Post-arc current of Forced-current-zero Vacuum Arcs

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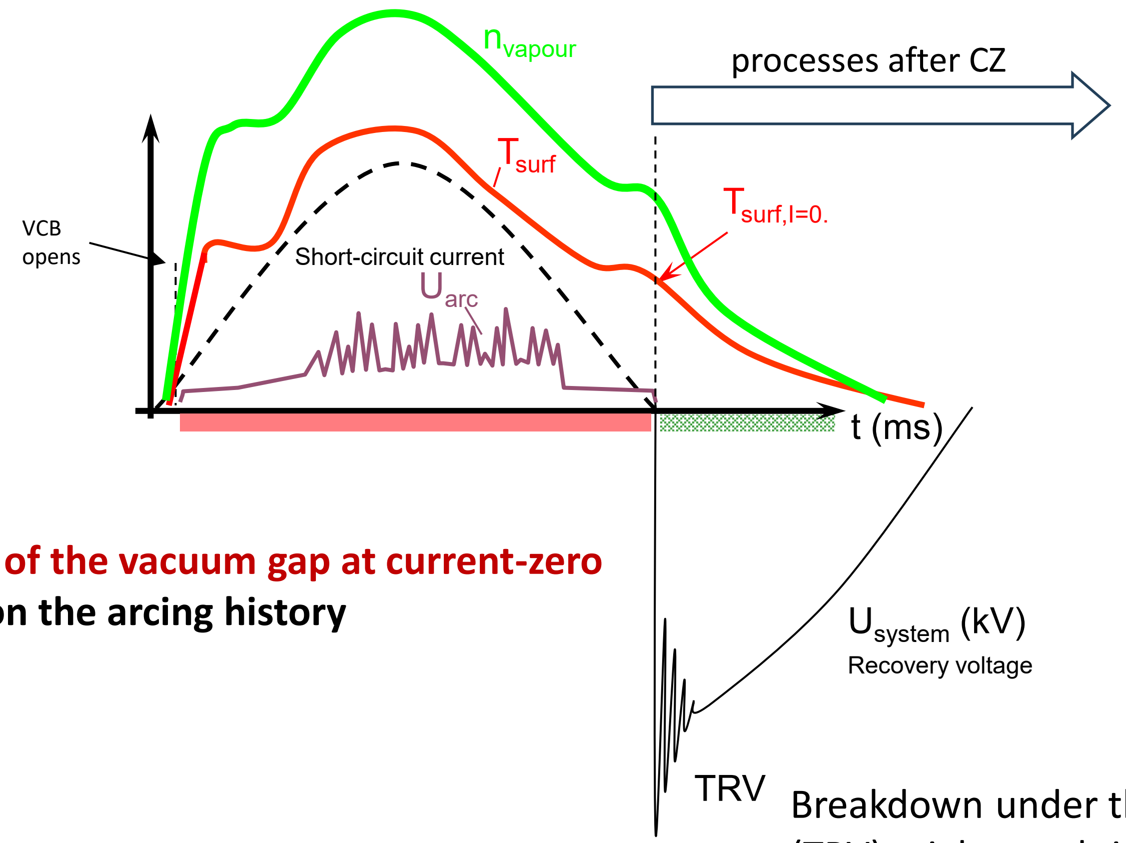
Arcing phase determines current-zero conditions



Condition of gap after CZ:

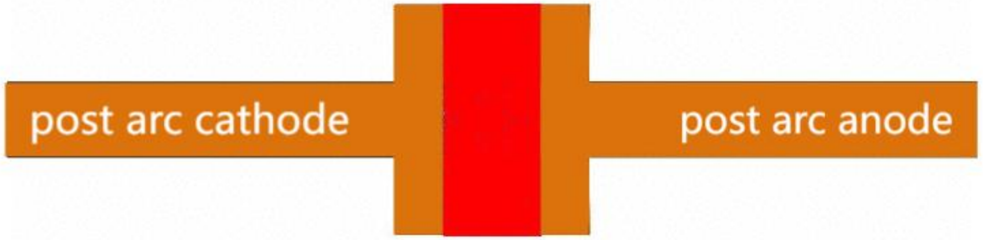
- Neutral metal vapor is evaporated from hot surfaces
- Contact surfaces are partly liquid and eject droplets.
- Plasma remains from the preceding arc and is collected under the rising voltage.

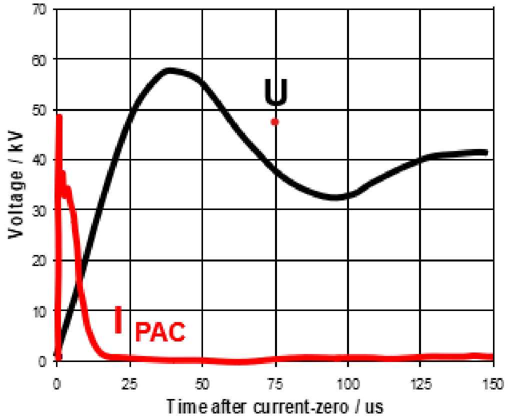
Condition of the vacuum gap at current-zero depends on the arcing history

Breakdown under the transient recovery voltage (TRV) might result in a failure of interruption.

Introduction

space charge sheath development and post-arc current

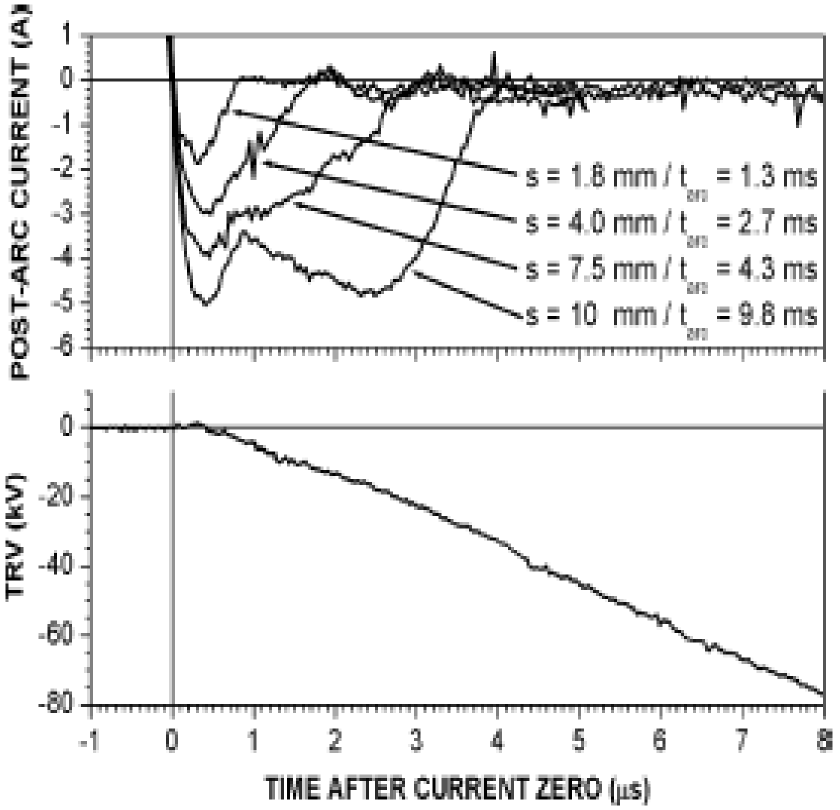




- The blue dots represents ions
- The red dots represents electrons
- A space charge sheath forms in front of the high voltage cathode and attracts ions and repels electrons until the gap is empty.
- The post-arc current is composed of ions impinging on the cathode, secondary electrons leaving the cathode and electrons collected by the anode
- In addition, there are ions and electrons recombining on the walls.

