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INFLUENCE OF VARYING GAPS BETWEEN TMF CONTACTS ON CONSTRICTED HIGH CURRENT VACUUM ARCS

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Abstract. The behavior of high current arcs in vacuum circuit breaker (VCB) is interesting for research and industrial development purpose which lead to further products. To improve the interruption capability of VCB, two approaches to control the arc have been proven successful. Applying transversal magnetic fields (TMF) on the arc is use for industrial VCB in medium voltage ranges. For greater gap distances the behavior of the arc is less thoroughly investigated. In this paper, the appearance of metal vapor arcs drawn by common TMF contacts in a vacuum-test-interrupter is investigated. An adapted drive mechanism enables to interrupt a fixed current with varying gaps from 5 to 25 mm and a constant opening time. Breaking operations with a 50 Hz current are observed with a high speed camera. With increasing gap distance a changed arc appearance can be observed. The goals of this work are to be understood as a feasibility study for optical evaluation methods for vacuum arcs under TMF.

Keywords: vacuum circuit breaker, VCB, TMF, constricted arcs, automatized evaluation.

1. Introduction

Vacuum circuit breakers are a main component of medium voltage grids and are used as power switches to ensure a safe operation under all switching cases according to the standard. The performance of VCB is dependent on different variables. One is the behavior during arcing. The aim is to distribute the converted interruption energy on the contact surfaces. Solutions are available by applying transversal (TMF) or axial magnetic fields (AMF) on the switching arc. In case of TMF the arc forms a constricted column, in dependence of the contact gap and the short circuit current, and starts moving over the contact surface. To investigate the exact behavior researcherss evaluate electrical and optical data during the arcing phase [1, 2]. The usage of electrical data has been established for years and the community is used to work with data of arc voltage and current. Some researchers measure the external magnetic field of the constricted vacuum arc to evaluate the rotation behavior, which also indicates the energy distribution on the surface [3]. In case of optical data the recording and the evaluation of data is not uniform. This makes comparability more difficult. First suggestions to improve comparability are given in [4]. In this paper the new approach based on [4] is used to evaluate recorded data during short circuit breaking operations of TMF contacts. Therefore an effective current of 20 kA (50 Hz) was interrupted with a vacuum test interrupter. In different test series the final gap distance during interruption is changed from 5 to 25 mm. The change of arc modes in the investigated window is well known and described by many researcherss [5]. The new evaluation method enables deeper insights and increases the available data. The focus of this paper is to show the possibilities of automatized data evaluation on the example of current density determination of constricted vacuum arcs under TMF.

2. Experimental Setup

A schematic diagram of the test setup is shown in Figure 1. Main part is a vacuum test interrupter which is evacuated by a two-level pump system. The measured pressure before and after each test series is below $4 \cdot 10^5$ Pa.

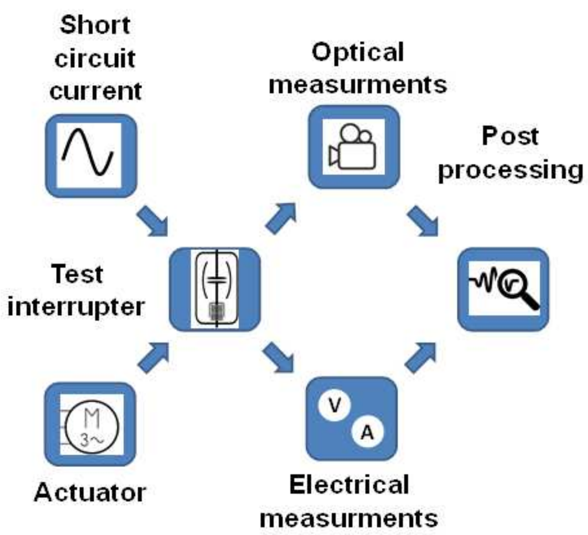


Figure 1. Schematic of test setup in combination with recorded data during the test series.

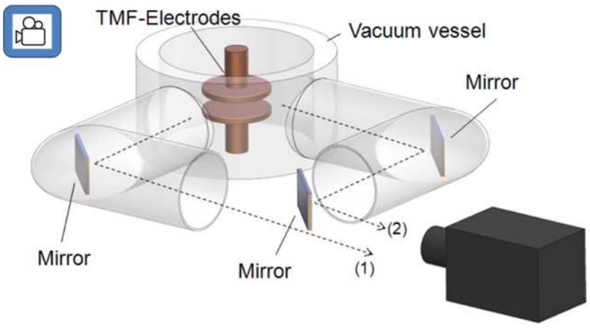


Figure 2. Schematic of optical plasma recording.

