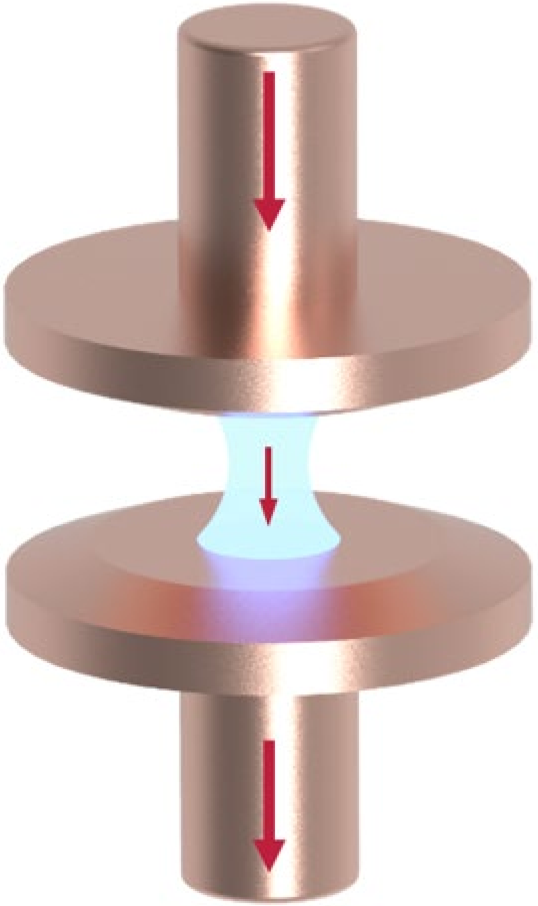
Diffuse arc is evenly distributed over the entire contact surface to reduce thermal stress

D. Gentsch

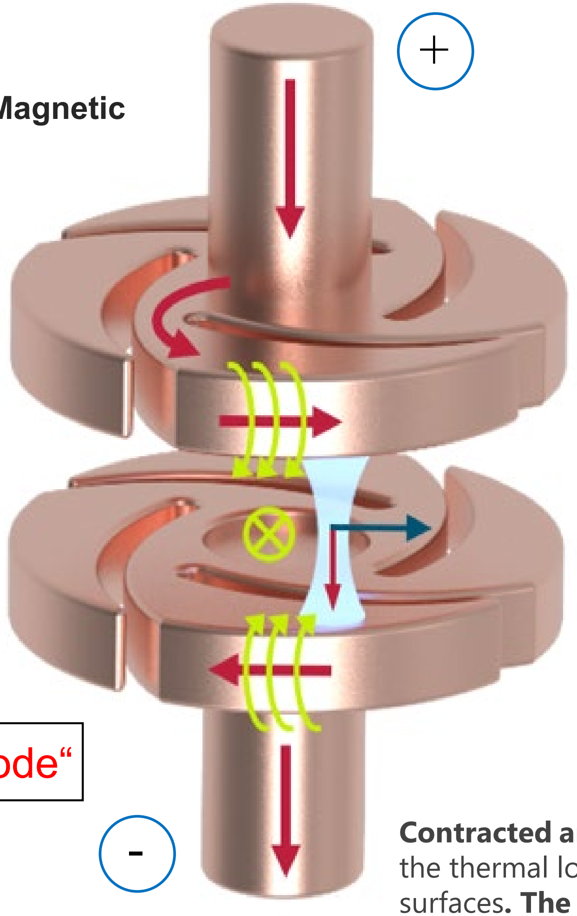
Boundary condition: Short-Circuit Current: **> 10kA**

Introduction

Schematic representation of different modes of the vacuum arc



Transverse Magnetic Field (TMF)



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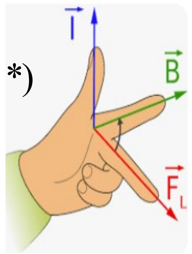
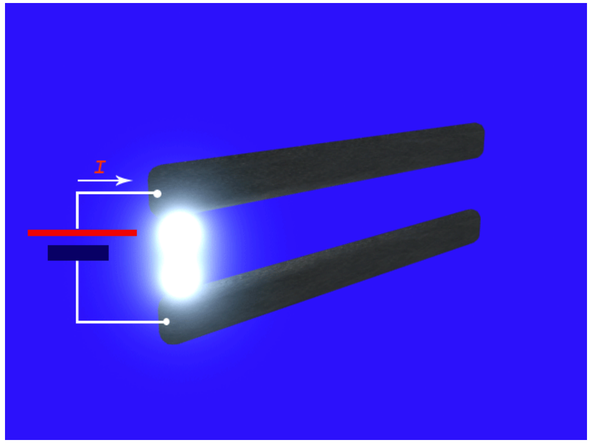
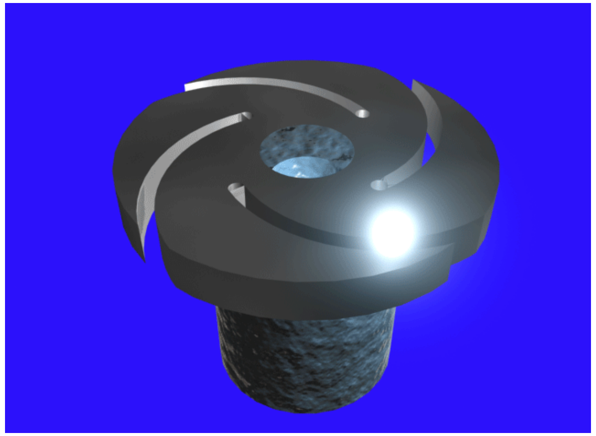






Contracted arc rotates to reduce the thermal load on the contact surfaces**. The technical current flow direction is shown**