- This collected charge i.e. the integrated post-arc current presents the number of charge carriers in between the contacts
- The charge is proportional to the interrupted arc current or better the di/dt?

Post-arc current and plasma

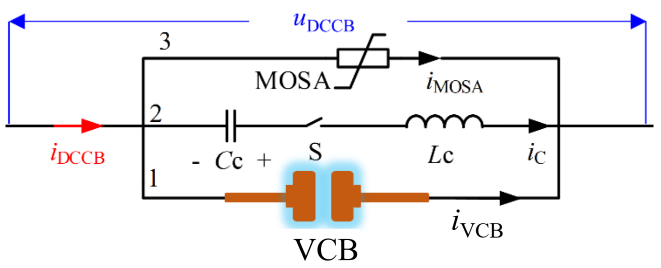


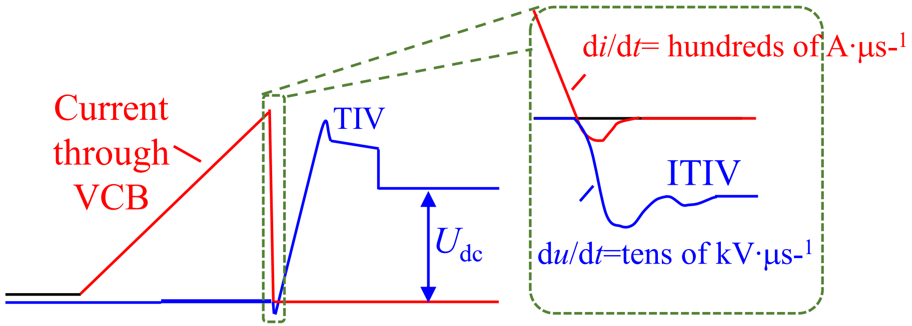
Source: K. Steinke, M. Lindmayer, K-D. Weltmann, 19th ISDEIV, Xian, pp.475-480, 2000

- Typical PAC measured after high current arcs with different arcing times and contact gaps.
- After high current arcs, the amount of residual plasma is much larger than after low current arcs.
- And the residual plasma stays much longer in the contact gap.
  – Reason is the higher density of metal vapor slowing down the ions via charge exchange and thermal collisions.
- **The presence of ions and electrons could impact the voltage recovery behaviour only for several µs up to several 10 µs after current-zero.**

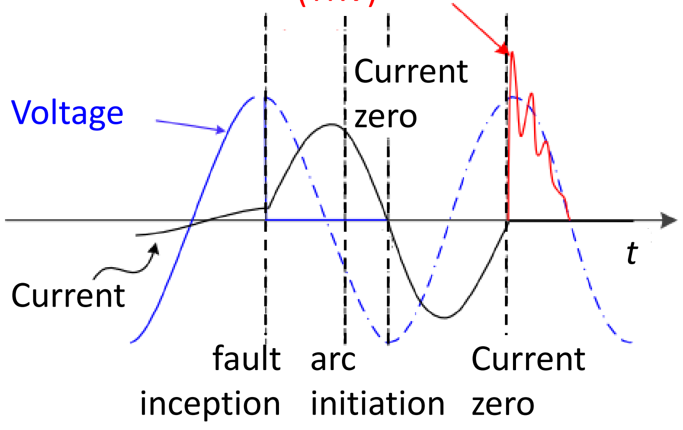
Motivation

DC interruption





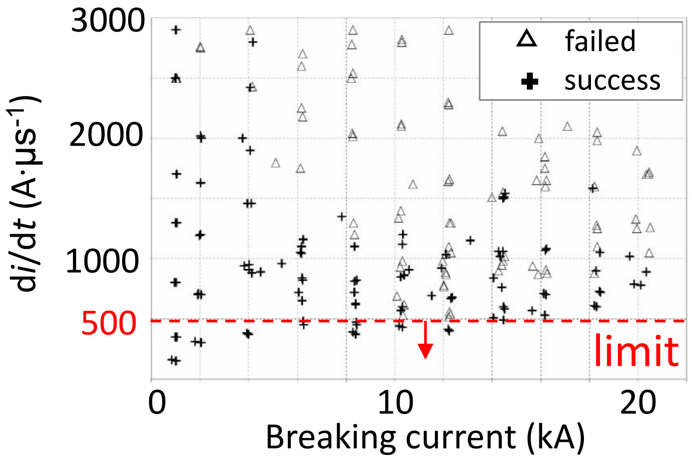
AC interruption



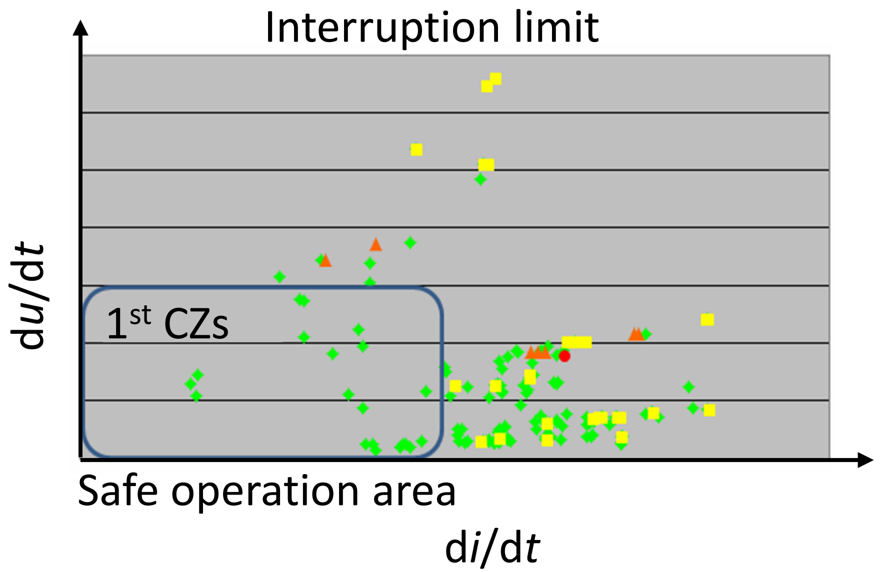
DC interruption	AC interruption
Rapid interruption by VCB (3~5 ms)	Longer arcing time (5~12 ms)
Steep ITIV	Slower ITRV (usually smaller than kV·μs-1)
Stressed by high TIV and then long U_{dc}	Stressed by high TRV and then power freq. volt.

Smeets, R. P. P. and N. A. Belda (2020). "High-voltage direct current fault current interruption: A technology review." High Voltage **6**(2): 171-192.

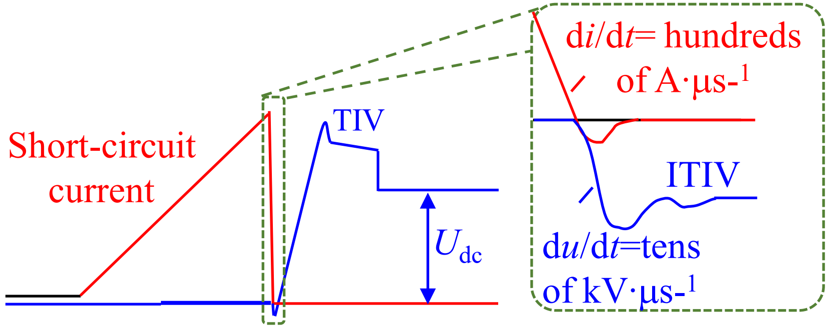
VIs must handle high d*i*/dt & d*u*/dt in DC interruptions



T. Heinz, et al., Direct current interruption with commercially available vacuum interrupters, ISDEIV2014, Mumbai, India, 2014, pp. 425-428.