The used contacts are spiral type and supply a transversal magnetic field (TMF) on the arc. The test interrupter is driven by a special actuator based on a servo motor to enable adjustable switching gaps and velocities. The current used for the breaking operation is a 50 Hz sinusoidal half-wave generated by a capacitor bank and coordinated coils. Wolf [5] explains the setup of the supply circuit in detail. This circuit generates a 20 kA RMS current. A 20 mΩ shunt measures the current. For voltage measuring a voltage probe (Tektronix) over the gap is used. A linear potentiometer connected to the interruption rod measures the contact gap. The electrical signals are transformed into light signals and transmitted via fibre optical cable to a HBM Gen7t transient recorder. In addition to the electrical measuring, the test interrupter enables an optical measurement over two 90° angle arms equipped with a mirror system according to Figure 2. The optical set-up is used to observe the metal vapor plasma between the separating contact from two perspectives. Therefore, rectangular tubes are used in combination with a mirror system to enable the recording of two optical paths with one high-speed camera. The utilized high-speed camera is a Redlake MotionPro X4 with an aperture f/16 and a recording frequency of 50500 Hz. No additional filter is used. The high-speed camera integrates brightness

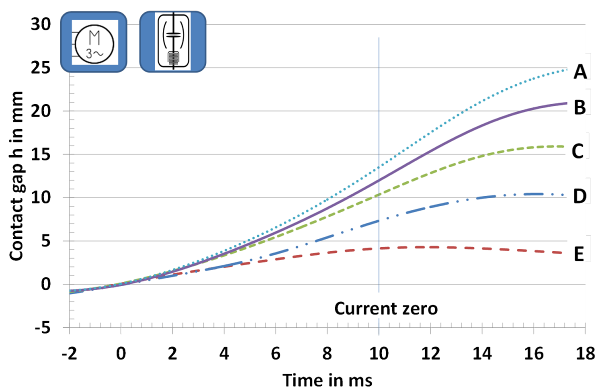


Figure 3. Exemplary course of five different interrupting gaps used for the test series.

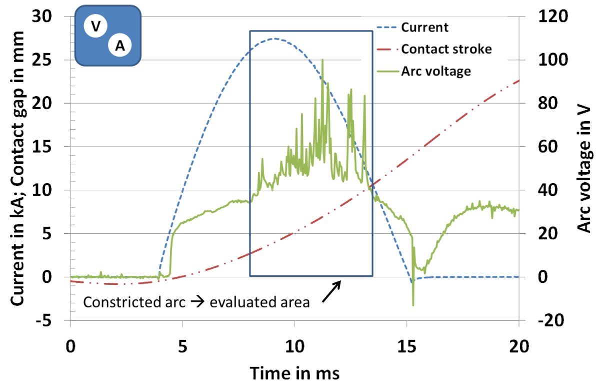
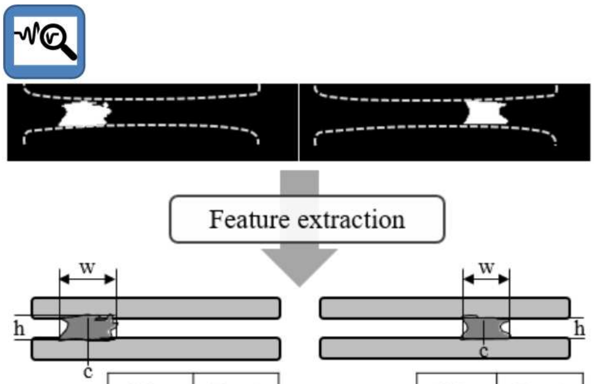


Figure 4. Exemplary course of one interruption operation with current, gap and voltage measurement, used for the test series.

levels within 1 µs. The camera sensor has 255 bit levels to differentiate brightness. The first 50 bit levels are presumed to be noise of background reflection and scattered light. In the test series five different contact gaps with a final gap from 5 to 25 mm are chosen. According to Figure 3 the contact spring is tightened over 3 mm to supply a contact force of 2 kN. The capacitor bank is switched onto the test interrupter at a time immediately after 0 ms. This leads to arcing times in a range of 9 ms for each interrupting test. All gaps are tested with five current applications. One representative breaking operation is displayed in Figure 4. The interrupter opens shortly after the zero crossing of the half wave current and an arc ignites. The arc voltage rises to ranges between 20 and 40 V. At one point the voltage starts to change its potential with spikes up to 100 V. In this area the plasma of the vacuum arc constricts to one defined arc column. With a falling current of the half wave the arc mode returns to a diffuse arc with a smooth voltage signal until the arc is extinguished at the zero crossing of the current. The behavior of the constricted arc column will be evaluated in the next steps.

3. Post-processing

For an automated analysis the images are simplified using a separation with an Otsu threshold and a morphological filtering. Weber [4] presents the exact processing of the images. The binarized images deliver different features of the recognized objects and enable a detailed evaluation of the recorded data. One representative image and its features is shown in Figure 5. From the recorded plasma image geometrical properties such as height, width and position on the contacts are extracted. The images and the electrical data are coordinated using the voltage step as a reference for the first plasma phenomena. To evaluate the plasma behaviour in dependece of the contact gaps over optical observation, the averaged high of the plasma in all five test series according to Figure 3 is considered. The size of objects is derived by calculating the length



	Side view	Front view		Side view	Front view
Width w (px)	40	37	Center of mass c (px)	58,6	149,4
Height h (px)	20	17	Area (px)	579	487

Figure 5. Schematic for post-processing of optical recorded data.

each pixel represents, which is done with the known diameter of the contacts. A reference picture is taken for this purpose. Subsequently the derived pixel to length ratio is then used for every calculation. With a 63 mm diameter contact, the ratio is 0.74 mm per pixel.

