The impact of capacitor bank inrush current on field emission current in vacuum

Citation for published version (APA):

Koochack-Zadeh, M., Hinrichsen, V., Smeets, R. P. P., & Lawall, A. (2010). The impact of capacitor bank inrush current on field emission current in vacuum. In *Proceedings of the 2010 24th International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV), August 30 - September 3, 2010, Braunschweig, Germany* (pp. 210-213). Institute of Electrical and Electronics Engineers.
<https://doi.org/10.1109/DEIV.2010.5625787>

DOI:

[10.1109/DEIV.2010.5625787](https://doi.org/10.1109/DEIV.2010.5625787)

Document status and date:

Published: 01/01/2010

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

The Impact of Capacitor Bank Inrush Current on Field Emission Current in Vacuum

M. Koochack Zadeh¹, V. Hinrichsen¹, R. Smeets² and A. Lawall³

¹Technische Universität Darmstadt, Landgraf-Georg-Str. 4, 64283 Darmstadt, Germany

²Kema T&D Testing Services, Utrechtseweg 310, 6812 AR Arnhem, Netherlands

³Siemens AG, Energy Sector, Rohrdamm 88, 13629 Berlin, Germany

Abstract- Field emission current measurements during the recovery voltage are investigated to understand the origin of restrikes in vacuum interrupters in case of the interruption of capacitive loads. Measurement and analysis of very small field emission currents (0.01 – 1 mA) from the current zero crossing until the restrike are performed both in an experimental circuit as well as in a full-power test-circuits with commercially available vacuum circuit breakers (up to 36 kV rated voltage). Furthermore, the influence of pre-arcing at contact closing under inrush currents in the range of some kA and kHz on the field emission characteristics after capacitive current switching is investigated. The number of making operations as well as the amplitude of the inrush current is varied. A clear relation between inrush current during closing and field emission current after interruption was established.

I. INTRODUCTION

Interruption of capacitive loads results in an increased dielectric stress of interrupters. The amplitude of the recovery voltage is at least twice the system voltage. In cases where the interrupter is not able to withstand this stress, a restrike happens at voltage peak and the capacitive load can be charged to a multiple of the system voltage peak value [1].

In contrast to the interruption of capacitive loads with comparatively low currents up to some hundred Amperes, the inrush making current by switching on an uncharged capacitor bank is about some kA up to several tens of kA in the ‘back-to-back’ switching situation. According to the IEC circuit breaker standard [2] for back-to-back capacitive switching the amplitude of the inrush making current is 20 kA and its frequency is 4.25 kHz.

During the making operation of the vacuum interrupter, the electrical field stress between the contacts rises as the gap spacing between the contacts decreases. At a certain gap spacing and a high enough field stress, the gap distance can no longer withstand the electrical stress and dielectric breakdown between the contacts occurs. From this moment until the first contacts touch, the inrush current flows through a vacuum arc (pre-arcing). During this time interval the contact surface melts locally due to the arc’s energy

input to the contacts [3]. This can lead to contact welding after contact touch, which will be broken during the next contact opening. New micro-protrusions build up on the contact surface, which may result in a higher electrical field enhancement and therefore higher field emission current.

Field emission current measurements are performed immediately after current zero during the recovery voltage phase to understand the origin of restrikes in vacuum interrupters in case of capacitive load switching. The influence of the pre-arcing, the number of making operations and the amplitude of the inrush current on the contact surface condition is studied. This is done with the help of field emission current measurement after current interruption and calculation of the field enhancement factor and emitting area using the Fowler-Nordheim-Equation (FNE).

II. TEST-CIRCUITS

A. Field Emission Current Measurement during Recovery Voltage

Measurement of very small field emission currents after interruption of capacitive loads during recovery voltage is performed both in an experimental circuit in the high-voltage lab (set-up “a”) as well as in a full-power test-circuit (set-up “b”). The equivalent circuits of the both set-ups “a” and “b” are presented and explained in detail in [4].

The field emission current is measured using a coaxial shunt resistor protected with gas arresters and anti-parallel power diodes. During high current flow (making and breaking currents) the diodes are conducting, therefore no current can flow through the measurement shunt and it is protected from high currents. Alternatively, to avoid measurement errors during recovery voltage the small field emission current ($\mu\text{A} \dots \text{mA}$) must flow only through the measurement shunt and not through the diodes. For this reason the voltage drop across the shunt must be lower than the diodes’ threshold voltage. To increase the maximum permissible voltage across the shunt and therefore the maximum measureable field emission current, in each anti-parallel branch three diodes are connected in series.

As the current through the interrupter during recovery

This work is sponsored from KEMA T&D Testing Services as well as Siemens AG Energy Sector, Power Distribution Division, Medium Voltage.

voltage contains also a capacitive component due to the interrupter's stray capacitance, compensation of this current is necessary. Different on-line and off-line compensation methods for different applications are explained in detail in [4].