ERIKSSON, T., et al., A low loss mechanical HVDC breaker for HVDC Grid applications, CIGRE 2014, Paris.



Large d*i*/dt → High residual particles

Steep d*u*/dt → Fast removal of charges

Post-arc current connects to movement of charges

- Featured with large values
  - S. Tokoyoda, et al.: reported a typical value of 118A (@d*i*/d*t* =397 A·μs^{-1}, d*u*/d*t*=18 kV ·μs^{-1})

- Unclarified relation with DC interruption performance

peak arcing current | d*i*/d*t* at CZ | d*u*/d*t* of ITIV | peak ITIV

arcing memory, plasma density, plasma dissipation, voltage withstanding

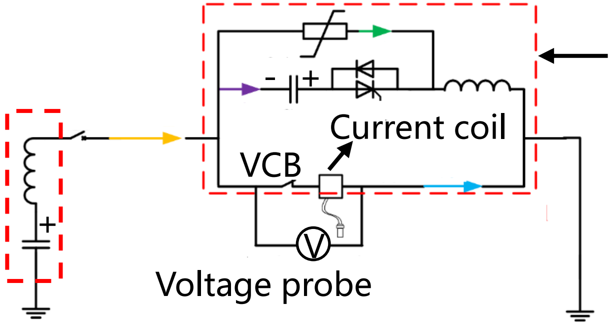
post-arc current

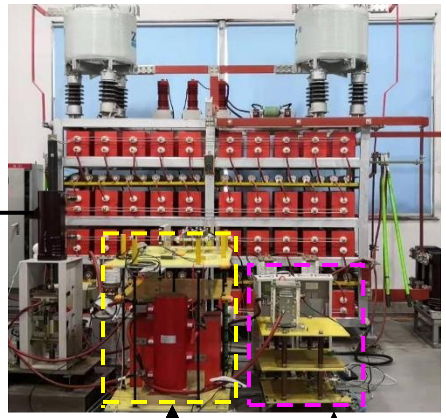
current interruption

Intentional experimental investigation

- Features of post-arc current in DC interruption
  - Amplitude
  - Duration
  - Quantity of residual charges
- Factors that influence the post-arc current
  - Amplitude of the breaking current
  - Polarity of the breaking current
  - Current derivative at the forced current zero
  - Gap length between electrodes at the forced current zero
- Analysis about post-arc current and the performance of the VI

Circuit & Measurement configuration

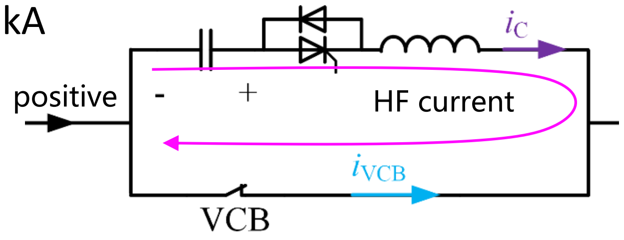




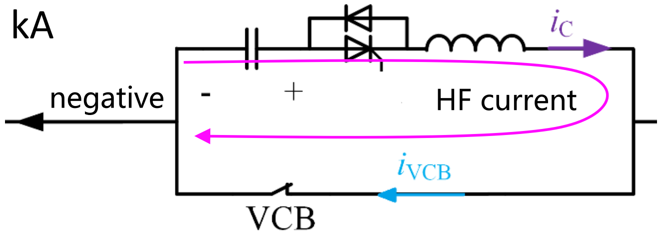
- Current source
  - Generating a current of 35 Hz, simulating the DC fault current
- Active mechanical DCCB
  - Rated 10 kV
  - Peak TIV=1.5 p.u.
  - High frequency injection current of 5.7 kHz.
- Data acquisition system
  - Current measured by a Rogowski coil, having a dynamic range extending from mA to tens of kA
  - Voltage is measured by an HV probe
  - Data transferred by HBM modules
  - Data registered at a remote device.

Investigated testing cases

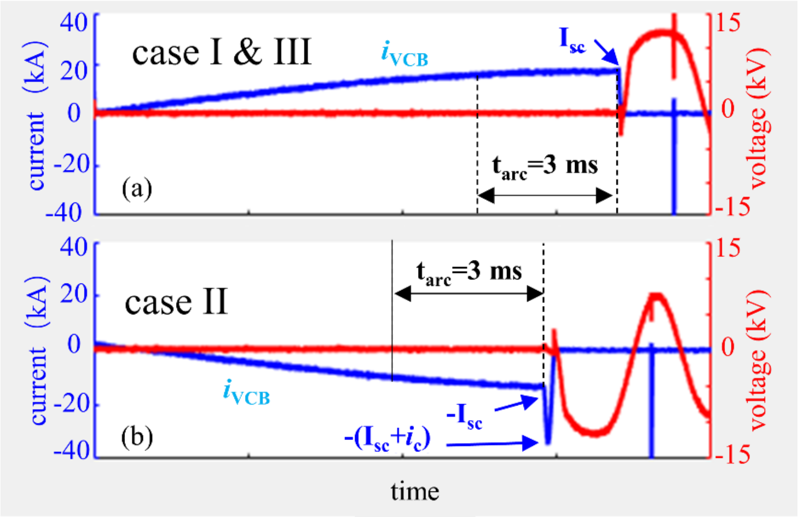
- Basic experiments (case I)
  - Interrupts +0.5 ~ +20 kA
  - d*i*/d*t* ranges 200~1100 A·μs^{-1}



- Comparative experiments (case II)
  - Interrupts -0.5 ~ -5 kA
  - d*i*/d*t* ranges 200~1100 A·μs^{-1}



- Comparative experiments (case III)
  - Reduced gap length
  - Other configurations=case I

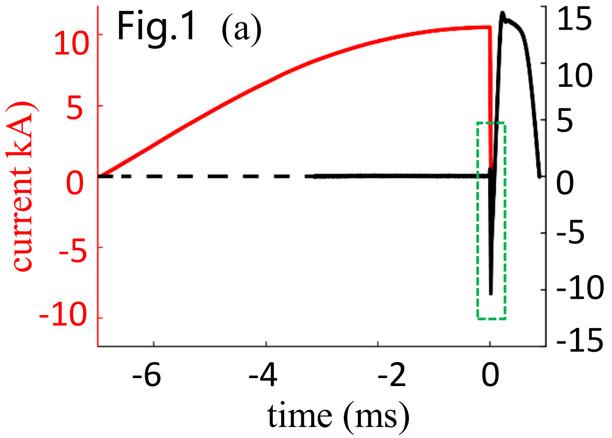


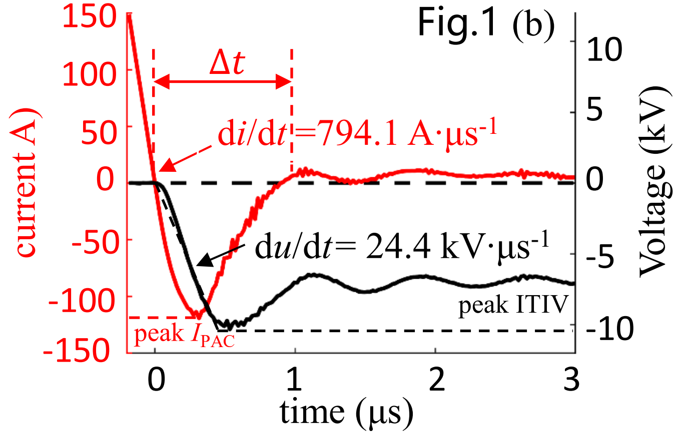
	Case I	Case II	Case III
Breaking current polarity	+	-	+
Gap (mm)	7	7	4
t_{arc} (mm)	3	3	3