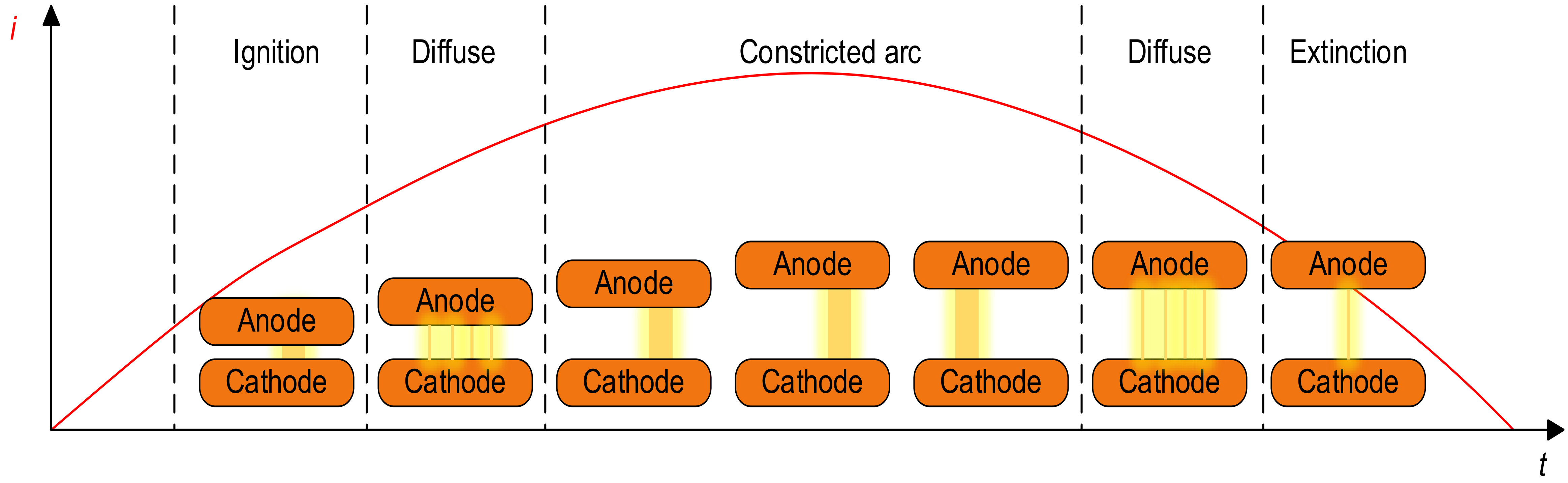
D. Gentsch

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

Introduction

Schematic representation of different modes of the vacuum arc

- **Various arc modes TMF** depends on current and gap
- **Contact erosion** influence by arc mode



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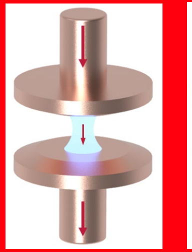
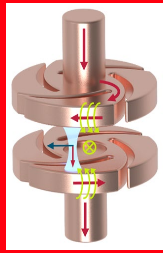
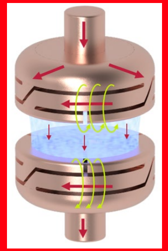
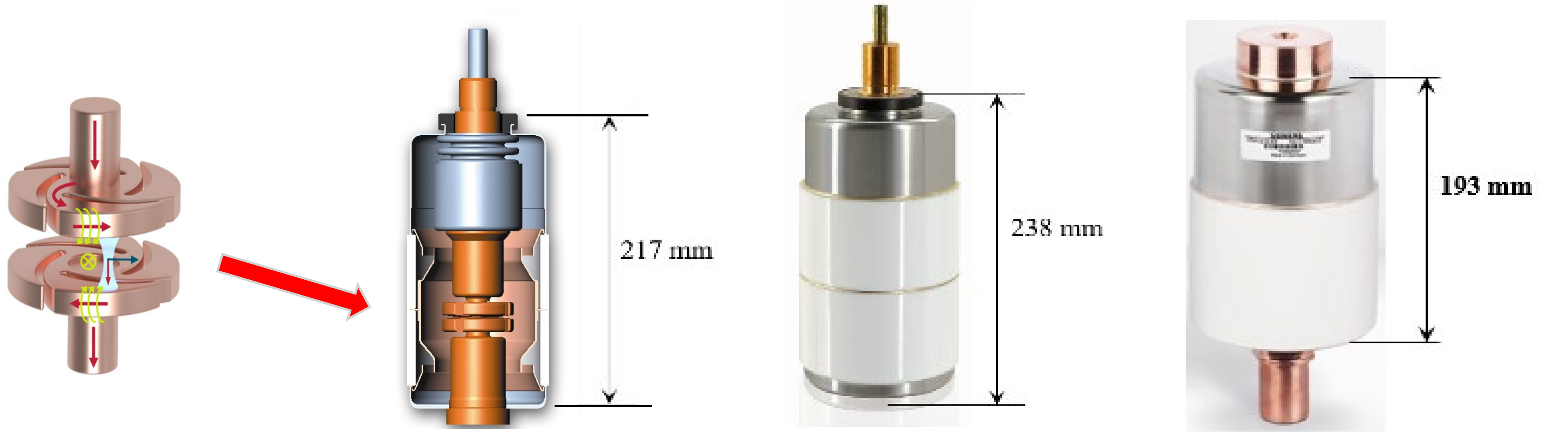




Vacuum interrupter in the loop of low frequency interruption

Basic circuit and interruption under low frequency current load

VI´s used for the calculation of the interruption performance boundaries



Examples of compact vacuum interrupter :

Left side type: ABB

VG – Series: (24kV – 31.5kA – 2500 A) – **217 mm**; (36kV – 31.5kA – 3150 A) – **238 mm**