B. Closing of Vacuum Interrupter under Charged Capacitive Bank

Fig. 1 shows the test circuit. At the beginning the vacuum interrupter (test sample) is open. The capacitor bank C_{m0} is charged to U_L . After closing the interrupter the capacitor C_{m0} will discharge through the inductor L_{m0} and the interrupter. During closing operation at the moment of pre-strike the inrush current starts to flow at a certain gap distance d_0 through the vacuum arc, resulting in pre-arcing until contact touch. The inrush current continues to flow, until it is damped to zero. Frequency and amplitude of the inrush current can be varied with varying capacitor C_{m0} , inductor L_{m0} and charging voltage U_L . For an interrupter with $u_n = 17.5$ kV and $C_{m0} = 45$ μ F, $L_{m0} = 220$ μ H the amplitude and frequency of the inrush current are as follows (assuming pre-strike at voltage maximum):

$$\hat{i}_{\text{inrush}} = 6 \text{ kA}; f = 1.6 \text{ kHz}$$

Fig. 2 shows an oscillogram of the inrush current and gap spacing between the contacts. From the figure it is seen that in this example the vacuum arc pre-strikes at a gap distance of $d_0 = 2$ mm. The pre-arcing time $t_{\text{pa}} = t_1 - t_0$ is 1.6 ms. That means the inrush current flows for almost three cycles as a vacuum arc. Its amplitude is 6 kA in the first cycle. This leads to contact welding and consequently changes of the contact surface condition, field enhancement and field emission current during the next opening operation.

Fig. 1. Experimental set-up for closing the interrupter under charged capacitor bank. C_{m0} : capacitor bank, R_L : limiting resistance, RC: Rogowski coil

Fig. 2. Oscillogram of inrush current and contacts gap spacing

III. MEASUREMENT RESULTS AND DISCUSSION

A. Field emission current

The measurements are performed on one phase of a vacuum circuit breaker with nominal voltage of $u_n = 17.5$ kV and nominal gap distance of $d_n = 8$ mm. Commercial interrupters as well as non-regular interrupters each having certain process modifications are used for the measurements. The maximum recovery voltage applied to the interrupter is 80 kV. The capacitive current can be varied between 20 A and 500 A. The amplitude of the inrush current is varied between 6 kA and 11 kA. The number of making operations is varied $n = 1, 3$ and 5 times.

The measurement procedure for all the test samples is called “10×10-measurement”. It consists of ten test series. Each test series includes at first making operations under inrush current (n -times) and subsequently ten-times capacitive current interruption without inrush current. Fig. 3 shows one measurement example of a non-regular interrupter.

The measurement shown in Fig. 3a and 3b is done after one time ($n = 1$) closing with inrush current of 6 kA amplitude. Afterwards a breaking current of 20 A flows through the interrupter for 80 ms. At first current zero after opening the breaker the arc is extinguished and the power frequency recovery voltage with the amplitude of ~ 80 kV is applied across the interrupter. It is seen that the measurement of field emission current is possible immediately at rising recovery voltage.

Fig. 3. a) Measurement example of a non-regular interrupter with gap spacing of 8 mm. i_e : field emission current, U_{VAC} : recovery voltage, rs: restrike. b) Zoom of “a”. c) Calculated surface parameters for 8 cycles after current zero until the restrike occurs

In this example (Fig. 3) a restrike is observed after the eighth cycle of the voltage. The measurement of field emission current could be continued further even after the restrike. It is observed that the field emission current varies a lot (between some 100 μ A and some mA) until the restrike occurs. Afterwards, the field emission current stays more or less constant. Fig. 3c shows the calculated surface parameters i.e. the field enhancement factor and the emitting area. These parameters are calculated according to FNE assuming a constant middle shield potential.

In the example shown in Fig. 3 the amplitude of the field emission current directly before the restrike is 1.2 mA. During the measurements it is observed that some restrikes happen after high field emission current. It is also sometimes observed that the field emission current increases continuously during recovery voltage until a restrike occurs. These kinds of restrikes seem to be related to field emission current. But there are also measurements in which a very small field emission current (ca. 100 μ A) flows but nevertheless restrikes are observed.

From the 10 $\times$ 10-measurement on this non-regular interrupter 16 restrikes out of 100 operations are observed. One of these restrikes occurs during the first 10 ms. Fig. 4 shows the relative frequency of restrikes for certain ranges of the field emission current.

$$\text{Relative frequency} = n_{rs}(i_e) / n_{total}(i_e) \quad (2)$$

where $n_{rs}(i_e)$ is the number of restrikes in which a certain range of field emission current has flown before restrike occurs and $n_{total}(i_e)$ is the total number of measurements from 100 for the same range of field emission current. Different ranges of the field emission current are shown in Fig. 4 on the x-axis.

It is seen from Fig. 4 that for this interrupter the probability of restrike is higher for field emission currents above 500 μ A.

Fig. 5 shows the 10 $\times$ 10-measurement on a commercial vacuum interrupter. Each curve represents one test series including one making operation at 6 kA inrush current and subsequently 10 times capacitive current interruption (20 A) without inrush current at closing. The amplitude of the recovery voltage in all 100 measurements is 75 kV. Each point in the curves shows the maximum of field emission current for one single measurement. Among 100 measurements no restrike is observed on the commercial vacuum interrupter.