Experiment

Typical waveforms and definitions of quantities

- A record of interrupting +10 kA





peak I_{PAC}=119.3 A

$\Delta t \approx 1\ \mu s$

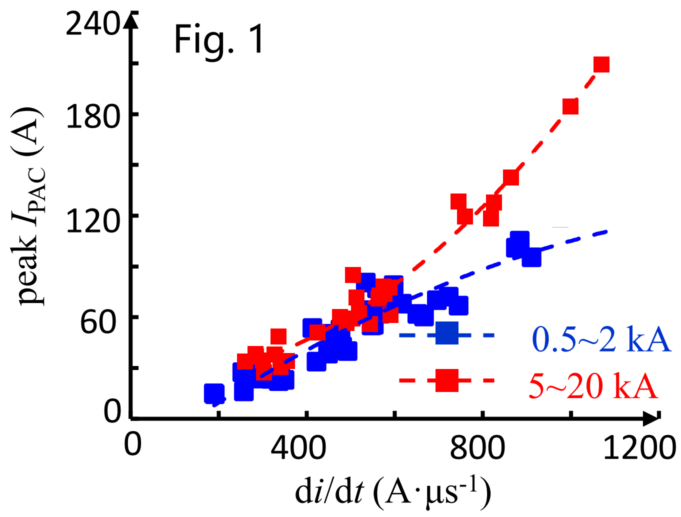
$\int i_{PAC} dt = 76.2\ \mu C$

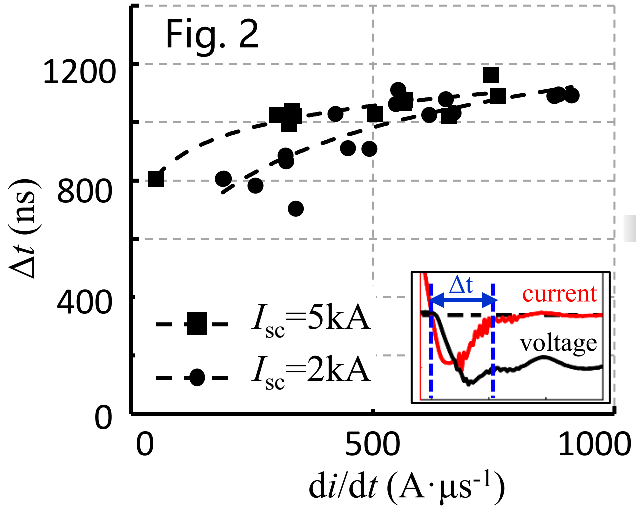
peak ITIV= -10.3 kV

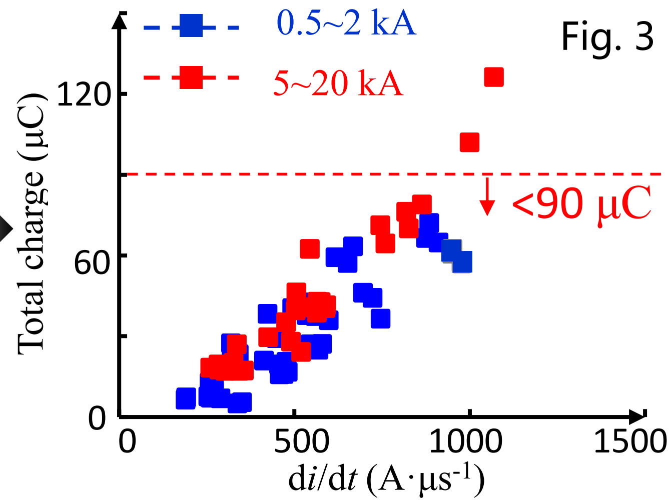
- Quantities that characterize the post-arc current
  - d*i*/d*t* & Peak post-arc current I_{PAC}
  - duration
- Quantities that characterize the ITIV
  - d*u*/d*t* & peak ITIV

Results

Interrupting positive current, gap length=7 mm (case I)







- Peak post arc current does reach a very high value but its duration is much shorter than in AC cases.
- Considering that d*u*/d*t* is much higher than RRRV in AC interruption, the high peak post arc current infers much faster movement of charged particles and as a result, a sheath developing faster.
- Total charges during PAC in DC interruption have approximate order of magnitude as AC interruption.

Influence of pre-CZ arcing current on post-arc current

- Fig. 1 and Fig. 2: different breaking currents but peak arcing currents in case II compare with that in case I.
- Post-arc currents in in case II compare with that in case I.

Influences start from not earlier than the moment of peak current

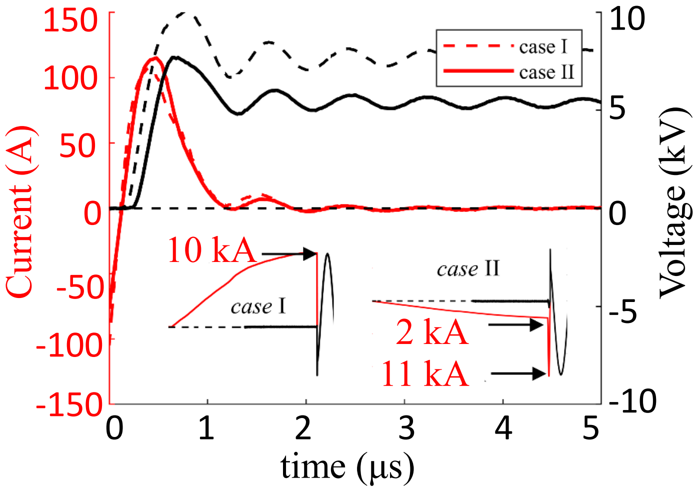


Fig. 1

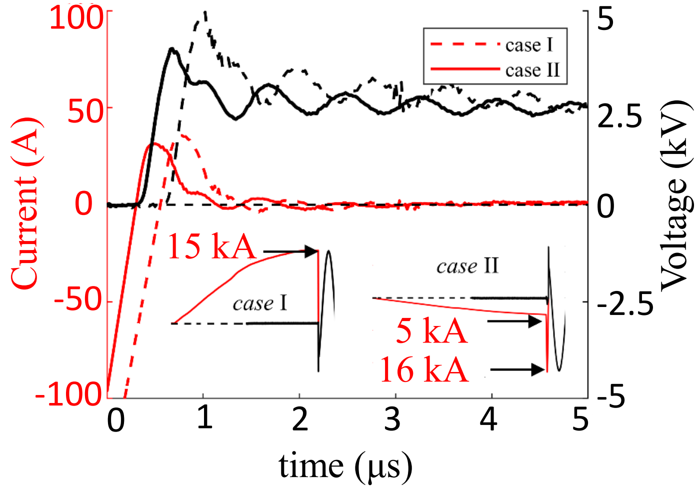
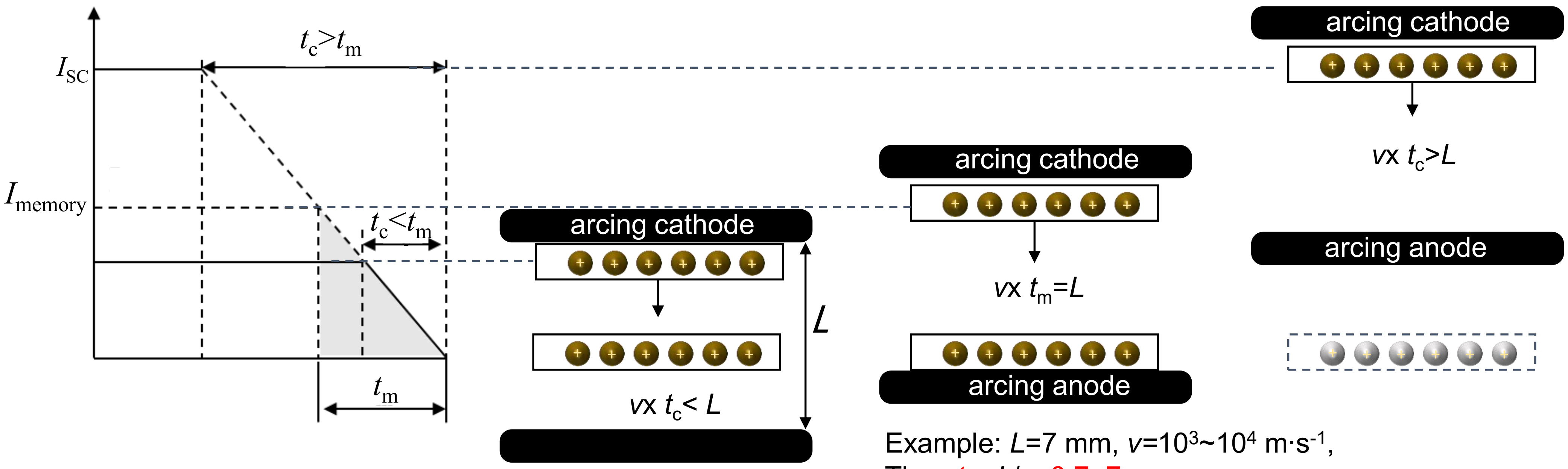


