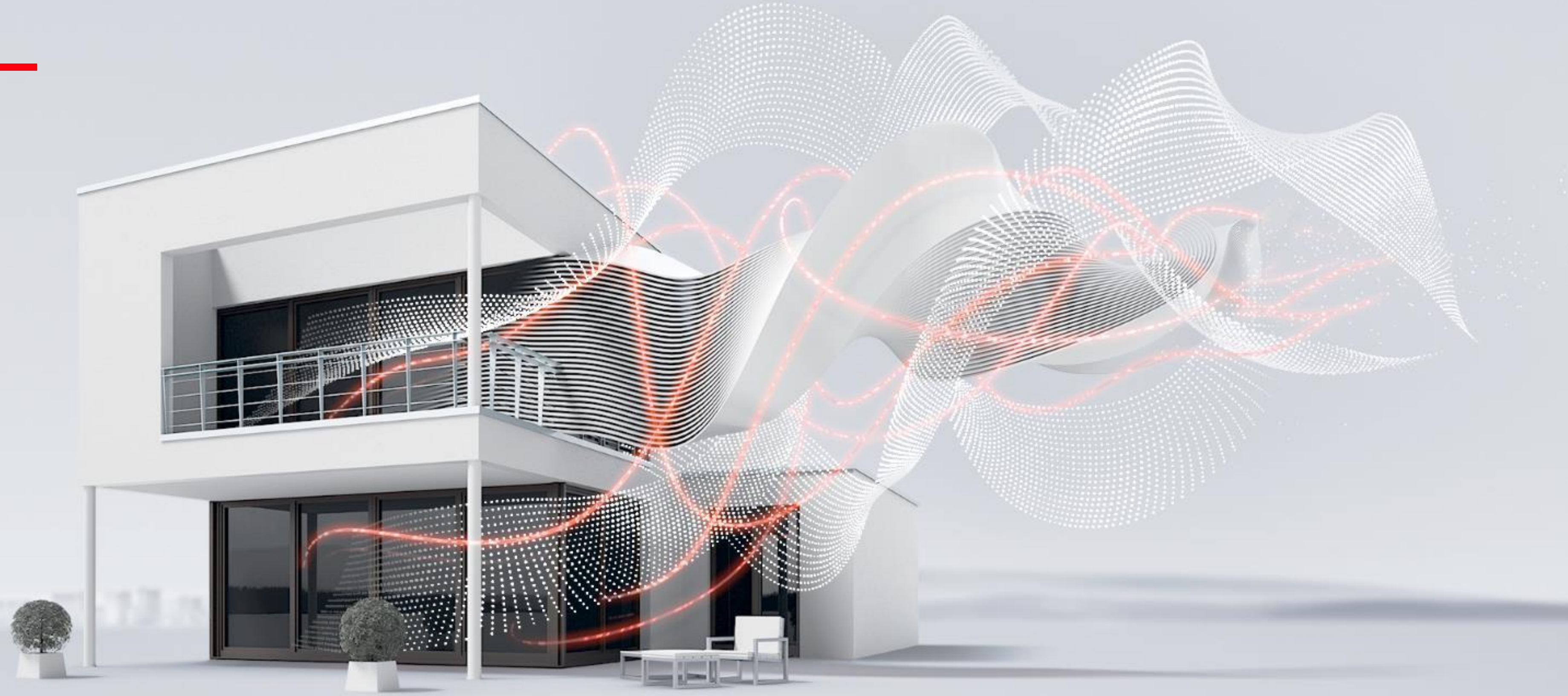

02 / 03 SEPTEMBER 2022

PERFORMANCE OF IN-SERVICE SHUNT CAPACITOR SWITCHING DEVICES

Application of vacuum interrupter

Dr. Dietmar Gentsch R&D – ABB AG – ELDS – Ratingen

PERFORMANCE OF IN-SERVICE SHUNT CAPACITOR SWITCHING DEVICES

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- **Introduction**
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- **Vacuum interrupter in the loop of shunt capacitor switching**
  - Basic circuit and interruption in capacitor circuit
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SF_6 Free

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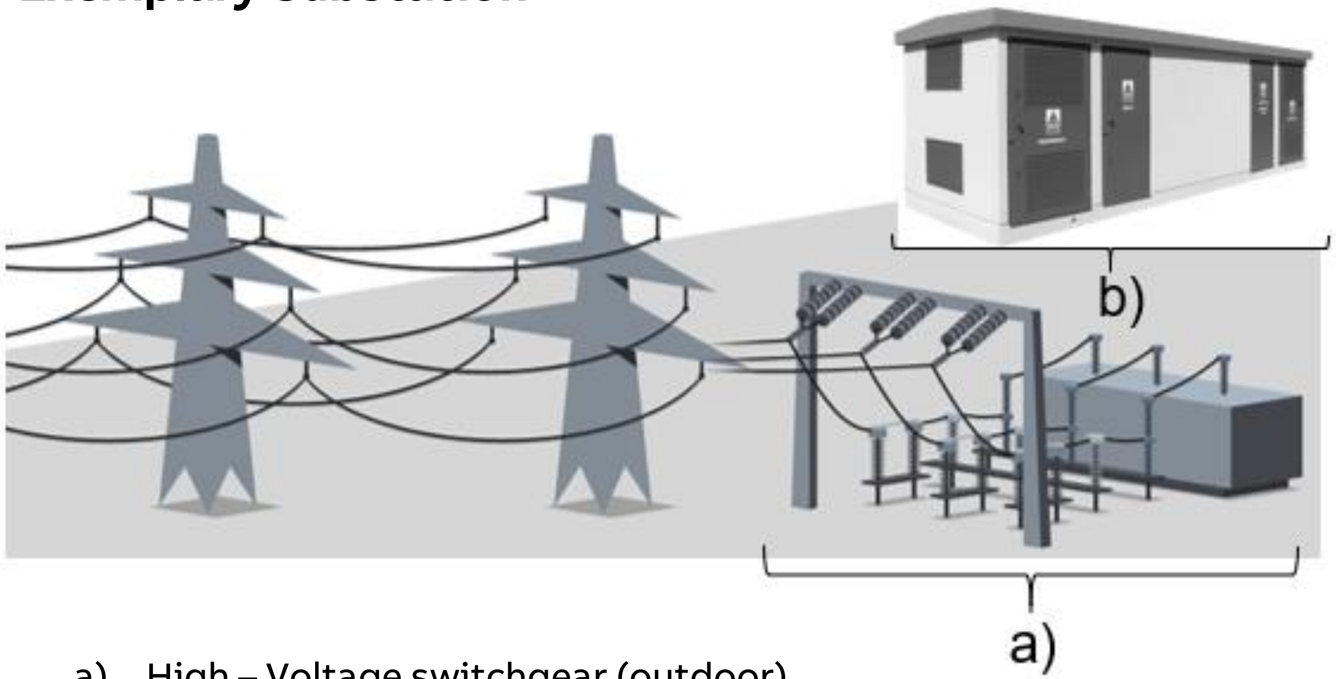
Introduction

Exemplary Substation



a) High – Voltage switchgear (outdoor)

