INFLUENCE OF ABLATION ON DIFFERENTIAL ARC RESISTANCE

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Abstract. The influence of ablation on the \( \frac{du}{di} \) behavior of an arc in a model gas circuit breaker was examined. Specifically the transition from a state without ablation in the nozzle towards states with ablation was of interest, since prior work indicated that for high currents the voltage becomes constant or \( \frac{du}{di} \) gets even positive if ablation is present. Measurements with different blow pressures and rectangular DC currents of varying amplitude were compared, using PMMA-nozzles and dry air as blowing gas. Ablation was measured by weighing the nozzle, scanning the cross section, and using a coordinate measuring machine. The results agreed well, and confirmed that higher pressure shifts the \( \frac{du}{di} \) curve towards more favorable values.

Keywords: axially blown arc, ablation, passive oscillation, MRTS, HVDC CB.

1. Introduction

Unlike in AC, the interruption of DC currents requires the creation of an artificial current zero crossing. Today in DC transfer switches, such as metal return transfer switches (MRTS), the passive oscillation circuit is used. An LC-circuit is connected in parallel to a gas circuit breaker. If the arc has a negative differential resistance \( \frac{du}{di} \), the damping of the oscillation in the LC-arc-loop is negative, and eventually will lead to current zero in the breaker. If the arc voltage is not falling with increasing current, passive oscillation fails and additional circuitry is needed which actively brings the current to zero. Previous work at HVL and others indicated that a high amount of ablation leads to \( \frac{du}{di} \) being positive, but did not analyze it in detail.

2. Setup

The setup used was previously described in [3, 5]. It consists of a model gas circuit breaker, which uses gas bottles for a freely adjustable blow pressure and two contact pins of which one is movable to draw the arc. Dry air was used as a blowing gas. The inlet pressure is variable, the exhaust pressure is always fixed at 1 bar. Since no gas handling is required to access the parts, it is possible to remove and reinstall the nozzle in a matter of minutes, which made it possible to determine the ablation after each test in reasonable time.

For the measurements presented in this paper, three identical nozzles were produced. Each was used for a series of experiments of one pressure. In the following, these series are shown as 4.5 bar abs., 8.4 bar abs. and 12.7 bar abs., which refers to the inlet pressure of the nozzle. PMMA was chosen because it is transparent, making it possible to observe the arc. To allow separation along the axis of cylindrical symmetry, each nozzle consisted of two identical parts. This was achieved by milling the contour into two rectangular blocks of PMMA, which were bolted together. To ensure tightness, a rubber seal in a groove was used, and the alignment was guaranteed by dovel pins. Separating the nozzle allowed scanning the contour line in between experiments to track the changes in geometry, as described in sec.3.

The nozzle geometry is shown in fig.1 and identical to the one presented in [5]. The inlet directly attaches to the inlet pressure volume and has a diameter of 50 mm. Both the converging and the diverging part are conical, with half angles of 15° and 10° respectively. The throat was 70 mm after the inlet and was 20 mm in diameter initially. The contacts are copper-tungsten rods with 5 mm diameter, which were at the indicated axial positions of 40 mm and 120 mm.

Figure 1. Top: Image of one nozzle half as captured by flatbed scanner. The contour can be seen, as well as the grooves for the sealing cord and two of the six holes for dovel pins. Bottom: Extracted nozzle contour (solid), and position of contacts (dashed). Gasflow was from left to right, cathode was left, anode right.
3. Method

The ablation of nozzle wall material was determined using three different methods. First, the two halves where weighed with a scale, with which the mass could be determined with ±10 mg accuracy, giving ±20 mg certainty for the complete nozzle.

Secondly, the two halves were scanned with an off the shelf flatbed scanner. Assuming cylindrical symmetry, the change of the contour and the density of PMMA (1.188 mg mm⁻³) can be used to calculate the ablated mass. Additionally, this method shows the axial location of the ablation. The scanner used had a resolution of 4800 dpi, which gives a theoretical resolution of 5 µm per pixel. The gray scale images were aligned, cropped and converted to a binary image first, and the contour of the wall was extracted afterwards using MATLAB. Figure 1 shows one example image before processing and the result.