Fig. 2

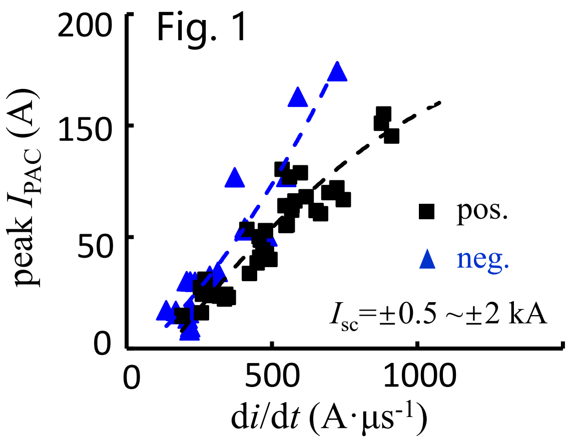
A simplified explanation

- A memory time exists.
- Plasma generated before t_m will not influence post-arc current due to collection by the arcing anode.
- Plasma produced during t_m will stay in the contact gap. The higher the d*i*/d*t*, the greater the portion remains.

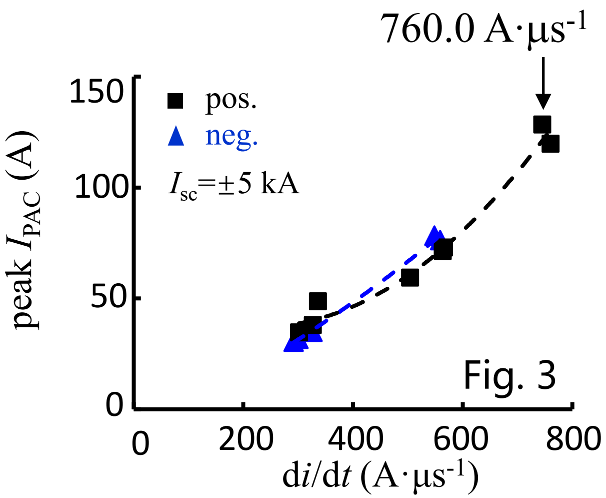


Example: L=7 mm, v=10^3~10^4 m·s^{-1},
Then t_m=L/v=0.7~7 μs

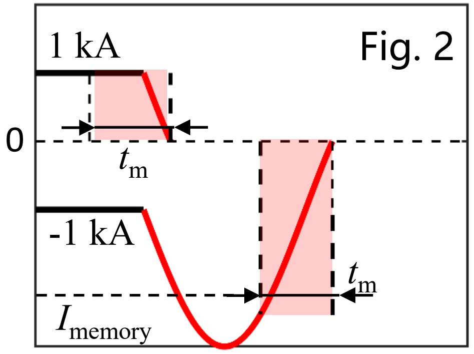
Findings from positive and negative current interruption



- When breaking current is small (±0.5~±2 kA), the post-arc current of negative current interruption is higher due to a greater I_{memory}.

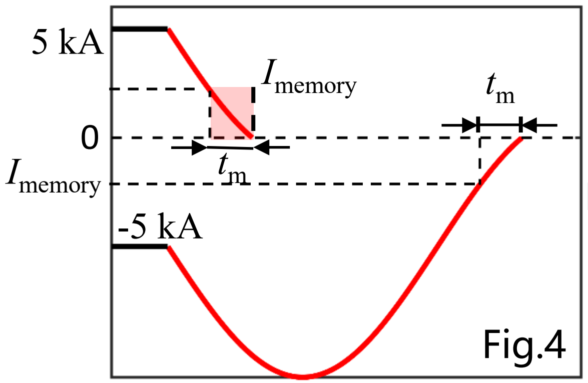


- When breaking current is higher, the post-arc current in two cases approach.



I_{memory}(negative) >I_{memory}(positive)

I_{PAC}(negative) >I_{PAC}(positive)



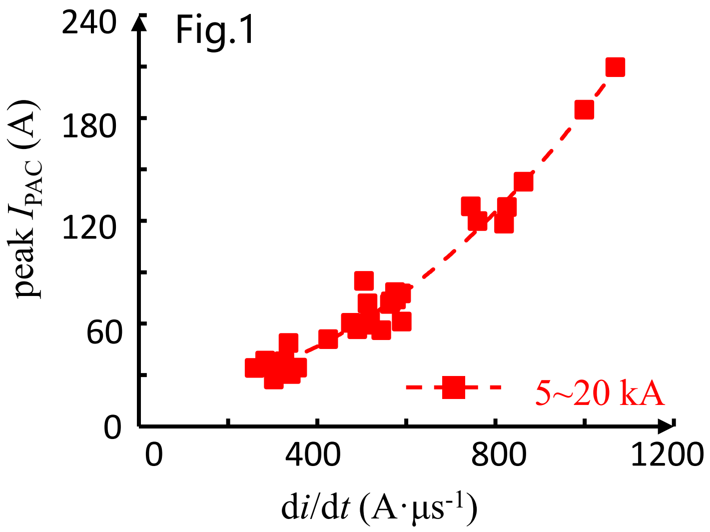
I_{memory}(neg.) =I_{memory}(pos.)

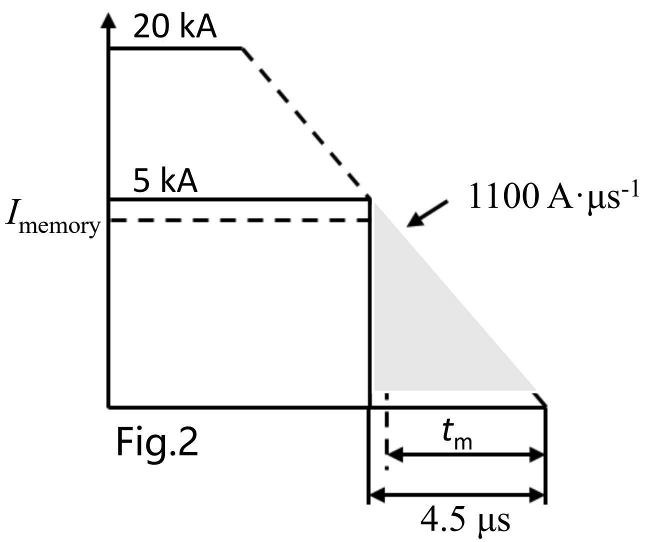
I_{PAC}(neg.) =I_{PAC}(pos.)