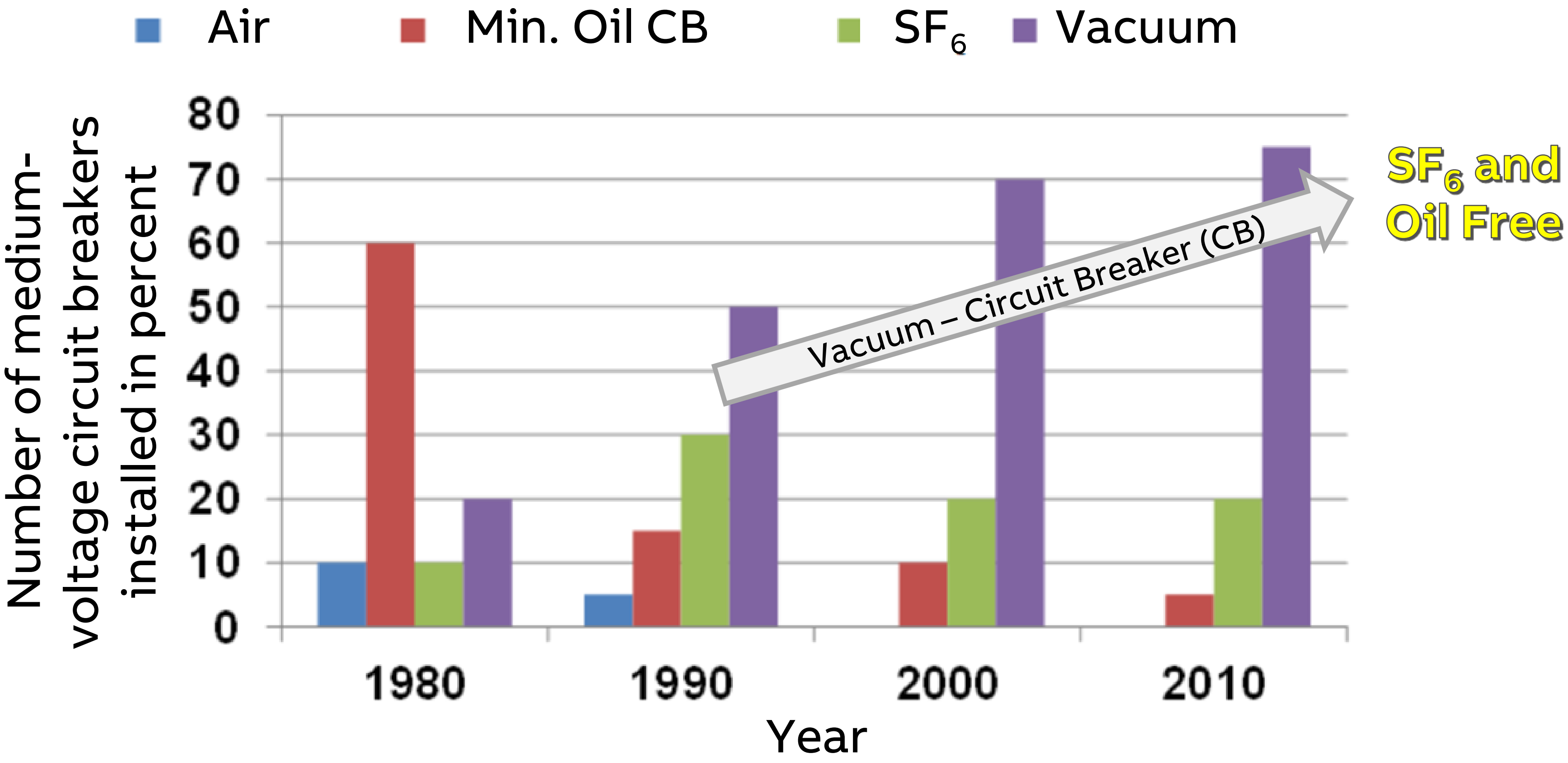
b) Medium – Voltage switchgear

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

Quelle: Diss. Kühn 2021

Introduction

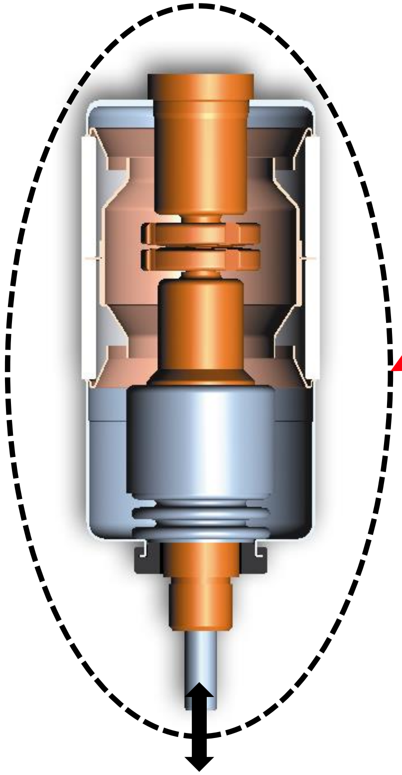
Vacuum Circuit breaker type
VD4: 12kV, 2000A, 40kA



Quelle: VDE 2015

Introduction

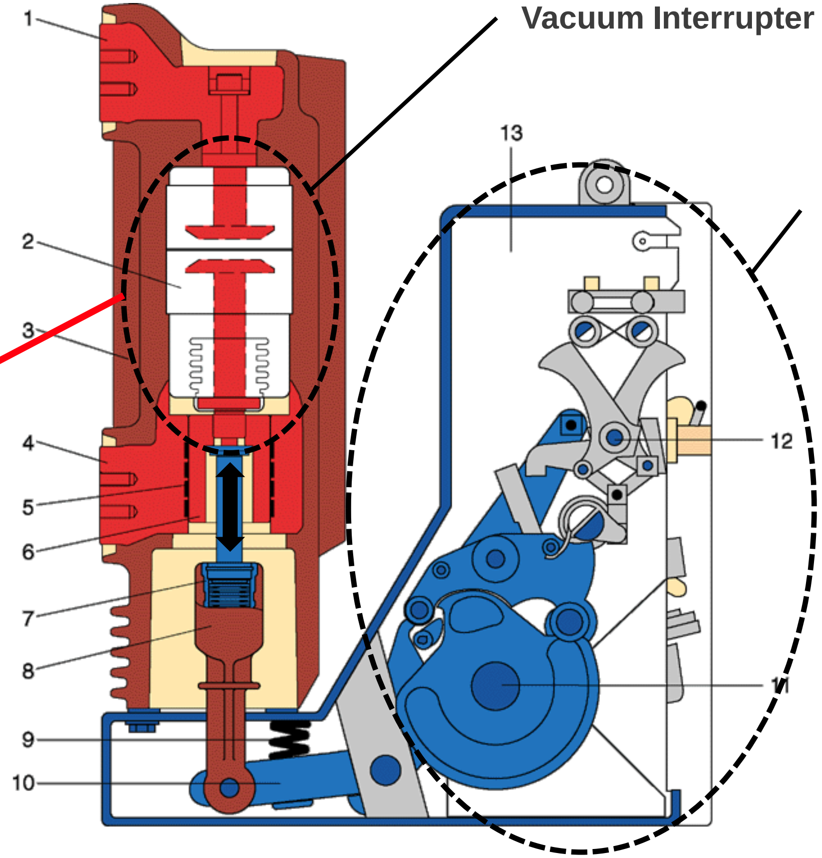
- Design of vacuum interrupter
- Principle On- and Off- operation
- Advantage and Disadvantages
- Application and Tests
- Security



Mechanical drive

Interruption element: Vacuum Interrupter

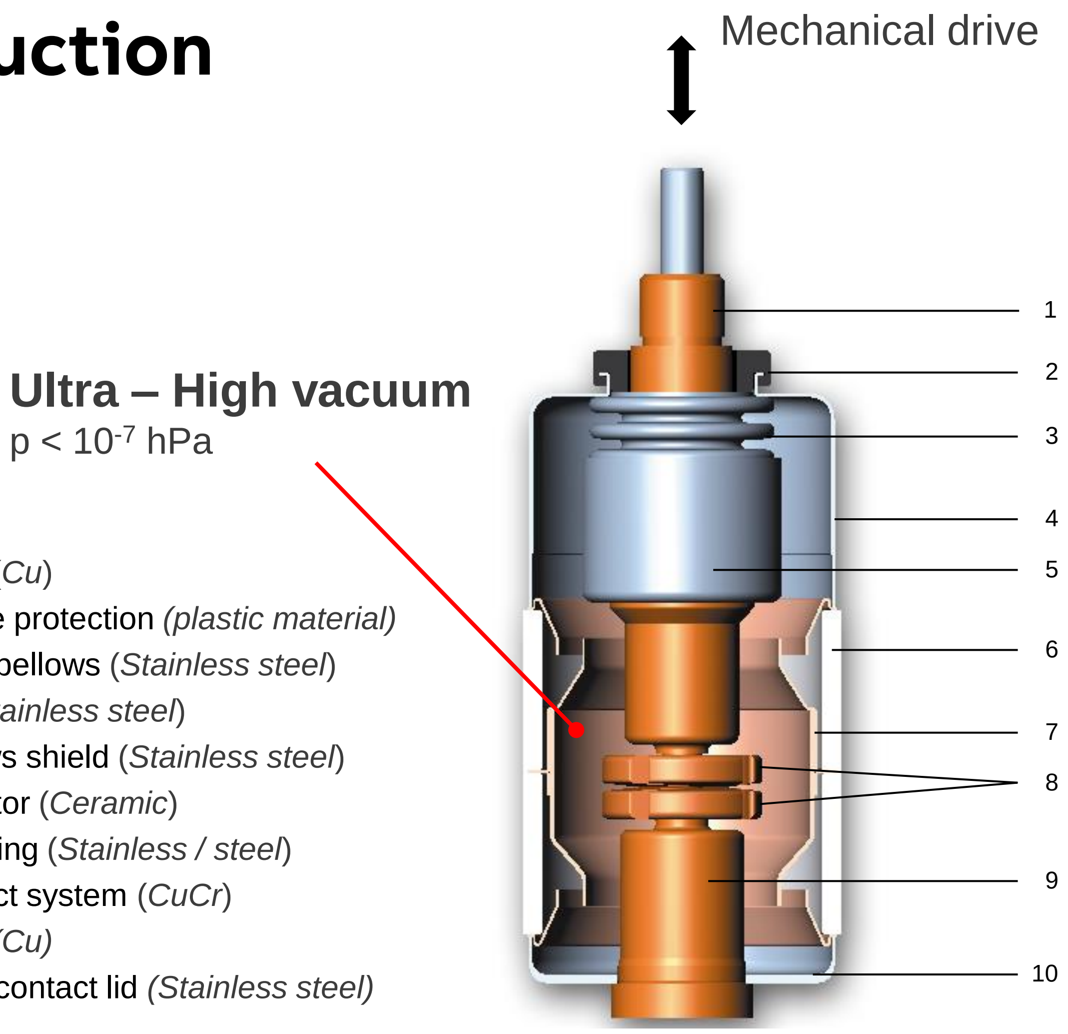
Drive to close and open the interruption contacts



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.

