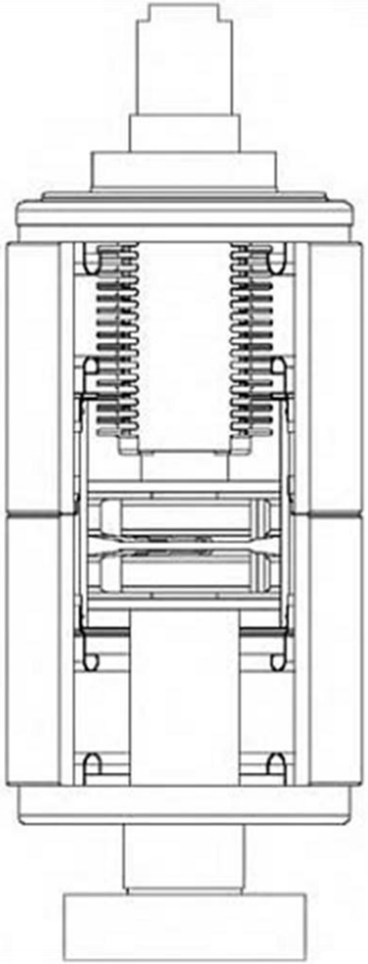


Paul G. Slade

CRC Press
Taylor & Francis Group
Boca Raton London New York

THE VACUUM INTERRUPTER

Theory, Design, and Application

THE GENERAL ASPECTS OF CURRENT INTERRUPTION

主讲人：刘志远
西安交通大学电气工程学院

西安交通大學
XI'AN JIAOTONG UNIVERSITY

OUTLINE

1. INTERRUPTION OF AC CIRCUIT
2. THE INDUCTIVE CURRENT INTERRUPTION
3. Interruption of Capacitive Circuits
4. CONTACT WELDING

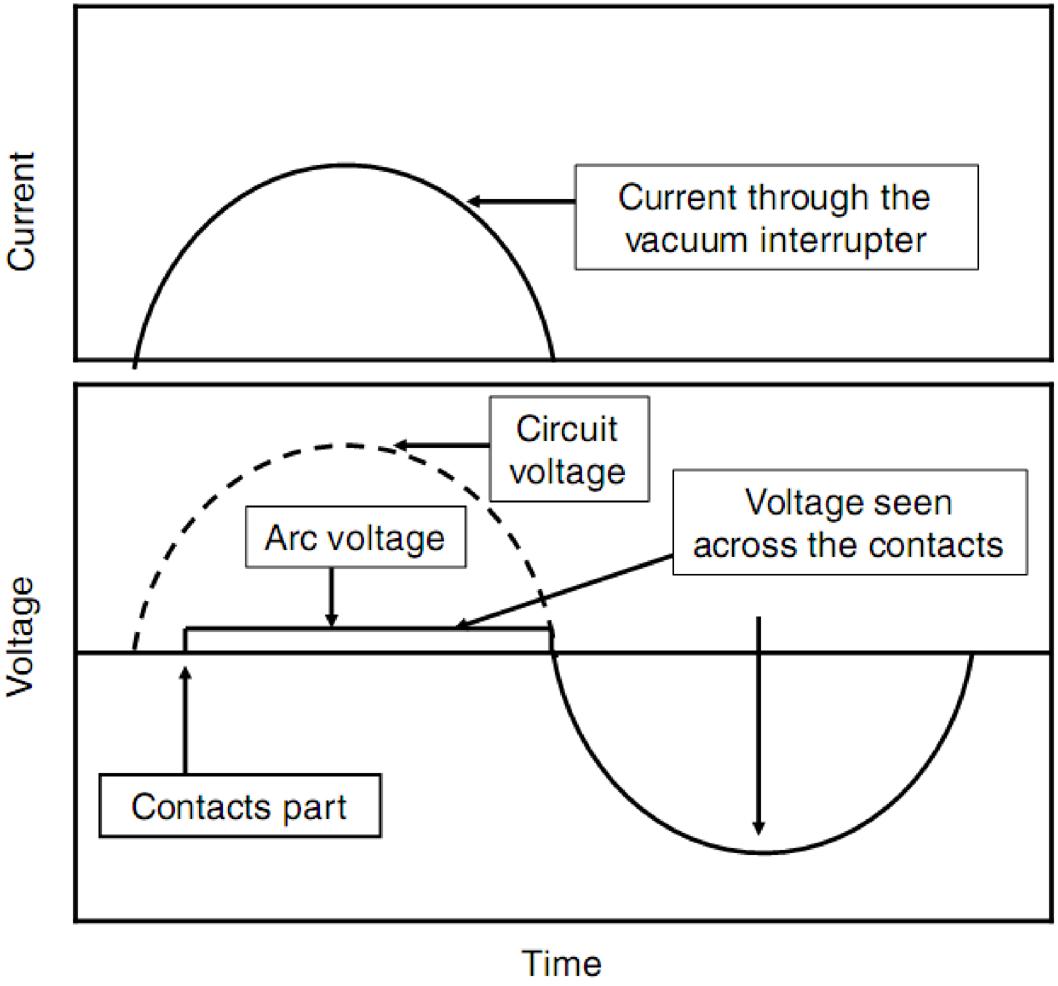
INTRODUCTION

THE CURRENT INTERRUPTION PROCESS

When a vacuum interrupter is called upon to open in an ac circuit, its contacts first part at a random point on the ac current wave

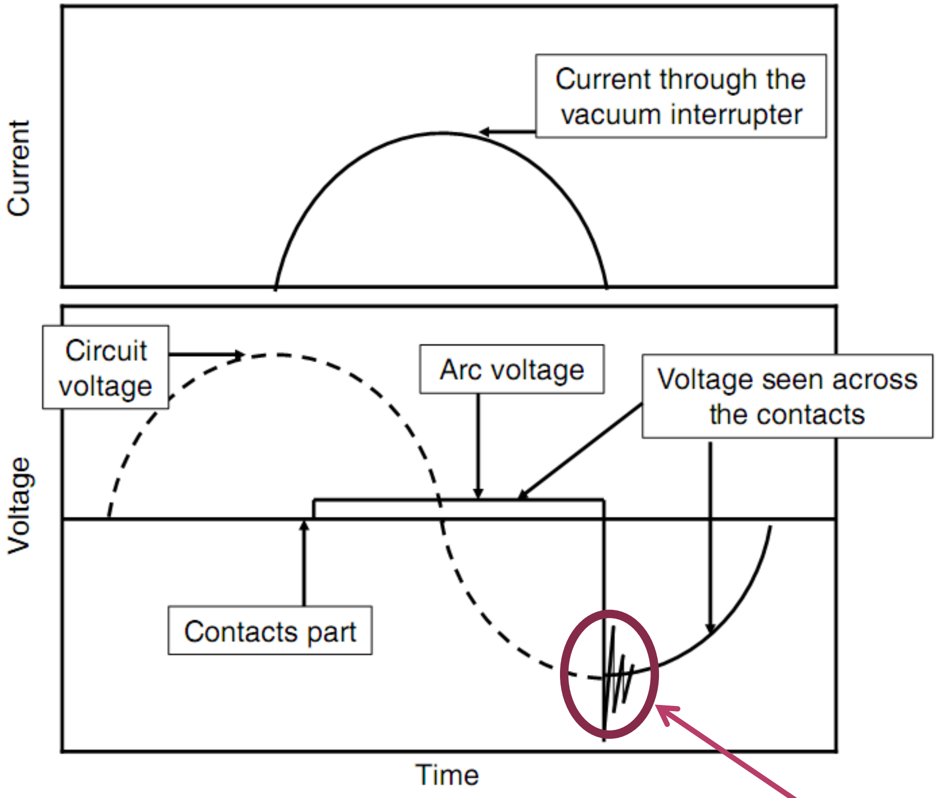
Once the contacts have parted and the vacuum arc has formed, the arc will continue to the natural current zero of the ac current.

At current zero, there is a very brief time when the contact gap changes from a relatively good conductor to a good insulator.



the TRV across the open vacuum Interrupter contacts after the interruption of ac current in a resistive circuit

CURRENT INTERRUPTION OF INDUCTIVE CIRCUIT



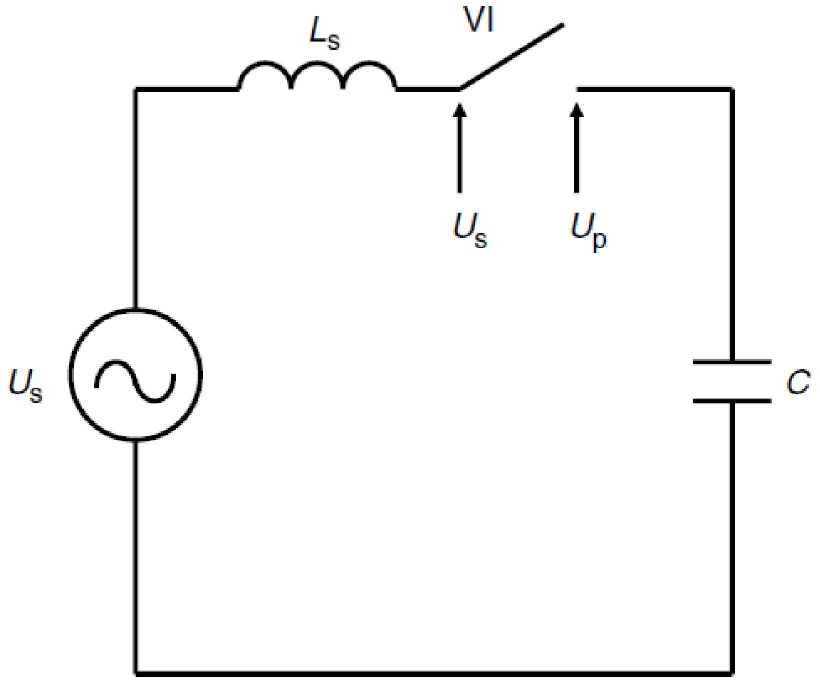
Schematic diagrams to show the TRV across the open vacuum interrupter contacts after the interruption of ac current in an inductive circuit.

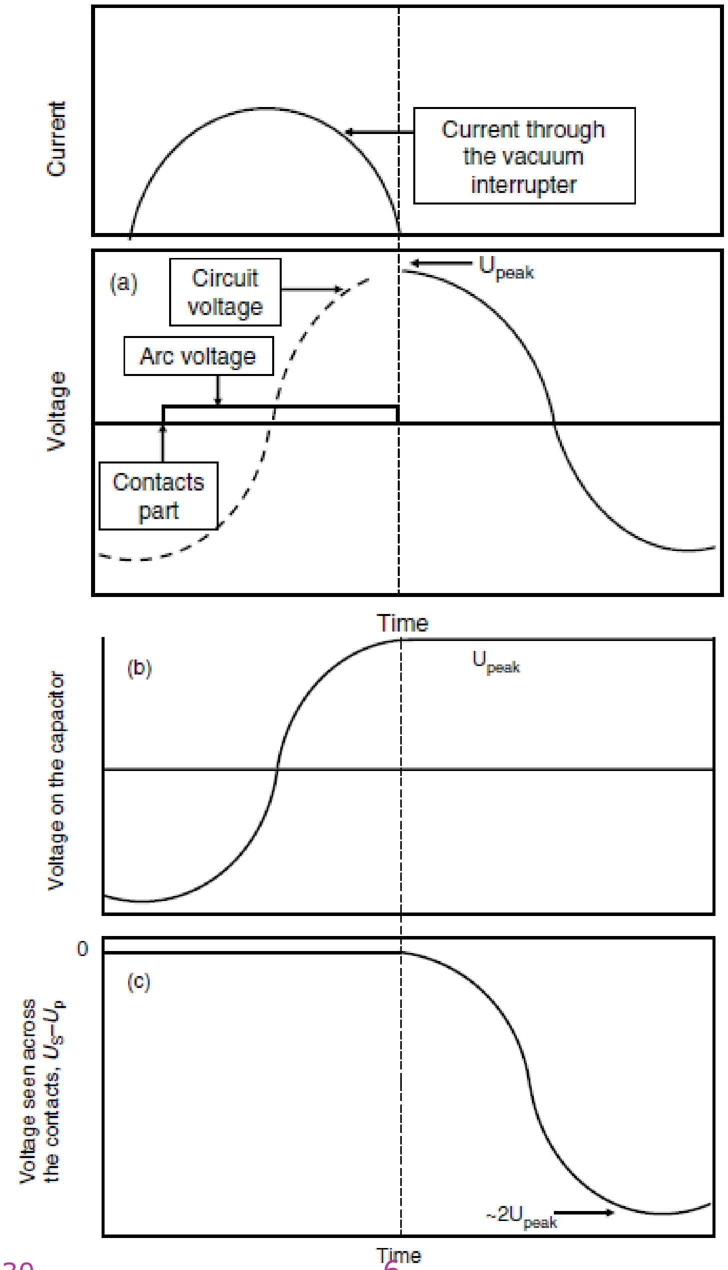
When the contacts open, the vacuum arc forms with an arc voltage, which continues to the natural ac current zero.

At current zero, when the arc extinguishes, the circuit voltage will be close to its peak value.

The shape of the recovery voltage that now appears across the open contacts is complicated by the small capacitance in all inductive circuit

CURRENT INTERRUPTION OF CAPACITIVE CIRCUIT





Schematic diagrams to show the TRV across the open vacuum interrupter contacts after the interruption of ac current in the capacitive circuit.

Vacuum Interrupter Theory Design and Application 2013-08-30

THE DEFINITION OF THE TRV

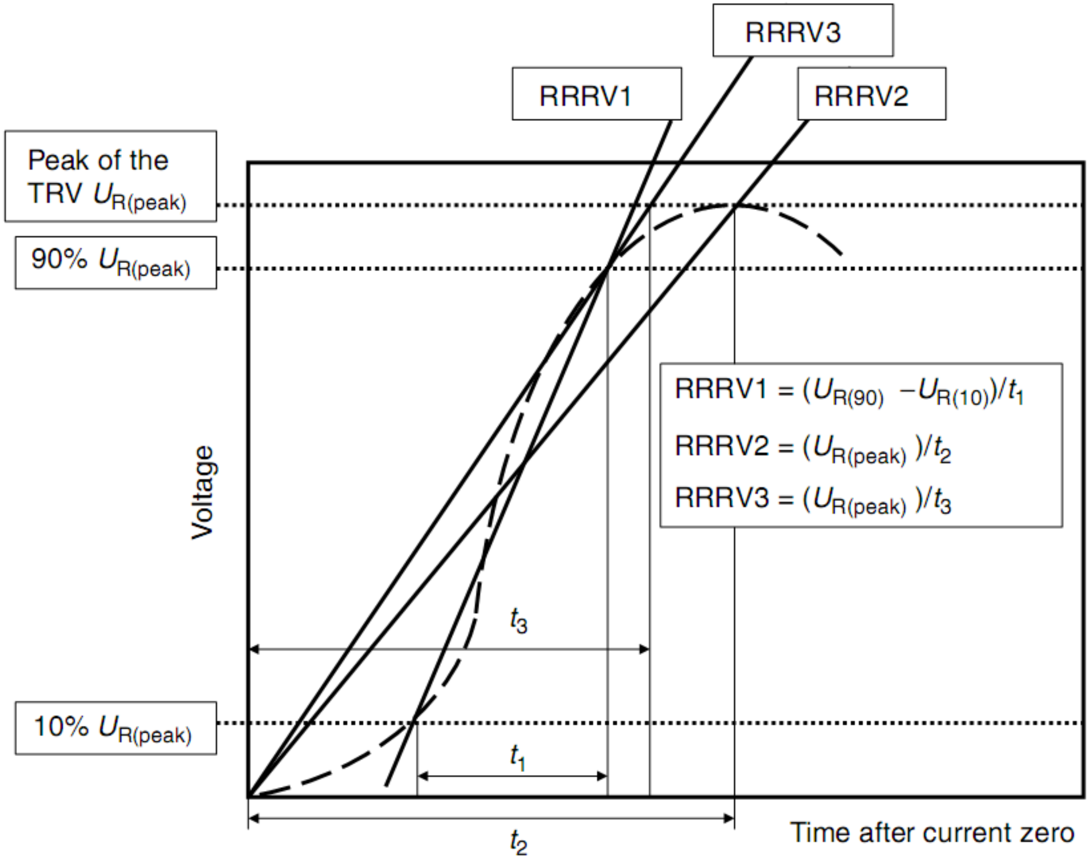
Any discussion of the changes in the contact gap after current zero should include the effects of a rapidly rising voltage pulse.

Unfortunately, the definition of the value of RRRV varies with each researcher.

For a vacuum interrupter designer, each way can be used without a problem.

TRV -the transient recovery voltage

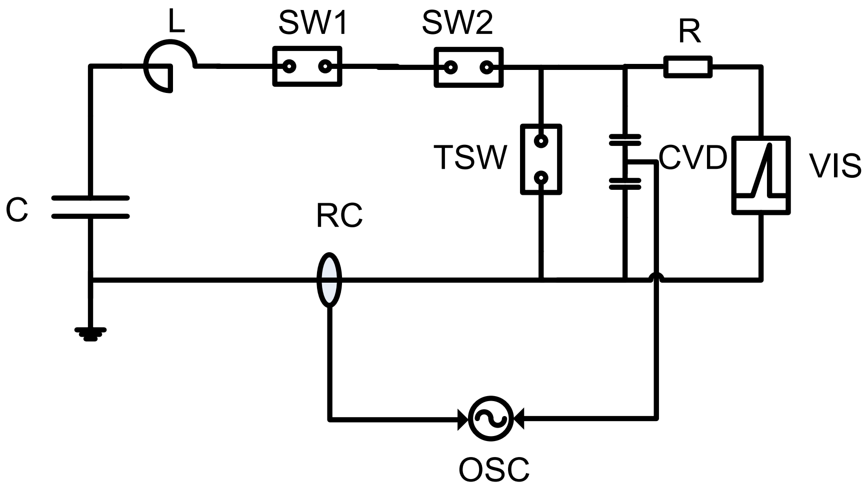
RRRV-the rate of rise of recovery voltage



The TRV showing three ways of measuring the RRRV.

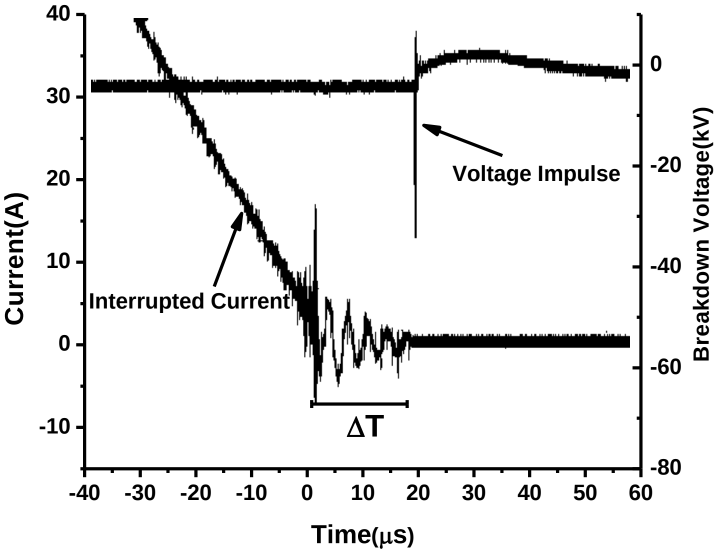
INTERRUPTION OF DIFFUSE VACUUM ARC FOR AC CURRENTS BELOW 2KA (RMS)

"FREE RECOVERY" METHOD TO INVESTIGATE THE DIELECTRIC RECOVERY BEHAVIORS



Sketch of experimental circuit.

C: Capacitor banks;
L: Reactors; SW1: Main switch;
SW2: Auxiliary switch;
TSW: Test switch; R: Resistor;
CVD: Capacitive voltage divider;
VIS: Voltage impulse source;
RC: Rogowski coil; OSC: Oscilloscope.



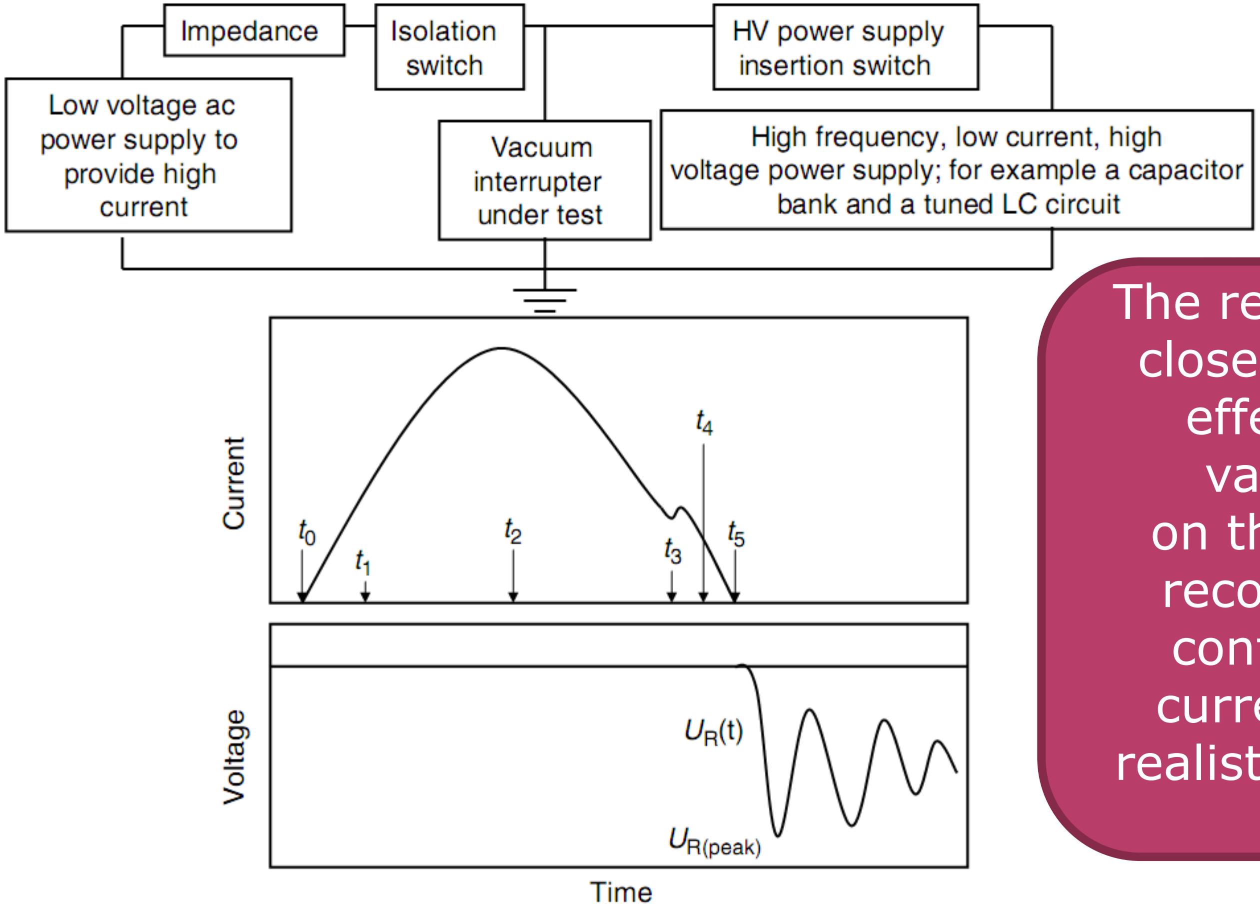
Waveforms around current zero point.

A vacuum arc is established.

The current is interrupted.

At a given delay following the arc extinction, a step function voltage pulse is applied.

THE WEIL–DOBKE SYNTHETIC CIRCUIT TO INVESTIGATE THE DIELECTRIC RECOVERY BEHAVIORS



Impedance

Isolation switch

HV power supply insertion switch

Low voltage ac power supply to provide high current

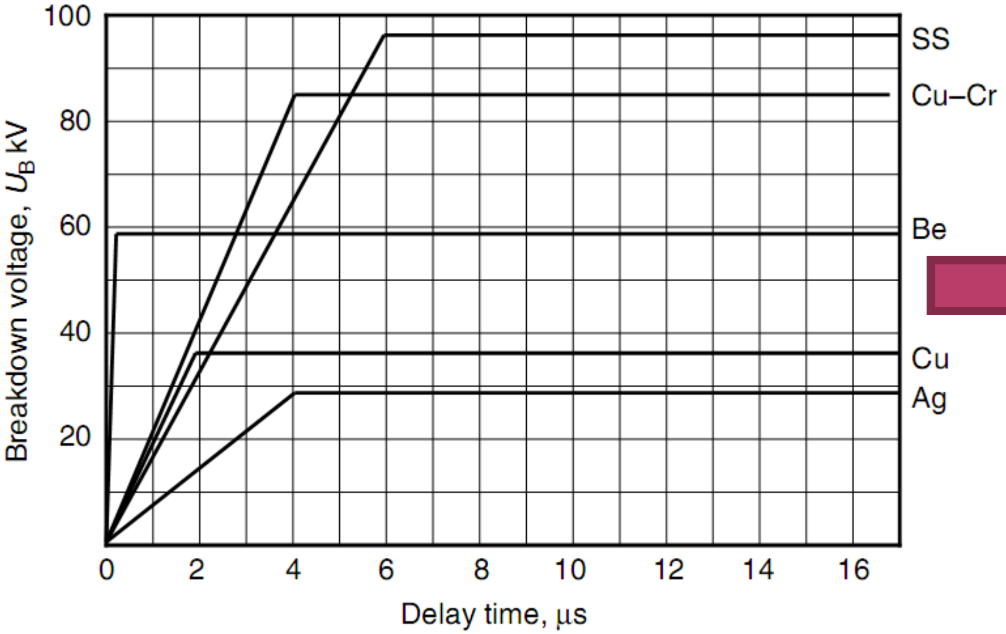
Vacuum interrupter under test

High frequency, low current, high voltage power supply; for example a capacitor bank and a tuned LC circuit

The Weil–Dobke synthetic circuit for evaluating the interruption performance of a vacuum interrupter

The researcher can closely relate the effects of the vacuum arc on the dielectric recovery of the contact gap at current zero for realistically shaped TRVs

THE EXPERIMENTAL RESULTS USING FREE RECOVERY METHOD



The recovery rate does depend on the contact material.