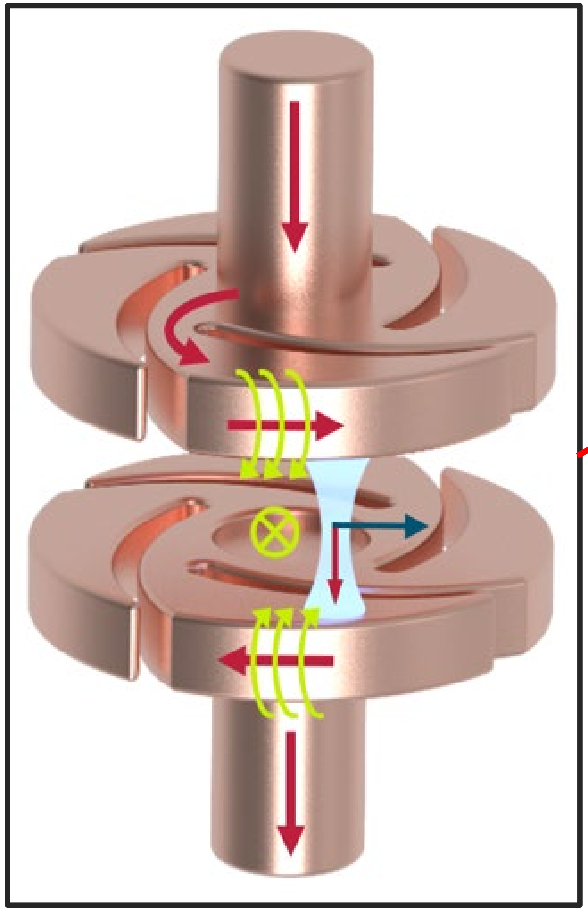
Right side type: SIEMENS

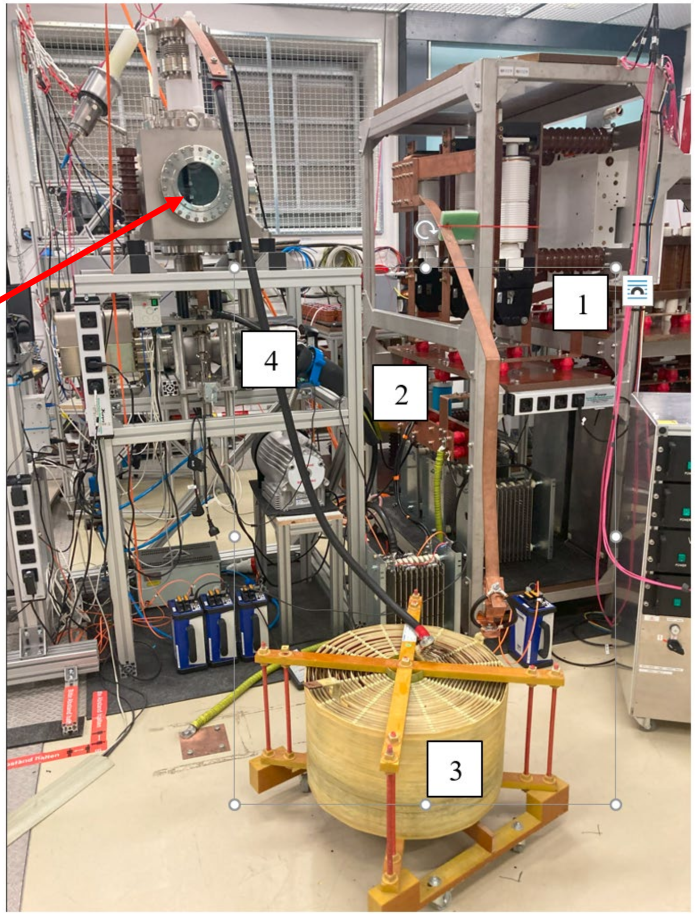
VSA12: – 0 – 40 (12kV – 40kA – 3150 A) – **193 mm**

INP SIEMENS ABB

Vacuum interrupter in the loop of low frequency interruption

Basic circuit and interruption under low frequency current load





Experimental setup :