$t_m \leq$5 kA/(760 A·μs^{-1})=6.6 μs

Findings to further confine t_m

- It’ s possible to estimate from the experiment a smaller upper limit of t_m.



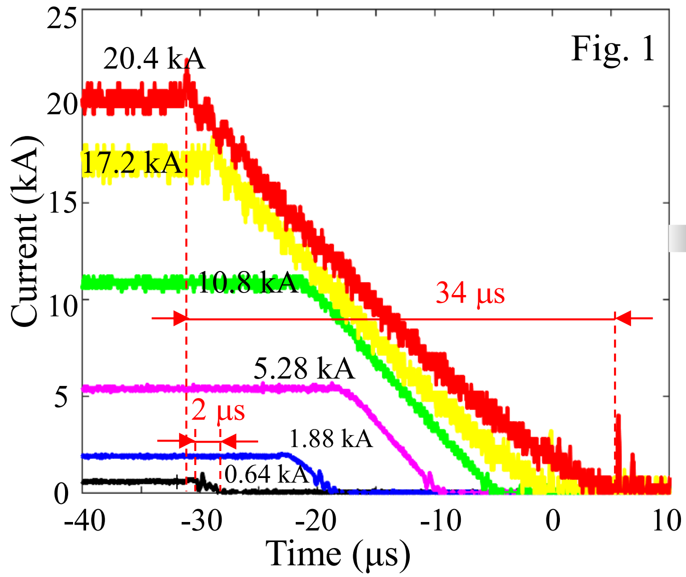


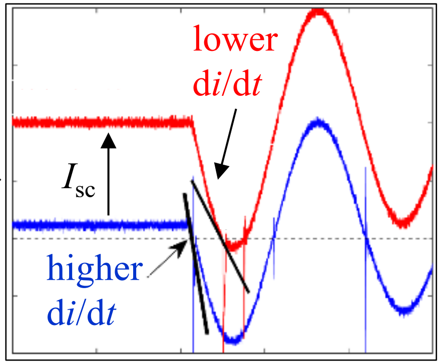
- Based on the experiment, the following calculation is valid:

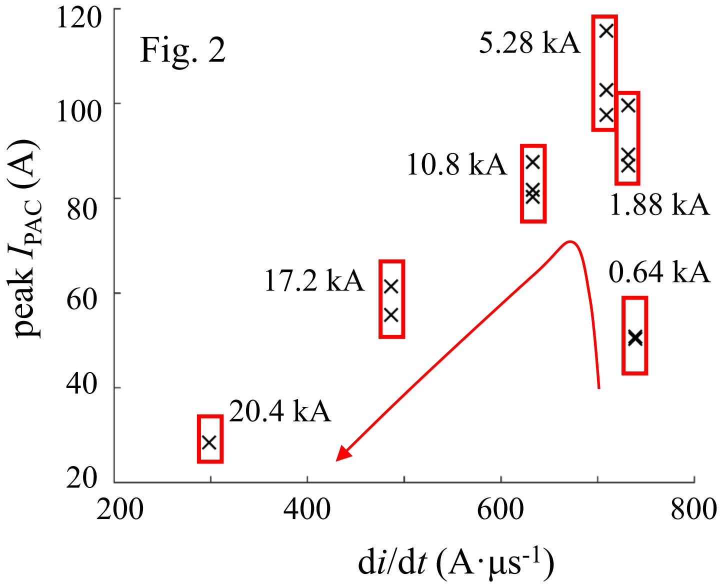
$$\max(di/dt) \times t_m \leq \min(I_{sc}) = 5\ \text{kA} \quad \text{e.g. } t_m \leq 5\ \text{kA}/(1100\ \text{A}\cdot\mu\text{s}^{-1}) = 4.5\ \mu\text{s}$$

Experiments with a fixed HF current and varied breaking currents

- I_{sc} = 0.64~20.4 kA, HF current fixed@ 22 kA/4.9 kHz, gap length L=7 mm.
- The post arc current first increases with breaking current increasing, but then it decreases when the breaking current exceeds 5 kA.
- These results confirm that t_m and I_{memory} exist, and both I_{memory} and di/dt can influence the post arc current.







Findings about *memory time*

- Peak post arc current is most influenced by the di/dt at current zero and the arcing current shortly before CZ.
- The upper limit of the 'memory time' is no longer than 4.5 μs as for the 7 mm contact gap.
- The calculation model infers that the 'memory time' is about 2 times the decay time constant (t_m=4.5 μs, τ=2 μs). Therefore, 'memory time' indirectly reflects how fast arc plasma are removed in the tested vacuum interrupter.

Experiments with gap length *L*=7 mm& *L*=4 mm

- I_{PAC}(7 mm)> I_{PAC}(4 mm)
- Δ*t*(7 mm)> Δ*t* (4 mm)

→

- Q_{PAC}(7 mm)> Q_{PAC}(4 mm)