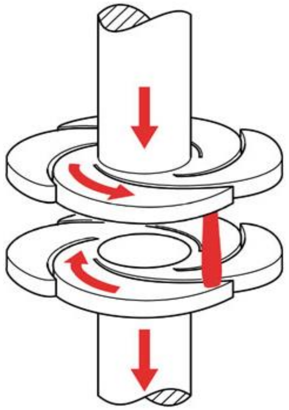
Introduction

Interruption performance vs. contact diameter:

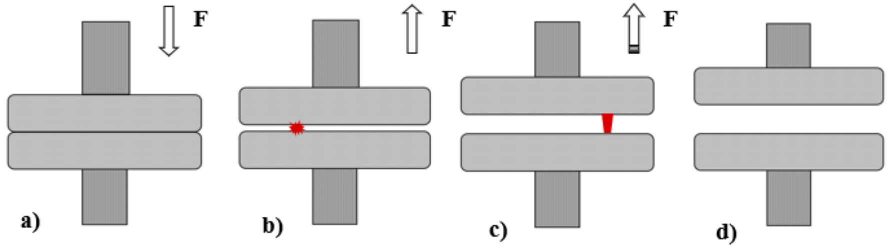
Transverse magnetic field (TMF) contacts:

- 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)

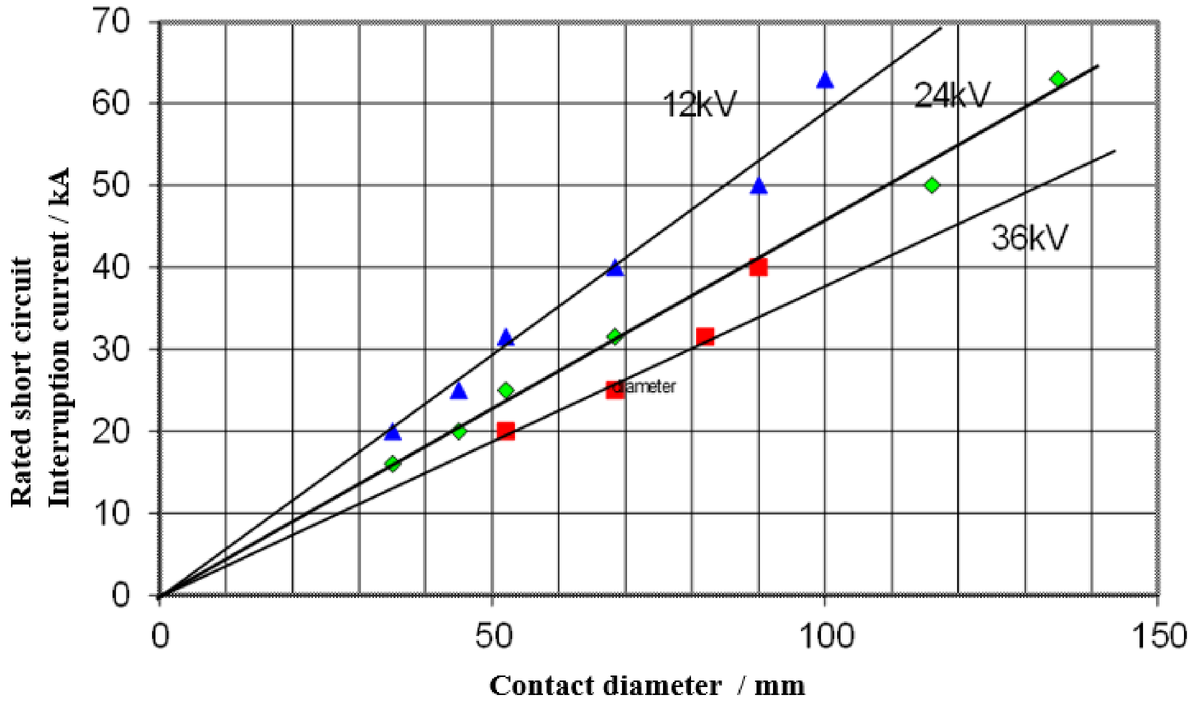
The interruption capacity of an interrupter is reached when the arc energy distributed over the contact surface reaches the physical limit



TMF Spiral contact



Closed | Interruption process in 4 steps: a) .... d) | Open



PERFORMANCE OF IN-SERVICE SHUNT CAPACITOR SWITCHING DEVICES

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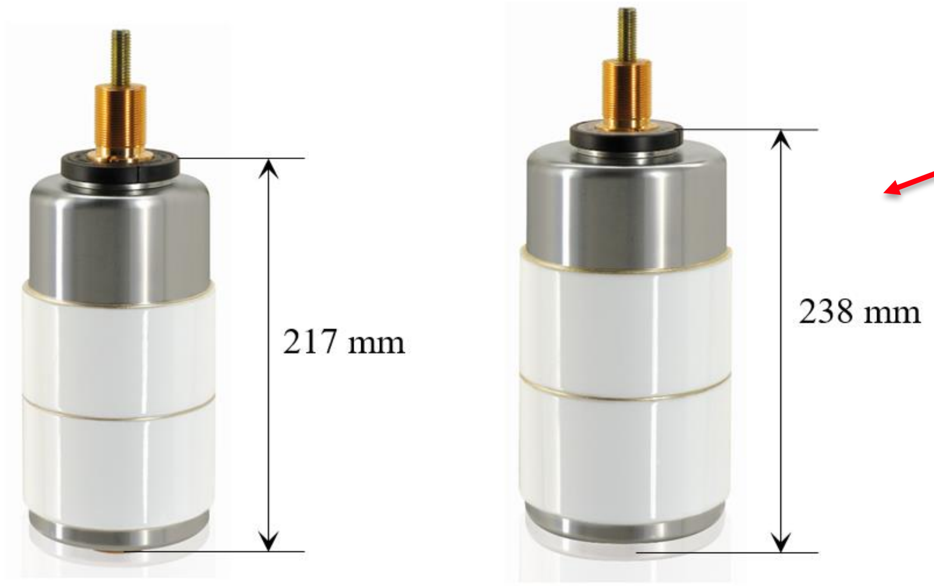


Dimensions of multipurpose “K–type” VI:

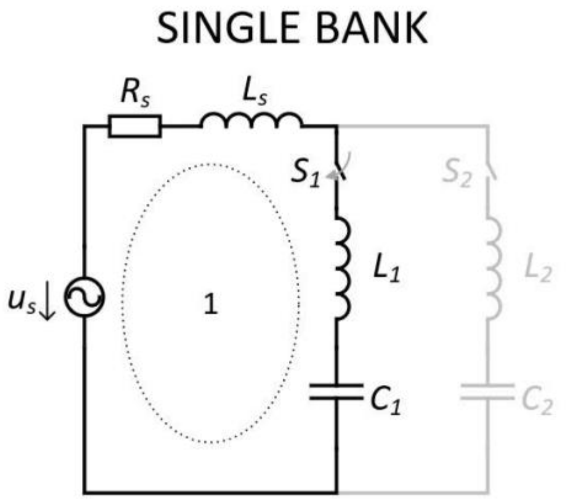
- VG6–K; VG6–S–K both 40.5kV/31.5kA with ϕ 109mm (left)
- VG8–K 40.5kV and 31.5kA and VG8–S–K 40.5kV/40kA with ϕ 125mm (right)
- VG8/VG8–K is applied for this study

Circuit breaker vacuum interrupter family:

- Maintenance free, robust, compact
- Optimized the VG- type series for ratings 1 … 52 kV and … 85 kA for multipurpose and switchgear application

PERFORMANCE OF IN-SERVICE SHUNT CAPACITOR SWITCHING DEVICES

Capacitive switching single bank



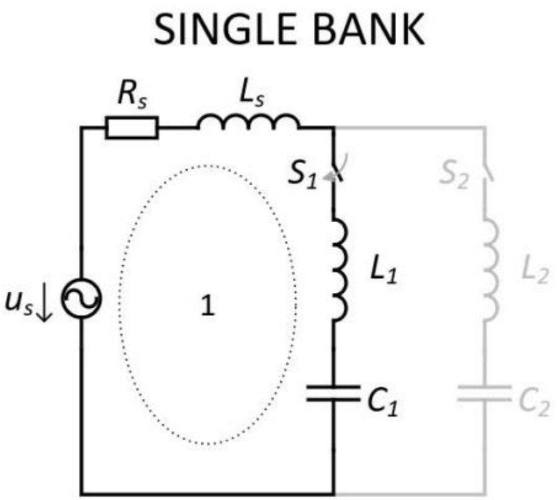
Single bank circuit involving a circuit breaker S1

<u>Different type of capacitive loads</u>:

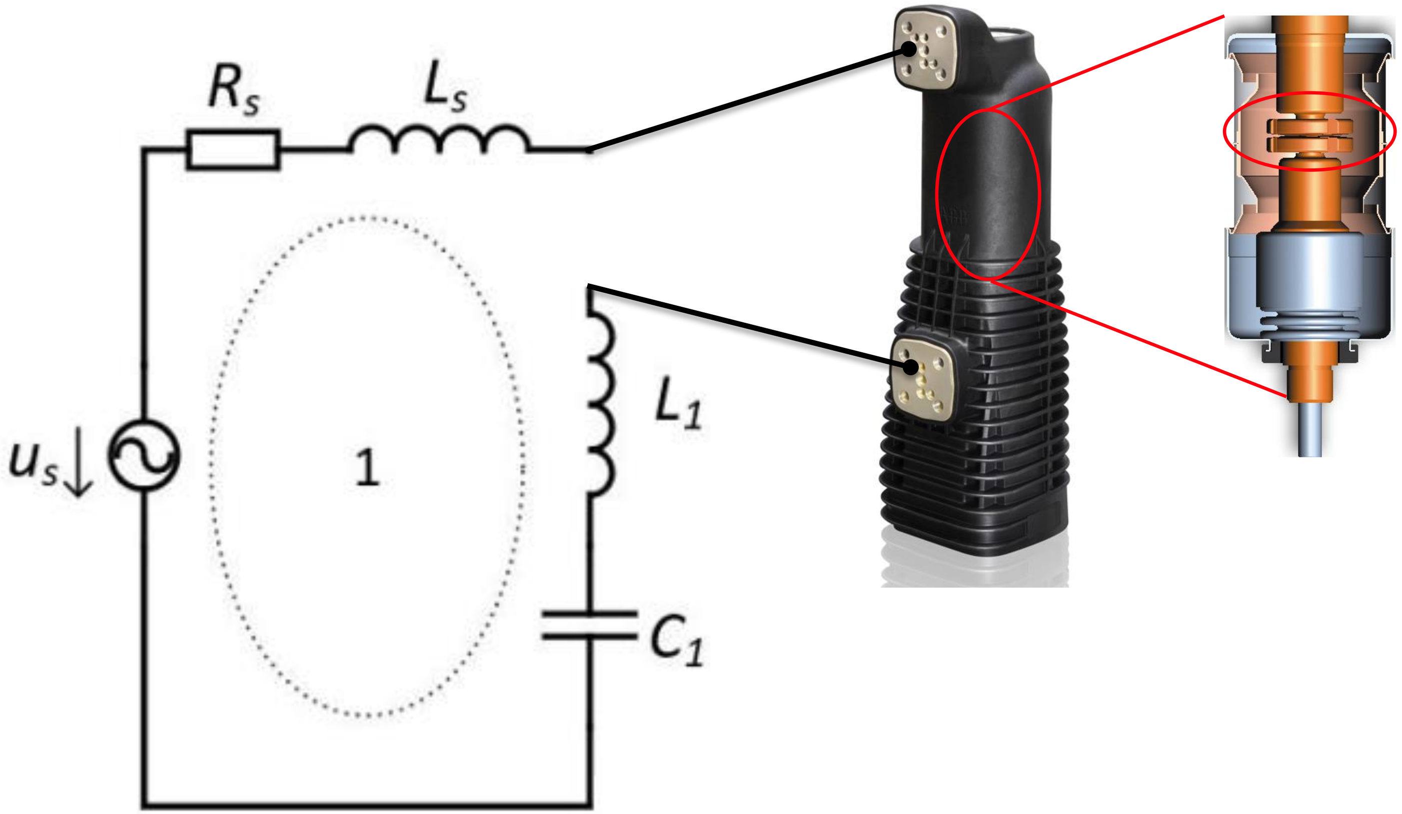
- Capacitive current switching is carried out to disconnect:
    - No load line, cables
    - Overhead lines with currents of about 50A
    - Or with almost daily frequent switching of capacitor banks at interruption currents up to 1000A:
        - Single capacitor bank
        - Back to back capacitor bank switching
- In the new innovative “K–type” technology a way of minimizing the roughness of contact surface and to reduce the extent of the molten volume during the pre-arcing while closing has been figured out.

PERFORMANCE OF IN-SERVICE SHUNT CAPACITOR SWITCHING DEVICES

Capacitive switching single bank



Single bank circuit involving a circuit breaker S1



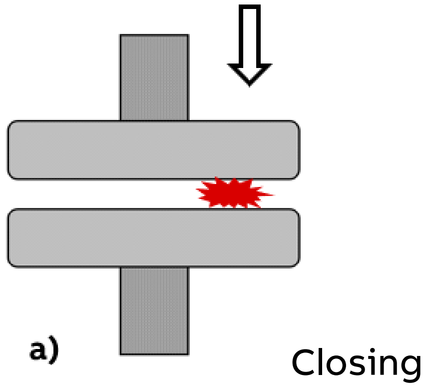
Example: U_{peak} = 12kV x sqrt(2/3) ~ 9.9kV = 1pu

PERFORMANCE OF IN-SERVICE SHUNT CAPACITOR SWITCHING DEVICES

Capacitive switching and phenomena

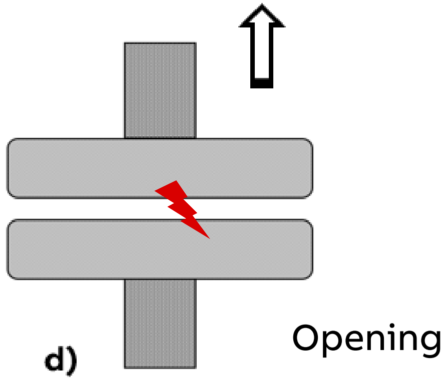
a) <u>Pre-ignition in the vacuum circuit during start-up generates</u>:

- An arc with concentration of the current in the ignition point.
- Melting of the arc base.
- Possible micro welding of the contacts at close.



d) <u>Opening the vacuum interrupter causes</u>:

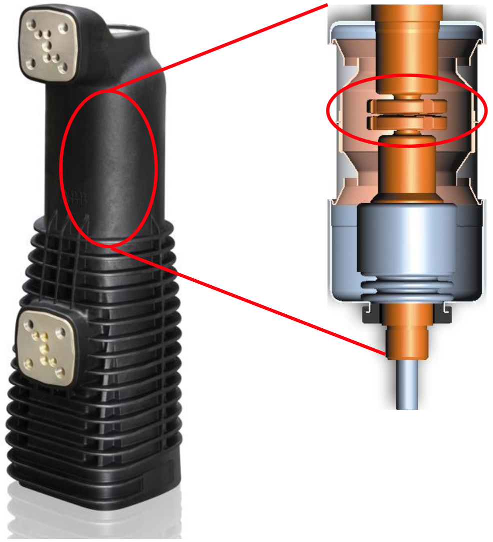
- Separation of contact; Break the micro weld.
- Generation of microtips with high electric field strength.
- Possible re – ignition when the interruption path is “fully” open.

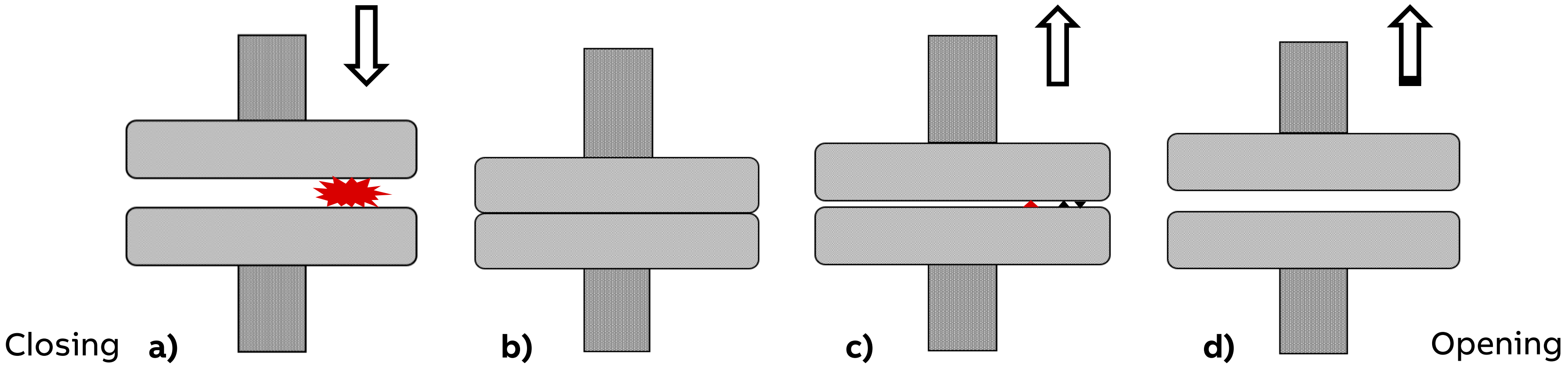


PERFORMANCE OF IN-SERVICE SHUNT CAPACITOR SWITCHING DEVICES

Capacitive switching single bank

Switching sequence a) … d)



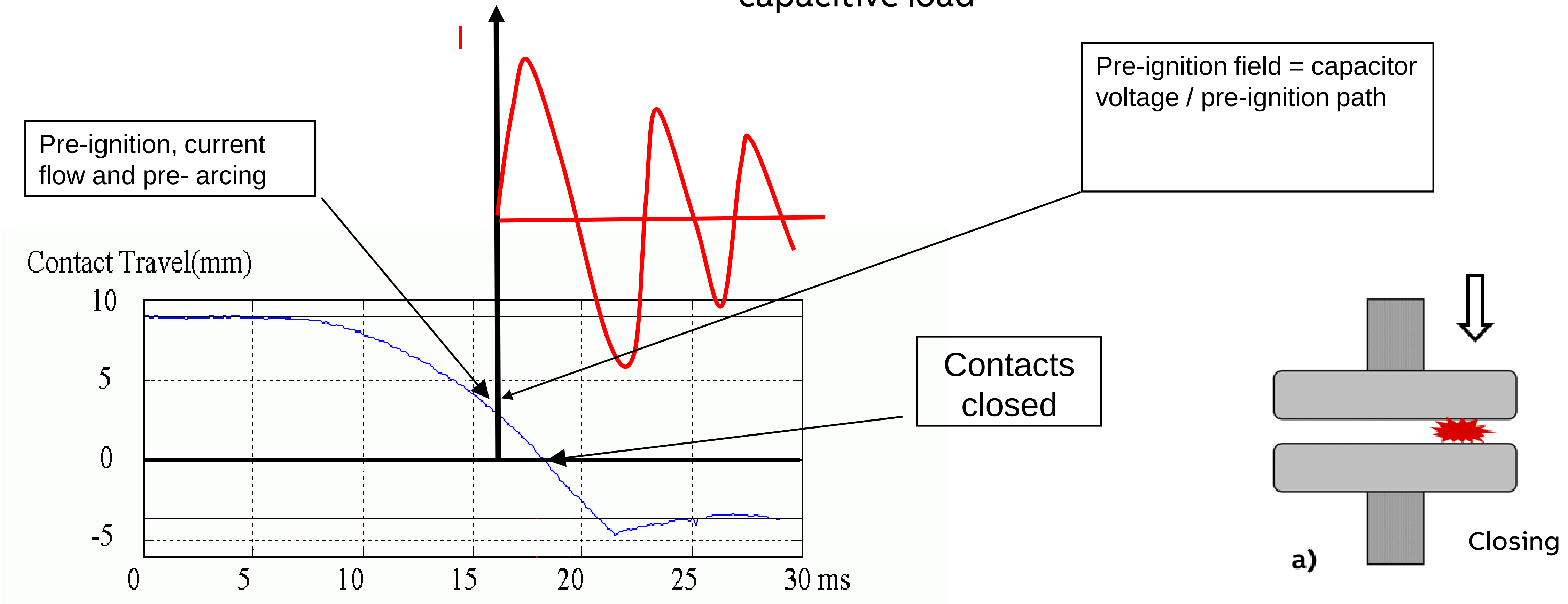


- Contacts approaching each other with pre-strike occurrence just before contact touch.
- Contact touch: After pre-arcing, contact bouncing duration and the “point-welding” under vacuum- and inrush- current condition.
- Contact separation: Break of micro-weld and capacitive current interruption.
- Increase of contact gap distance: Under voltage up to TRV peak.