1 – High current generator

2 – High voltage generator,

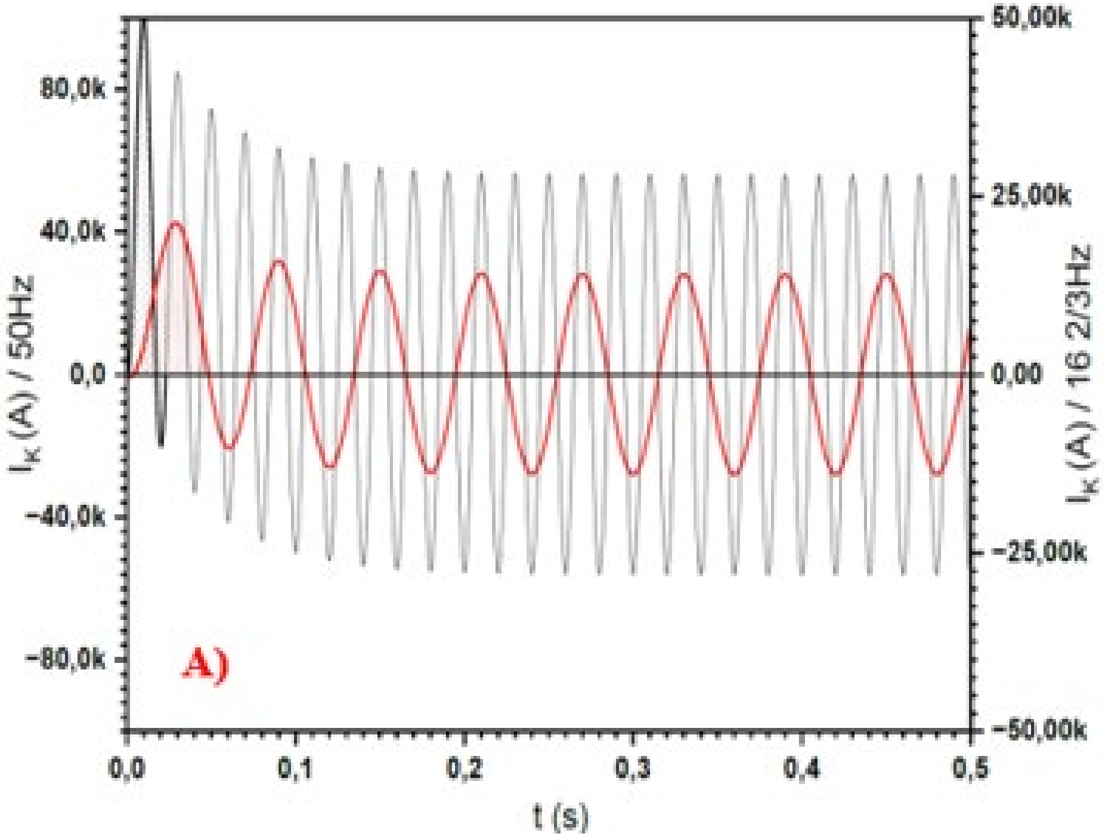
3 – Main coil

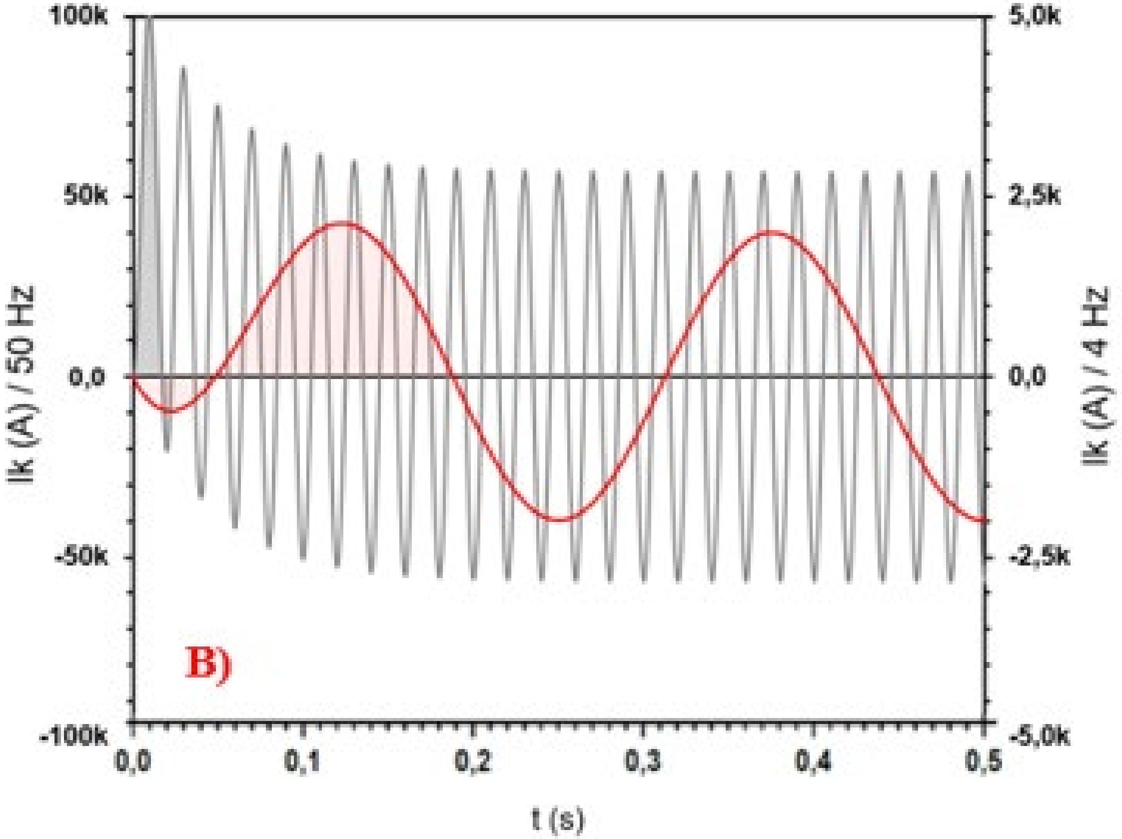
4 – Model vacuum interrupter

D. Gentsch

Vacuum interrupter in the loop of low frequency interruption

Simulation / Interruption under low frequency current load





Single phase short circuit current injection ; DC time constant (τ = L/ R) to 45ms reference at frequency **50**/ 60Hz at 40kA$_{rms}$ with **T/2= 10ms** compared to low frequency direct current interruption at:
A) 16.7Hz at 10kA$_{rms}$ – T/ 2= 30ms; B) 4Hz at 2kA$_{rms}$ – T/ 2= 125ms **Integral I x dt dotted area** at each curve

Vacuum interrupter in the loop of low frequency interruption

Calculation / Interruption under low frequency current load

Simulation results compare 50Hz to 16.7Hz (A) **and 50Hz to 4Hz** (B)

These **simulations evaluate** the VI's ability to **interrupt 40kA** $_{rms}$ at 50Hz and at **4Hz with 2000A** $_{rms}$

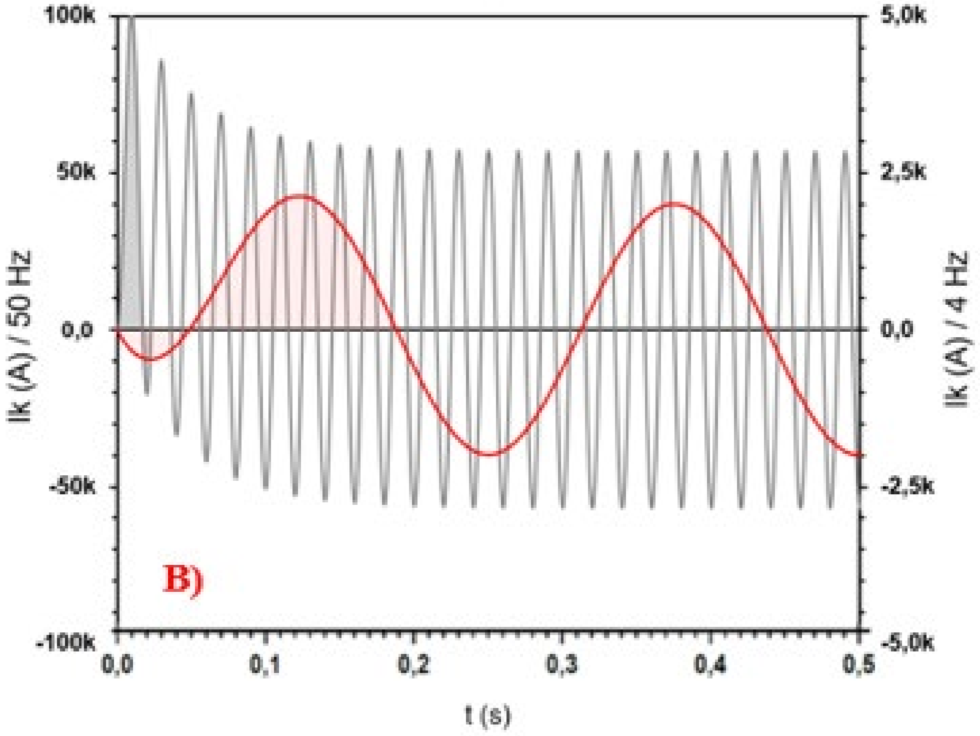
The three -phase simulation at 40kA $_{rms}$ provides insights into arcing time and transferred charge, calculated as:

$$C = \int I \cdot dt \quad (1)$$

where : C = transferred charge (As), I = current (A), t = arcing time (s)

At 50/60Hz , the maximum transferred charge reaches approximately **938As** when the breaker opens during the first half-cycle according to equation (1)

This is compared to values at lower frequencies , excluding the typical 35…45ms opening delay of standard VCBs, which would otherwise reduce the DC component.



Charge transfer [C] at 50Hz/40A $_{rms}$ and at 4Hz/2kA $_{rms}$

INP FROM IDEA TO PROTOTYPE SIEMENS ABB

Vacuum interrupter in the loop of low frequency interruption

Calculation / Interruption under low frequency current load

The **magnetic field configurations of TMF and AMF are designed** to influence arc motion and distribution or arc energy E during current interruption, thereby **enhancing the VI's performance under high -stress conditions**

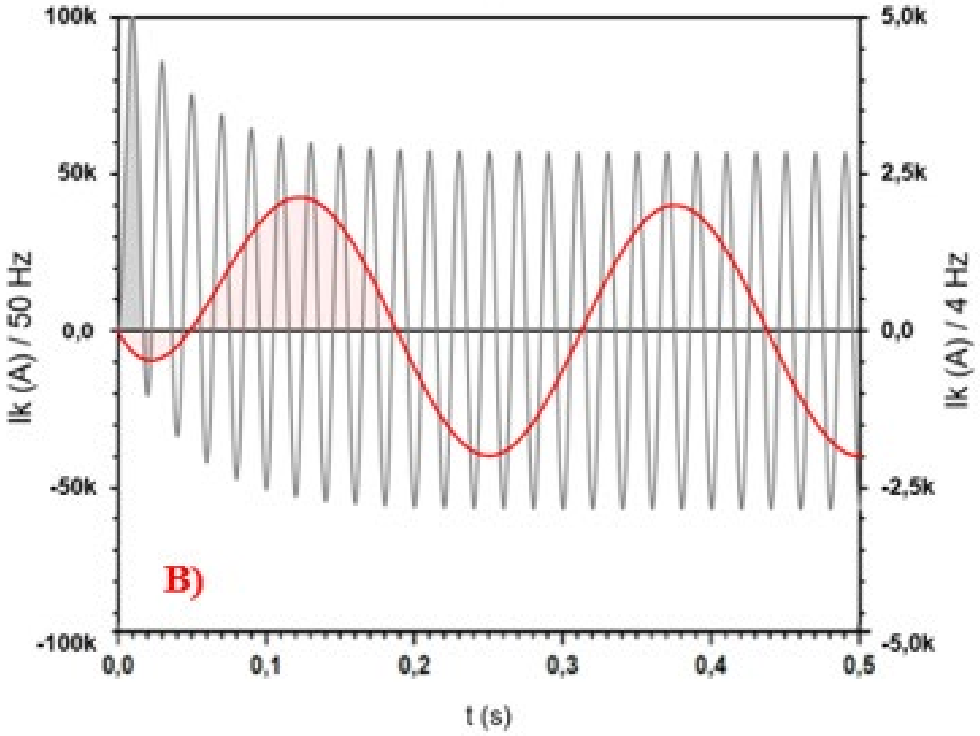
To **evaluate the thermal stress** imposed on the VI during current interruption, assuming a constant arc resistance, the energy input to the contacts can be quantified using the Joule integral, expressed as:

$$E = R \int I^2 \cdot dt \qquad (2)$$

where : E = is the energy dissipated (J), R = average arc resistance (Ohm), I = is the instantaneous current (A), t = is time (s)

This integral quantifies the total arc energy deposited into the contact system and vacuum interrupter through resistive heating during the arcing phase.