The contact gap recovers to its full strength very rapidly.

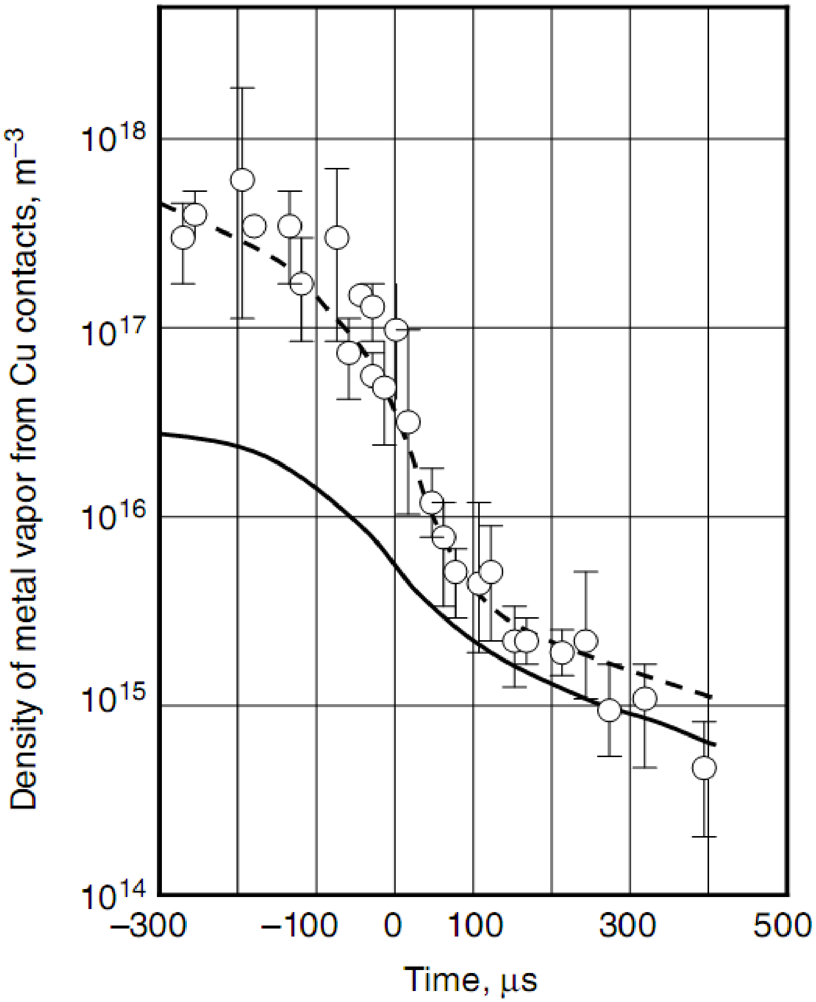
The free recovery of the vacuum contact gap after a current of about 200 A has been ramped to zero in <2 μs for a diffuse vacuum arc

THE METAL VAPOR DENSITY AFTER INTERRUPTING A SMALL CURRENT

The Cu is about 10^{17} atoms m^{-3} at current zero

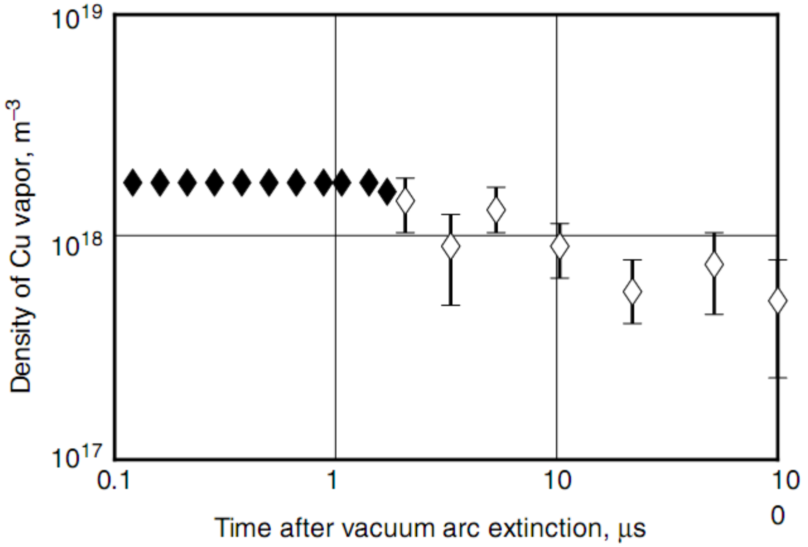
a pressure of less than about 10^{-2} Pa at the surface temperature of 2150 K

any breakdown of the gap has to be considered a "vacuum breakdown"

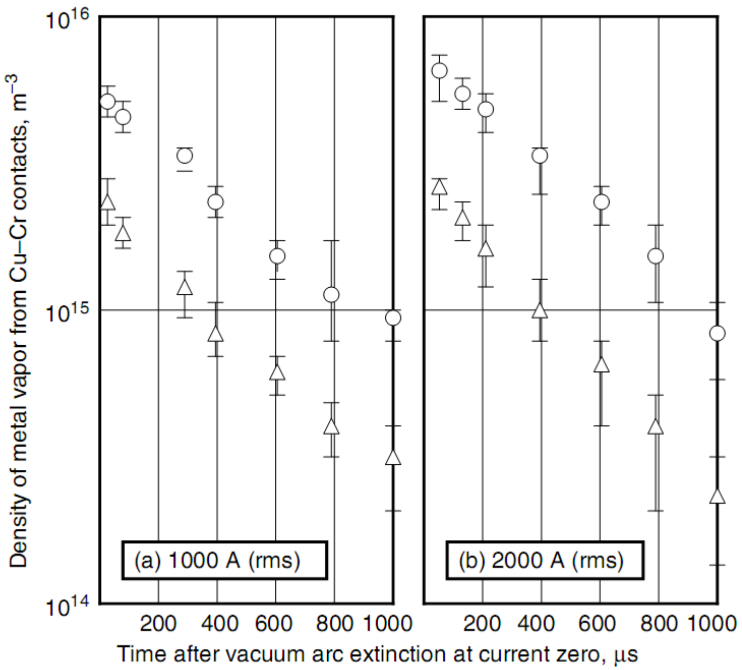


The Cu vapor density for a 50 Hz, 500 A (rms) diffuse vacuum arc at the center of a 14-mm contact gap before and after current zero

THE FURTHER INVESTIGATION OF THE METAL VAPOR DENSITY



The Cu vapor density in a 2-mm contact gap after the current for a 200A vacuum arc is ramped to zero in <2 µs

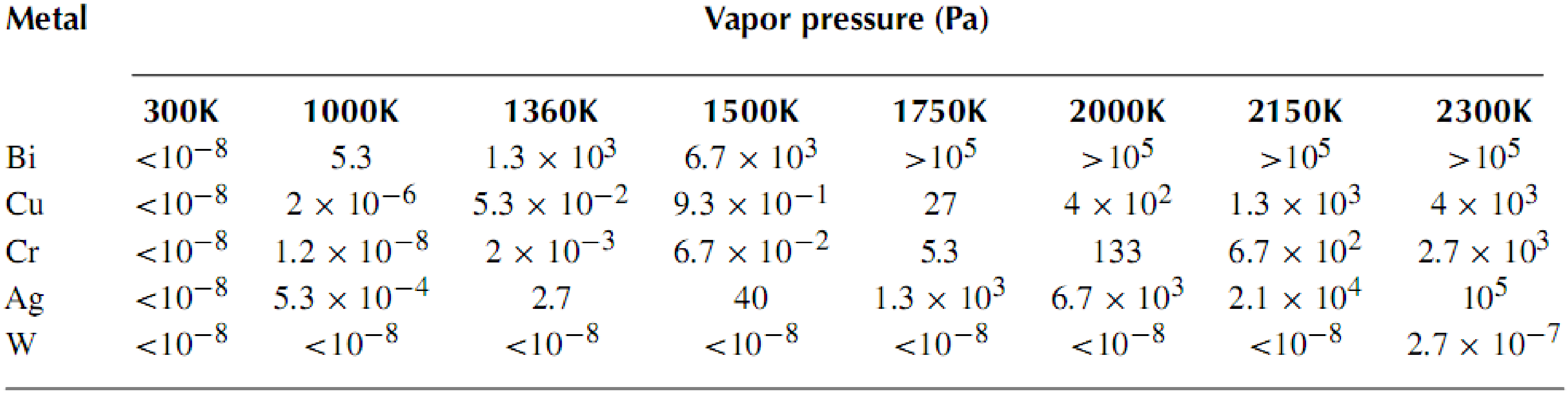


The vapor density of Cu and Cr from Cu−Cr contacts after current zero interrupting 50 Hz, ac currents of 1000 A (rms) and 2000 A (rms) : [○] Cu data, [△] Cr data

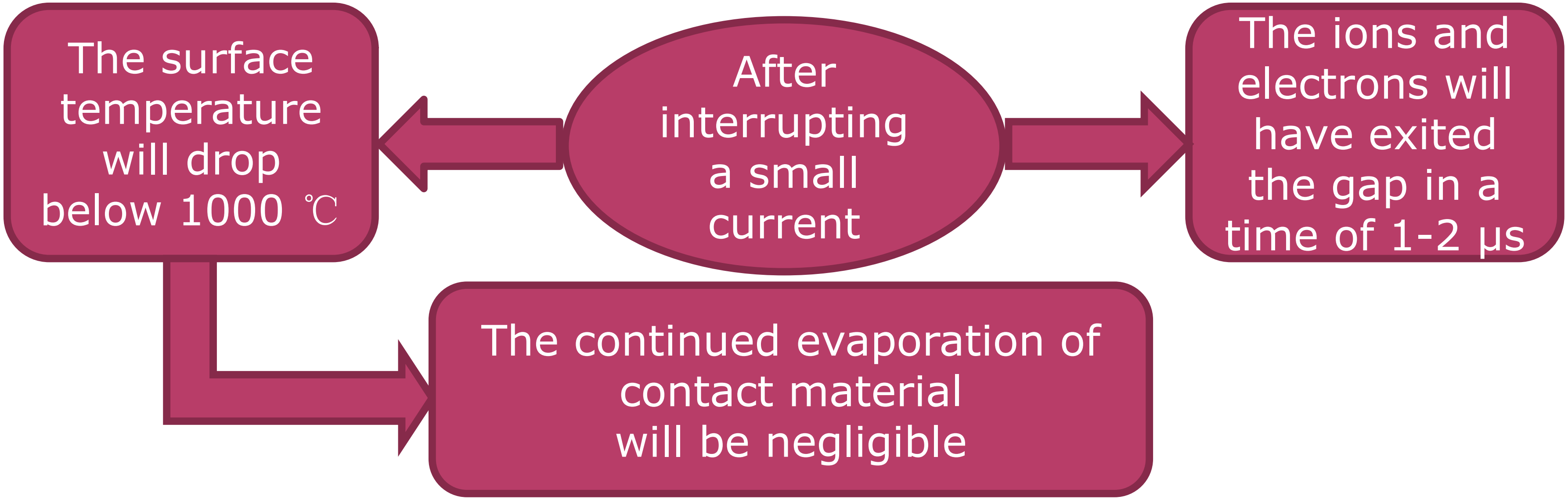
You would not expect the residual metal vapor to play a role in the re-establishment of the vacuum arc between the contacts.

THE SURFACE TEMPERATURE AFTER INTERRUPTING A SMALL CURRENT BELOW 2KA

Vapor Pressure of Contact Metals at Increasing Temperatures



Metal	Vapor pressure (Pa)							
	300K	1000K	1360K	1500K	1750K	2000K	2150K	2300K
Bi	$<10^{-8}$	5.3	1.3×10^3	6.7×10^3	$>10^5$	$>10^5$	$>10^5$	$>10^5$
Cu	$<10^{-8}$	2×10^{-6}	5.3×10^{-2}	9.3×10^{-1}	27	4×10^2	1.3×10^3	4×10^3
Cr	$<10^{-8}$	1.2×10^{-8}	2×10^{-3}	6.7×10^{-2}	5.3	133	6.7×10^2	2.7×10^3
Ag	$<10^{-8}$	5.3×10^{-4}	2.7	40	1.3×10^3	6.7×10^3	2.1×10^4	10^5
W	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	2.7×10^{-7}



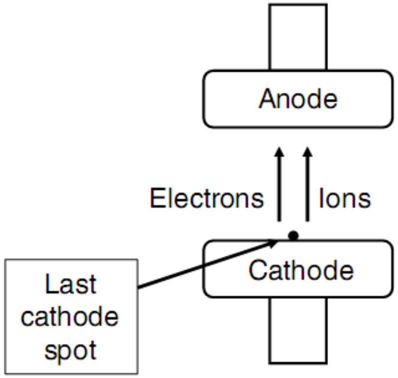
After interrupting a small current

The surface temperature will drop below 1000 ℃

The ions and electrons will have exited the gap in a time of 1-2 μs

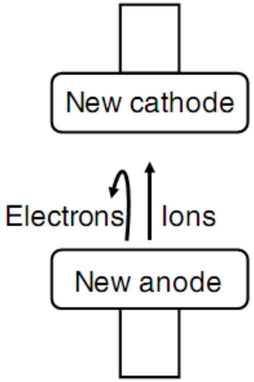
The continued evaporation of contact material will be negligible

THE STAGE AFTER INTERRUPTING A DIFFUSE VACUUM ARC



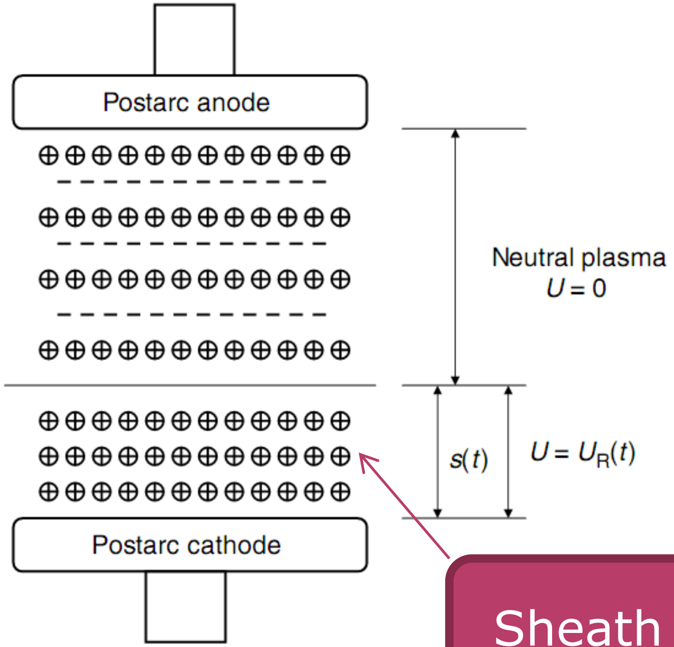
(a) Just before current zero

Both the electrons and the ions are moving away from the last cathode spot.



(b) Just after current zero

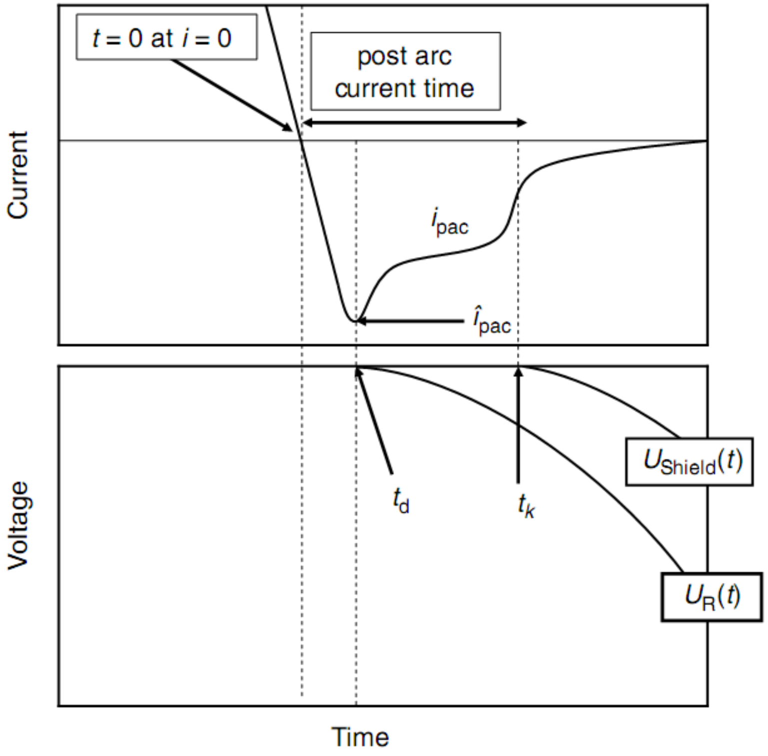
The ions continue their motion toward the new cathode, but the electrons reverse their direction toward the new anode



Sheath

The potential drop from the TRV will appear across the sheath

POST ARC CURRENT MODEL



Schematic diagrams showing the current zero region and the development of the post arc current during the rise of the TRV.

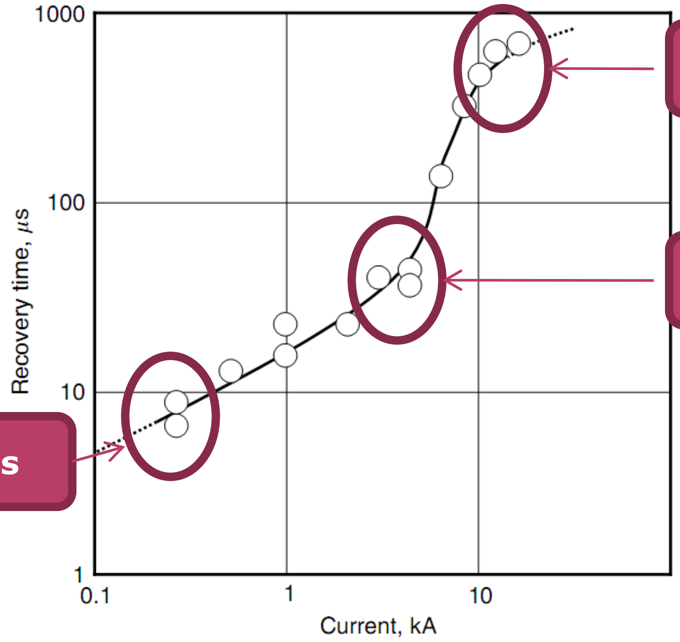
$$i_{pac} = A n_i e Z \left[v_{ie} + \frac{ds}{dt} \right]$$

A : the area of the contacts
v_{ie} :the velocity of the ions
s :the sheath's thickness
e : the electron charge
n_i : the ion density
Z : the mean ion charge

For ac currents up to 2 kA (rms), the value of the post arc current is very small. Its duration is a function of the final contact gap at current zero.

INTERRUPTION OF VACUUM ARC FOR AC CURRENTS ABOVE 2KA (RMS)

INTERRUPTION OF VACUUM ARC FOR AC CURRENTS ABOVE 2 KA(RMS)

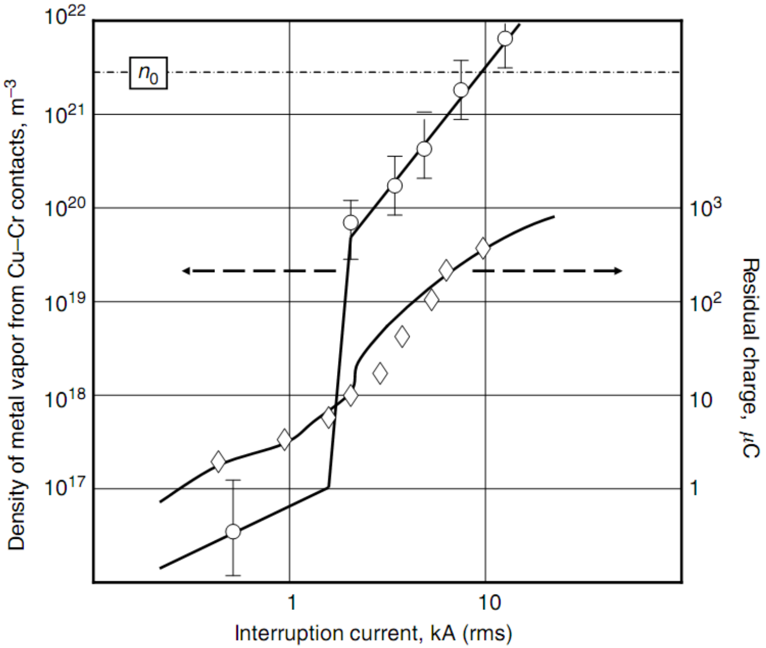


700 µs

40µs

7 µs

The free recovery time to a voltage of 38 kV as a function of vacuum arc current

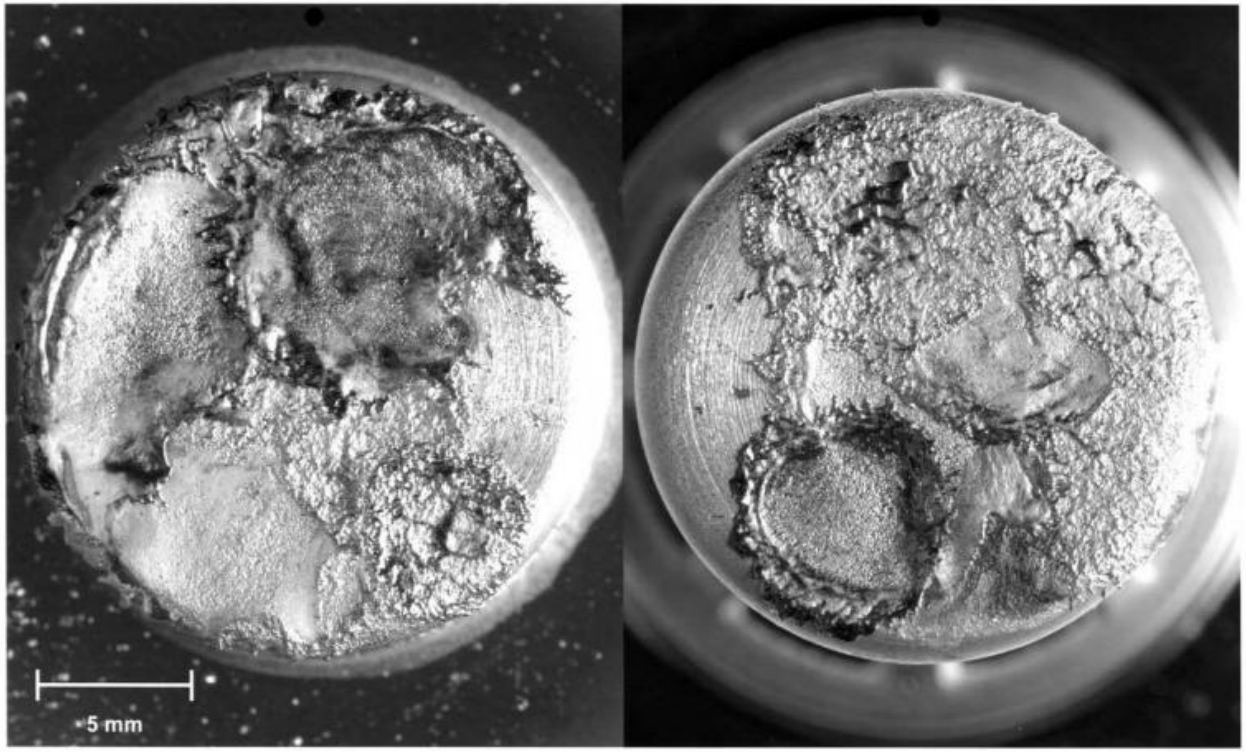


The metal vapor density and the residual electric charge between Cu–Cr contacts after the interruption of ac currents