PERFORMANCE OF IN-SERVICE SHUNT CAPACITOR SWITCHING DEVICES

Capacitive switching and phenomena

- Interruption operation (breaker to close) under capacitive load



PERFORMANCE OF IN-SERVICE SHUNT CAPACITOR SWITCHING DEVICES

Capacitive switching and phenomena (single capacitor bank)

- Inrush current:

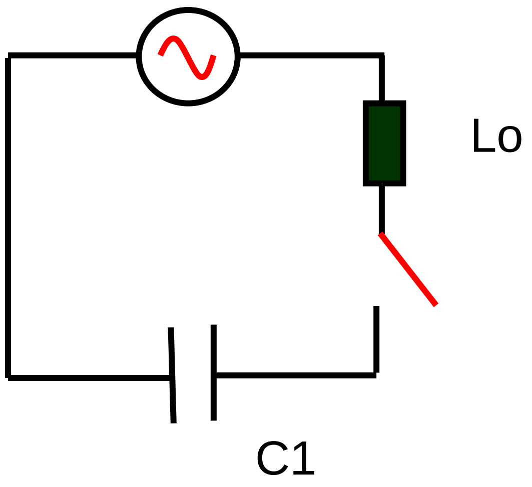
$$I_{inrush} = \sqrt{2} \cdot \sqrt{I_{SC} I_{C1}}$$

- Inrush frequency:

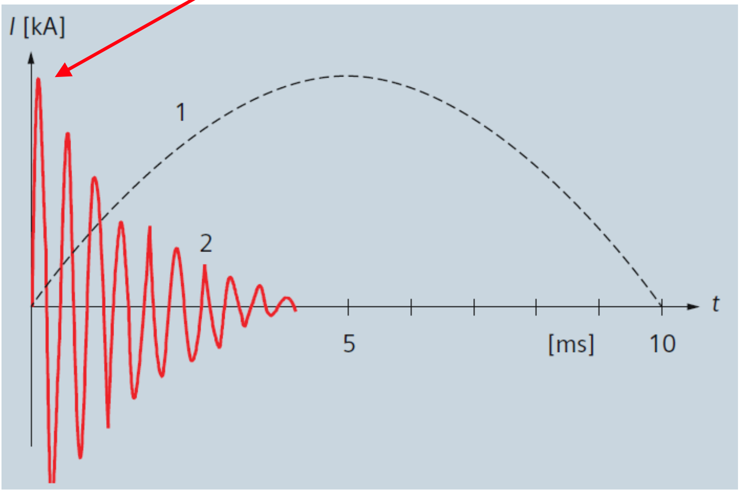
$$f_{inrush} = f_0 \cdot \sqrt{I_{SC}/I_{C1}} = \frac{1}{2\pi \cdot \sqrt{L_0 C_1}}$$

- Inrush current I_{sc}
- Rated capacitive current I_1

- Interruption operation (breaker to close) under capacitive load



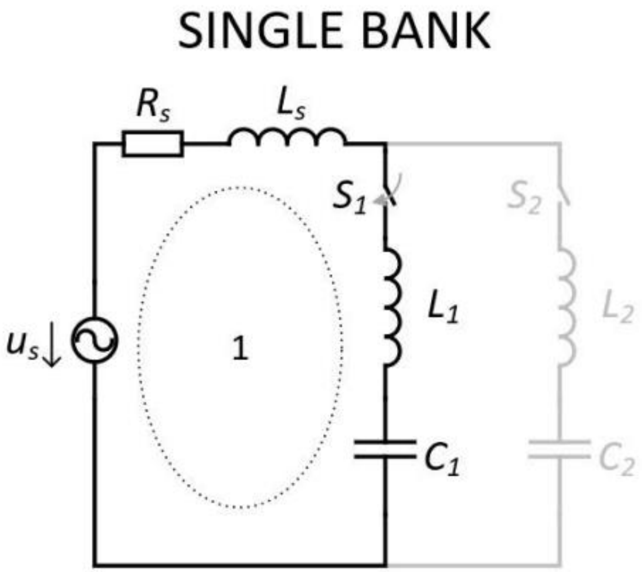
3…5kA / 300 … 450Hz (2)