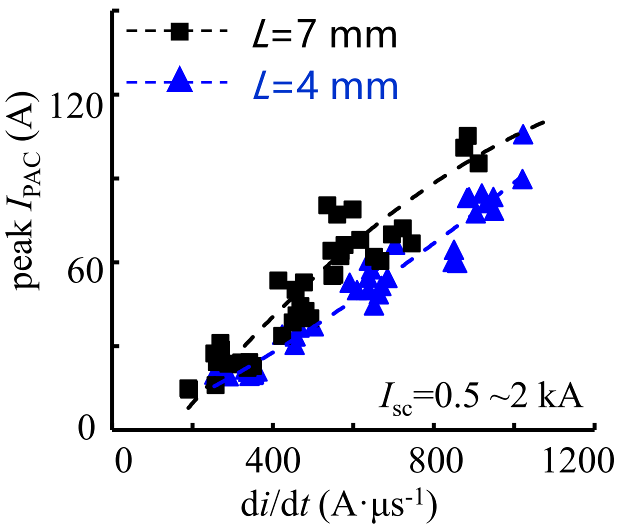


Fig. 1

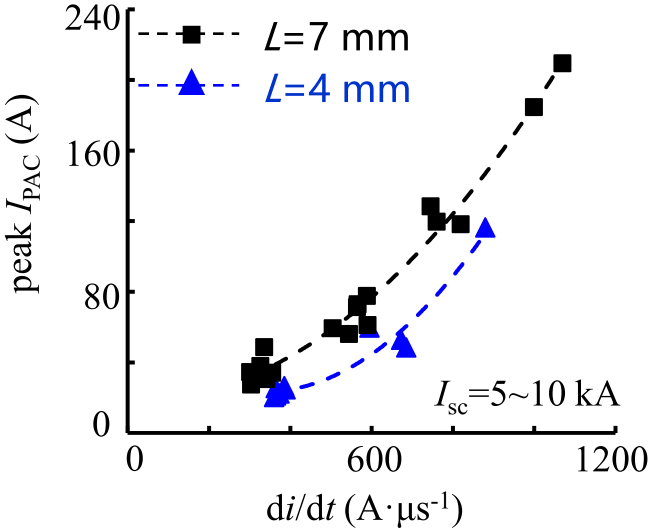


Fig. 2

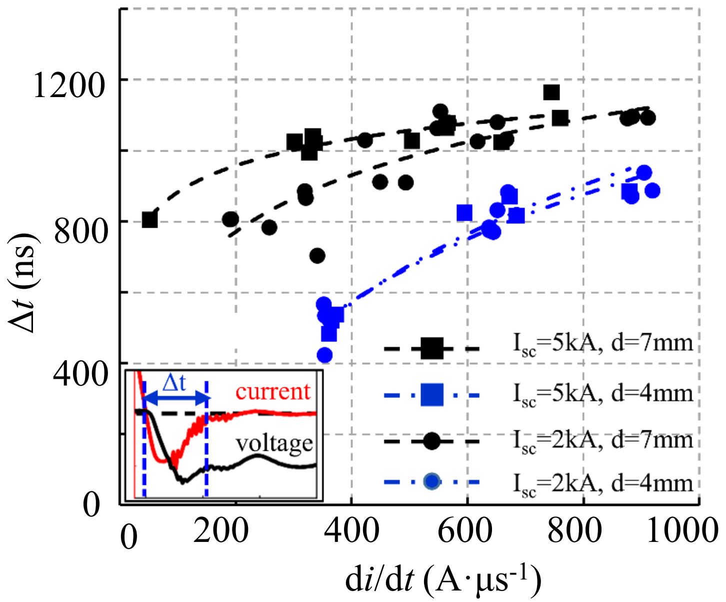


Fig. 3

Charges in the 7 mm and 4 mm contact gap

- Both the total residual charges and the average charge density are higher in the longer contact gap.
- Plasma diagnostics confirmed a larger number of ions when the gap length is longer(Lins, 1991).
- A possible reason is that fast moving ions have higher possibility to collide with neutrals in a longer gap so that they decay slower.

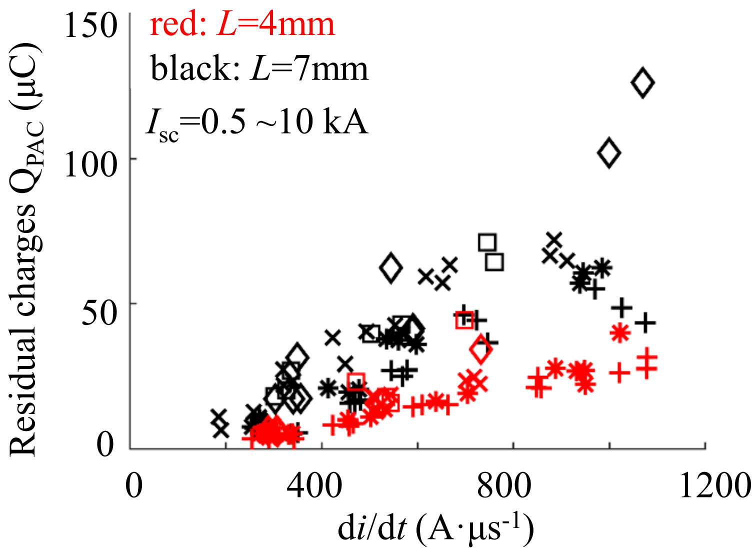


Fig. 1

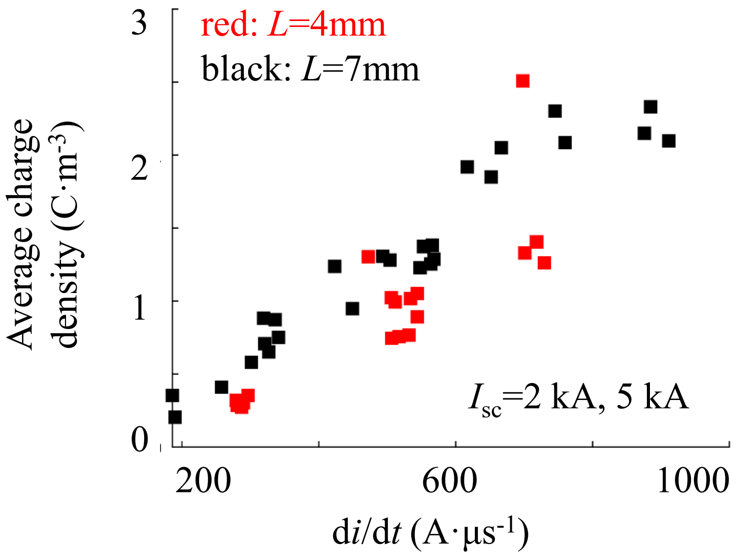


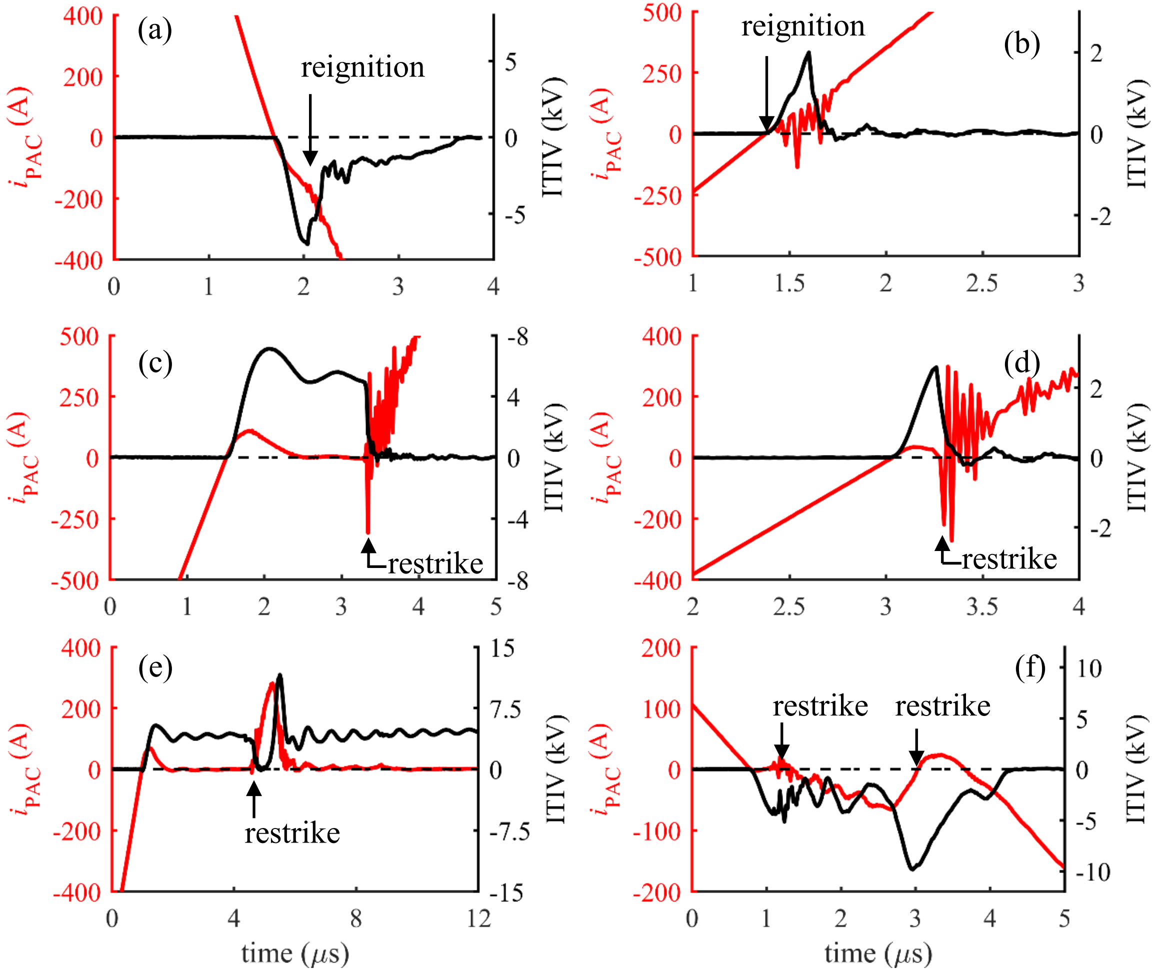
Fig.2

Results

Failure modes

Table 2. Descriptions of the occurring failure modes.