4. Results

The results of all evaluated optical data sets is shown in Figure 6. It depicts the height of a constricted plasma column, derived from the optically recorded data. The evaluation of the heigth also indicates the actual interruption gap. Thus, comparability between optical evaluation and results of the recorded electric measurement of switching gaps according to Figure 3 is expected. Due to the high noise, the presented data has been smoothed using a third degree polynomial function. The measured data of the 5 mm gap (E) could not be evaluated with this method, which is

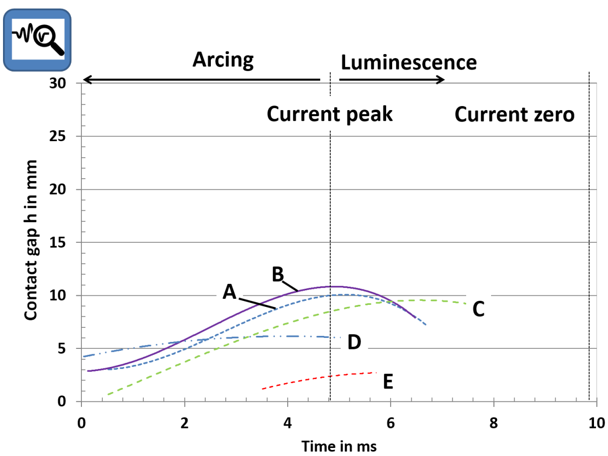


Figure 6. Optical evaluated opening curves.

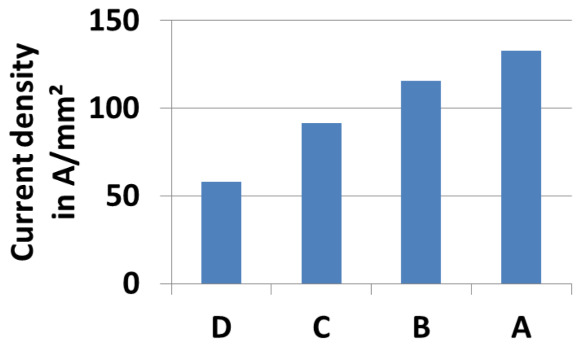


Figure 7. Current densities of constricted plasma columns in dependence of the contact gap.

assumed to be due to the arc mode. During switching operation with a final gap of 5 mm no observable constricted arc is detectable which affords another data treatment. For the other gaps (A – C) a comparison between electrical data (Figure 3) and optical data Figure 6 enables evaluation of the functionality of the approach but also of its restrictions. The graph of (E) does not start at zero mm, which is caused by the pixel based evaluation. Due to the high luminescence in the small gap more pixels are illuminated which leads to a misinterpretation. During the interruption process the different trajectories show similar courses. After 10 ms the current flow goes to zero, the evaluated curves show a decreasing gap which is related to the luminescences in the test set-up. The 90° recording angle enables the calculation of an ellipsoid arc column. The averaged column area during the constriction mode (marked in Figure 4 over the rectangle) is calculated. A reduction of the effective arc area in dependence of the final contact gap was discovered. Combining the optical and electrical data, while assuming an equal current flow over the calculated arc column and measured current flow, a current density can be estimated. The resulting current densities are shown in Figure 7.

In spite of the simplicy of the assumptions, the current densities are comparable to the ones reported in other works [6, 7]. The data show a connection between the current density and the final contact gap. The current density in the arc rises with the length of the final gap. This occurs due to the contraction of the plasma column which increases with the final gap. The reason for this constriction is assumed to be based on an interaction between the pinching force, the Lorentz force and the internal plasma pressure.

5. Discussion and Conclusion

The optical evaluation of vacuum arcs is an established tool to deduce arc properties. The variety of different cameras, optical observation methods and disfferent evaluation approaches complicate the comparison between the available results. In addition, the technology is becoming faster, which increases the number of images per test series. A manual evaluation requires the individual viewingof each image, which cannot be done in an acceptable period of time. A new method of evaluating recorded data concerning observation of vacuum arc is presented. It features an automatized tool based on LabView. A vacuum test interrupter is used to interrupt the same effective current of 20 kA under five different final contact gaps. A comparison between the measured contact gap and the optical evaluated contact gap shows the functionality and the limitations of the approach. The luminescence in the test setup could lead to a misinterpretation of data and shows that the optical investigation has to be combined with recorded electrical data to achieve a correct interpretation. Finally the areas of the different arcs are automatically determined to calculate the current densities of constricted arcs in dependence of the contact gap. The simple approach shows a rising current density with an increasing gap. The results of this work are to be understood as a feasibility study for optical evaluation methods and present a first step to automatically derive scientifically valuable data from optical observations of plasmas.

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