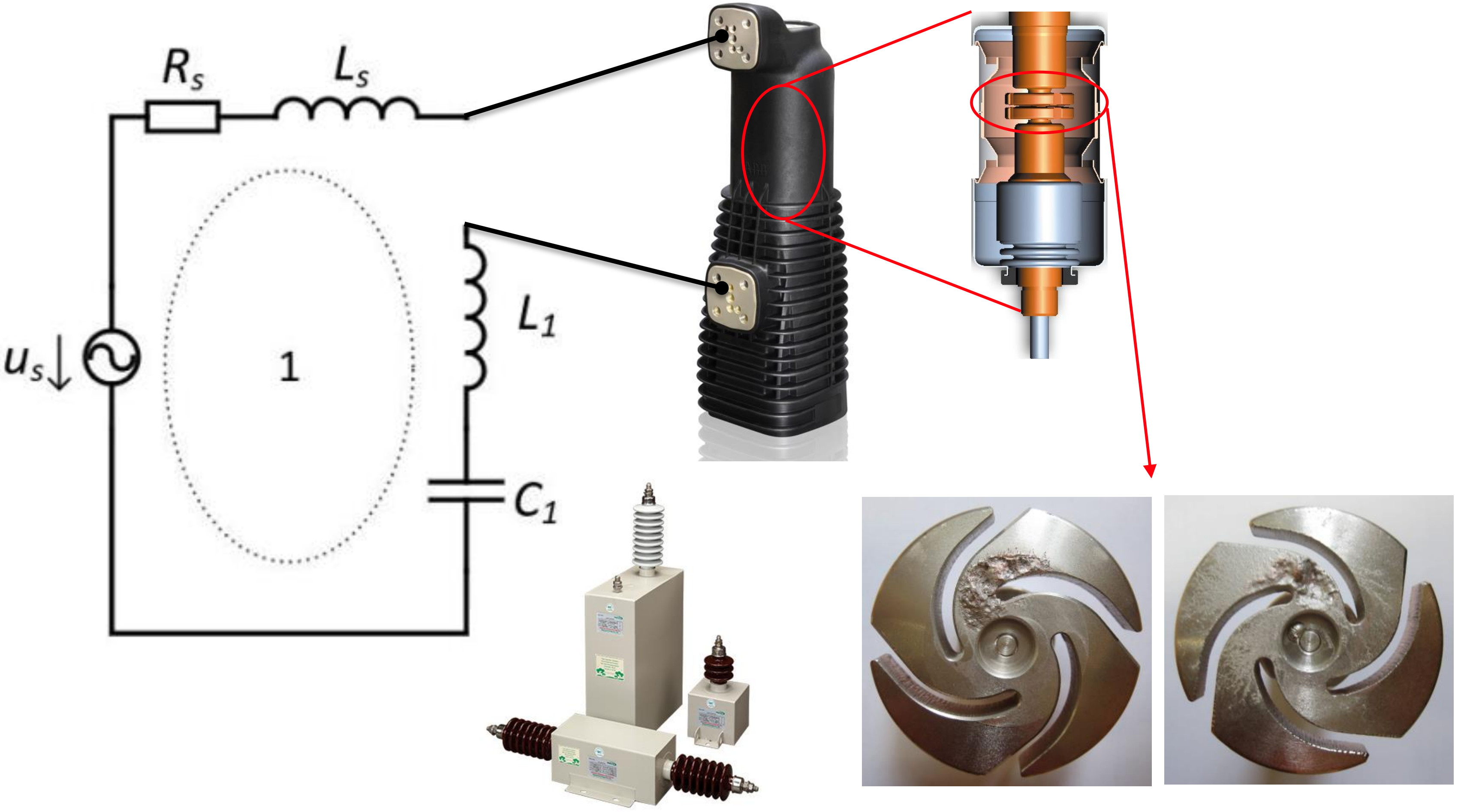


(1) AC current 50Hz

PERFORMANCE OF IN-SERVICE SHUNT CAPACITOR SWITCHING DEVICES

Capacitive switching single bank

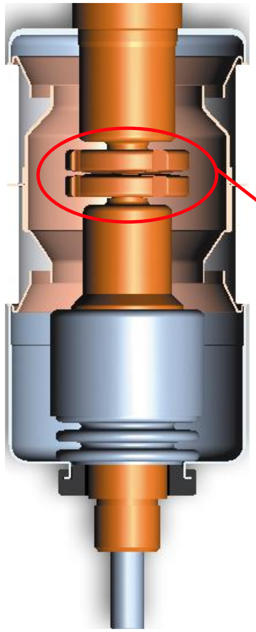


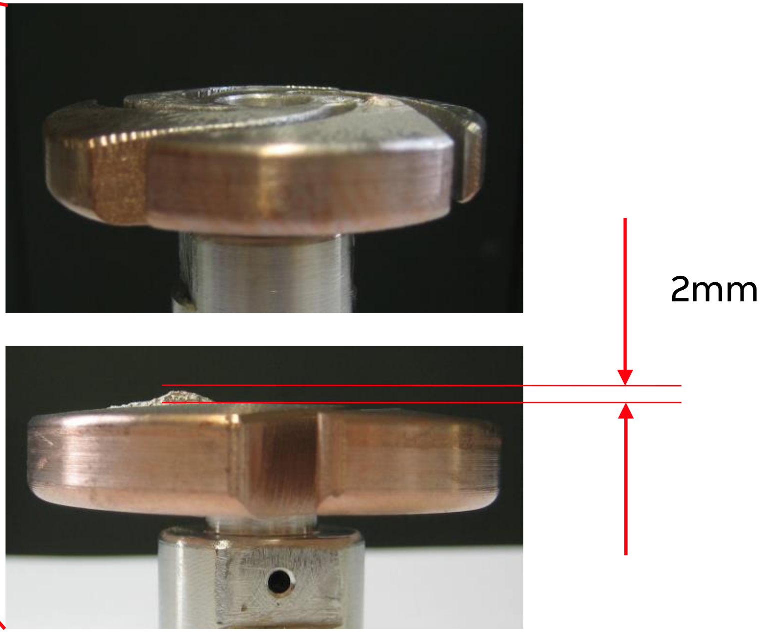


Single bank circuit involving a Circuit Breaker S1

PERFORMANCE OF IN-SERVICE SHUNT CAPACITOR SWITCHING DEVICES

Capacitive switching single bank





Contact material based on Copper – Chromium / CuCr

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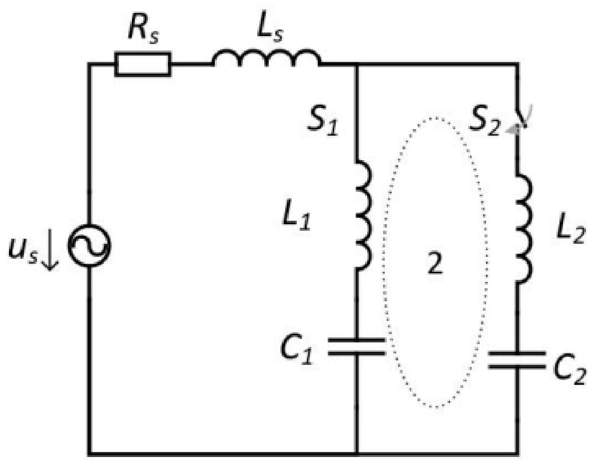
Capacitive switching and phenomena (back-to-back configuration)

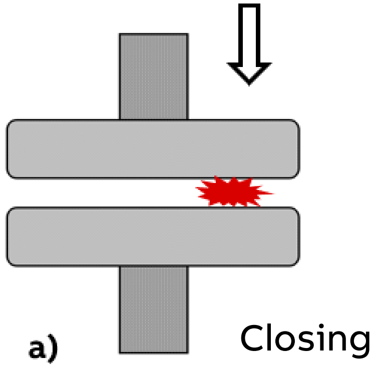
- Interruption operation (breaker to close) under capacitive load

BACK-TO-BACK



- Inrush current:

$$I_{inrush} = \sqrt{2} \cdot \sqrt{\frac{U_0}{f_0}} \cdot \sqrt{\frac{I_1 \cdot I_2}{(L_1 + L_2)(I_1 + I_2)}}$$



- Inrush frequency:

$$f_{inrush} = 4\pi \cdot \sqrt{f_0 U_0} \cdot \sqrt{\frac{(I_1 + I_2)}{(L_1 + L_2) I_1 \cdot I_2}} = \frac{1}{2\pi} \sqrt{\frac{(C_1 + C_2)}{(L_1 + L_2) C_1 \cdot C_2}}$$

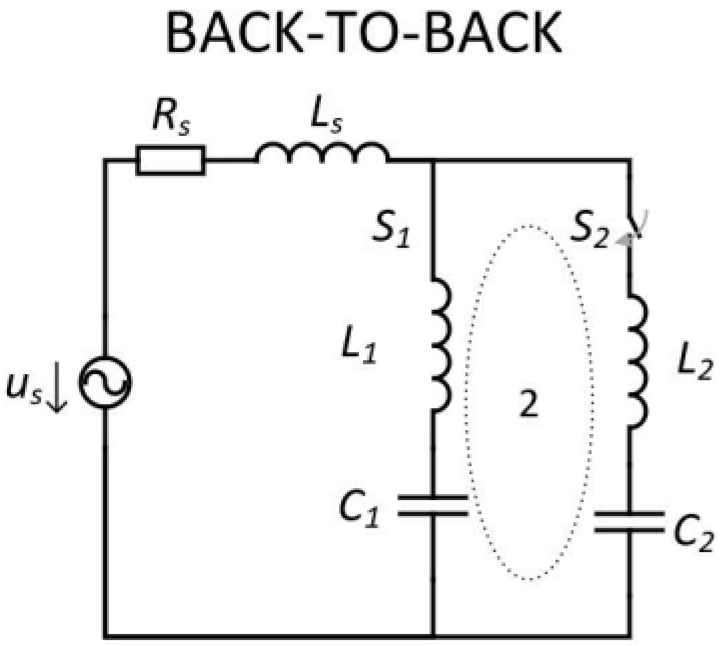
– Damping inductances Li

– Capacitor banks Ci

- Inrush currents go up to 20 kA and the frequencies are between 2000 and 4250 Hz

PERFORMANCE OF IN-SERVICE SHUNT CAPACITOR SWITCHING DEVICES

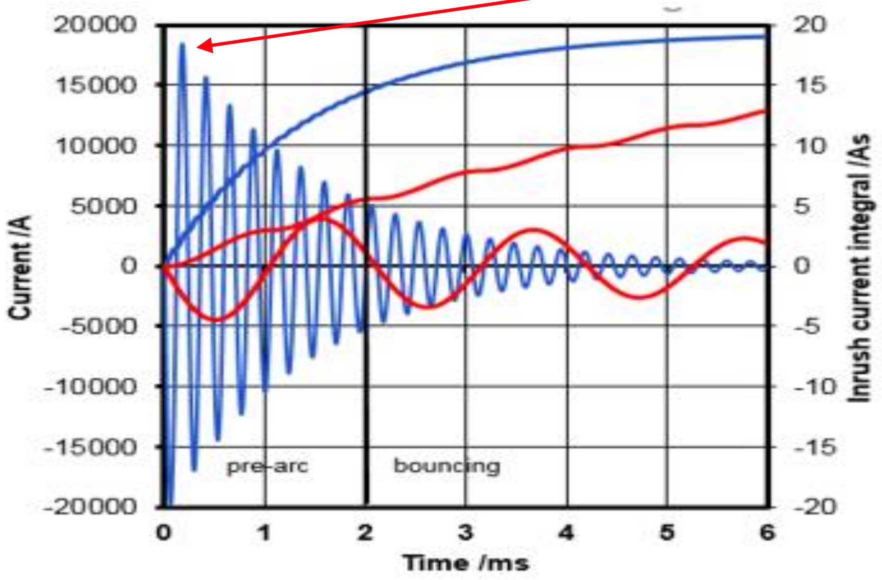
Capacitive switching and phenomena (back-to-back configuration)



B2B condition involving a Circuit Breaker S2

<u>Making operation with inrush current for B2B</u>:

- During the making operation the dielectric breakdown field strength of the approaching contacts just before closing were measured and compared.
- Making tests were performed with an inrush current of **20kA** with a frequency of **4250Hz**.



Calculated inrush current and ICI (inrush current integral) for single bank- ~3..5kA/300…450Hz and back-to-back capacitor banks

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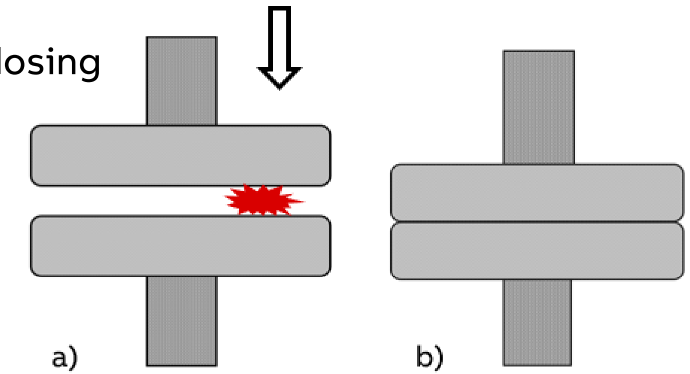

Inrush current

$$\text{energy [J]} = \int_{pre-arc}^{close} U_{arc}\ x\ I_I\ (t)\ dt$$

Pre- arc voltage

- The lower the average value of the field strength **the higher will be the period of pre-ignition time** with large remaining contact gap.
- **The total energy input** is generated by the pre-ignition, contact bouncing and arcing time duration at a given arc voltage Uarc (~ 20V) under the load of inrush current I (t) integral.
- Neglecting the energy emitted by radiation from the vacuum arcs, this total energy is inserted to heat and melt the contact surface. With the calculated **energy and arcing time duration the fused contact surface area can be roughly estimated**.
- The given **pre-arcing energy input and the "point-welding"** under current load at closed contacts will provide information about contact material transfer and the strength of the micro-welding before contact separation.