The recovery time increases sharply with current until at 12 kA

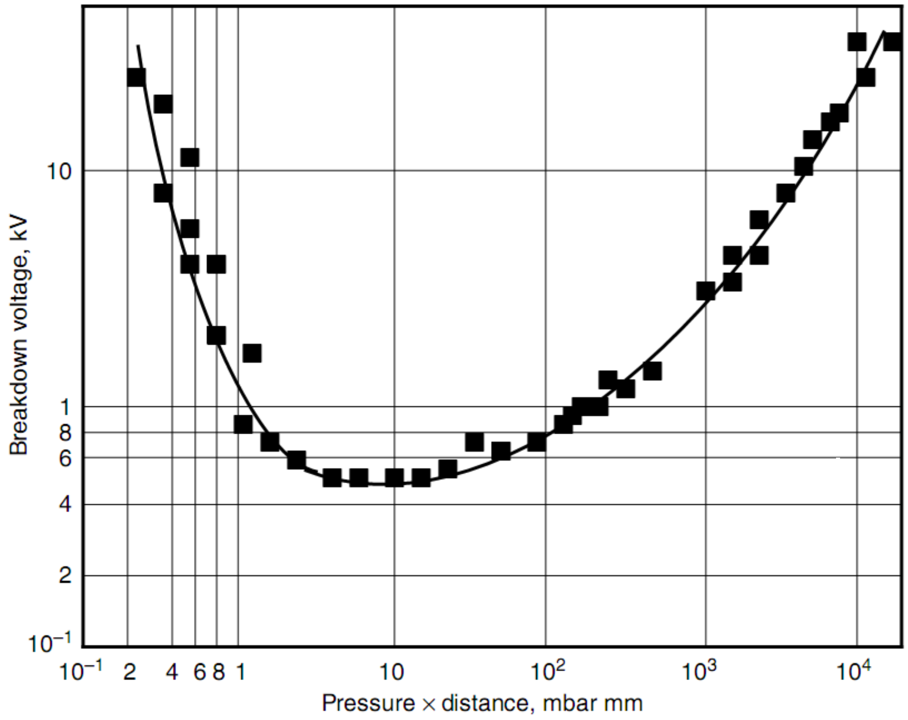
There seems to be a sharp distinction between the stationary vacuum arcs below about 4 kA and those above 6 kA

THE PHOTOGRAPH AFTER HIGH CURRENT INTERRUPTIONS



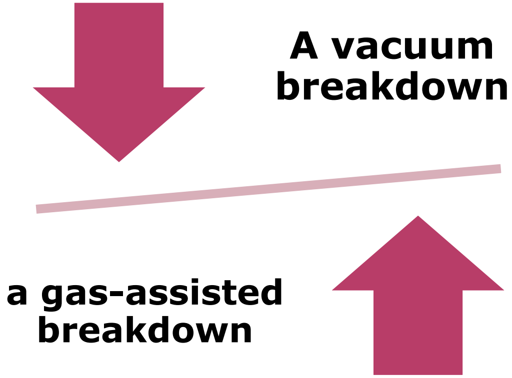
Contact erosion of a Cu–Cr (40 wt%) contact after the interruption of 8 kA (rms) transition vacuum arc 50 times showing the shallow erosion craters

THE THEORY FOR THE HIGH CURRENT INTERRUPTION



Paschen curve for a commercial vacuum interrupter with an AMF contact

It is imperative for the vacuum interrupter designer to ensure that the metal vapor density in the gap at current zero be less than about $10^{22}\ \mathrm{m}^{-3}$



A vacuum breakdown

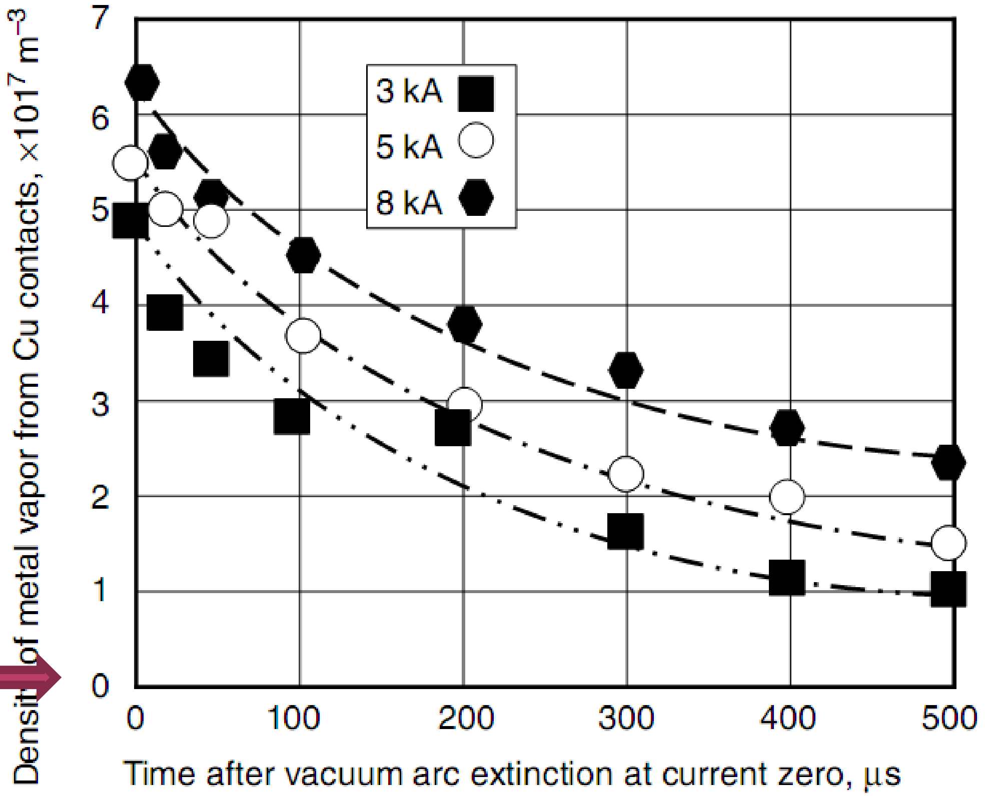
a gas-assisted breakdown

$$nd = \frac{pd}{kT}\,\mathrm{m}^{-2}$$

THE EFFECT OF AMF

In order to achieve this low-vapor density, a diffuse vacuum arc has to form as the current approaches current zero

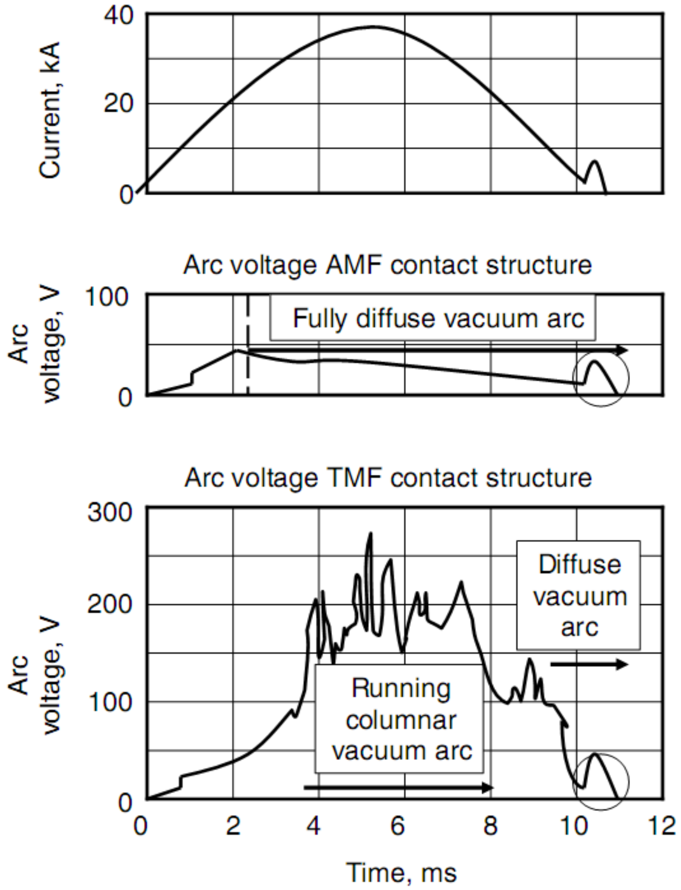
For ac currents above about 10 kA (rms), this is only possible if the AMF/TMF contact structures is used



The Cu vapor density after interrupting currents in the range 3–8 kA using Cu contacts with an AMF contact structure

INTERRUPTION OF HIGH CURRENT VACUUM ARCS

INTERRUPTION OF HIGH-CURRENT VACUUM ARCS



The arc voltage for a 25 kA(rms) vacuum arc between AMF and TMF contact structures

Arc voltage for AMF

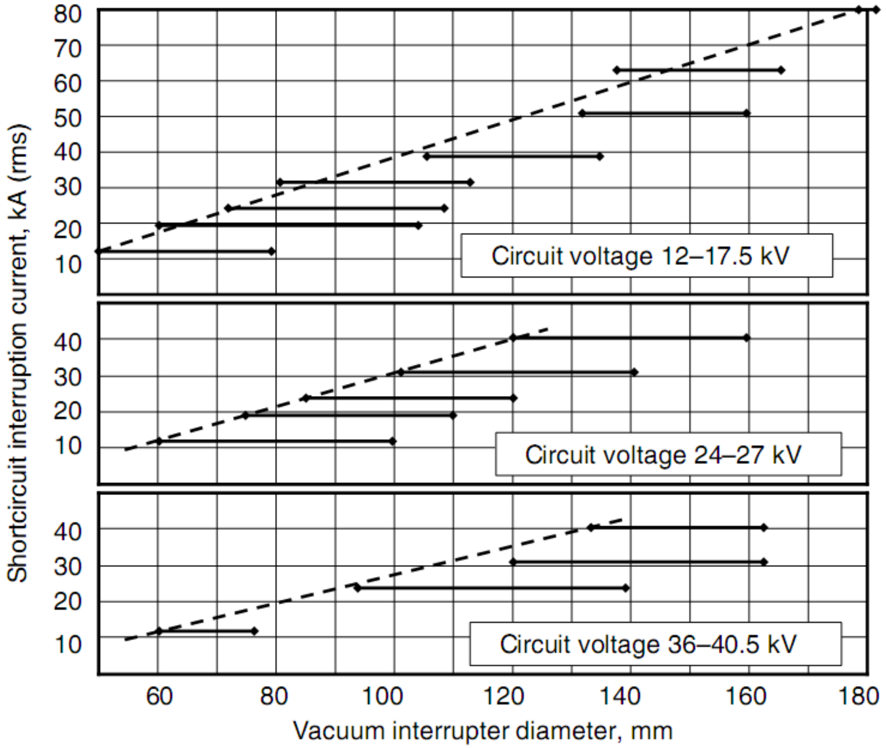
- smooth
- low

Arc voltage for TMF

- unstable
- high

The distribution of the energy from a 30 kA (rms) vacuum arc is equally effective for both the TMF and the AMF contacts

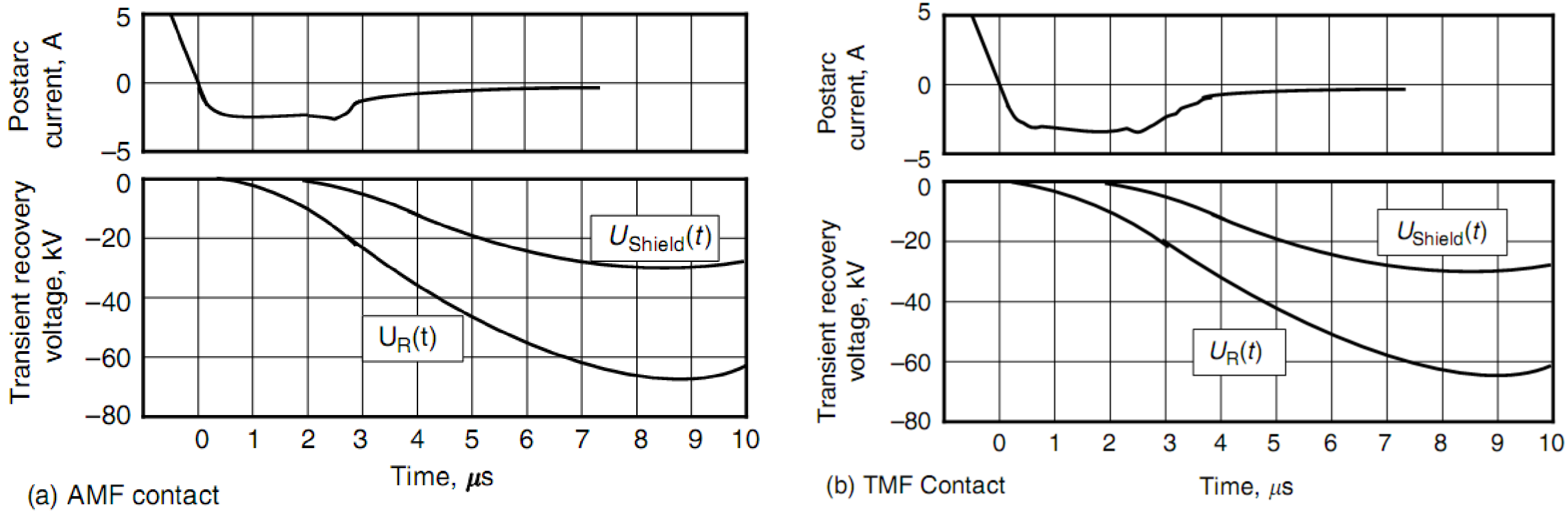
A COMPILATION OF HIGH-CURRENT INTERRUPTION PERFORMANCE FOR TMF AND AMF CONTACTS



A compilation of data taken from 12 vacuum interrupter manufacturers, for both TMF and AMF contacts, of the interruption limit as a function of current, circuit voltage, and vacuum interrupter diameter

The greater the vacuum interrupter's diameter, the higher the current it can interrupt; also the higher the circuit voltage, the greater the required vacuum interrupter's diameter to interrupt the same current.

POST ARC CURRENT FOR AMF AND TMF



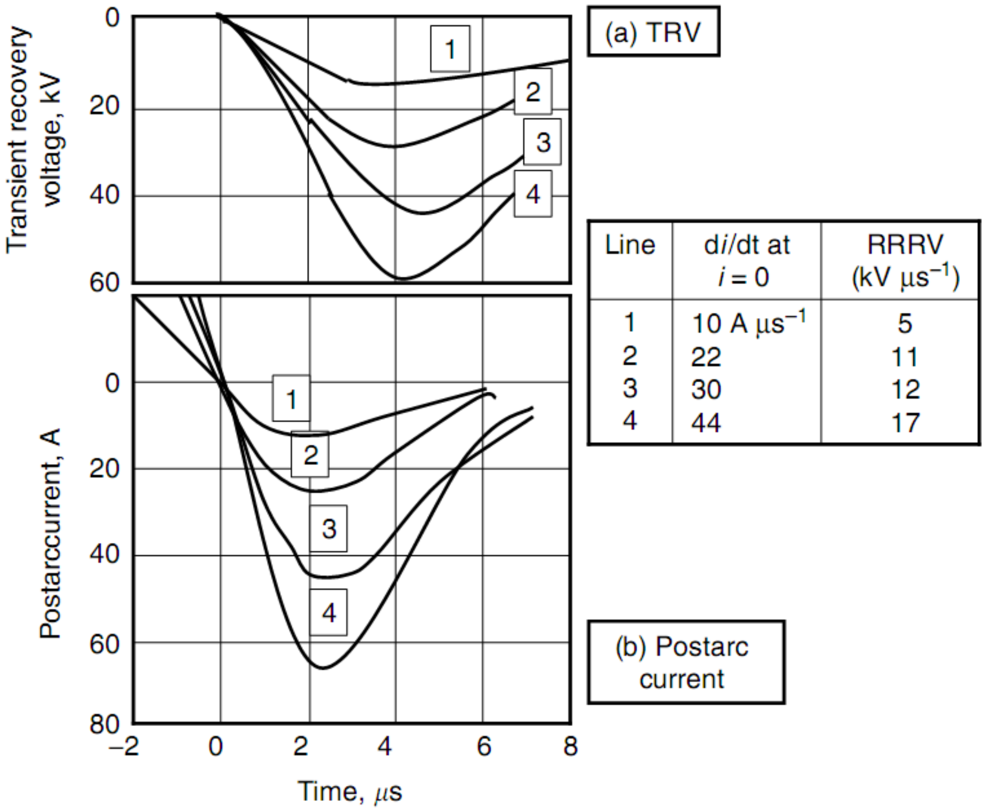
(a) AMF contact

(b) TMF Contact

The post arc currents (i_{pac}) for both the AMF and the TMF contacts after the 25 kA (rms) vacuum arc are almost identical

The columnar vacuum arc between the TMF contacts has transitioned into the diffuse mode long enough before current zero

POST ARC CURRENT AND HIGH-CURRENT INTERRUPTION



(a) TRV

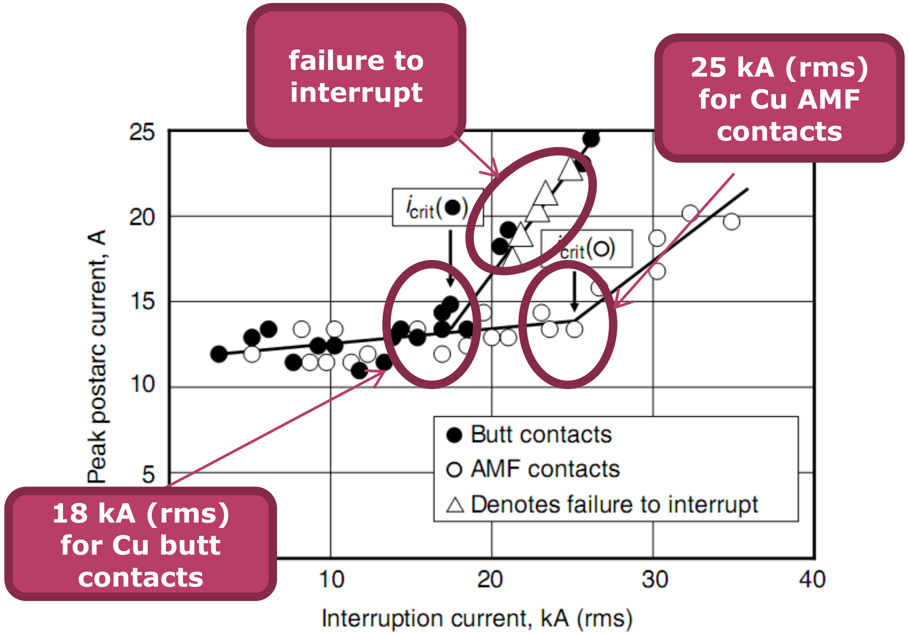
Line	di/dt at $i = 0$	RRRV (kV µs^{-1})
1	10 A µs^{-1}	5
2	22	11
3	30	12
4	44	17

(b) Postarc current

The post arc current is shown to strongly depend on the di/dt just before the current zero and the $dU_R(t)/dt$ and U_R(peak) just after the current zero.

The effect of di/dt on the (a) TRV and (b) post arc current

POST ARC CURRENT AND HIGH-CURRENT INTERRUPTION

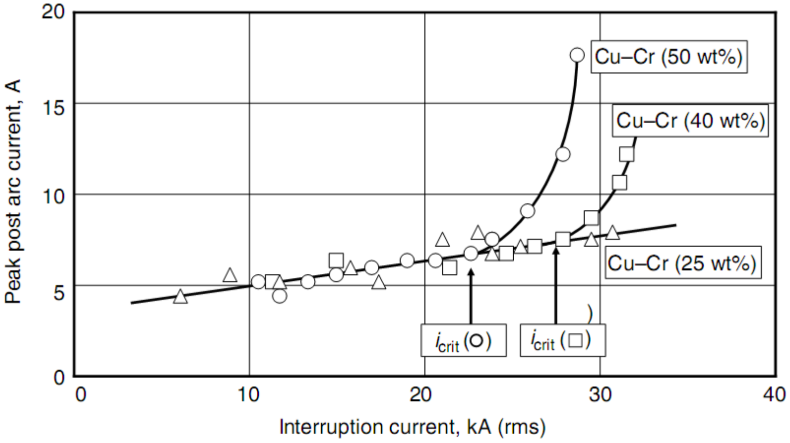


failure to interrupt

25 kA (rms) for Cu AMF contacts

18 kA (rms) for Cu butt contacts

The post arc current after the interruption of a vacuum arc as a function of circuit current for Cu butt and Cu AMF contacts

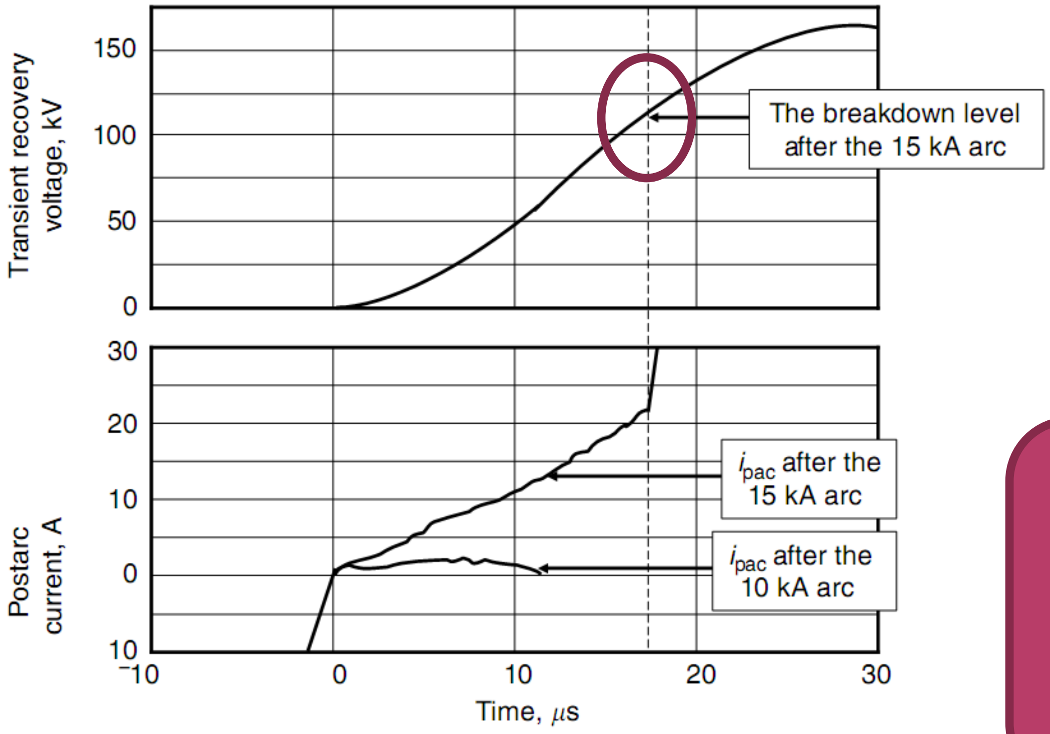


The post arc current after the interruption of a vacuum arc as a function of circuit current for Cu–Cr AMF contacts with different Cr content

The Cu AMF contacts interrupt a higher current successfully with the same post arc current of Cu butt contacts.

The highest Cu content (75 wt%) gives the lowest $\hat{\imath}_{pac.}$

POST ARC CURRENT AND HIGH-CURRENT INTERRUPTION



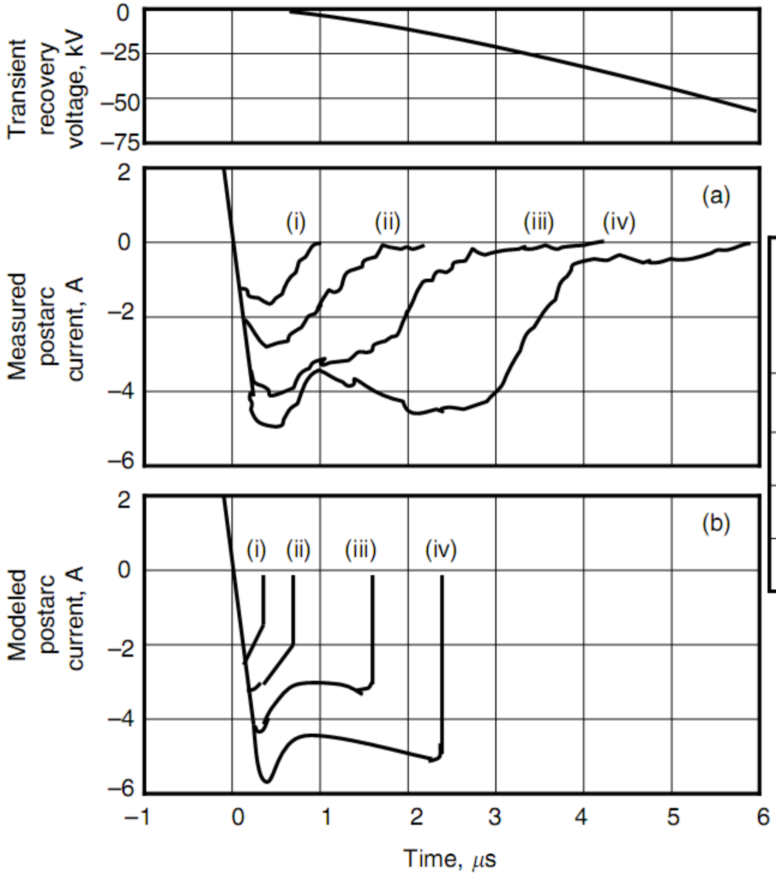
The post arc current after the interruption of a vacuum arc as a function of circuit current for Cu–Cr butt contacts for two circuit currents, 10 and 15 kA

At 15 kA, the high current stationary columnar vacuum arc would have formed.