It serves as a critical parameter for assessing the thermal endurance and erosion characteristics of contact materials under various magnetic field configurations.

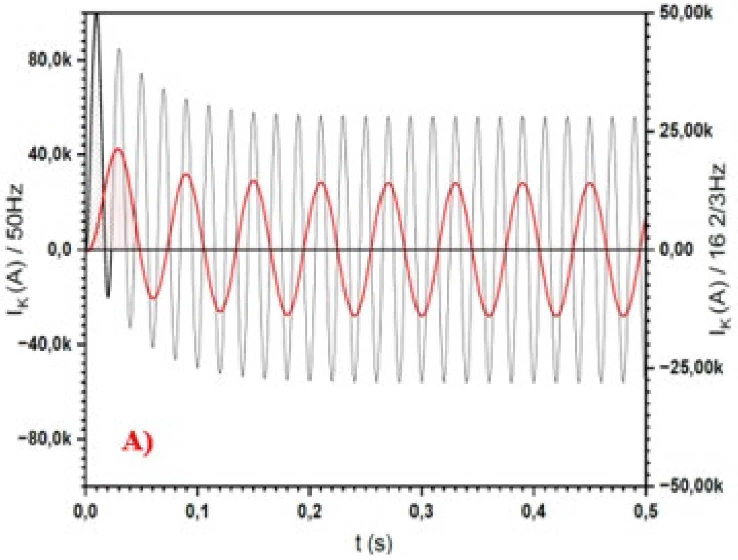


Energy dissipation [J] at 50Hz/40A rms and at 4Hz/2kA rms

Vacuum interrupter in the loop of low frequency interruption

Results / Interruption under low frequency current load

Simulation on 40kA/50Hz 10kA/16.7Hz



Boundary

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

A) 16.7Hz at $10kA_{rms}$ – T/ 2= 30ms

Integral I x dt dotted points at each curve

Result on charge transfer and Energy

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

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

$$E = R \int I^2 \cdot dt$$

Where: E is the **energy dissipated** (J)

R = average arc resistance (Ohm), I = is the instantaneous current (A), t = is time (s)

40kA – 50Hz – I x dt: 938C+73C = **1011C** / / / **10kA** – 16 2/3Hz – I x dt: 1153C+300C = **1453C**

40kA – 50Hz – R I² x dt: 214kJ+8kJ = **222kJ** / / / **10kA** – 16 2/3Hz – R I² x dt: 118kJ+ 10kJ = **128kJ**

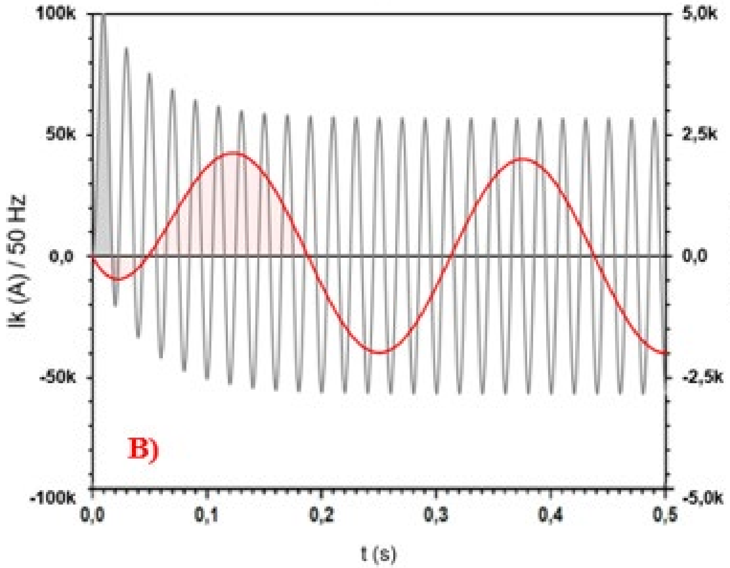
Vacuum interrupter in the loop of low frequency interruption

Results / Interruption under low frequency current load

Simulation on 40kA/50Hz 2kA/4Hz

Boundary

Result on charge transfer and Energy



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

B) 4Hz at $2kA_{rms}$ – T/ 2= 125ms

Integral I x dt dotted points at each curve

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

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

$$E = R \int I^2 \cdot dt$$

Where: E is the **energy dissipated** (J)

R = average arc resistance (Ohm), I = is the instantaneous current (A), t = is time (s)

40kA – 50Hz – I x dt: 938C+73C = 1011C / / / 2kA – 4Hz – I x dt: 184C+15C = 199C

40kA – 50Hz – R I² x dt: 214kJ+8kJ = 222kJ / / / 2kA – 4Hz – R I² x dt: 20kJ+ 0.7kJ = 20.7kJ