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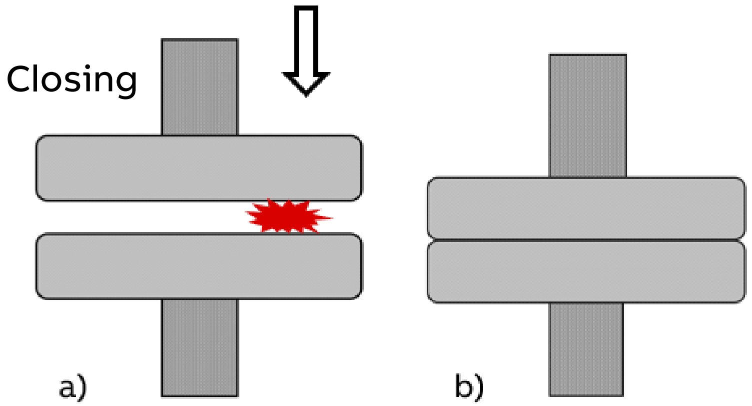
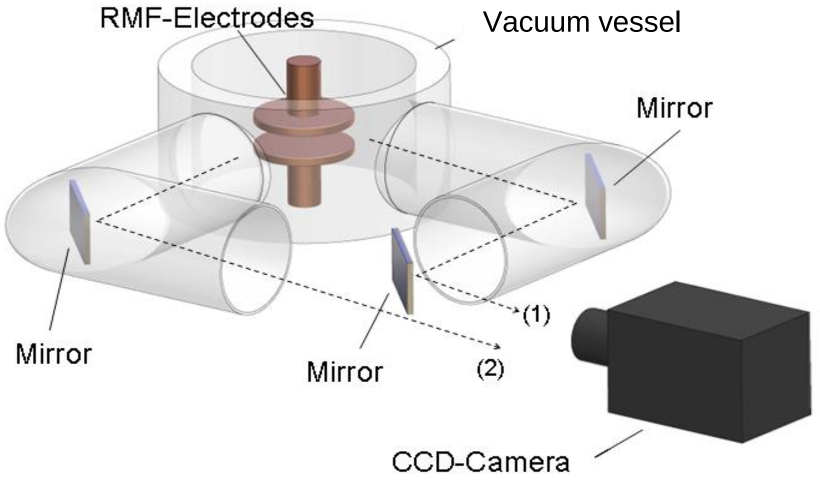
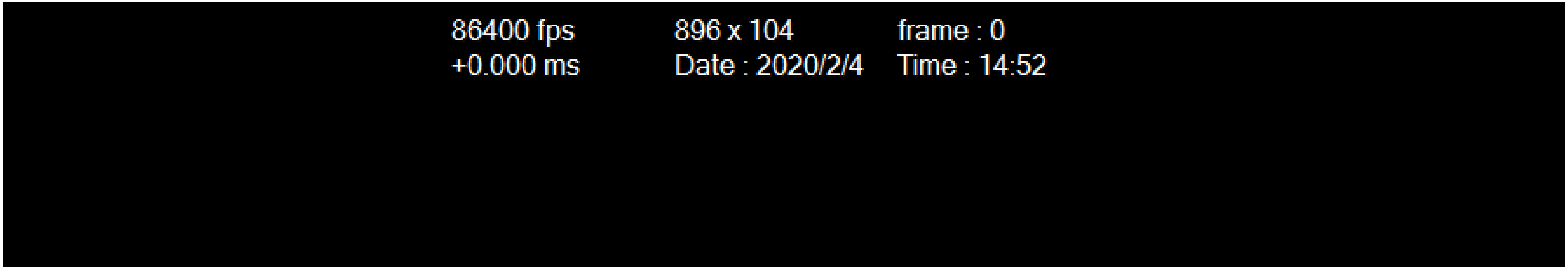
Capacitive switching and phenomena (back-to-back configuration)



<u>Contact closing sequence under the condition 40.5kV / 20kA</u>:

- **Pre-ignition of arc 2.5ms** before contact touch at vacuum test set-up with transparent window.
- The VCB´s VI gap was kept at 17mm in “static” open position, the closing speed was about 1.1m/s.





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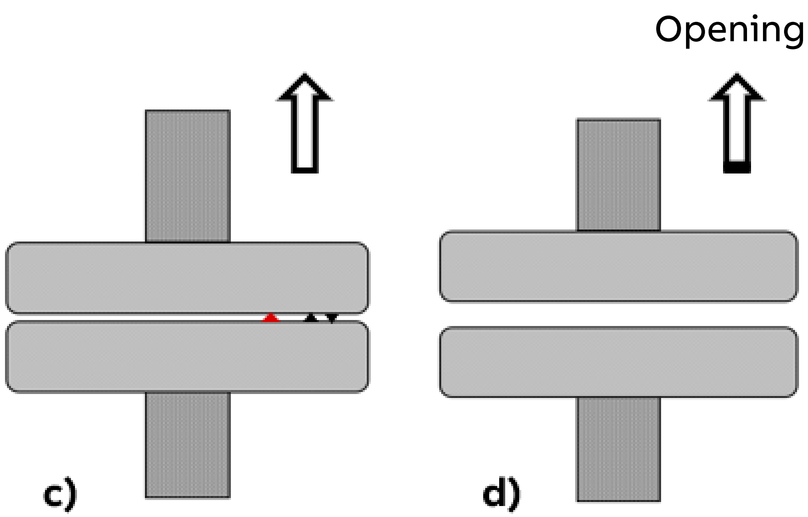

Opening operation with transient recovery voltage sequence according to IEC 62271-100:

- Opening operations @ 40,5kV rated voltage were performed with a capacitive switching current of 400A as stipulated in the standard with a transient recovery voltage (TRV) with a peak of 81kV following (1-cos ωt) function.

The capacitive current switching test consists of the following test cycles:

- **80 close – open (CO)** interruption operations (BC2)
- **24 open** (O) operations (BC1)

- **For Class C1** “Low” probability of re-strike; 1 re-strike is allowed in 104 operations.
- **For Class C2** “Very low” probability of re-strike, no re-strike is allowed in 104 operations and entire type-test sequence.

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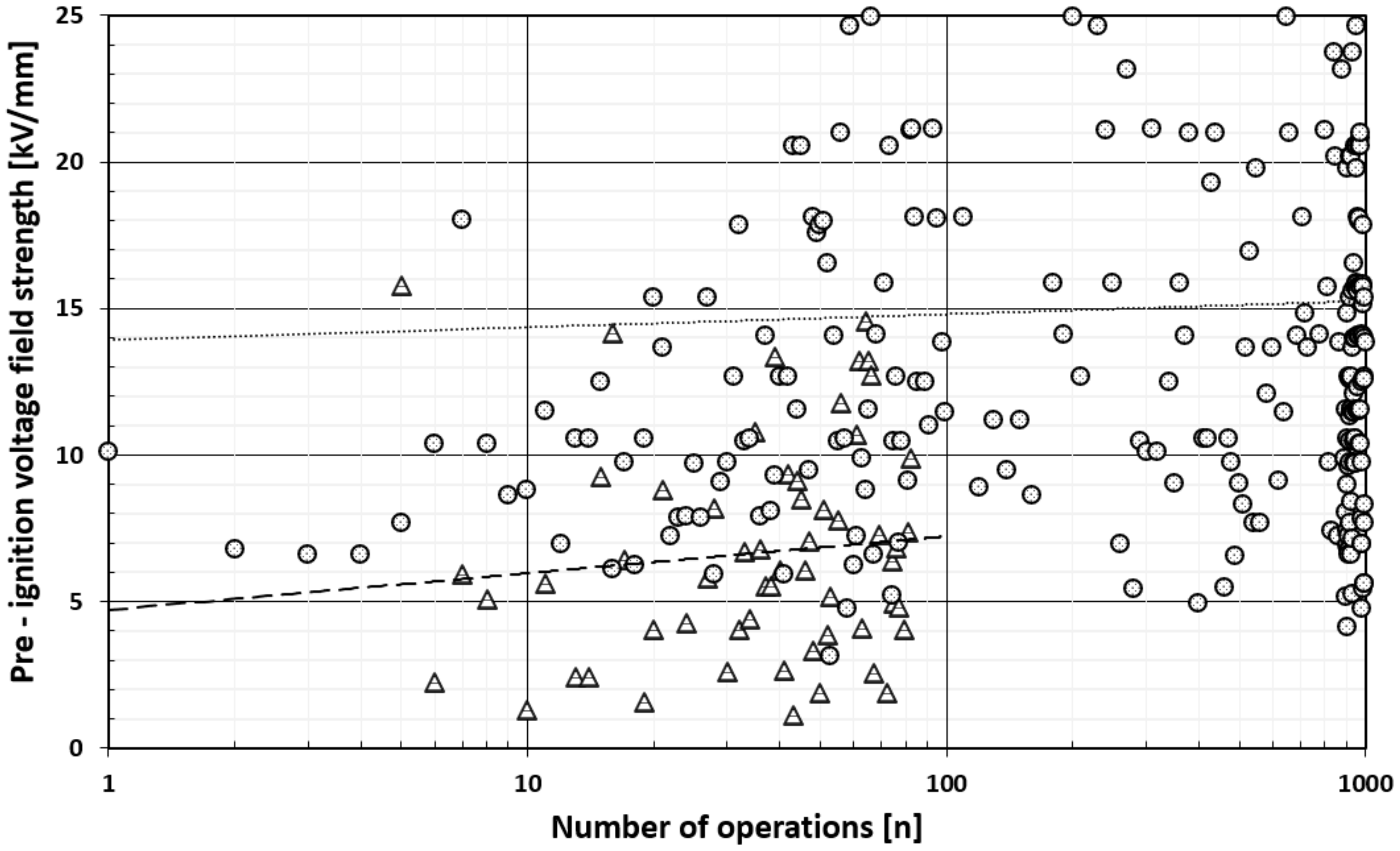
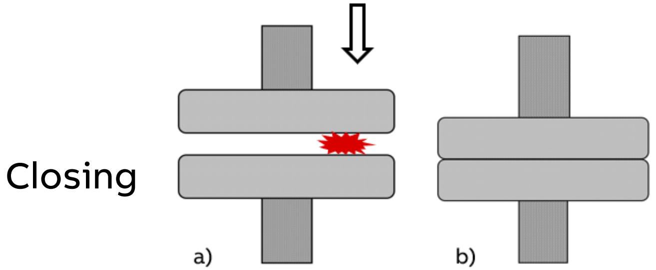