It is seen from Fig. 5 that each test series has a different behavior but they all follow the same trend which is a decrease of the field emission current (conditioning effect) with increasing number of switching operations at 20 A. That means each interruption results in a lower field emission current during recovery phase. Most of the test series show that after 10 interruptions the value of the field emission current decreases from mA range to some 10 μ A.

Fig. 4. Relative frequency of restrikes for certain ranges of the field emission current. 10 $\times$ 10-measurements on non-regular interrupter with contact gap distance of 8 mm

Fig. 5. 10 $\times$ 10-measurements on a 17.5 kV commercial interrupter. Each curve is one test series (ts). The red, dashed curve is the average of all ten curves.

It is observed that interrupting current of 500 A has an even stronger conditioning effect. After only one single 500 A interruption the field emission current falls down to some 10 μ A.

B. Impact of the Inrush Current

To study the impact of inrush making current on the field emission current during recovery phase and consequently on the contact surface condition and parameters (β and A_e), the amplitude of the inrush currents as well as the number of making operations are varied and for each condition the 10 $\times$ 10-measurement is performed. The amplitude of the recovery voltage is 70 kV and the contact gap distance remains constant during the measurements.

Fig. 6 shows the field emission current average curves of 10 $\times$ 10-measurements for the following making operations:

- A: $i_{inrush} = 6 \text{ kA}$; 1 making operation
- B: $i_{inrush} = 6 \text{ kA}$; 3 making operations
- C: $i_{inrush} = 11 \text{ kA}$; 1 making operation

Fig. 7 and 8 show the calculated average values of surface parameters β and A_e for the same conditions as of Fig. 6.

It is observed, that for the same inrush current amplitude but a different number of making operations the values of the field emission current after current interruption are almost the same (A and B). But in case

the inrush current is increased from 6 kA to 11 kA, an increase of approximately three times of the field emission current is observed (C). The same result is obvious in the surface parameters. Therefore, the higher the inrush current, the less dielectrically favorable is the contact surface condition after contact opening and, consequently, the higher is the field emission current.

The impact of the inrush current is also studied using full-power test-circuit at KEMA (see [4]). The measurements are done on a commercial circuit breaker with nominal voltage of 36 kV and nominal gap distance of 20 mm. The amplitude of the applied recovery voltage is ~ 80 kV. Here, two different inrush currents are compared:

D: $i_{\text{inrush}} = 530$ A; $f = 280$ Hz

E: $i_{\text{inrush}} = 20$ kA; $f = 4.25$ kHz (standard back to back)

The results show that in case “D” the field emission current after capacitive interruption is very low (some μA). In case “E” the amplitude of the field emission current even reaches some 100 μA although the gap distance is 20 mm (see measurement results in [4]). Of course amplitude and duration of the capacitive current have an influence on the value of the field emission current. The amplitude of the capacitive current in both cases (D and E) is 400 A. As it is explained in III-A the current flow during opening has a positive conditioning effect on the surface condition. It is observed that for shorter arcing time the conditioning effect of the breaking current is lower than for longer arcing time.

Fig. 6. Average measured values of field emission currents for 10×10-measurements for cases A, B and C

Fig. 7. Average calculated values of field enhancement factors β for 10×10-measurements for cases A, B and C

Fig. 8. Average calculated values of emitting areas A_e in logarithmic scale for 10×10-measurements for cases A, B and C

IV. CONCLUSION

The impact of the inrush making current on the field emission current during recovery after capacitive current interruption is studied in this work. It is observed that the amplitude of the inrush current has a large influence on the field emission current. In case of higher inrush making current higher field emission current is observed after current interruption.

The dependency of occurring of restrikes on the field emission current is studied as well. For the commercially available vacuum interrupters no restrikes are observed. For non-regular interrupters restrikes are observed more frequently after field emission current greater than 500 μA . However some restrikes are also observed at lower field emission currents.

The likelihood of restrikes during capacitive switching is a proper figure to control the production quality of vacuum interrupters. Hence, by using this method the stability of the production process of vacuum interrupters can be evaluated.

ACKNOWLEDGMENT

The authors gratefully acknowledge KEMA T&D Testing Services for their assistance in capacitive switching testing. They would like also to thank Siemens AG Energy Sector, Medium Voltage for the supply and preparation of the test objects.

REFERENCES

- [1] P. G. Slade “The vacuum interrupter: theory, design, and application”, CRC Press, 2008.
- [2] IEC Intl. Standard on high-voltage switchgear and controlgear, IEC Standard 62271-100 Edition 2.1, 2008.
- [3] P. G. Slade, R. K. Smith, E. D. Taylor, “The effect of contact closure in vacuum with fault current on prestrike arcing time, contact welding and the field enhancement factor” Proc. of the 53th IEEE Holm Conf. on Electrical Contacts, 2007.
- [4] M. Koochack Zadeh, V. Hinrichsen, S. Kuivenhoven, “Measurement of field emission current during switching of capacitive current in vacuum” 24th Intl. Symp. on Discharges and Electrical Insulation in Vacuum, Braunschweig, Germany, Aug. –Sep. 2010, to be published.

E-mail of authors:

koochack_zadeh@hst.tu-darmstadt.de