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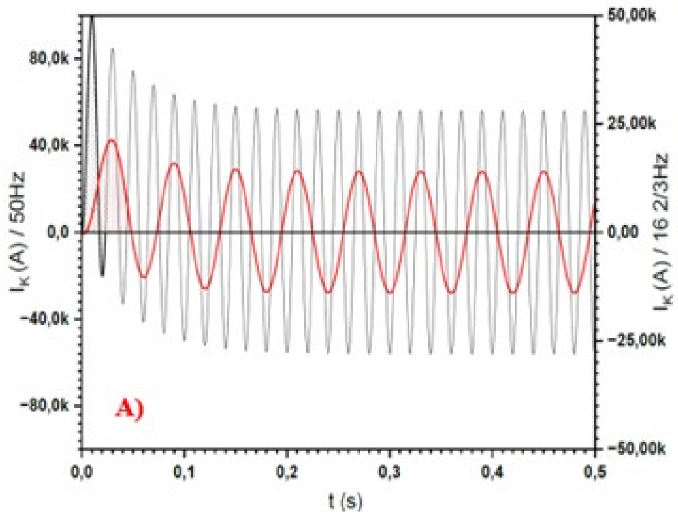
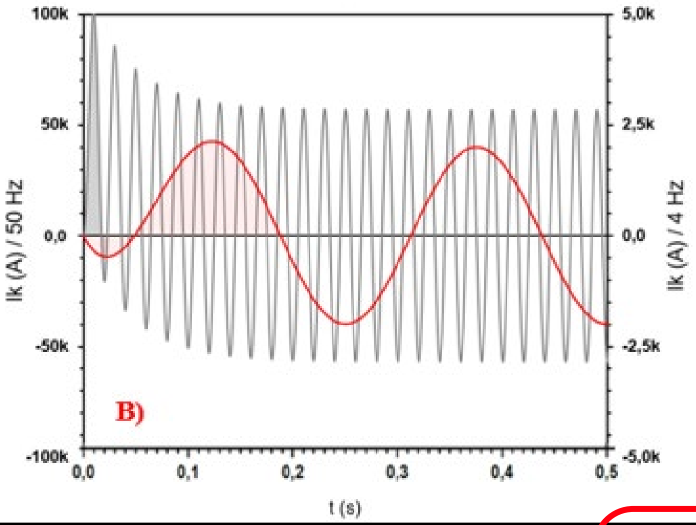
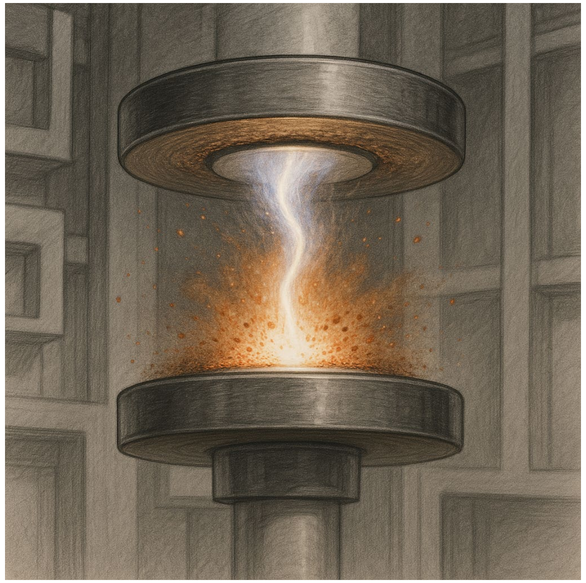
Vacuum interrupter in the loop of low frequency interruption

Results / Interruption under low frequency current load







Frequency	Current	Arcing time (T/2)	I dt major loop	R I² dt major loop	I dt minor loop	R I² dt minor loop
50/60Hz	40kA$_{rms}$	10…8ms	938As	214kJ	73As	8kJ
16.7Hz	10kA$_{rms}$	30ms	1153As	118kJ	300As	10kJ
4Hz	2kA$_{rms}$	125ms	184As	20kJ	15As	0.7kJ

Heat accumulation within the vacuum interrupter, compared to 50/60Hz application at 40kA / @ 4Hz at 2kA – 10 times lower

INP FROM IDEA TO PROTOTYPE SIEMENS ABB

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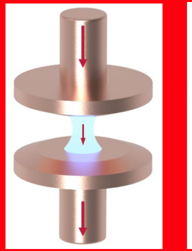
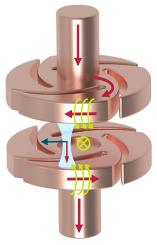
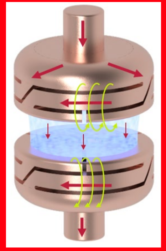
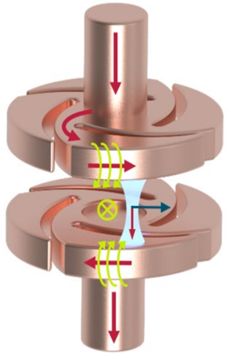
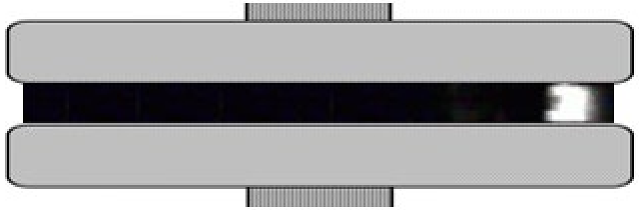




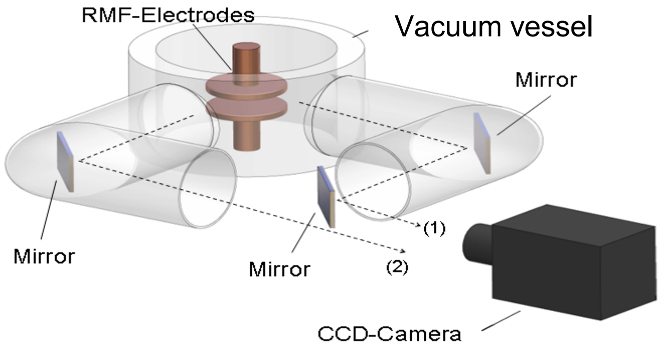
Vacuum interrupter in the loop of low frequency interruption

High speed arc observation / Interruption under low frequency current load



„TMF – Mode“

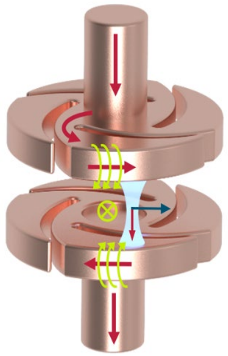




40kA interruption @ 50…60Hz / Arcing time 8ms / 68mm Contact diameter / Contact stroke 10mm

Vacuum interrupter in the loop of low frequency interruption

High speed arc observation / Interruption under low frequency current load



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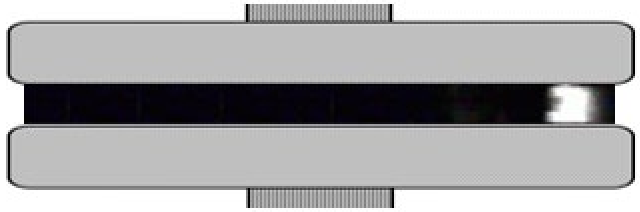
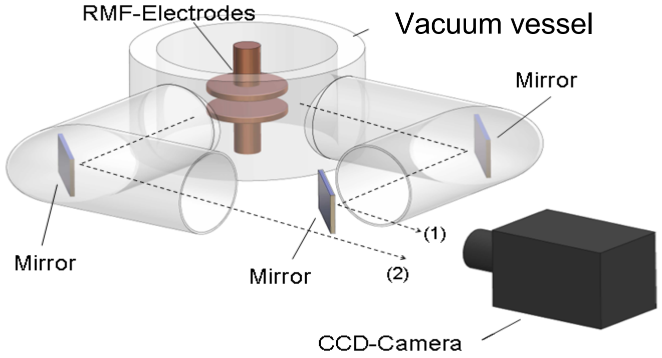




2kA interruption @ 2…4 Hz / Arcing time ~ 125ms / 68mm Contact diameter / Contact stroke 10mm