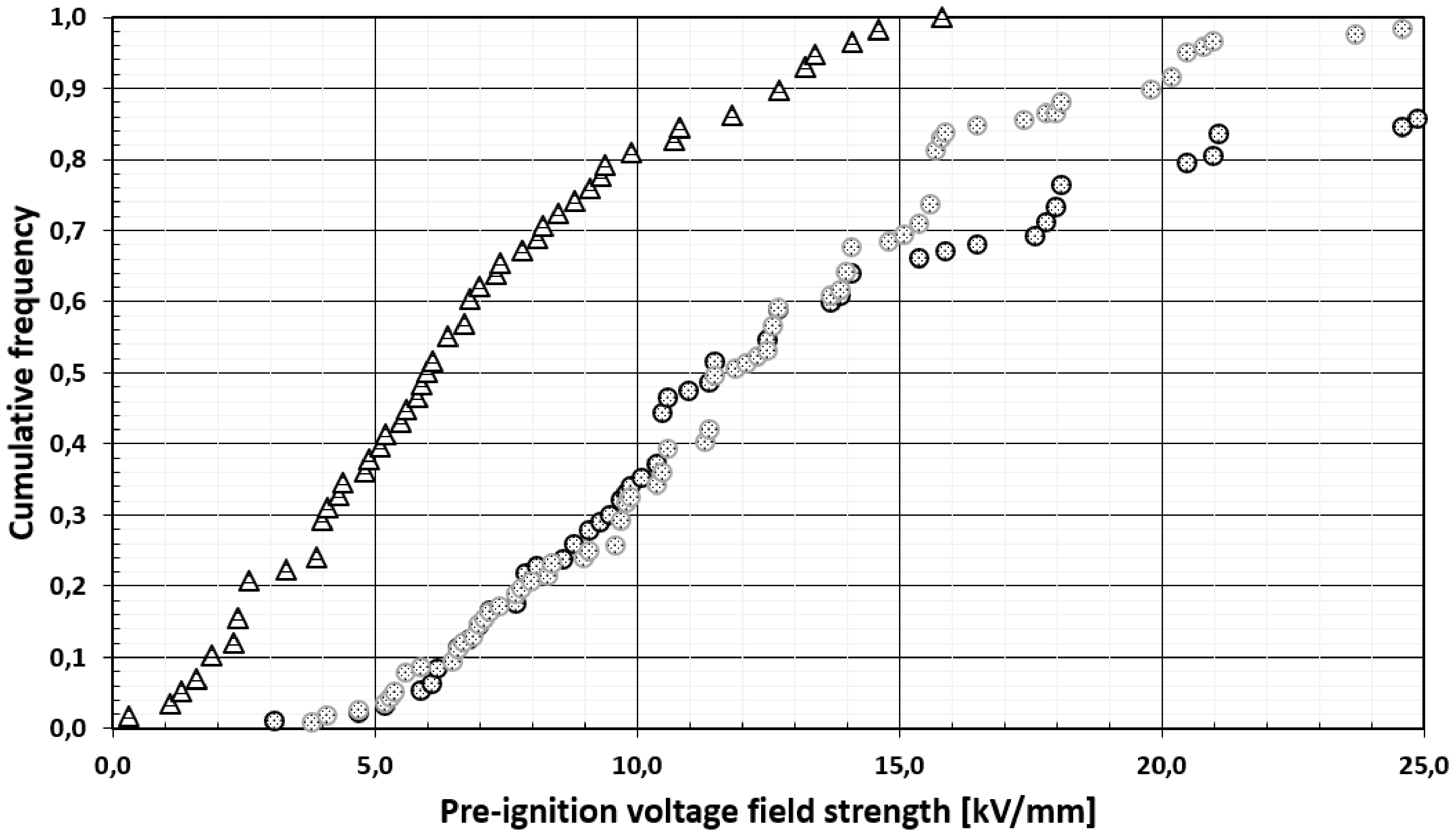


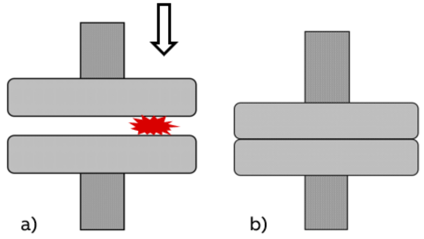
Abscissa logarithmic view: at closing operation under rated voltage of 40.5kV measured pre-ignition breakdown field strength while contacts are approaching each other:

- VG8 with ▲ up to n=100 (trend ---) and extended number VG8–K.
- Dot • shape up to n=1000 (trend ···).
- The average value for VG8 is 6.5 kV/mm and for VG8–K type it is 12.0 kV/mm.

PERFORMANCE OF IN-SERVICE SHUNT CAPACITOR SWITCHING DEVICES

Capacitive switching and phenomena (back-to-back configuration)





The cumulative probability of pre-ignition voltage field strength versus field strength in linear scale:

- VG8 with ▲ up to n=100
- Extended number VG8–K with ● dot shape up to n=100, with ● up to n=1000.

→ Using standard technology, the average pre-ignition probability is lower, than using “K–type” technology.

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    - Comparison with a ”C3” testing within the study up to 1000 +
- **Discussion/Summary**

PERFORMANCE OF IN-SERVICE SHUNT CAPACITOR SWITCHING DEVICES

Capacitive switching and phenomena (back-to-back configuration)

Based on the average arcing time:

- At 60Hz frequency the time between two current zero crossings in a three-phase system amounts to 2.7ms, assuming an equal distribution of the arcing times the quotient 2.7ms divided by the measured average arcing time leads to the equivalent number of operations for that particular phase taking into account a time window between 0ms and 2.7ms.
- Calculation: (2.7ms / 0.6ms (average arcing time at open)) x 1000 operations = 4.500 “equivalent” operations in one phase under the assumption of an equal distribution of the arcing time in that phase as minimum value.
- For the complete breaker with three phases this results in a total number three times of 4.500 operations = 13.500 “equivalent” operations!
- More than 10.000 operations in line with the extended mechanical endurance class M2.

PERFORMANCE OF IN-SERVICE SHUNT CAPACITOR SWITCHING DEVICES

Discussion

There are two reasons for the material transfer:

1) **Erupted metal particles** from the molten surface areas and
2) **Rupture of the welded areas** during opening operation.

- That was the reason to test the new “K–type” VI for extended capacitive current switching test up to 1000 switching operations to load the VI similar to the loading in actual service life.

  Remarkable: No re-strike observed during the entire 1000 switching operations.

- In addition to Class C1 and C2 for capacitive current switching, our proposal is to add Class C3 in IEC standard which qualifies the breaker for extended capacitive current switching for 1000 switching operations without any restrike.

PERFORMANCE OF IN-SERVICE SHUNT CAPACITOR SWITCHING DEVICES

Summary

- The new “K–type” technology for vacuum interrupter has been tested up to 1000 switching operation instead of 104 operation stipulated in the standard to qualify the VI´s as class C2 for capacitive switching, without any re-strike.

<u>There are some aspects which improves the VI “K–type” capacitive switching performance by keeping all other properties intact</u>:

- **Less erosion** occurs at the contact surfaces **under pre-arcing** and at making operations.
- **Mechanical properties** of the contact **improve in many aspects by the formation of a brittle net** inside the molten material which reduces the risk of re-ignition.
- **Better physical properties** of the contact material even up to the **melting point causes reduced micro-welding** at the contact surfaces with results in a smooth fracture surface and less separation force while opening.
- Furthermore, an **arc erosion resistance improvement is noticed even up to an enormous number of rated current interruption** operation.
- **All other important VI properties** including the dielectric performance with corresponding shielding concept, the short circuit current interruption capability as well as the overall dimension **are identical to the standard VI technol**ogy.

The **capacitive current switching duty for reactive power compensation** in industrial or utility MV networks is characterized by frequent, **day to day or even hour by hour, making of high frequency and high amplitude inrush currents**, interrupting of low to moderate currents and by a low rate of rise of, but high value, recovery voltage. The superior performance of breaker equipped with VI “K–type” for capacitive current switching has been demonstrated by the tests conducted. The tests were planned in a way to represent the actual number of switching in real service condition.

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