At current zero, there would have been hot spots on the new cathode and a high enough density of metal vapor in the contact gap.

Initiate a gas breakdown

POST ARC CURRENT AND HIGH-CURRENT INTERRUPTION



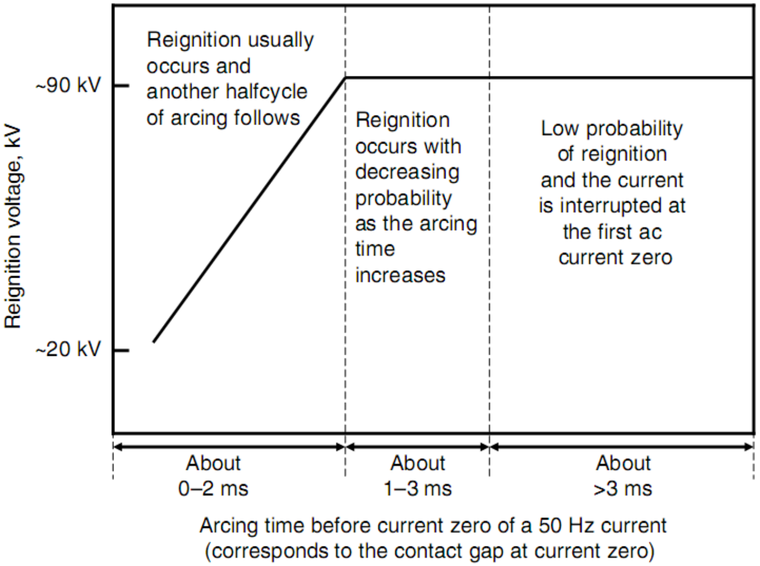
Trace	Contact gap at $i = 0$, mm	Approx. current at contact part, kA	Arcing time before $i = 0$, ms
i	1.8–2.0	38	1.8
ii	4	76	2.7
iii	7.5	69	4.5
iv	10	13	6

The post arc current pulse as a function of opening time before current zero for an AMF contact structure, comparing experimental data with a calculation using the sheath model

The opening time before the current zero has a marked affect on the value and duration of the i_{pac}.

INTERRUPTION OF AC CIRCUITS WHEN CONTACTS OPEN JUST BEFORE CURRENT ZERO

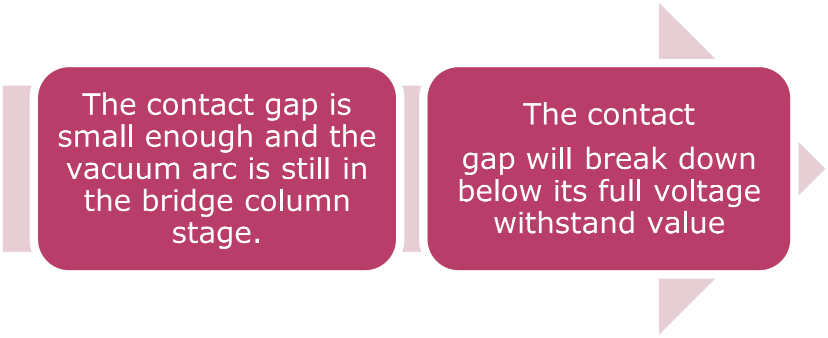
INTERRUPTION OF AC CIRCUITS WHEN CONTACTS OPEN JUST BEFORE CURRENT ZERO



The expected interruption performance at the first current zero for Cu–Cr contacts Subjected to a high-ac current, as a function of the time before current zero the contacts initially open

Probability of Interruption at the First Current Zero as a Function of the Contact Parting Time before Current Zero for One Style of TMF Contact, Vacuum Interrupter

Experiment	Contact part is	Time to the first current zero (ms)	Probability of interrupting at first current zero
A	Shortly before CZ	0–3	Nearly zero for all currents
B	Around current peak	>3–6	30–80% 70–80% through 36 kA 50% at 40 kA 35–55% above 40 kA
C	Just after one current zero and before current peak	>6	Nearly 100% through 40 kA 60–85% above 40 kA



The contact gap is small enough and the vacuum arc is still in the bridge column stage.

The contact gap will break down below its full voltage withstand value

THREE STAGES OF CURRENT INTERRUPTION

1

- The residual plasma in the contact gap dominates the first stage after the current zero. It can be described using the sheath model.

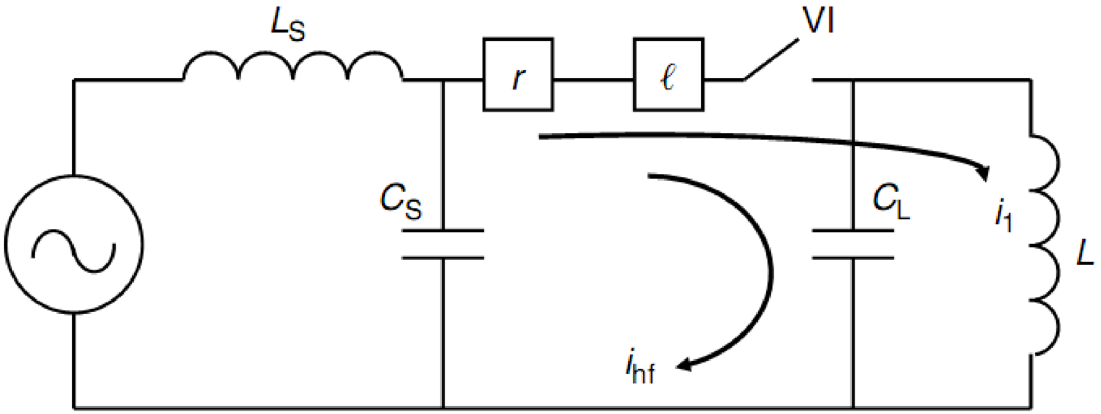
2

- The vapor density dominates the second stage as the TRV increases after the post arc current has decreased to zero.

3

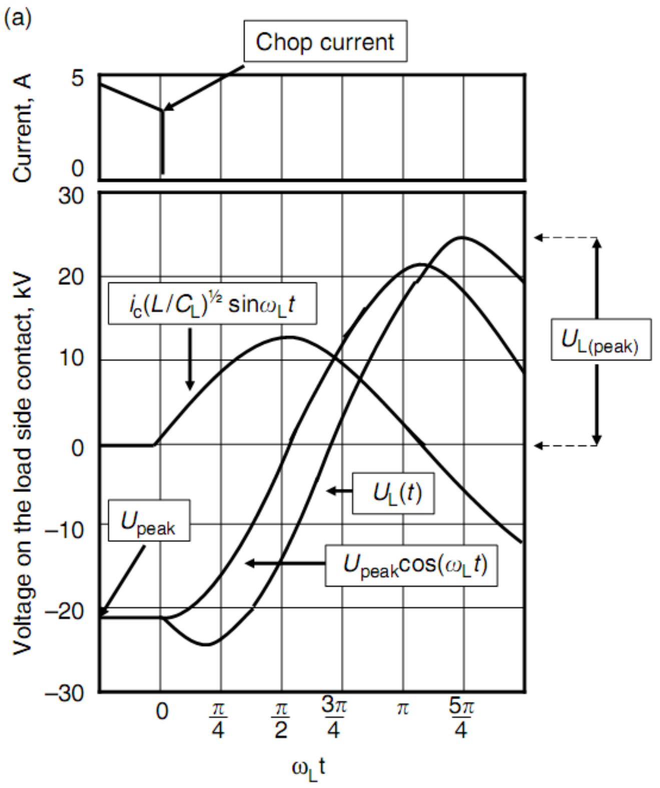
- The third stage is the full recovery of the contact gap to its full design high-voltage withstand value.

A SCHEMATIC DIAGRAM OF AN INDUCTIVE CIRCUIT

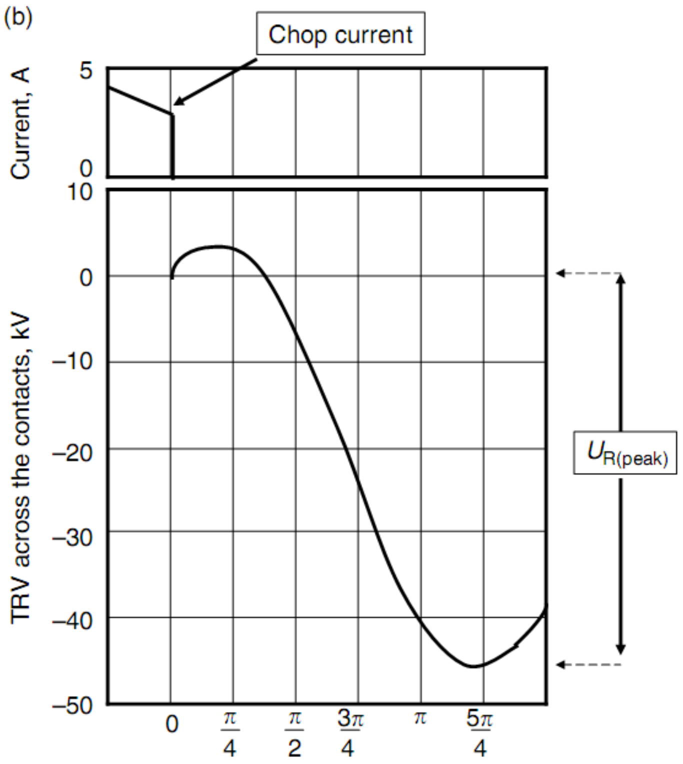


L :the load inductance,
C_L : the load side stray capacitance,
L_S : the inductance on the source side,
C_S :the source sidestray capacitance,
ℓ : the small inductance,
r : the resistance
VI : the vacuuminterrupter

THE ANALYSIS OF INITIAL TRV ACROSS THE CONTACTS



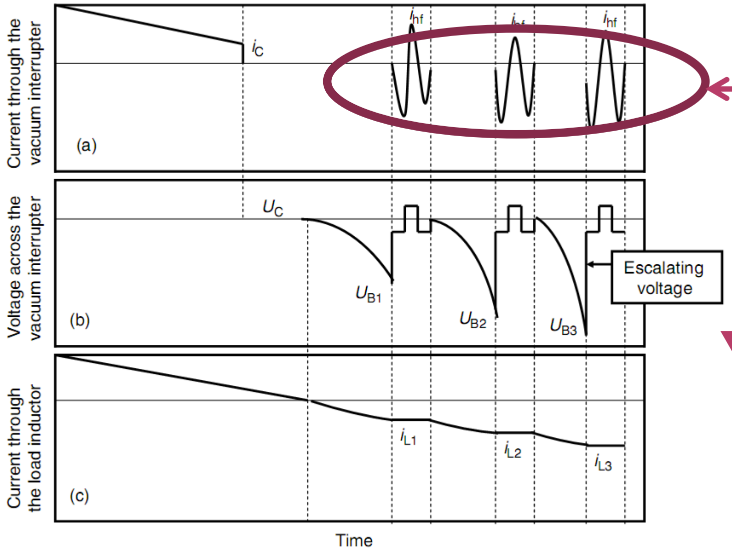
The voltage $U_L(t)$ on the load side of the vacuum interrupter for the peak of the supply voltage Upeak =−21 kV and iC = 3A, L = 12 mH, CL = 800 pF.



The TRV UR(t) across the vacuum interrupter's contacts for the peak of the supply voltage Upeak =−21 kV and i_C = 3A, L = 12 mH, C_L =800 pF

$$U_R(t) = U_{peak} - [U_{peak}\cos(\omega_L t) \pm i_C[L/C_L]^{1/2}\sin(\omega_L t)].$$

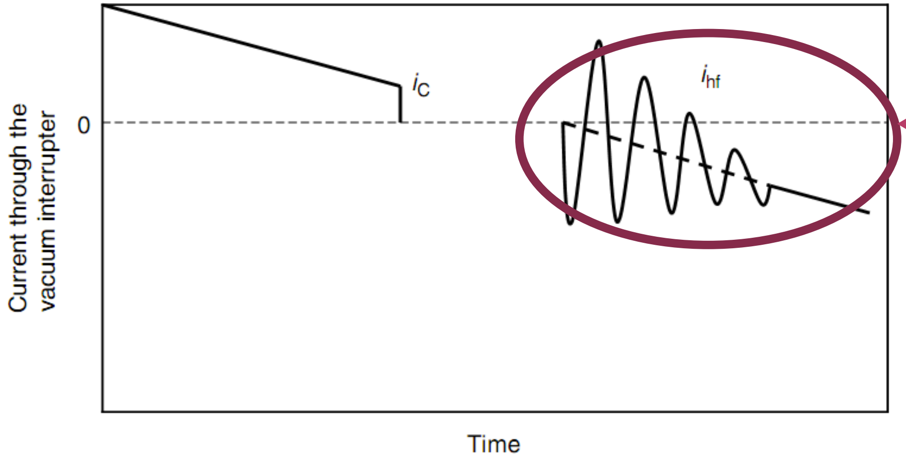
THE RESULTS OF THE ANALYSIS



Imposed high frequency current

Escalating voltage

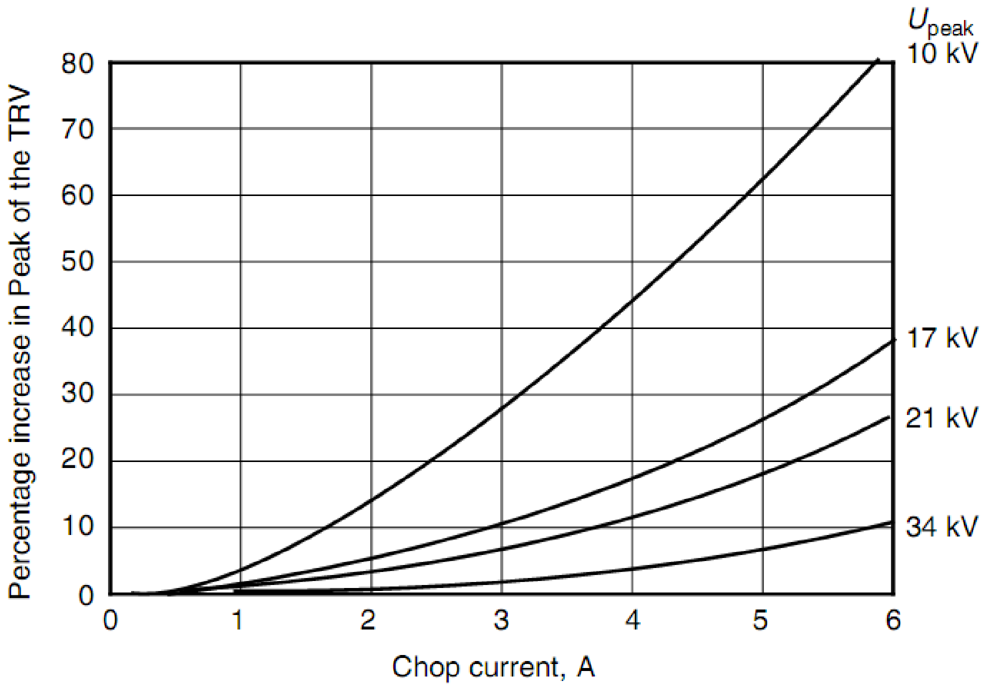
Schematic diagrams of the voltage escalation event



No current zeroes are obtained and the vacuum arc burns until the next ac current zero

A schematic diagram showing the reignition of the main circuit current if there is a failure to interrupt the high-frequency current superimposed on it

THE RELATION BETWEEN CHOP CURRENT AND TRV.



The percentage increase in the peak value of the TRV as a function of chop current.

Percentage increase in the peak of the TRV as a function of the chop current and the peak of the supply voltage U_{peak} = 10–34 kV and L = 12 mH, C_L = 800 pF

INTERRUPTION OF CAPACITIVE CIRCUIT

- **LOW-CURRENT INTERRUPTIONG OF CAPACITIVE CIRCUITS**
- **SWITCHING CAPACITOR CIRCUITS**
- **LATE BREAKDOWN AND NONSUSTAINED DISPURIVE DISCHARGES**
- **CAPACITOR SWITCHING**

Example of opening velocity calculation to withstand TRV in capacitive switching

24kV

gap=12mm

$$\frac{U_{\text{peak}}\left[1-\cos(\omega t)\right]}{d(t)} < E_{\text{crit}}.$$

E1 **=(design peak BIL/12 mm)**
= 125kV/12mm
= 1.04×10^{7} V/m

E2 **= (design peak 1-min withstand voltage/12 mm)**
=1.414 × 50kV/12mm
=5.9×10^{6} V/m

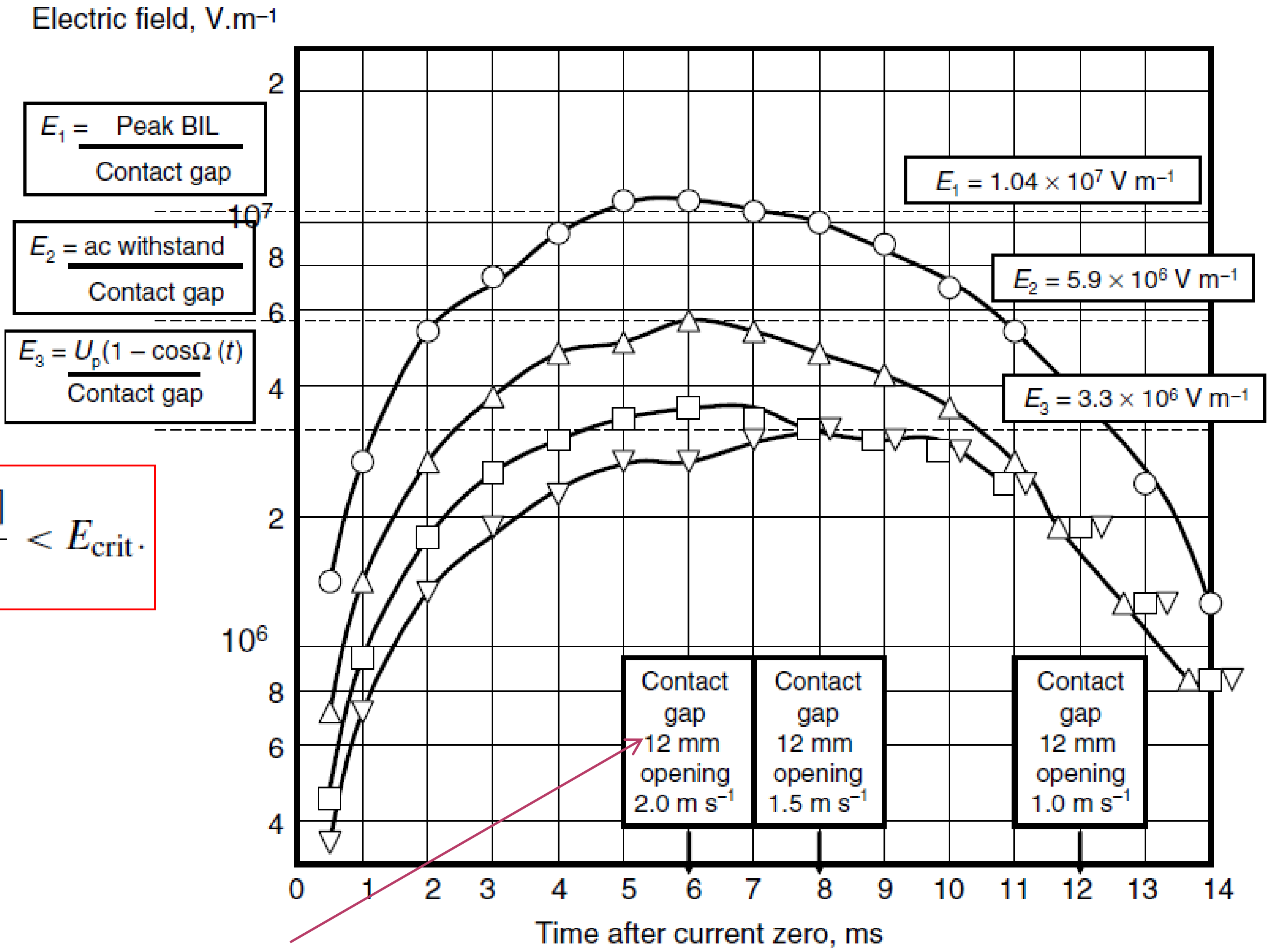
E3 **= (peak of the TRV/12 mm)**
= (24kV/1.732) ×1.414 ×2/12mm
= 3.3×10^{6} V/m

Example

24kV

gap=12mm

$$\frac{U_{\text{peak}}\,[1-\cos(\omega t)]}{d\,(t)} < E_{\text{crit}}.$$

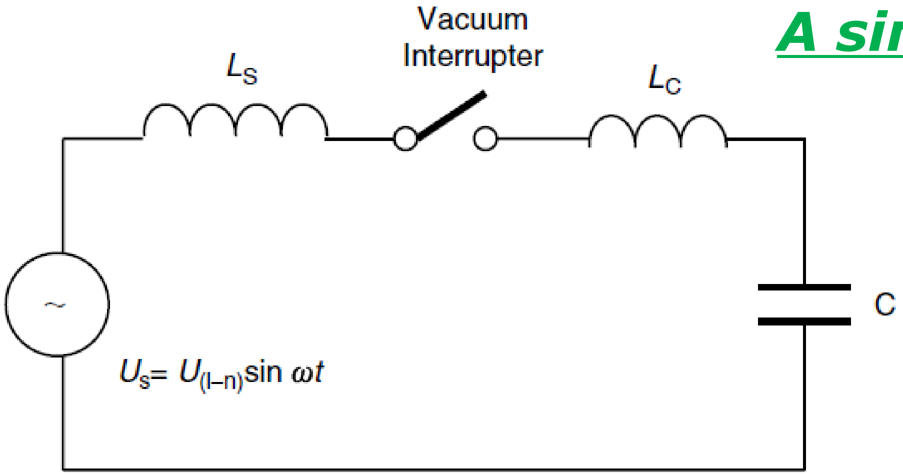


Opening speed should be >2 m s^{-1}

The gross field (*E* =[capacitive circuit TRV/contact gap]) *as function of time* after current zero for contacts opening just before current zero to a 12-mm gap in a three-phase, ungrounded, 24 kV circuit and of contact opening speed (0.5 ms^{-1} [◦], 1 ms^{-1} [△], 1.5 ms^{-1} [□], 2 ms^{-1} [▽]);

SWITCHING CAPACITOR CIRCUITS

INSERTING CAPACITOR BANKS



A single capacitor bank circuit

A single capacitor bank switching

L_S: the inductance of the source

L_C: the local inductance in the capacitor's cable

(typical values : 10–30 μH)

The contacts close → a prestrike arc → the inrush current

$$i_{R1}(t) = \frac{(\sqrt{2}U_{(\ell-n)} \sin \omega t_{cl}) \sin \omega_0 t}{Z_C}$$

$\omega = 2\pi f$

$Z_C = (L_T/C)^{1/2}$

$L_T = L_S + L_C$

$\omega_0 = 1/(L_T C)^{1/2}$

L_T :μH and C :μF

Example 1:

System voltage : 15 kV
C: 60 μF,
L_S : 1 mH,
L_C : 20 μH

$$i_{\mathrm{R1(peak)}} = \frac{\sqrt{2} \times 15 \times 10^3 \times \sqrt{60 \times 10^{-6}}}{\sqrt{3}\sqrt{1020 \times 10^{-6}}} \approx 3\,\mathrm{kA}$$

$$\text{frequency} \approx 0.65\,\mathrm{kHz}.$$

i_{sc}: the system's rated short-circuit current

i_L: the capacitor bank's rated load current

Estimate $i_{R1(peak)}$ f_{IR}

$$i_{\mathrm{R1(peak)}} = \frac{\sqrt{2U^2_{(\ell-\mathrm{n})}}}{\sqrt{L_{\mathrm{T}}/C}} \approx \sqrt{2}\sqrt{U_{(\ell-\mathrm{n})}\omega C}\sqrt{\frac{U_{(\ell-\mathrm{n})}}{\omega L_{\mathrm{s}}}} \approx \sqrt{2(i_{\mathrm{sc}} \times i_{\mathrm{L}})}$$

$$f_{\mathrm{IR}} = f\sqrt{\frac{i_{\mathrm{sc}}}{i_{\mathrm{L}}}}$$

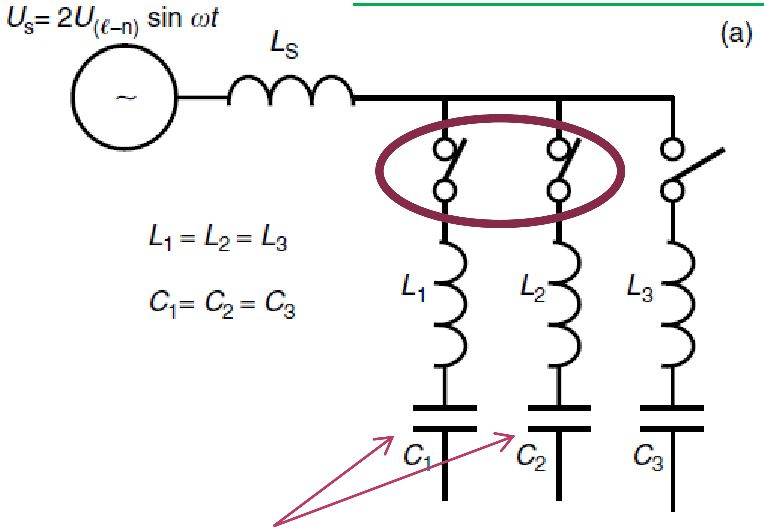
Example 2:

i_{sc} = 23 kA

i_L = 196 A

$i_{R1(peak)}$ =3 kA f_{IR} =0.65 kHz

Back-to-back capacitor switching



The local capacitor circuits dominate the inrush current

$$i_{R2}(t) = \frac{\left(\sqrt{2}U_{(\ell-n)} \sin \omega t_{cl} \sin \omega_0 t\right)}{Z_C}$$

Example 3:

$C_1 = C_2 = C_3 = 60\mu F$

$L_1 = L_2 = L_3 = 20\mu H$

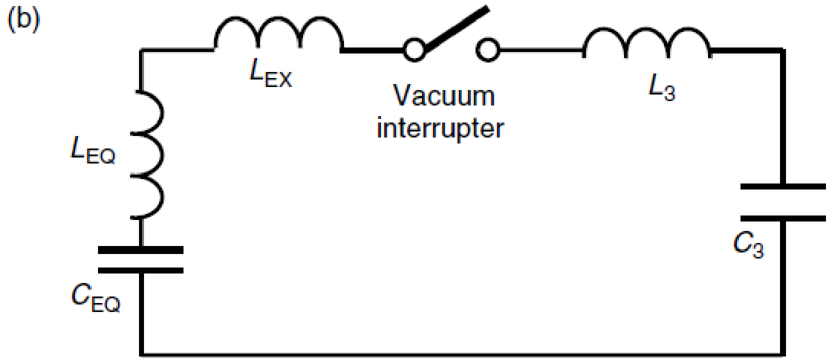
System voltage: 15 kV

$L_{EX} = 20\mu H$

⇩

$$i_{R2(\text{peak})} = \frac{\sqrt{2} \times 15 \times \sqrt{40}}{\sqrt{3} \times \sqrt{50}} \approx 11\text{ kA}$$

$$\text{frequency } f \approx 3.6\text{ kHz}$$



A back-to-back capacitor bank circuit.

$$L_{TP} = L_{EQ} + L_{EX} + L_3 \qquad C_T = \frac{C_{EQ} \times C_3}{C_{EQ} + C_3}$$

$$L_{EQ} = \frac{L_1 \times L_2}{L_1 + L_2} \qquad C_{EQ} = C_1 + C_2$$

L_{EX}: the capacitor banks inductance
the bus inductance

CAPACITOR SWITCHING

Capacitor banks are switched perhaps once or twice a day

⬇

60% up to 300 times a year

a further 30% up to 700 times a year

Standards

IEEE(C37.04a-2003 and C37.09a-2005)

Inrush current : 20kA 4250Hz

IEC (62271-100:2003)

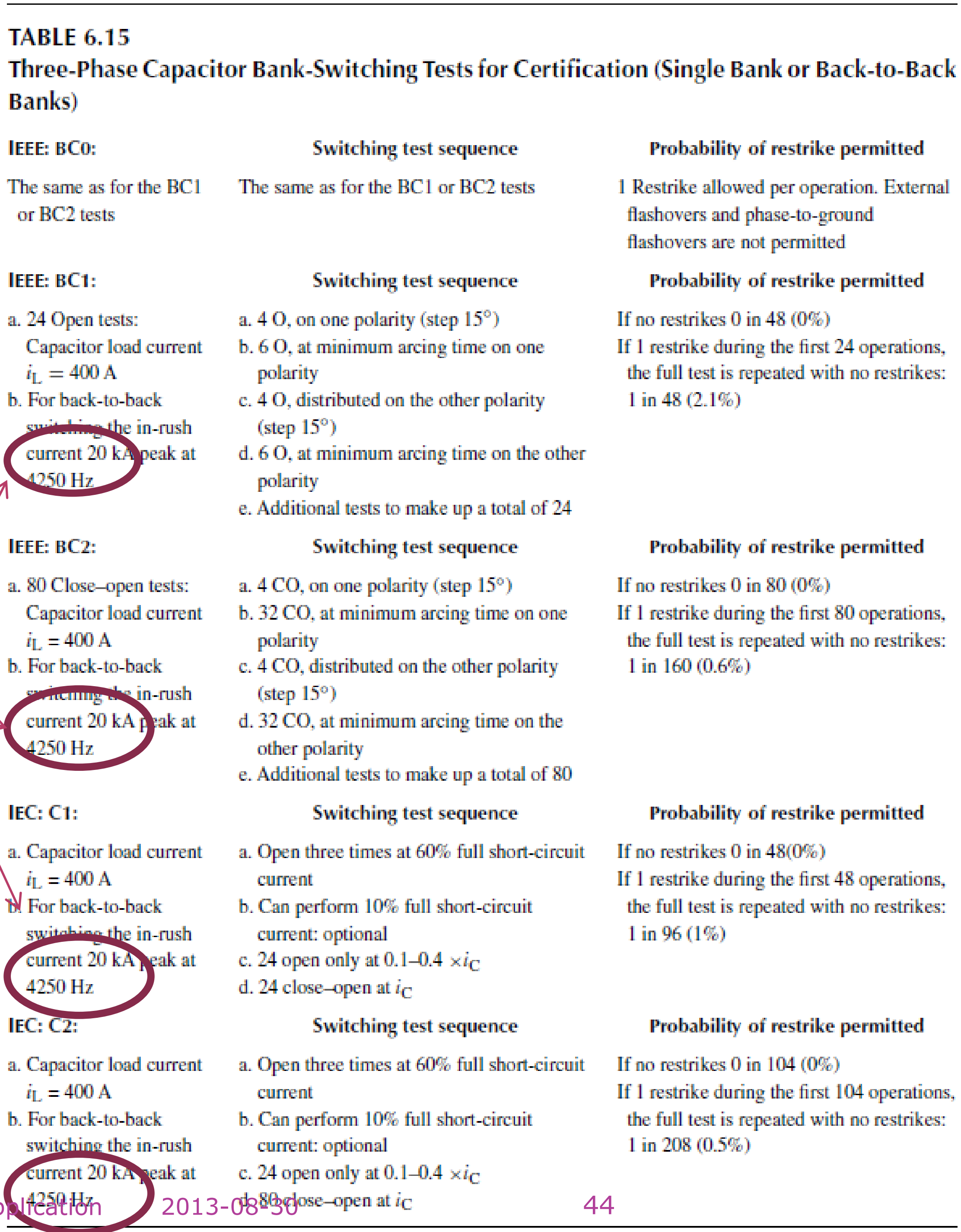


TABLE 6.15

Three-Phase Capacitor Bank-Switching Tests for Certification (Single Bank or Back-to-Back Banks)

IEEE: BC0:	Switching test sequence	Probability of restrike permitted
The same as for the BC1 or BC2 tests	The same as for the BC1 or BC2 tests	1 Restrike allowed per operation. External flashovers and phase-to-ground flashovers are not permitted

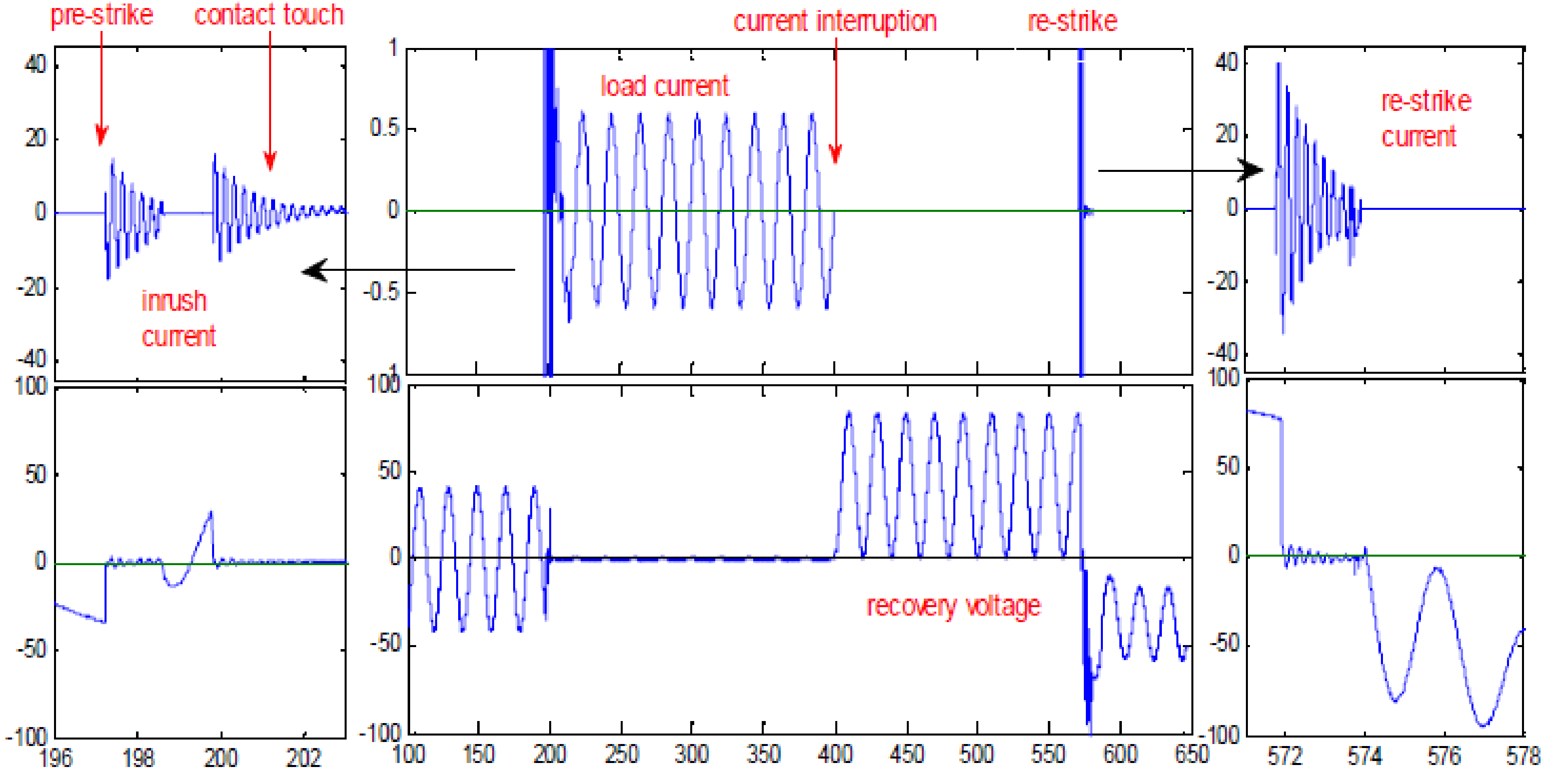
IEEE: BC1:	Switching test sequence	Probability of restrike permitted
a. 24 Open tests: Capacitor load current $i_L = 400$ A b. For back-to-back switching the in-rush current 20 kA peak at 4250 Hz	a. 4 O, on one polarity (step 15°) b. 6 O, at minimum arcing time on one polarity c. 4 O, distributed on the other polarity (step 15°) d. 6 O, at minimum arcing time on the other polarity e. Additional tests to make up a total of 24	If no restrikes 0 in 48 (0%) If 1 restrike during the first 24 operations, the full test is repeated with no restrikes: 1 in 48 (2.1%)

IEEE: BC2:	Switching test sequence	Probability of restrike permitted
a. 80 Close–open tests: Capacitor load current $i_L = 400$ A b. For back-to-back switching the in-rush current 20 kA peak at 4250 Hz	a. 4 CO, on one polarity (step 15°) b. 32 CO, at minimum arcing time on one polarity c. 4 CO, distributed on the other polarity (step 15°) d. 32 CO, at minimum arcing time on the other polarity e. Additional tests to make up a total of 80	If no restrikes 0 in 80 (0%) If 1 restrike during the first 80 operations, the full test is repeated with no restrikes: 1 in 160 (0.6%)

IEC: C1:	Switching test sequence	Probability of restrike permitted
a. Capacitor load current $i_L = 400$ A b. For back-to-back switching the in-rush current 20 kA peak at 4250 Hz	a. Open three times at 60% full short-circuit current b. Can perform 10% full short-circuit current: optional c. 24 open only at 0.1–0.4 $\times i_C$ d. 24 close–open at i_C	If no restrikes 0 in 48(0%) If 1 restrike during the first 48 operations, the full test is repeated with no restrikes: 1 in 96 (1%)

IEC: C2:	Switching test sequence	Probability of restrike permitted
a. Capacitor load current $i_L = 400$ A b. For back-to-back switching the in-rush current 20 kA peak at 4250 Hz	a. Open three times at 60% full short-circuit current b. Can perform 10% full short-circuit current: optional c. 24 open only at 0.1–0.4 $\times i_C$ d. 80 close–open at i_C	If no restrikes 0 in 104 (0%) If 1 restrike during the first 104 operations, the full test is repeated with no restrikes: 1 in 208 (0.5%)

Back-to-back switching with VCB



Back-to-back switching with VCB

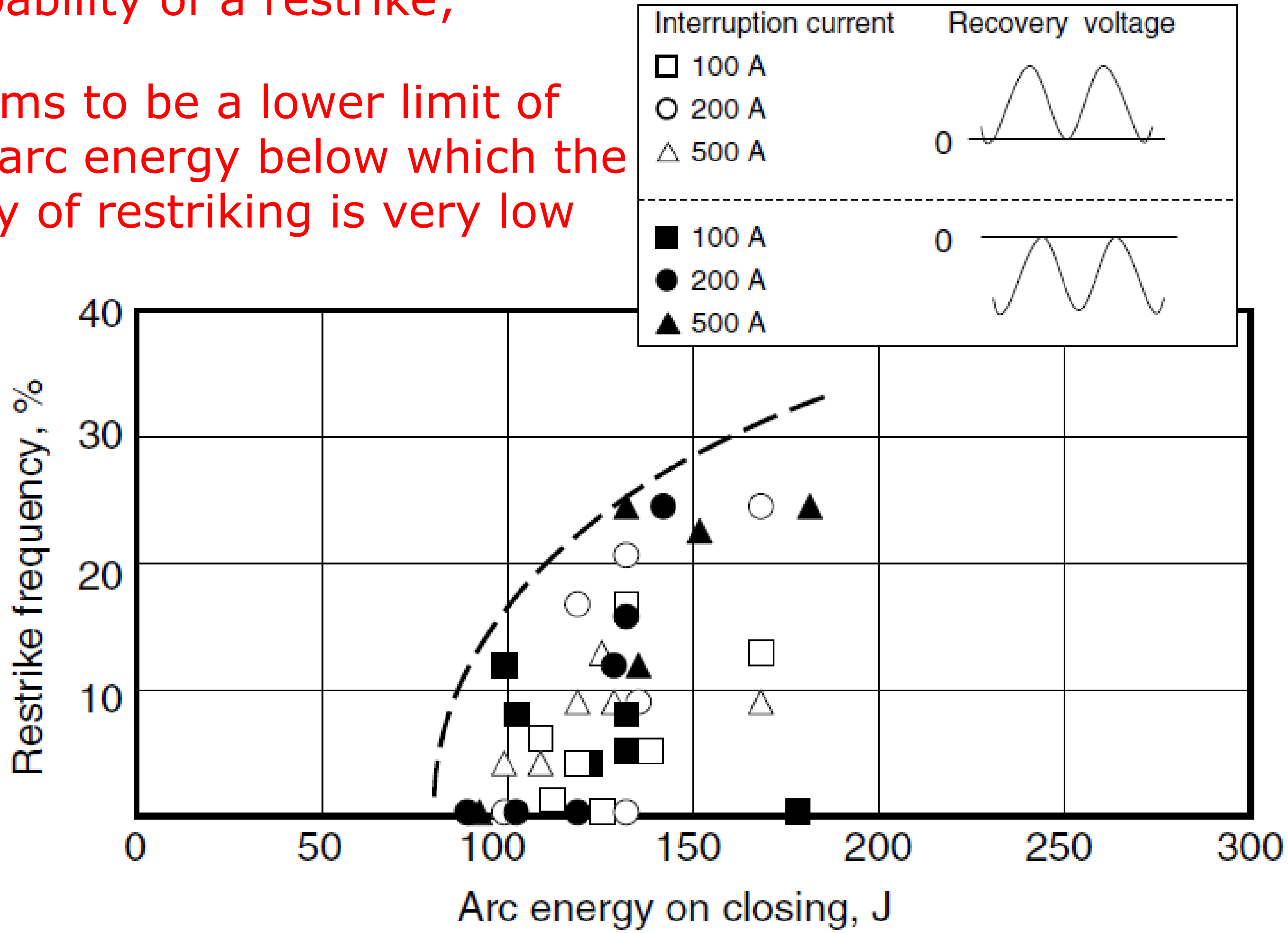
Challenges from the high frequency inrush current arc v.s. power frequency prestrike arc:

1. **20kA inrush current for many circles v.s. power frequency current may not reach its peak during the prestrike period.**
2. **4250HZ leads to prestrike arc changes its polarity many times for anode and cathode, however, it does not for a power frequency prestrike arc.**
3. **A prestrike arc in a close operation shortens it length gradually until contacts mate. The vacuum arc is columnar mode v.s. an opening arc that lengthens and expends its volume.**

(1) restrikes is dependent on the energy of the prestrike arc;

(2) At the highest prestrike arc energy, there is a 30% probability of a restrike;

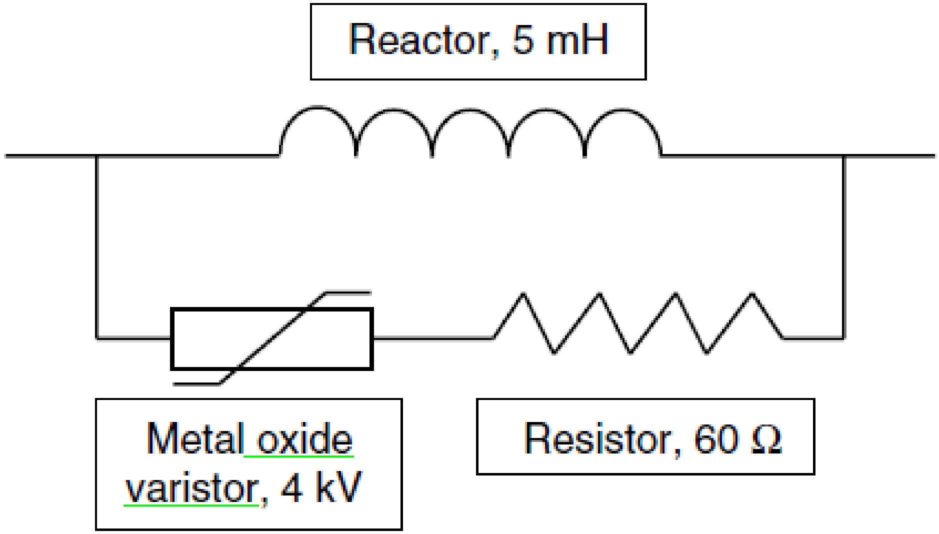
(3) there seems to be a lower limit of prestrike arc energy below which the probability of restriking is very low



The probability of restrikes while switching a capacitor bank with Cu–Cr contacts after disconnecting a capacitor bank as a function of the prestrike arc energy

How to limit the inrush current ?

First: permanently placing a fixed reactance



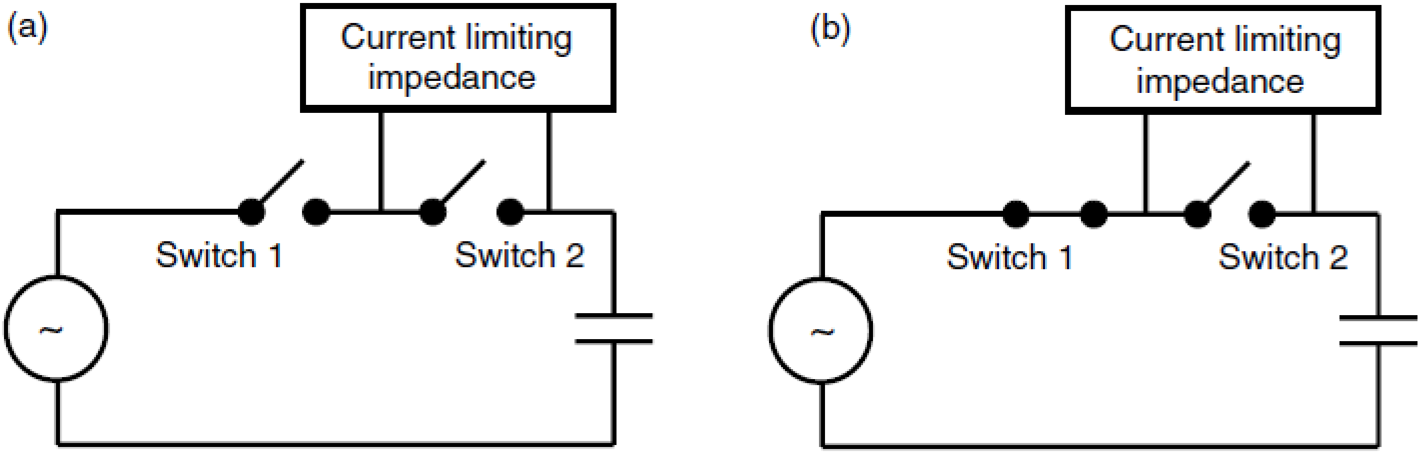
One example of a current-limiting reactor for limiting the inrush current when a capacitor bank is connected

Disadvantages:

1. **Increase energy losses**
2. **reduce the effectiveness of the capacitors**

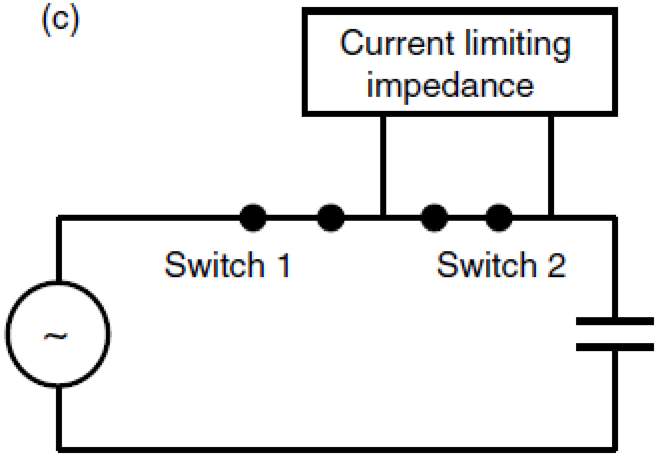
Second: momentarily inserting a current-limiting impedance

Schematic 1:



(a) Both switches open

(b) switch 1 closes while switch 2 remains open, the capacitor bank is connected with a limited inrush current