Failure modes	Illustration	Description
Re-ignition	(a)	The re-ignition occurs before the PAC reaches peak value.
	(b)	Current increases continuously after *CZ*. No obvious PAC can be observed.
Restrike	(c)	PAC falls to zero but later on restrike happens.
	(d)	Restrike occurs when PAC is falling
	(e)	Restrike happens but at last interrupts.
	(f)	Twice reignition.



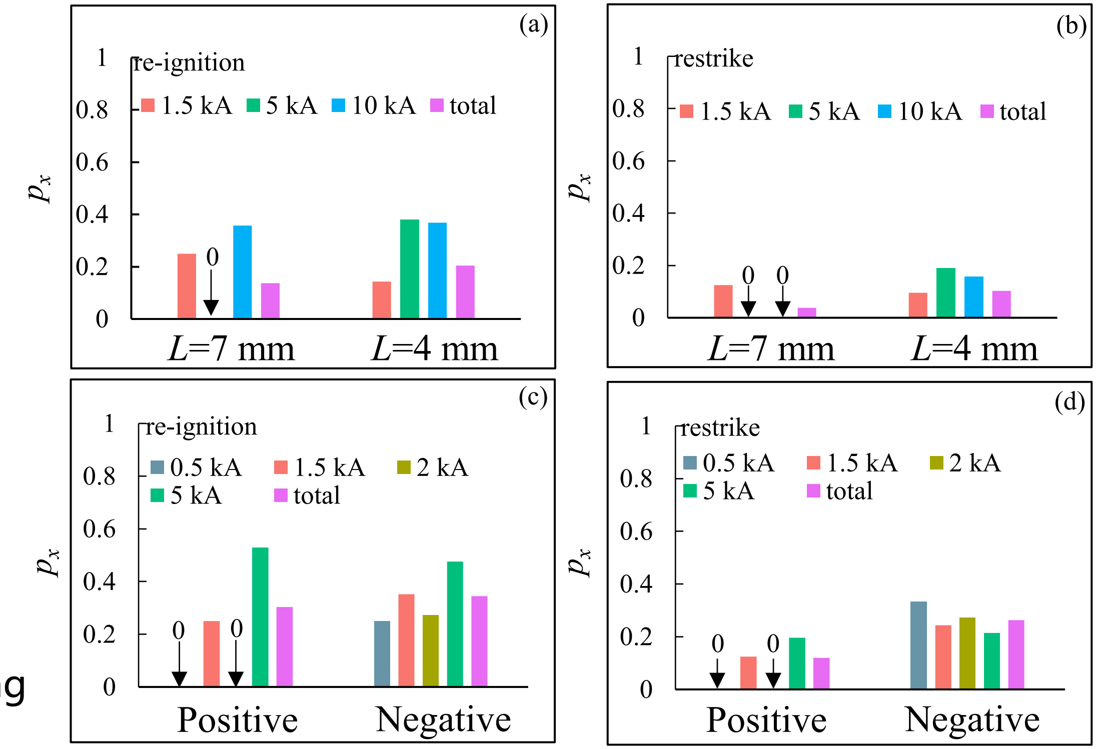
Results

Statistics of failure modes

- The portion of reignition and restrike occurred in groups of tests is defined by

$$p_x = \frac{n_x}{n_{re-ignition} + n_{restrike} + n_{success}}$$

(n_x- $n_{\text{reignition}}$ or n_{strike})

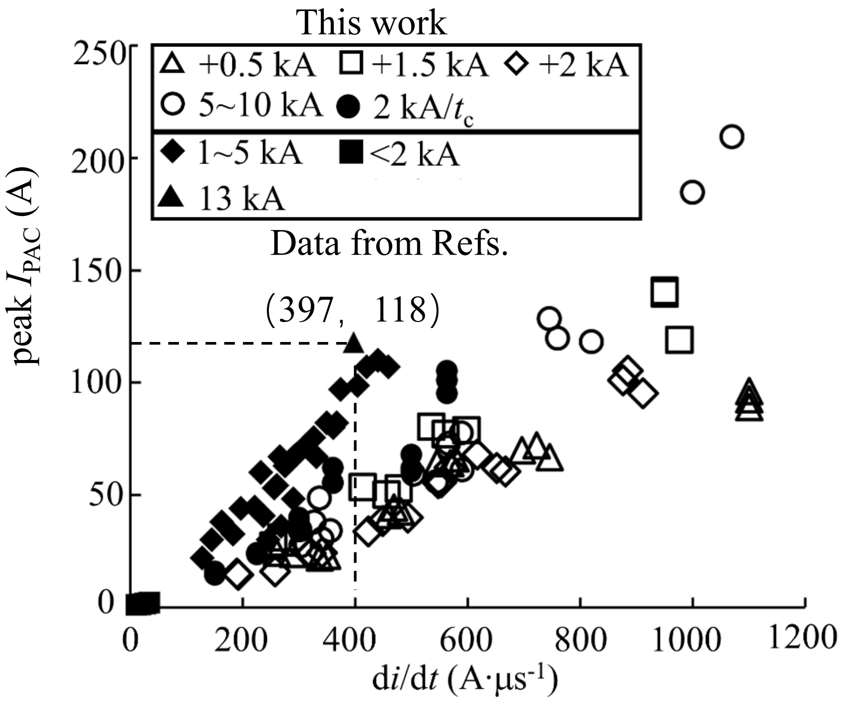


- ➢ Re-ignitions happen more frequent than restrikes.
- ➢ The 4 mm gap length causes apparent increase of restrikes when interrupting 5 kA and 10 kA.
- ➢ Influence of gap length on re-ignition is less obvious.
- ➢ As for interrupting negative current, both re-ignitions and restrikes increase obviously.
- ➢ Fig. (d) shows the possibility of restrike in negative current interruption is almost independent on breaking current because the much higher peak arcing current causes these restrikes.

Discussion

Common characteristics of post-arc current in DC interruption

- When d*i*/d*t* >100 A·μs^{-1}， the higher the d*i*/d*t*，the greater value the peak post-arc current can reach.
- The magnitude of the post-arc current in DC interruption can be 1 to 2 orders of that in AC interruptions.
- A longer contact gap leads to higher post-arc current.
- Post-arc current is independent on breaking current because of memory time effect.



S. Tokoyoda, et al., 5th ICEPE-ST, 2019

S. E. Childs, et al., IEEE Trans. Plasma Sci., 1983

X. Li, et al., 4th ICEPE-ST, 2017

Summary

- We found that the post arc current of the vacuum interrupter after interrupting high di/dt and followed with very high du/dt can reach tens of amperes to more than 200 A but of relatively short duration. However, there is no such evident inclination that higher post arc current will result in more probable interruption failures.
- A longer electrode separation will bring about more intense residual charge and larger post-arc current but it does not impair the interruption performance of the VI. On the contrary, chances of interruption failure rise when shortening the electrode separation from 7 mm to 4 mm.
- The much higher peak current regarding to negative current interruption does reduce the interruption capability. It implies that the surface condition such as the temperature of the contacts is deeply influenced by peak current, which imposes a negative impact on the recovery of dielectric strength. Further investigations should be focused on the surface condition and the evolution of the post arc metal vapor.
- The ‘memory time’ of the used VI is no more than 4.5 μs, given a gap length L=7 mm, during which time the arcing current can influence the post arc current. It possibly indicates the order of magnitude of the decay time constant of plasma in the VI.

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