„TMF – Mode“

Vacuum interrupter in the loop of low frequency interruption

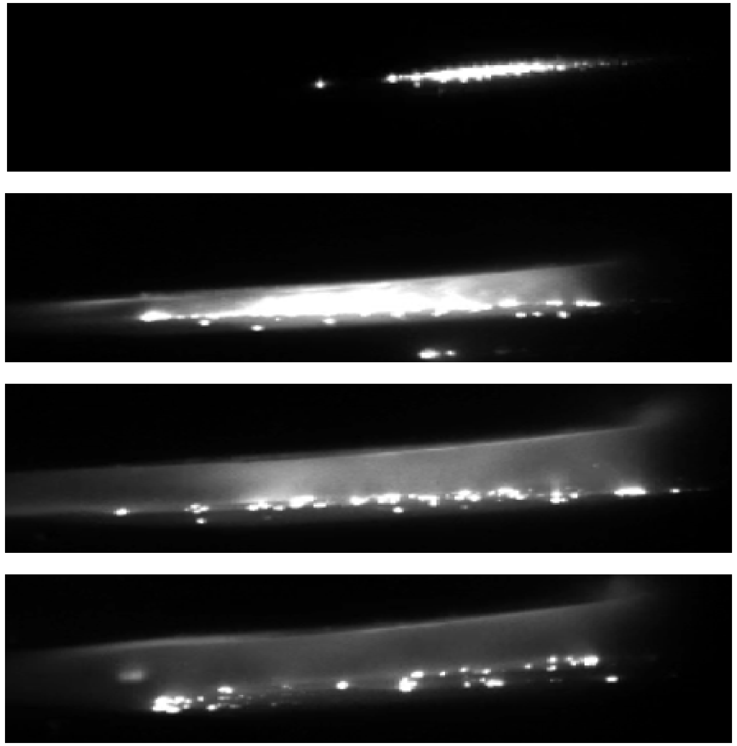
High speed arc observation / Interruption under low frequency current load

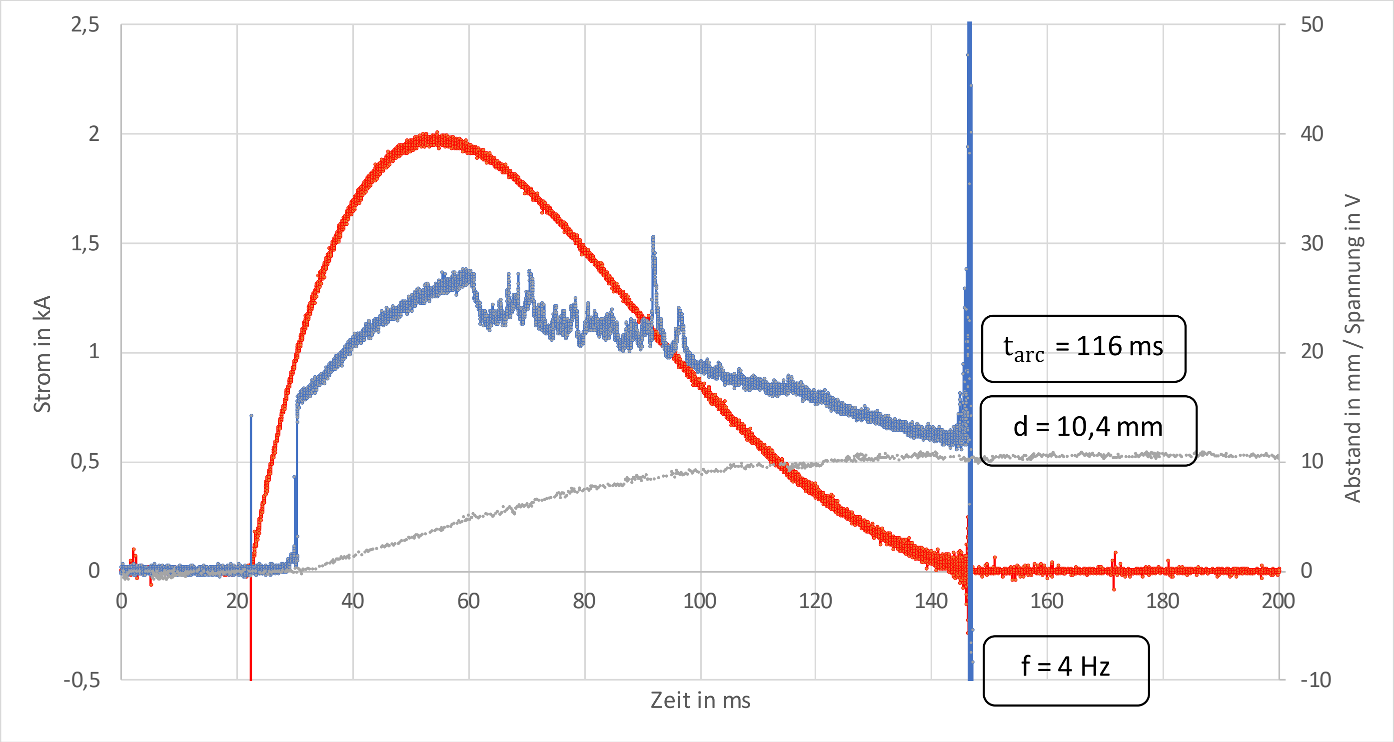
a)

b)

c)

d)