(c) switch 2 is closed shorting the current-limiting impedance

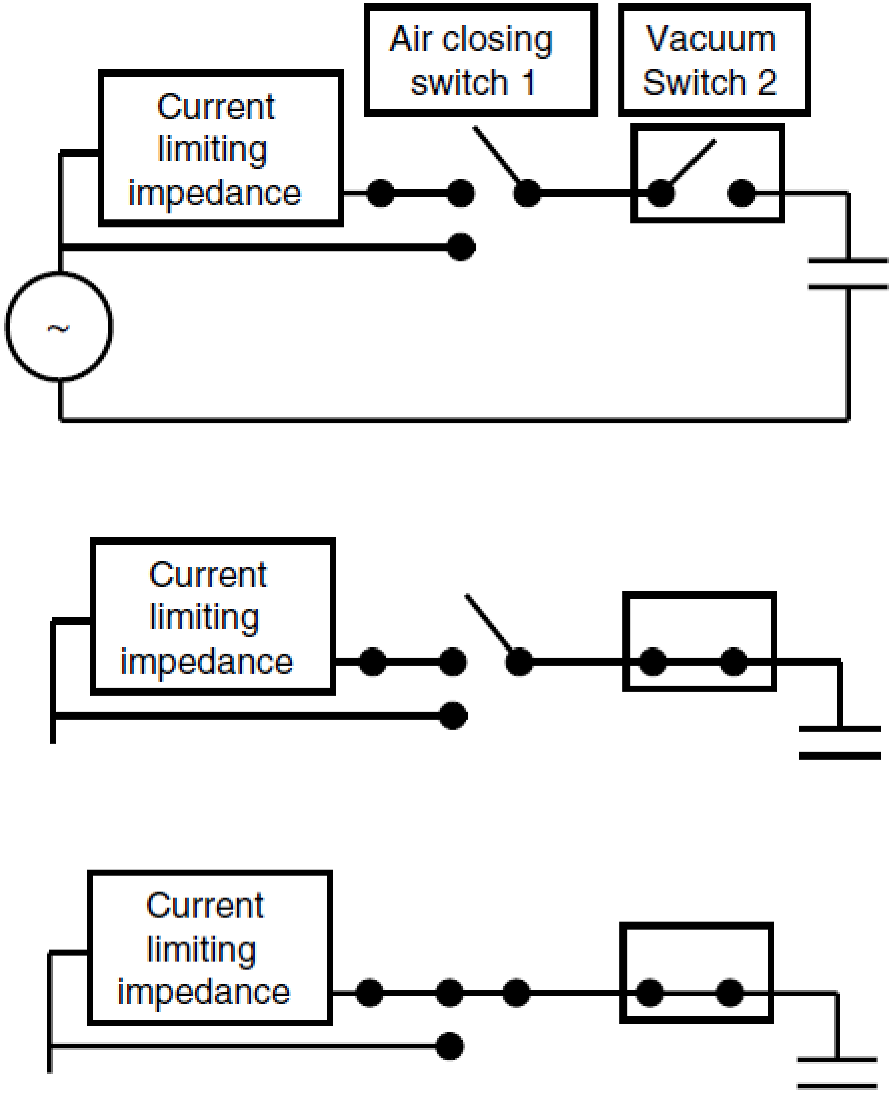
Disadvantages:

a complex switching and coordination function

A scheme for connecting a current-limiting impedance for connecting a capacitor bank

Schematic 2:

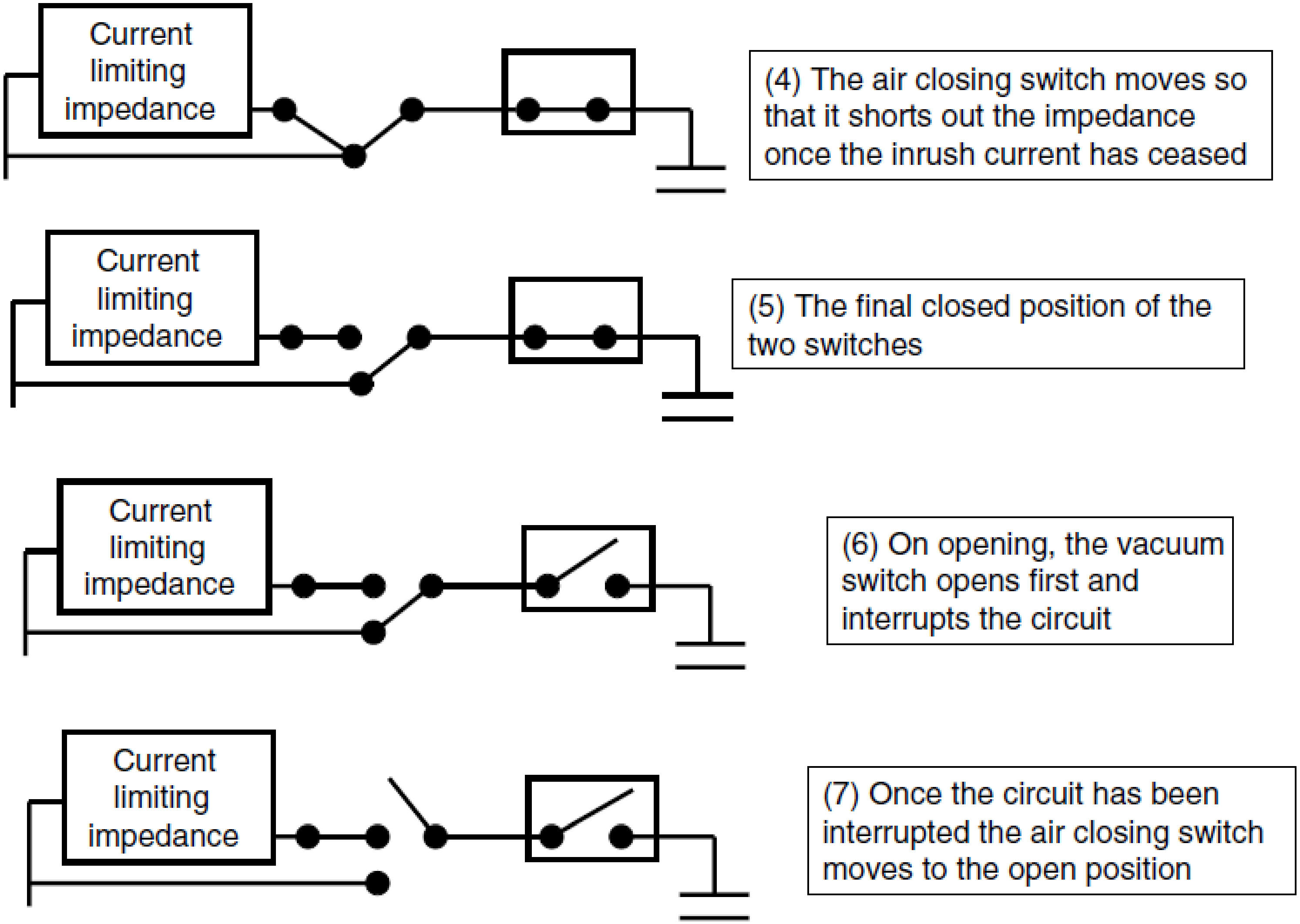
Schematic showing the use of a vacuum capacitor switch in series with an air, making switch to momentarily insert a current-limiting impedance.



(1) The air closing switch and the vacuum switch are open

(2) The vacuum switch closes

(3) The air switch closes and inserts the impedance momentarily and limits the inrush current



(4) The air closing switch moves so that it shorts out the impedance once the inrush current has ceased

(5) The final closed position of the two switches

(6) On opening, the vacuum switch opens first and interrupts the circuit

(7) Once the circuit has been interrupted the air closing switch moves to the open position

Schematic showing the use of a vacuum capacitor switch in series with an air, making switch to momentarily insert a current-limiting impedance.

Third: synchronizing the closing of the vacuum interrupter

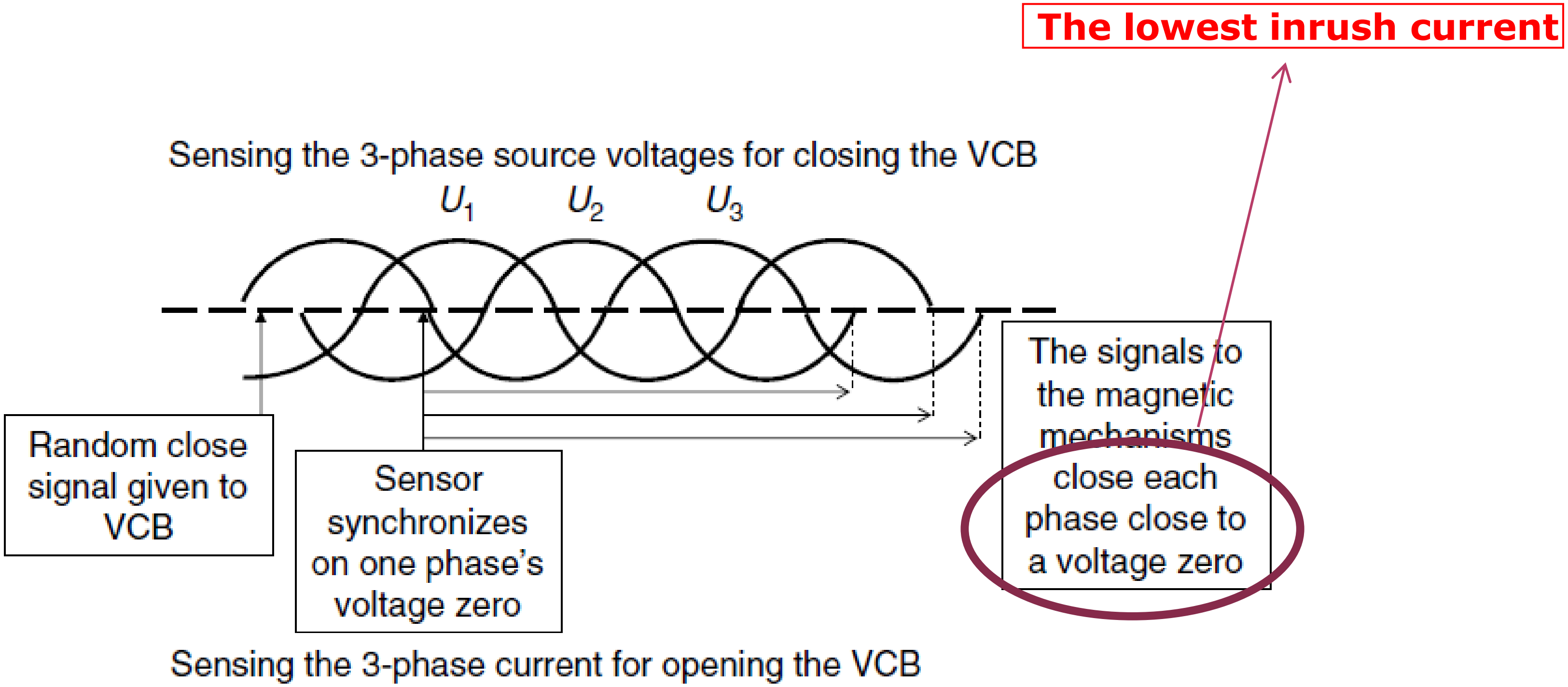
Make permanent mechanism

system voltage is close to zero
(a single capacitor bank)

the parallel bank voltage is close to zero
(a back to back capacitor bank)

each phase must close separately
(a three-phase system)

A magnetic mechanism on each phase



The lowest inrush current

Sensing the 3-phase source voltages for closing the VCB

Random close signal given to VCB

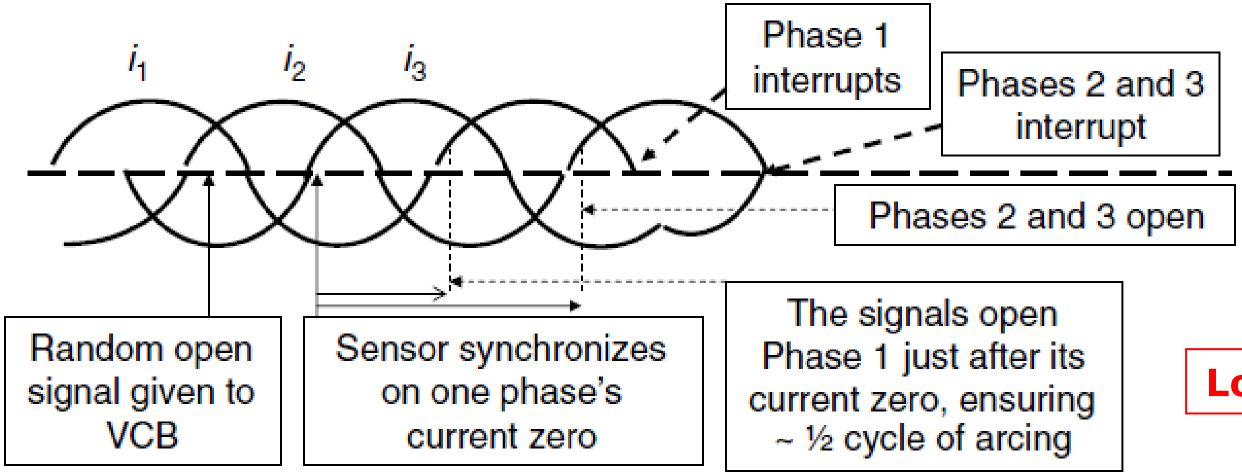
Sensor synchronizes on one phase's voltage zero

The signals to the magnetic mechanisms close each phase close to a voltage zero

Sensing the 3-phase current for opening the VCB

The synchronous closing of a vacuum circuit breaker with magnetic mechanisms

A magnetic mechanism on each phase



Phase 1 interrupts

Phases 2 and 3 interrupt

Phases 2 and 3 open

Random open signal given to VCB

Sensor synchronizes on one phase's current zero

The signals open Phase 1 just after its current zero, ensuring ~ ½ cycle of arcing

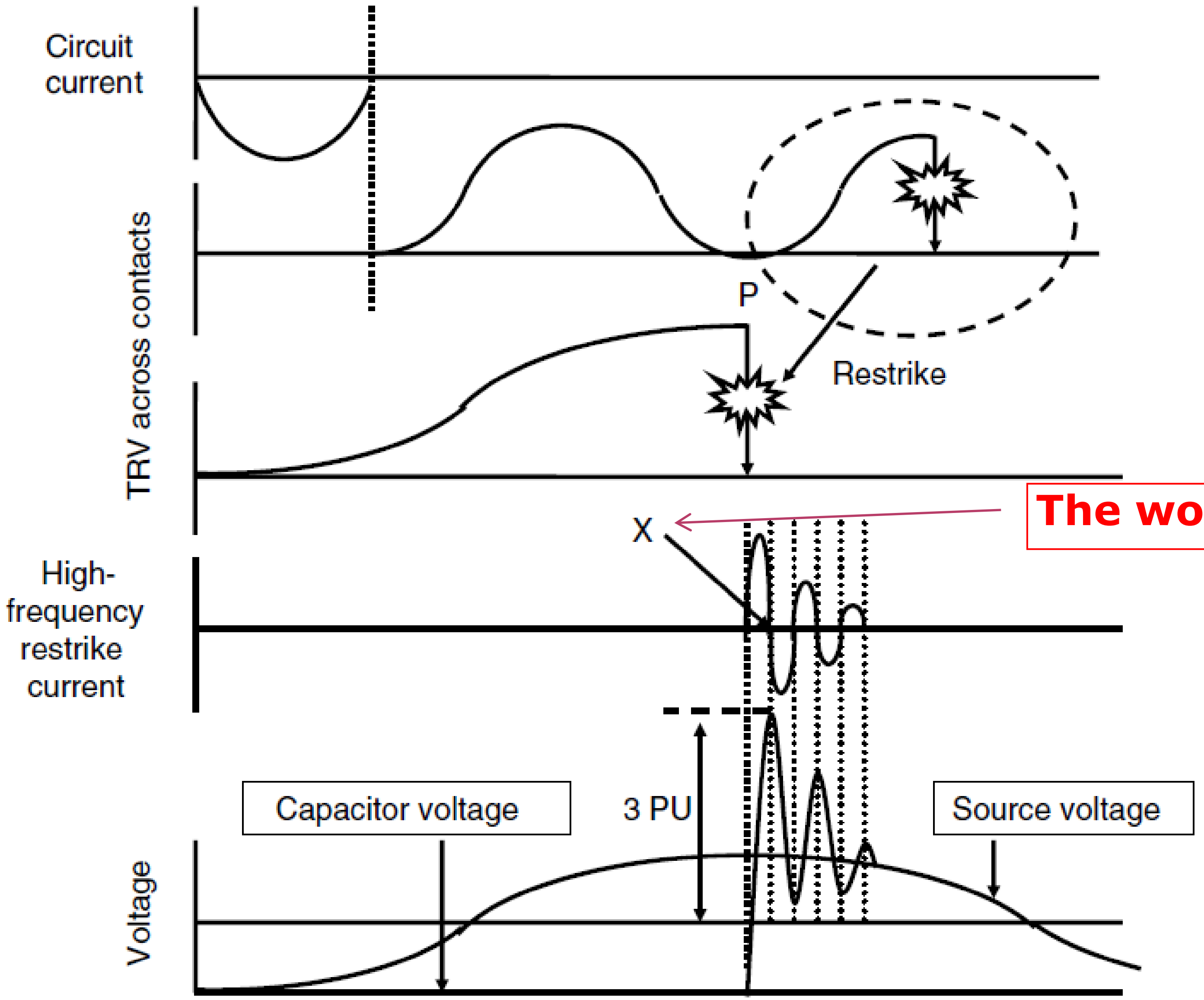
Long arcing time

Conditioning

contacts will be far enough apart withstand the peak voltage

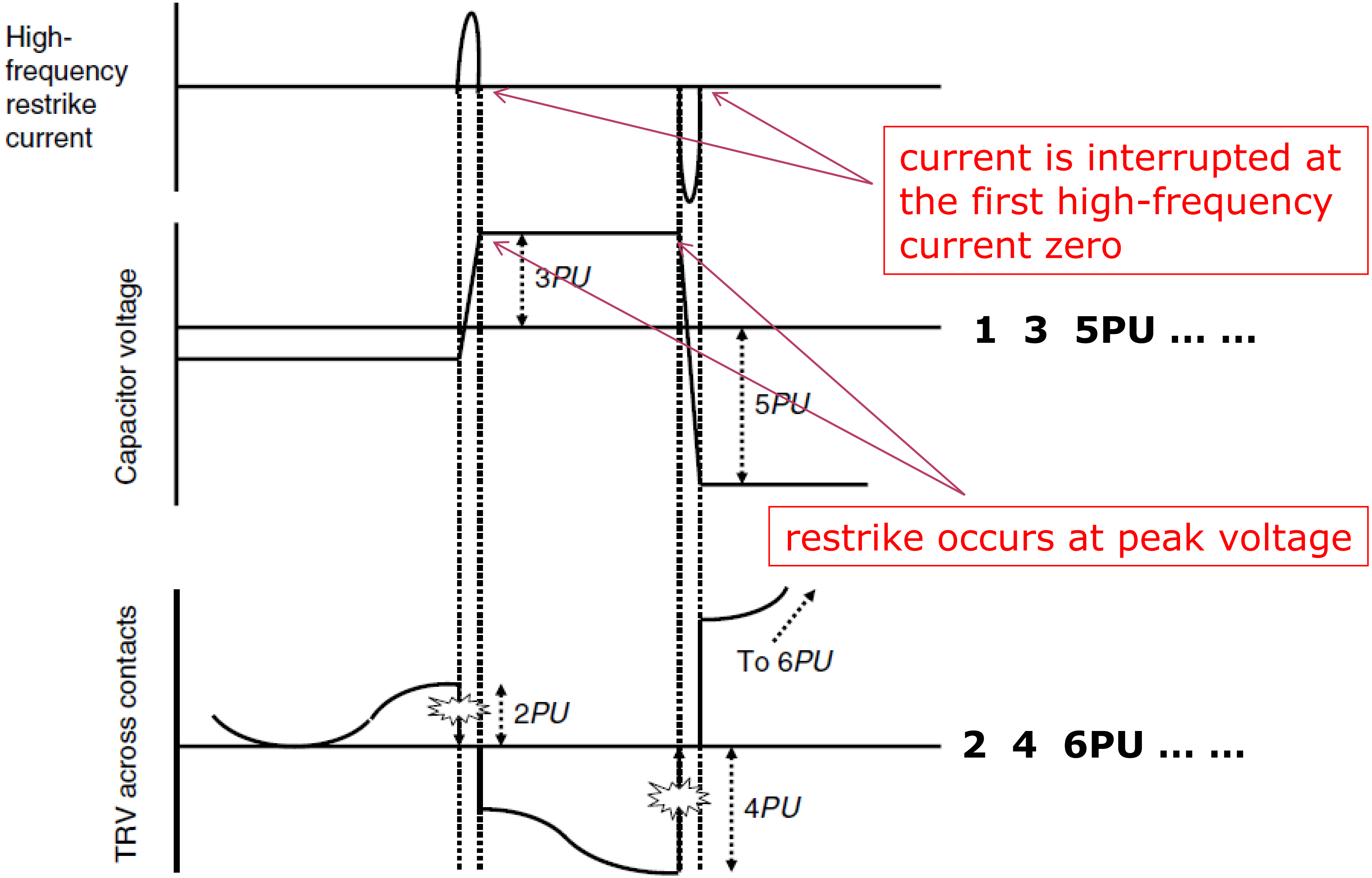
The synchronous opening of a vacuum circuit breaker with magnetic mechanisms

3.2.2 DISCONNECTING CAPACITOR BANKS



The worst case

Schematic showing the effect of a restrike at the capacitor switch when peak recovery voltage is reached.



current is interrupted at the first high-frequency current zero

1 3 5PU … …

restrike occurs at peak voltage

2 4 6PU … …

Schematic of a worst-case scenario when the first restrike at the capacitor switch occurs at the peak of the recovery voltage and the high-frequency current is interrupted at its first current zero. It also shows the possible further voltage escalation events

a successful capacitor switch

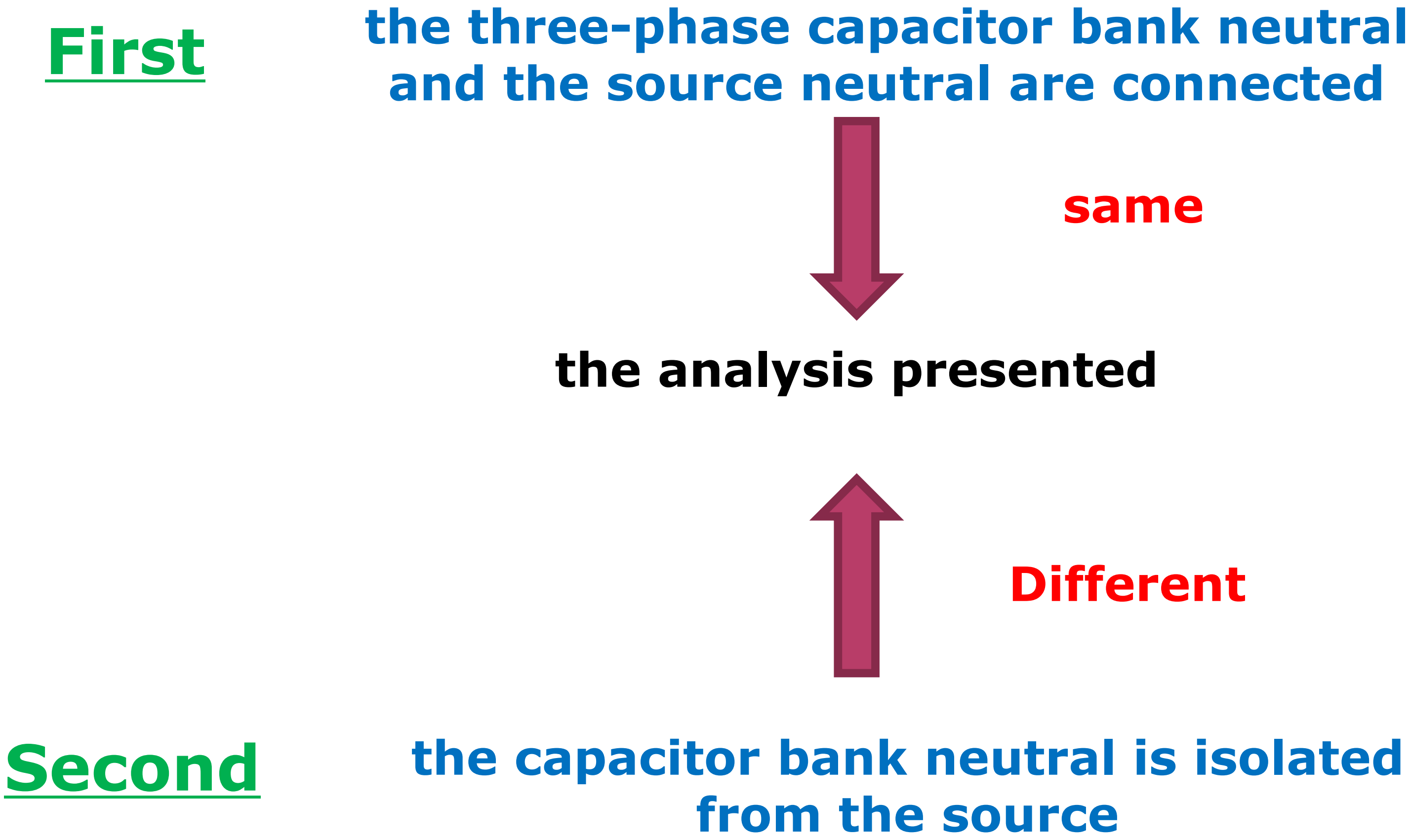
Peak recovery voltage:75 kV

The inrush current :6 kA

Spring Mechanism

A practical capacitor switch using a vacuum interrupter with Cu–W (10 wt%) contacts. (Courtesy Joslyn Hi-Voltage.)