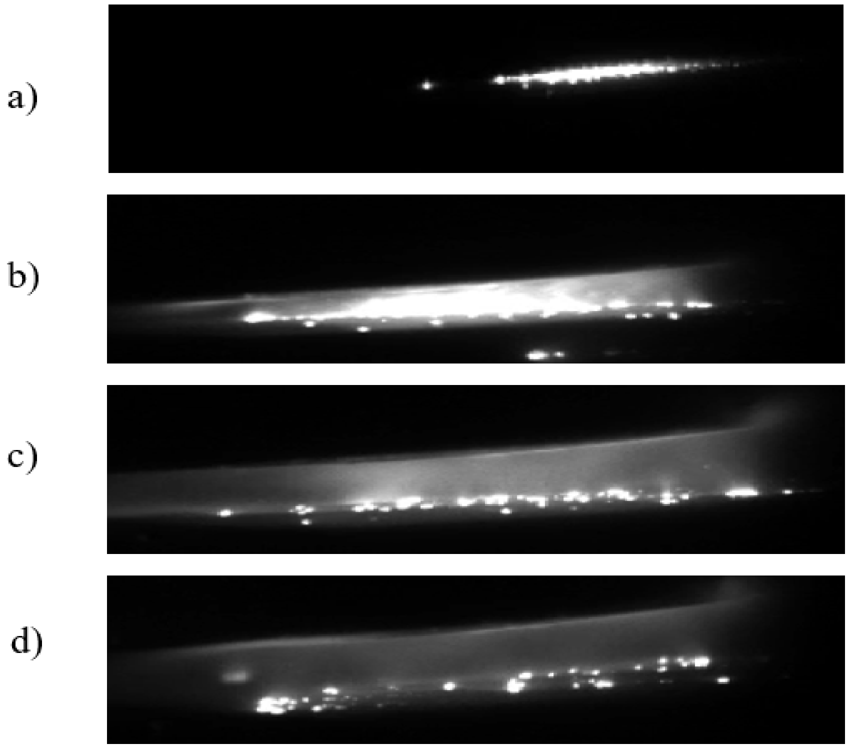


$2kA_{peak}$ interruption @ 2…4 Hz / 68mm Contact diameter / Contact stroke 10mm

„TMF – Mode“

Vacuum interrupter in the loop of low frequency interruption

High speed arc observation / Interruption under low frequency current load



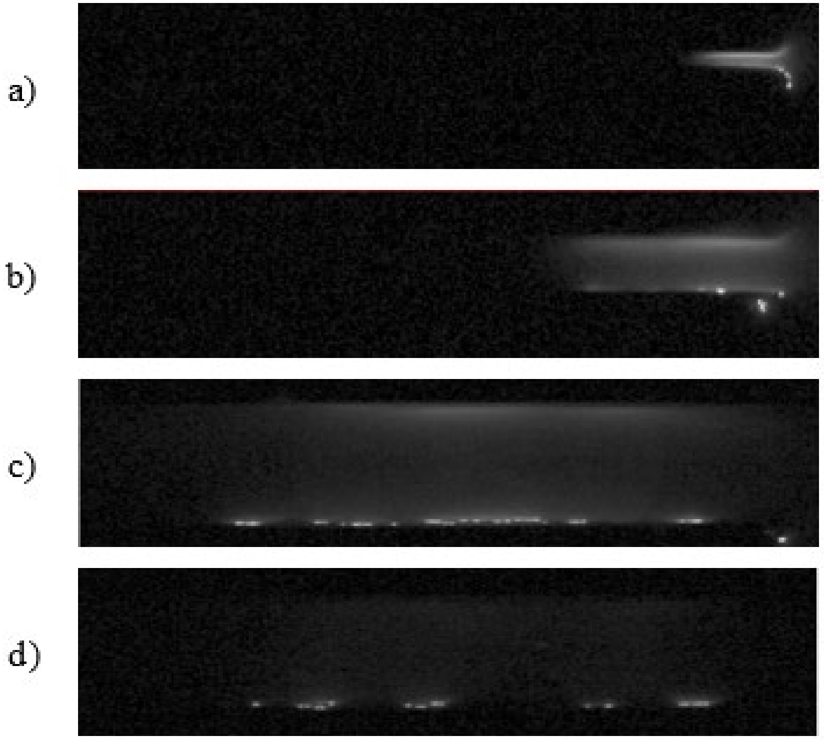
- **Butt and TMF – Contact** with CuCr 25-35 wt.%
  Arc images at the instants:
  - a) 2ms
  - b) 5ms
  - c) 20ms
  - d) 145ms
- After arc ignition 2000A$_{rms}$ (from top to bottom). Experimental conditions.
- Anode on the top, cathode on the bottom. The total arcing duration is approximately **125ms ~ 4Hz**.
- At TMF contacts rotation of cathode spots are visible.

2kA$_{rms}$ interruption @ 4Hz / 68mm Contact diameter / Contact stroke 10mm

„AMF – Mode“

Vacuum interrupter in the loop of low frequency interruption

High speed arc observation / Interruption under low frequency current load



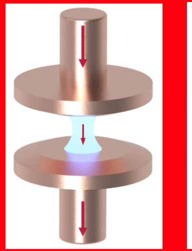
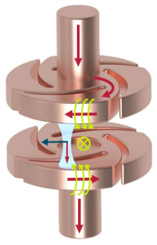
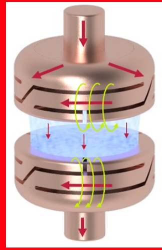
- **AMF – Contact** with CuCr 40-50 wt.%
  Arc images at the instants:
  - a) 1ms
  - b) 5ms
  - c) 20ms
  - d) 170ms
- After arc ignition 1300A_{rms} (from top to bottom).
- Experimental conditions compare.
- Anode on the top, cathode on the bottom the total arcing duration is approximately **200ms ~ 2.4Hz**

1.3kA_{rms} interruption @ 2.4Hz / 68mm Contact diameter / Contact stroke 10mm

A G E N D A

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, simulation and interruption under low frequency current load
  - Study and calculation of charge transfer and energy input, research and interruption at 2 … 4Hz
  - Arcing focused on Butt- / TMF- and AMF- contact systems
  - Dynamics of Arc analysed by means of High-Speed camera technique
- **Discussion / Summary**

Vacuum interrupter in the loop of low frequency interruption

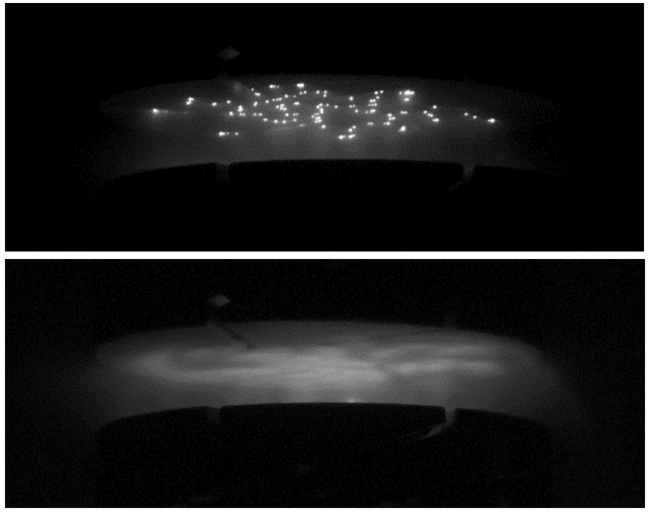
Summary :

- ❖ Vacuum circuit breakers (VCBs), originally designed for 50/60Hz, have also been used in lower-frequency rail networks
- ❖ In green energy systems like wind turbines, pumped storage, solar converters, battery storage and shipboard power temporary faults at low frequencies lead to longer arcing times before current zero
- ❖ An arcing event at **4.0Hz with 2kA$_{rms}$** results in a charge transfer of **184As**, which is factor **5 times less** compared to **938As** typically **seen in 50Hz systems at 40kA$_{rms}$**

This study identifies key factors for successful interruption :

- **Contact erosion limit** : Max. 2.5mm total
- **Material erosion** : Varies by current category < 4kA and between 4…10kA
- **Material transport** : Negligible during operation
- **Contact heating** : Up to 450° C is acceptable for VIs
- **Dielectric integrity** : Maintained despite arc impact on internal surfaces.

These results confirm the robustness and adaptability of VCBs and switchgear for emerging low-frequency use cases - such as in renewable energy systems, special industrial processes or railway applications.



Images of the cathode surface (top) and anode surface (bottom) recorded at the instant of maximum current, 2000A

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