3.2.3 SWITCHING THREE-PHASE CAPACITOR BANKS



First

the three-phase capacitor bank neutral and the source neutral are connected

same

the analysis presented

Different

Second

the capacitor bank neutral is isolated from the source

The Differences

Case 1: synchronous closing and opening

$$\left.\begin{array}{ll}\textbf{Phase A:} & 2.5 \times \sqrt{2}U_{(\ell-\mathrm{n})} \\ \textbf{Phase B:} & \left(1+\{\sqrt{3}/2\}\right) \times \sqrt{2}U_{(\ell-\mathrm{n})} \\ \textbf{Phase C:} & \left(1+\{\sqrt{3}/2\}\right) \times \sqrt{2}U_{(\ell-\mathrm{n})}\end{array}\right\} \textit{Maximum values}$$

Case 2: The three phases of the capacitor switch do not open and close at the same time

substantially higher

The peak voltage → **the synchronous opening case**

3.2.4 RECOVERY VOLTAGE, RESTRIKINNG AND NSDDS AFTER CAPACITOR SWITCHING

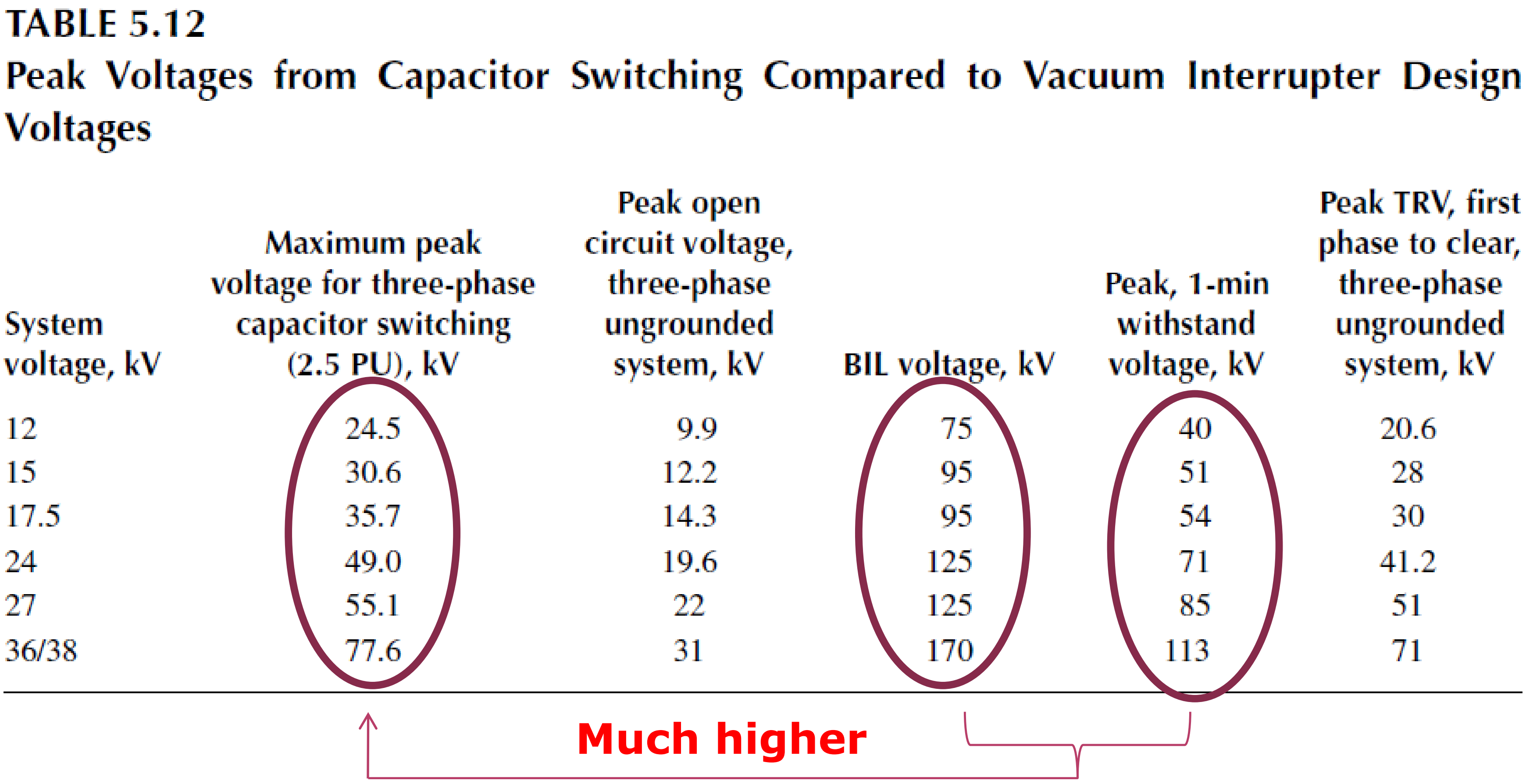


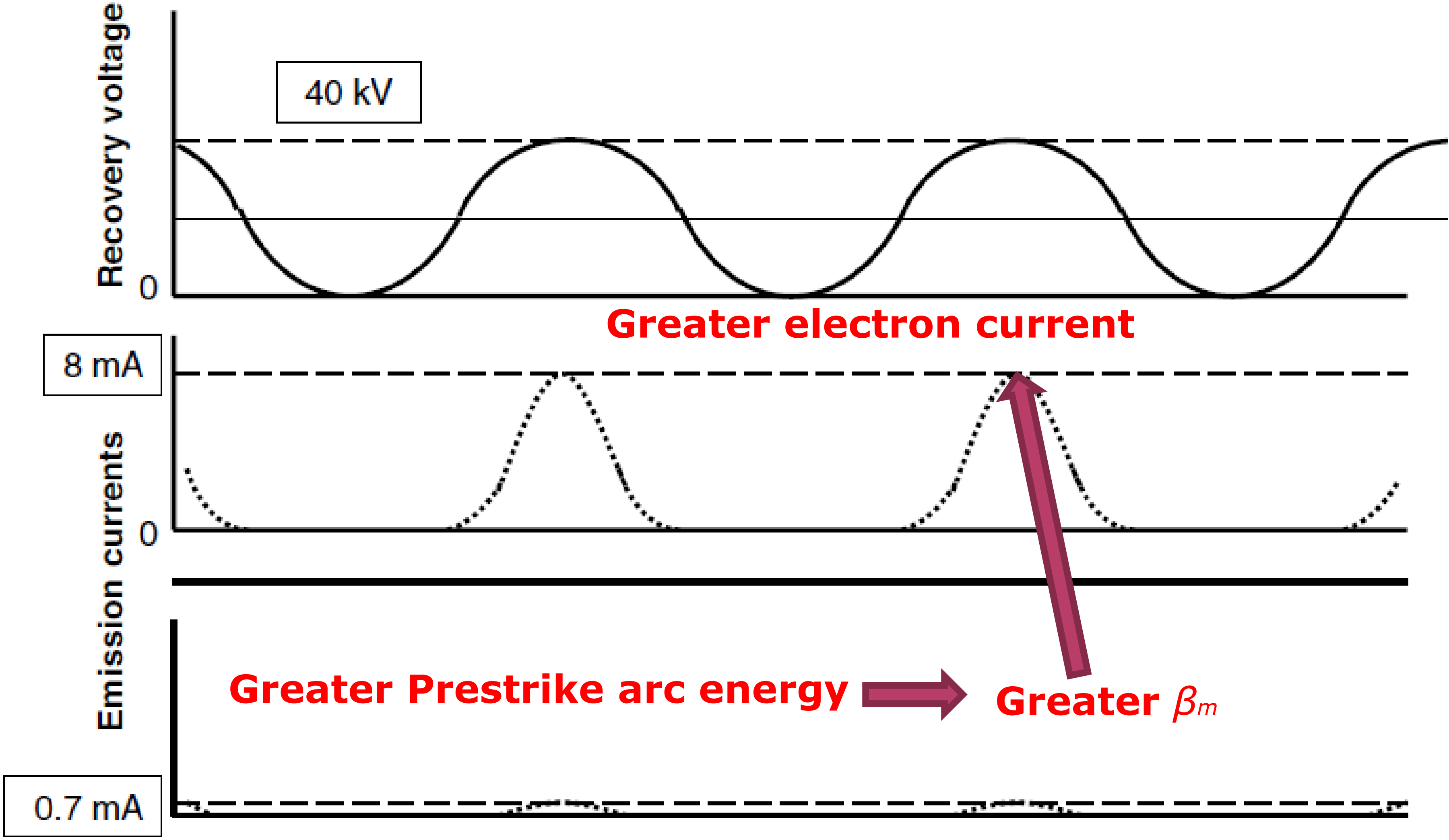
TABLE 5.12

Peak Voltages from Capacitor Switching Compared to Vacuum Interrupter Design Voltages

System voltage, kV	Maximum peak voltage for three-phase capacitor switching (2.5 PU), kV	Peak open circuit voltage, three-phase ungrounded system, kV	BIL voltage, kV	Peak, 1-min withstand voltage, kV	Peak TRV, first phase to clear, three-phase ungrounded system, kV
12	24.5	9.9	75	40	20.6
15	30.6	12.2	95	51	28
17.5	35.7	14.3	95	54	30
24	49.0	19.6	125	71	41.2
27	55.1	22	125	85	51
36/38	77.6	31	170	113	71

Much higher

Possible reasons: microdischarges, microparticles



Greater electron current

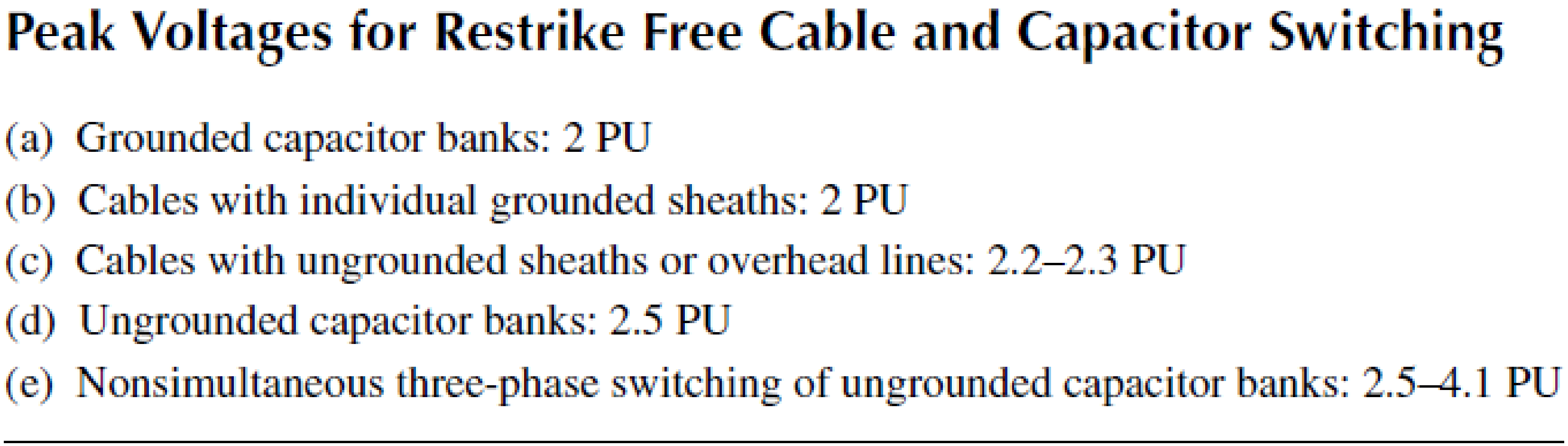
Greater Prestrike arc energy → Greater β_m

Examples of measured emission currents between Cu and Cr contacts after connecting a capacitor bank with an inrush current of 6.3 kA (peak) and disconnecting it.

3.2.5 SWITCHING CABLES AND OVERHEAD LINES

Similarly to a capacitor

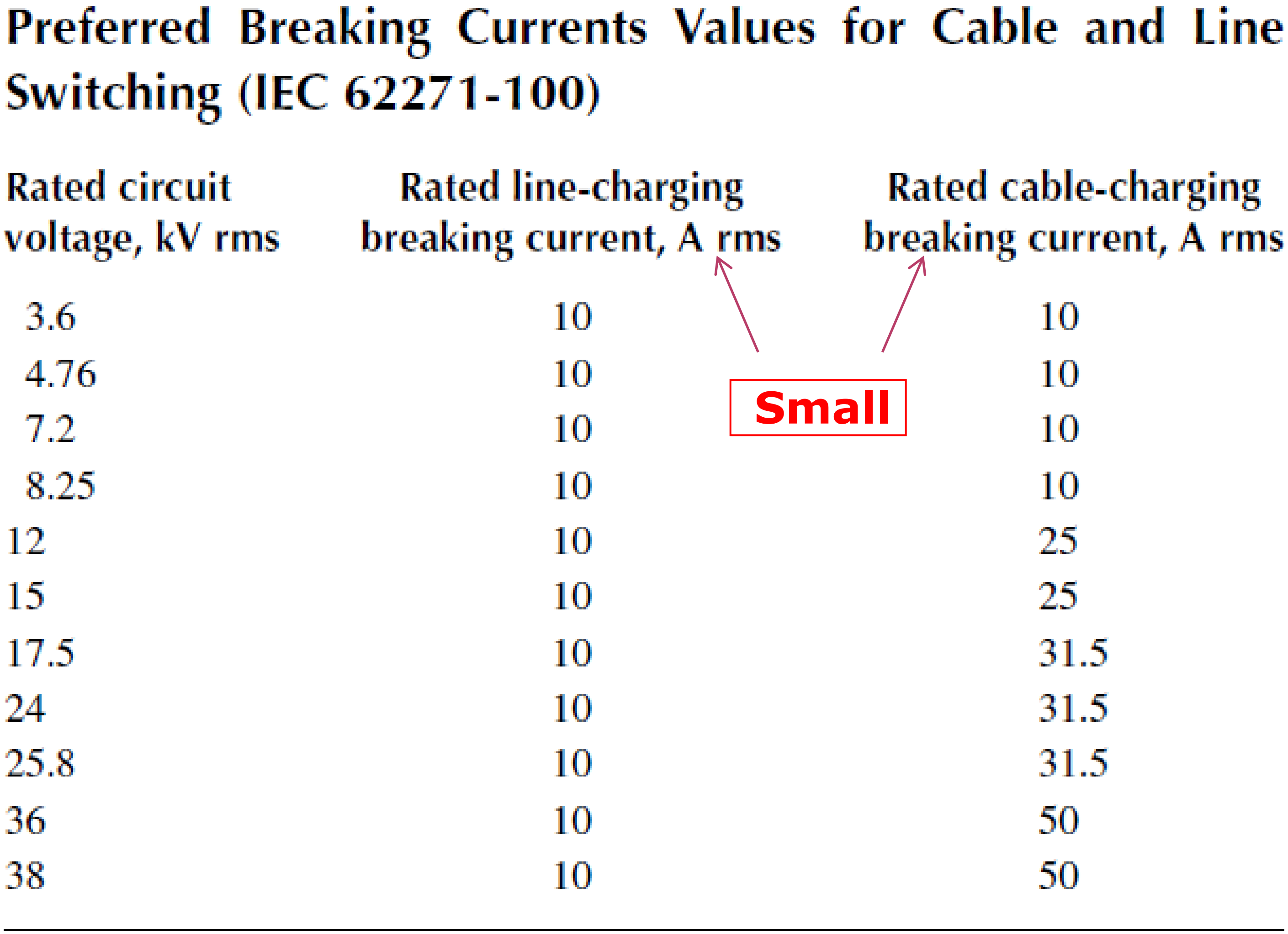
The capacitance is distributed



Peak Voltages for Restrike Free Cable and Capacitor Switching

(a) Grounded capacitor banks: 2 PU
(b) Cables with individual grounded sheaths: 2 PU
(c) Cables with ungrounded sheaths or overhead lines: 2.2–2.3 PU
(d) Ungrounded capacitor banks: 2.5 PU
(e) Nonsimultaneous three-phase switching of ungrounded capacitor banks: 2.5–4.1 PU

When a cable, with an open, remote end is disconnected, the interrupter switches just the charging current of the cable.



Preferred Breaking Currents Values for Cable and Line Switching (IEC 62271-100)

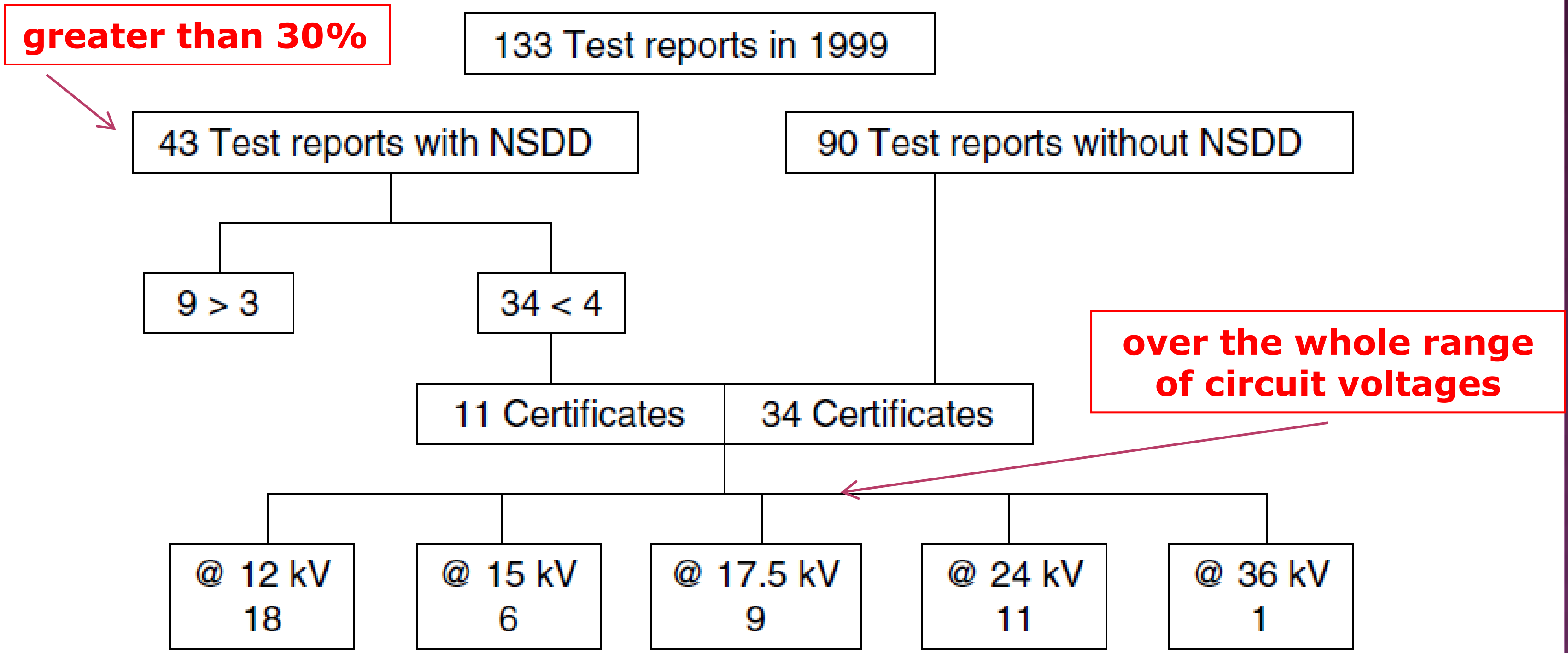
Rated circuit voltage, kV rms	Rated line-charging breaking current, A rms	Rated cable-charging breaking current, A rms
3.6	10	10
4.76	10	10
7.2	10	10
8.25	10	10
12	10	25
15	10	25
17.5	10	31.5
24	10	31.5
25.8	10	31.5
36	10	50
38	10	50

Small

3.3 LATE BREAKDOWN AND NONSUSTAINED DISRUPTIVE DISCHARGES

NSDD: *Nonsustained Disruptive Discharges*

In the circuit breakers standards (e.g., IEC, IEEE/ANSI) these self-restoring, late breakdowns are termed N*SDD*



greater than 30%

133 Test reports in 1999

43 Test reports with NSDD

90 Test reports without NSDD

9 > 3

34 < 4

11 Certificates

34 Certificates

over the whole range of circuit voltages

@ 12 kV 18

@ 15 kV 6

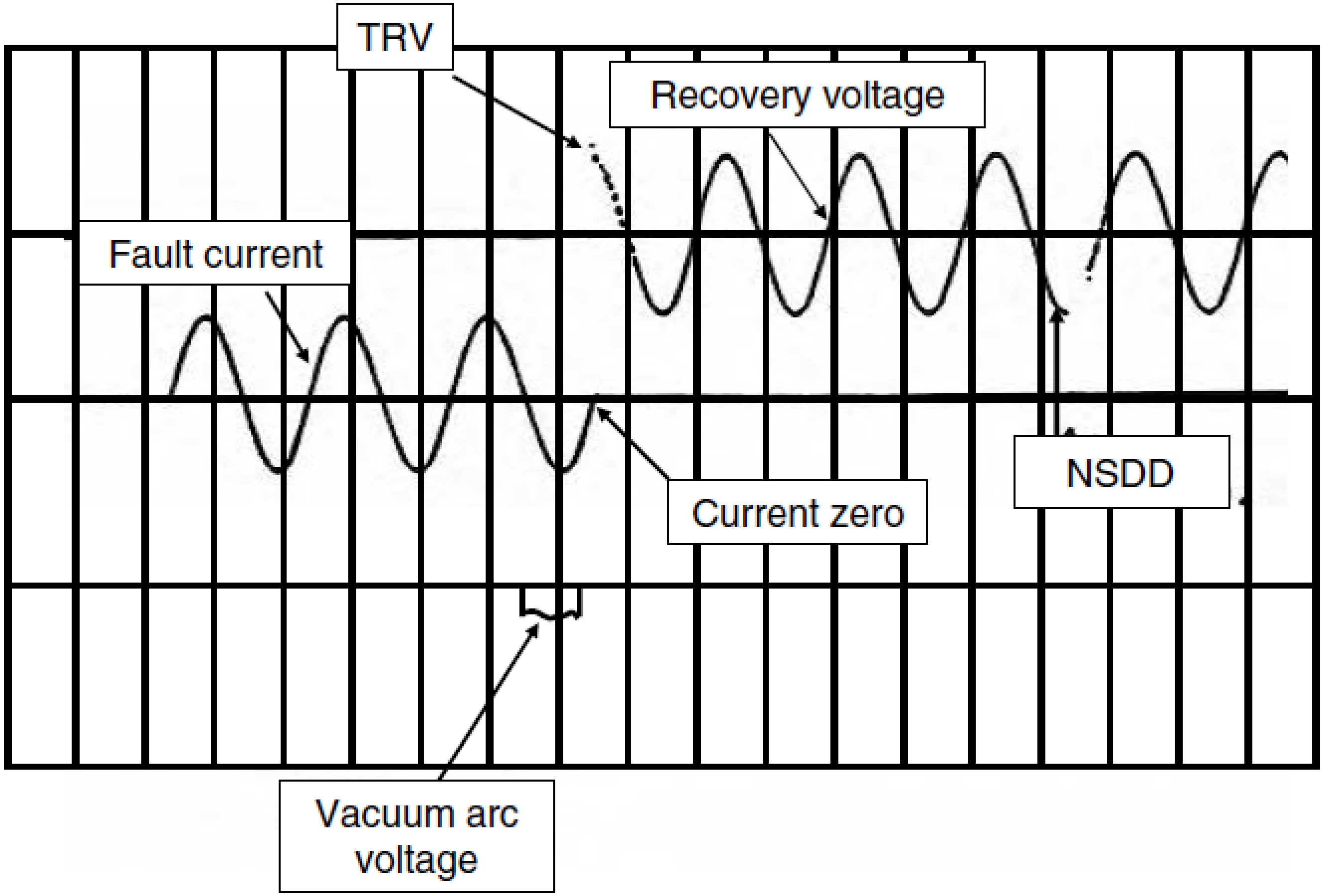
@ 17.5 kV 9

@ 24 kV 11

@ 36 kV 1

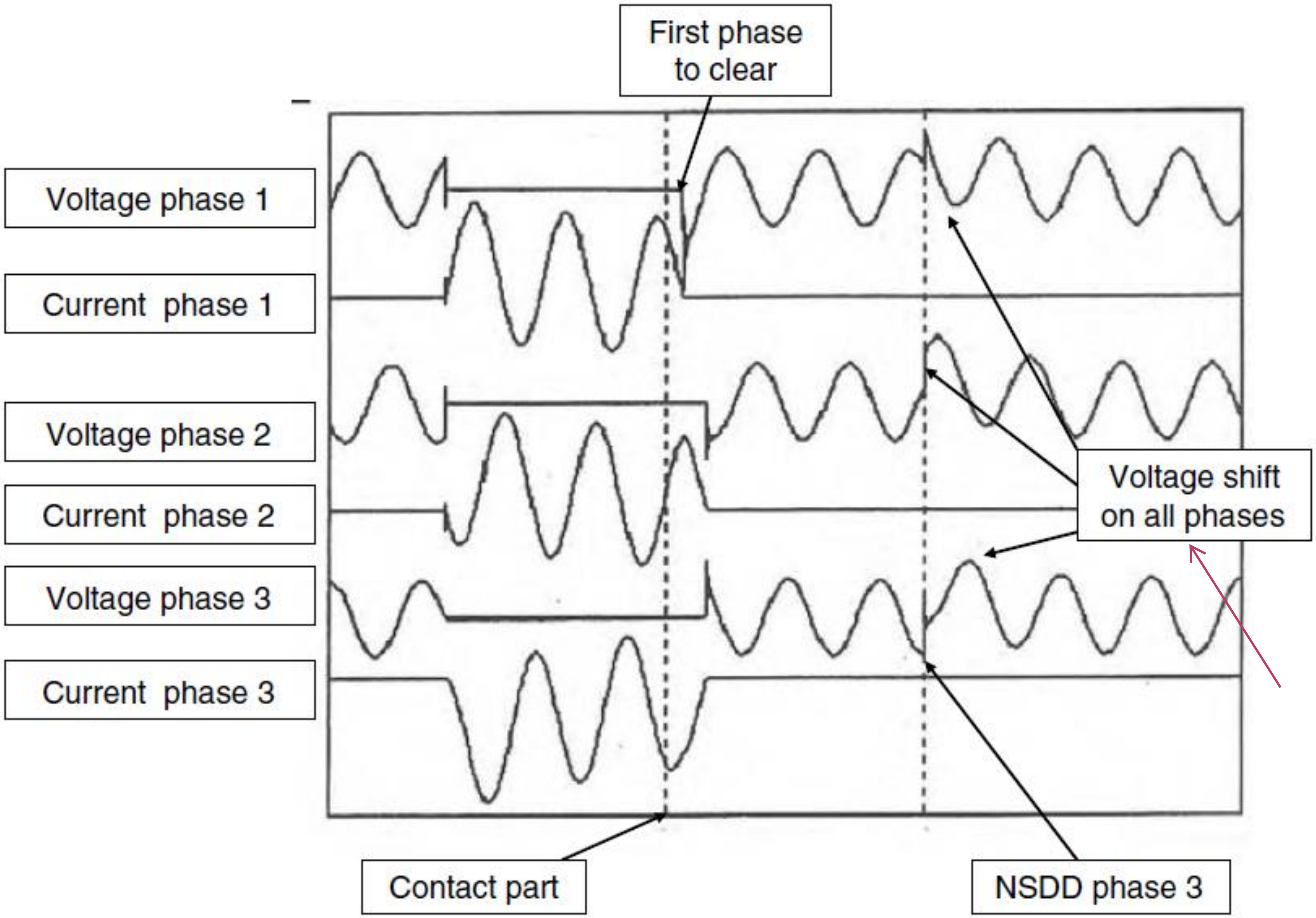
The occurrence of NSDDs during certification testing at the KEMA Testing Laboratory(Holland) in 1999

EXAMPLE 1: NSDD in a single-phase circuit



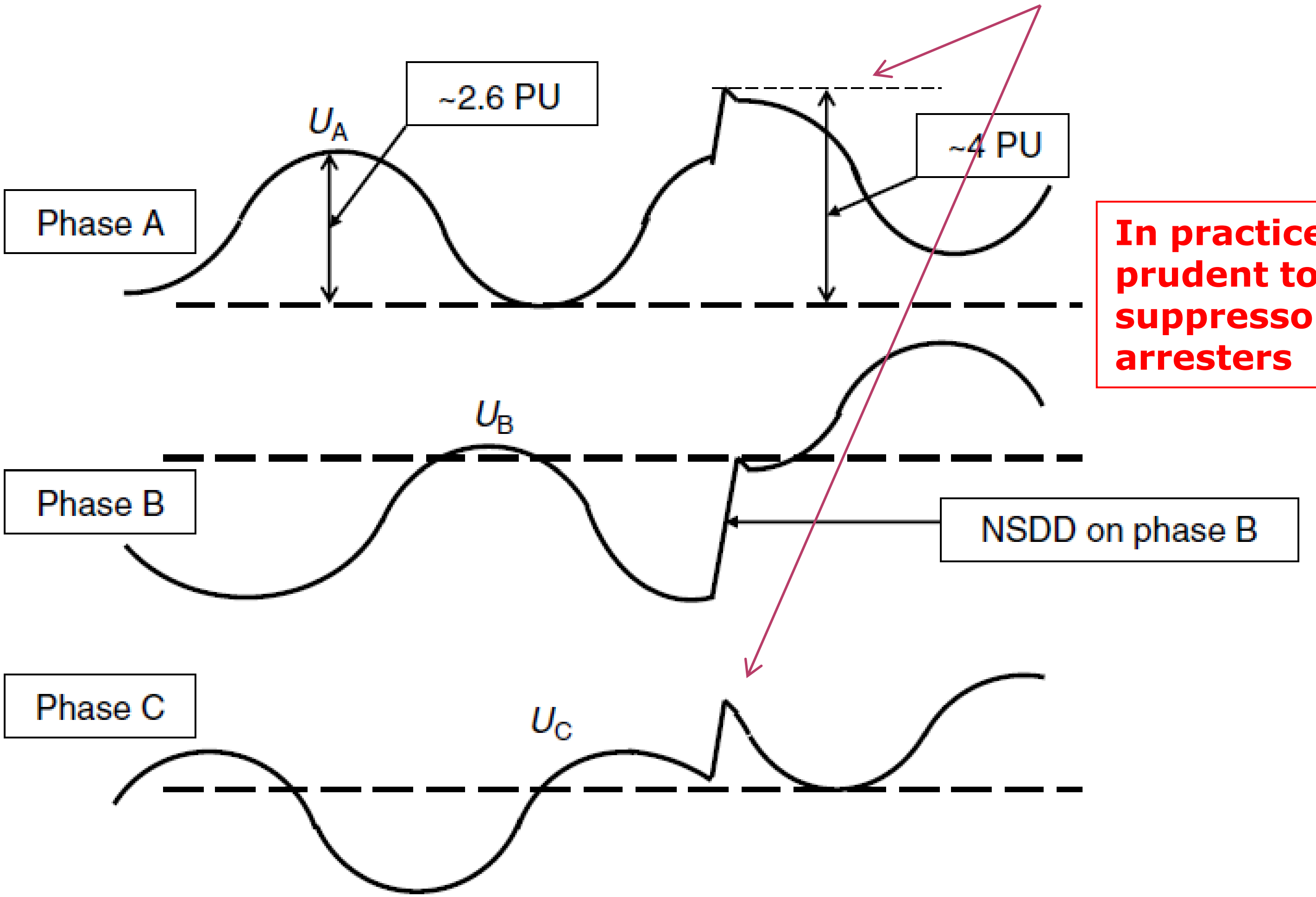
An example of an NSDD after the interruption of a single-phase fault current

EXAMPLE 2: NSDD in a three-phase ungrounded system. circuit



An example of an NSDD occurring on one phase after the interruption of a three-phase fault in an ungrounded circuit.

EXAMPLE 3: NSDD in a three-phase ungrounded capacitor bank



NSDD can result in a shift of the neutral voltage

In practice it may be prudent to install surge suppressors or lightning arresters

An example of an NSDD while switching a three-phase ungrounded capacitor bank

NSDD --- No definitive physical explanation at present

Experimental observations :

1 The occurrence of a late breakdown decreases exponentially with time after current interruption

2 Late breakdowns can occur after switching all current levels

3 The probability of late breakdown occurrence increases as the voltage impressed across the vacuum contact gap increases

.

.

.

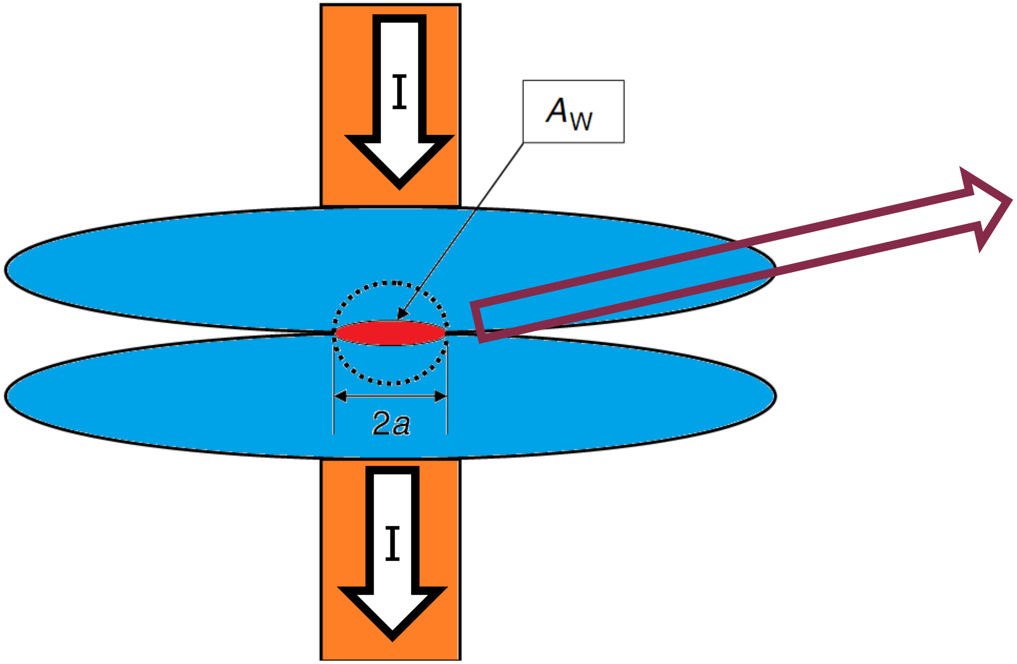
.

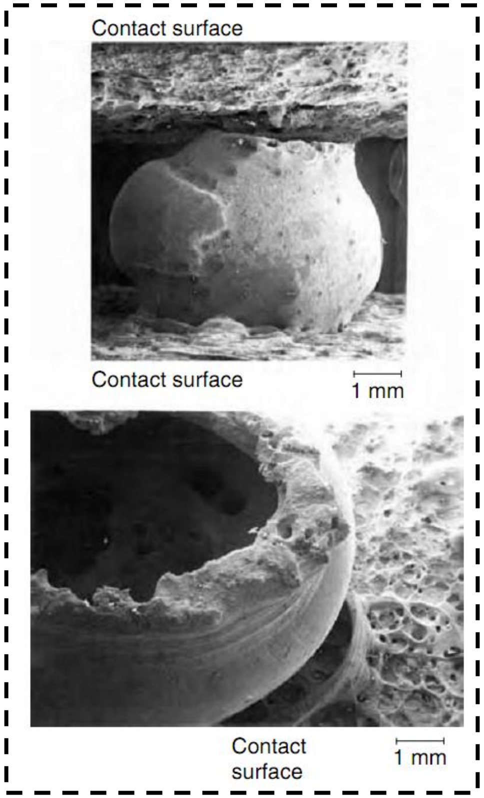
.

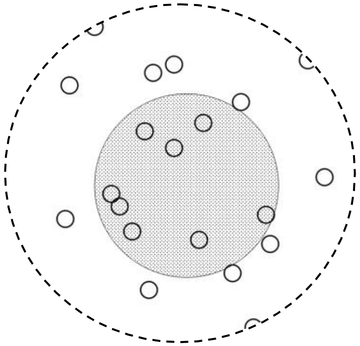
.

CONTACT WELDING

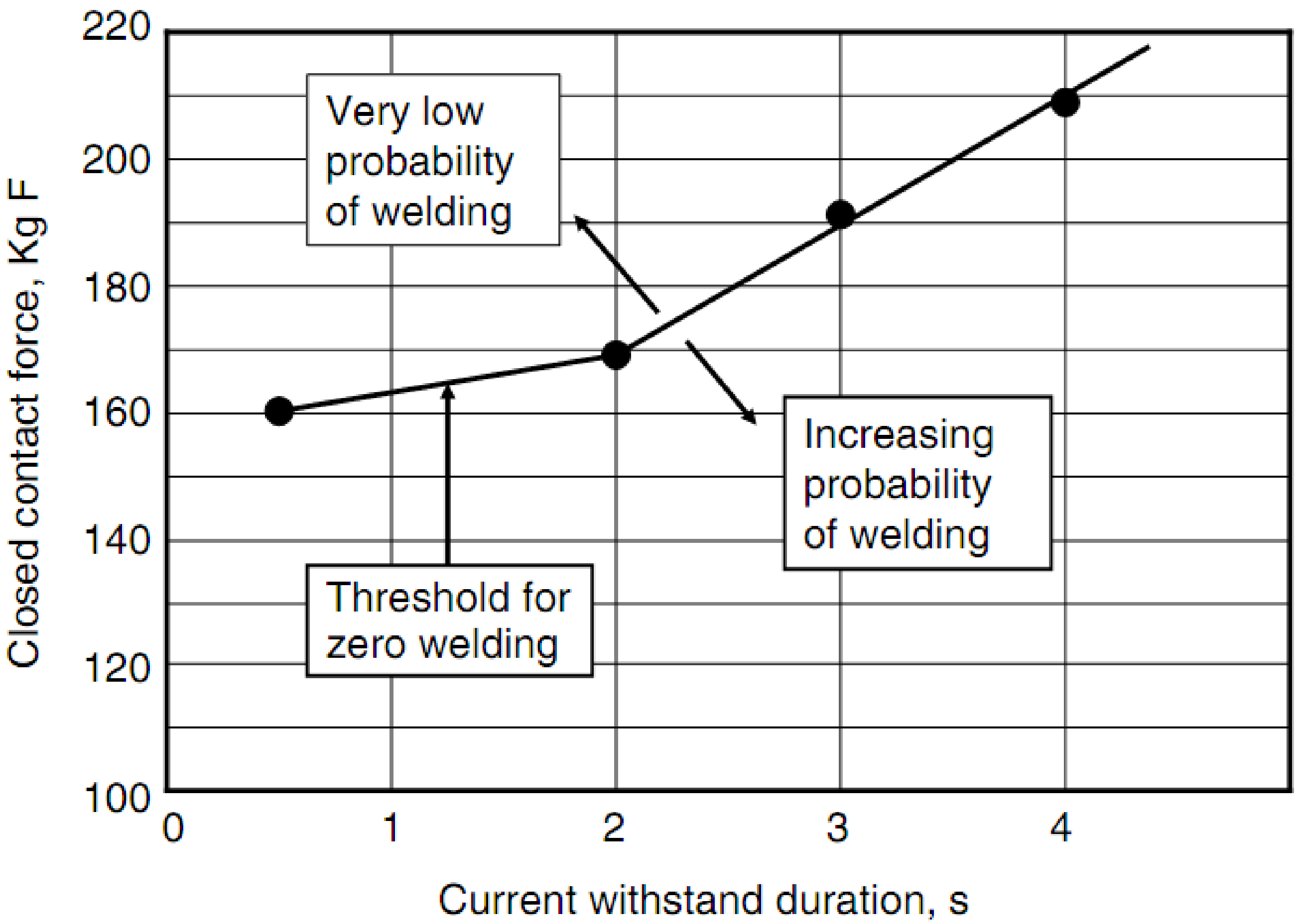
WELDING OF CLOSED CONTACTS





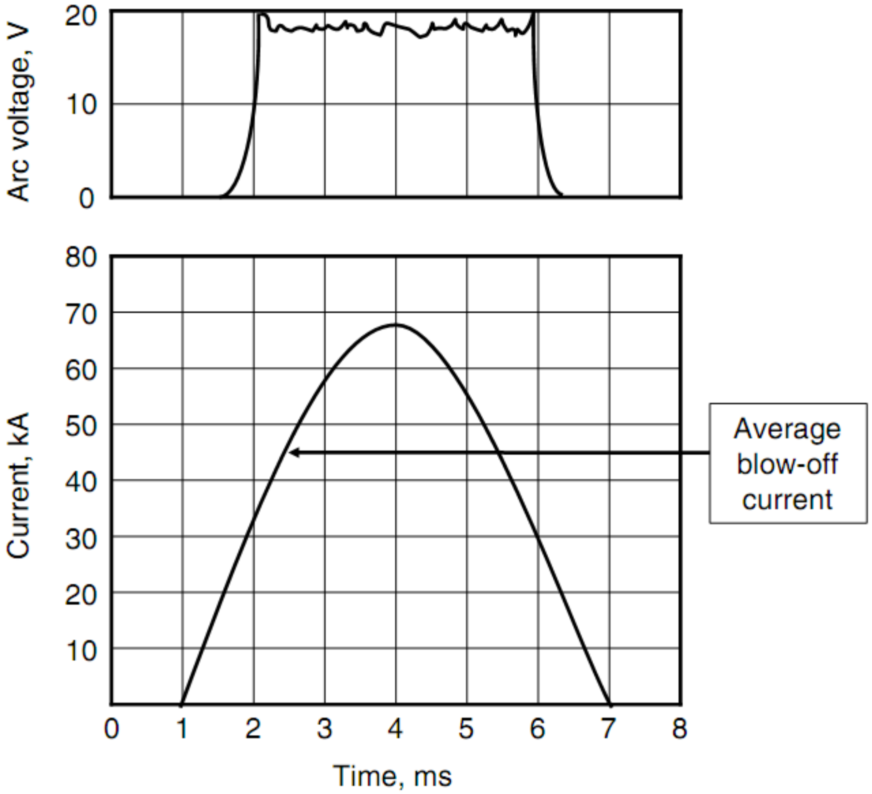


WELDING OF CLOSED CONTACTS WHEN SHORT FAULT CURRENT PASSES THEM



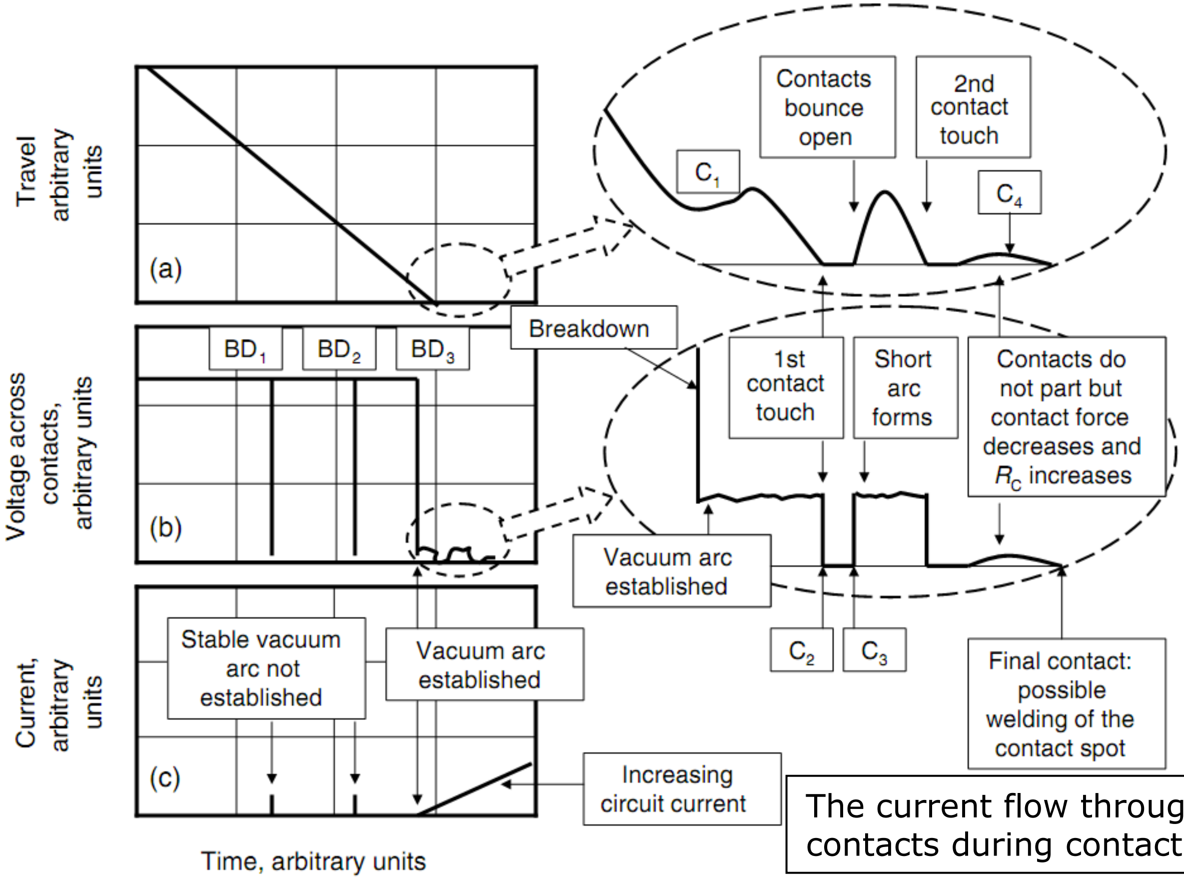
The probability of CuCr25 contacts welding as a function of the closed contact force and the duration of the 20kA (rms) current

WELDING OF CLOSED CONTACTS WHEN SHORT FAULT CURRENT PASSES THEM



Current pulse through butt-shaped Ag-WC contacts showing the average current where blow-off force resulted in the contacts opening and the formation of a short high current arc. Here the contacts blow apart at 45kA and no welding is observed.

WELDING WHEN CONTACTS CLOSE ELECTRICAL CIRCUITS



The travel showing contact bounce

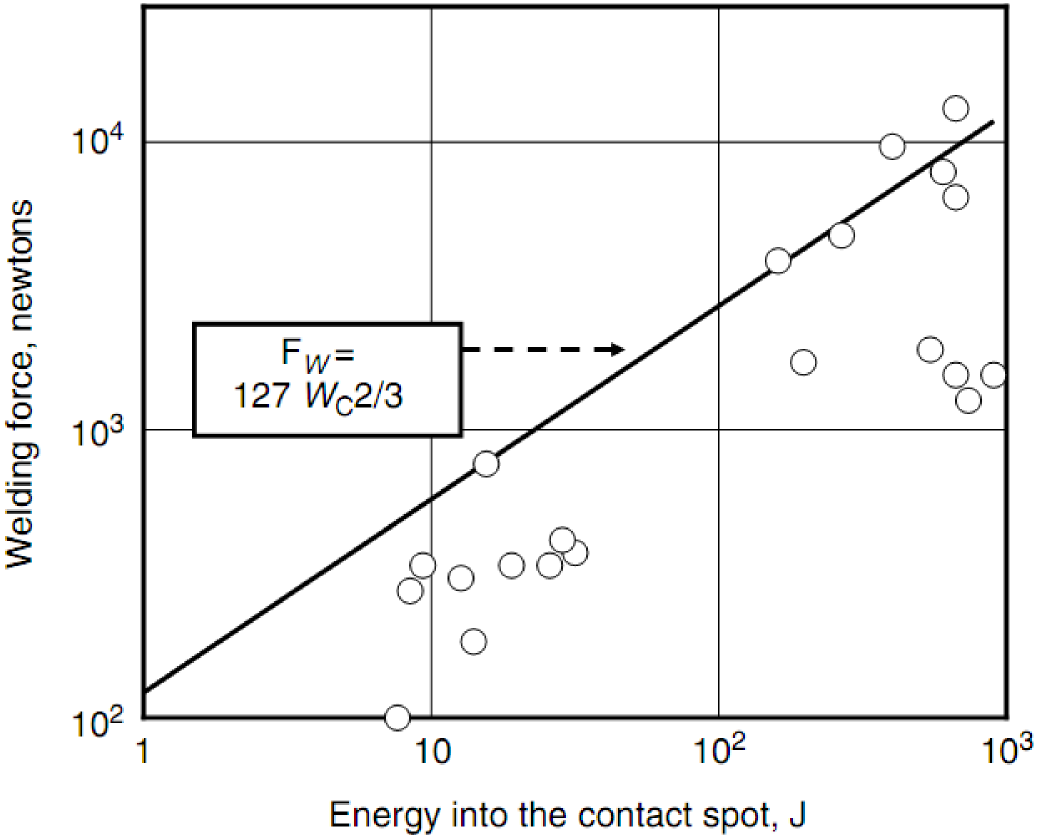
The prestrike breakdown, arcing , and arc formation during the contact bouncing

The current flow through the contacts during contact closing

Schematic diagrams of vacuum interrupter contact closing

WELDING WHEN CONTACTS CLOSE ELECTRICAL CIRCUITS

The maximum welding force as a function of the energy input into the contact spot



$$\boxed{F_W = K W_C^{2/3},}$$

For silver : $F_W = 67\ W_C^{2/3}$

For copper : $F_W = 127\ W_C^{2/3}$

$$K = \Gamma\pi \left\{ \frac{3}{4\pi\delta\left[c_V\left(T_m - T_0\right) + c_L\right]} \right\}^{2/3}.$$

Energy from the breakdown arc + Energy from the bounce arc(s)
+Energy from contact spot, heating

$$W_C = \lambda_1 \int_{t(BD)} U_A i(t)\,dt + \lambda_2 \int_{t(BC)} U_A i(t)\,dt + \int_{t(C)} U_C i(t)\,dt,$$

THANKS