As a third method, the inner contour of the nozzle was determined by a coordinate measurement machine (CMM) Mitutoyo KN815, which is usually used to compare workpieces to the specifications. This machine determined the radius every 5 mm along the axial direction, by measuring 8 points along the circumference. Since the machine was not available at the laboratory, it was only feasible to measure each nozzle before use, and two of the three after the complete series of experiments. The accuracy of these measurements was given by the roundness of the circles, which was about 20–40 µm before and 30–100 µm after all the experiments.

To create the test currents, the FPDCS current source as described in [6] was used. As shown in figure 2, each experiment consisted of two phases: During the pre-current phase, only a small current is flowing while the downstream contact moves from the closed position to the open position. This way, an arc is established. Towards the end of this phase, the current is slightly increased and the valves of the blowing system are opened. As soon as the gas flow has reached a steady state and the contact has stopped its movement at the final position, the main current phase is started. During this time, the current is increased and held at its set value for 10 ms. All results that are shown in section 4 are calculated only from the values of the main current phase.

After each measurement, the nozzle halves were weighed and the contour was scanned with the flatbed scanner, to determine the ablation. Two measurements per current setting were done to ensure repeatability, while keeping the total number of experiments - and therefore ablation - for each nozzle low, to ensure the geometry is as similar as possible for all tests. For the same reason, the measurements were done in ascending order, starting at 300 A up to 1400 A. The measurements with 100 A and 200 A however were done afterwards, when it became clear that they are desired to complete the data set. Since the ablation values of 300 A were already at the edge of the measurement range, the 100 A and 200 A tests were done with an adapted current shape. The inductance of the current source was increased, to reduce ripple and prevent the current to go to zero. Additionally the duration of the main current phase was increased from 10 ms to 40 ms, to increase the amount of ablation towards measurable values. During the complete measurement series, the throat diameter increased by a maximum of 10%, which did not change the arc voltage measurably. This was confirmed by repeating the first test at the very end.

4. Results

According to the considerations described in [5] and [7], the voltage and current data of the high current phase was evaluated using the median value instead of the mean, to be more robust against fluctuations. The error bars in figures 3 and 4 are indicating the 15.9 and 84.1 percentiles. Those percentiles give meaningful results even if the voltage fluctuations are not gaussian, and equal the standard deviation if they are. Figure 4 shows the du/dt behavior is more favorable for higher blow pressures. For 4.5 bar, the voltage curve is falling up to about 400 A, and is slightly rising until it becomes flat above. For 8.4 bar the rising part is less pronounced and for 12.7 bar the rising part is not observed anymore. The curve gradually transitions into a flat regime around 800 A to 1000 A. Additionally, the overall arc voltage and arc power is higher for higher blow pressures, as shown in fig. 3.

Table 1 shows the mass that was ablated during the entire measurement series, for all three pressures. The CMM measurements agree very well with the weight measurement whereas the flatbed scanner results overestimate the mass loss by about 10%. Figure 6 shows the nozzle geometry change of the 12.4 bar series, as determined by the 29 measured circles of the CMM, and the scan. It can be seen that upstream of the throat (< 70 mm), the scan overestimates the ablation, whereas downstream it shows less in comparison with
The scanning technique produced valuable results, with low current but long duration with tests of high weight measurements were used for figures 5 and 6. 40 ms are included, which had a similar specific ablation vol. even though the theoretical accuracy was not achieved.

5. Discussion

The scanning technique produced valuable results, even though the theoretical accuracy was not achieved. It was not possible to detect the edge of the contour on the scans with single-pixel resolution, since the edge is visible as a brightness gradient of roughly 20 px, or 100 μm. To improve the edge detection accuracy, painting the surface with different marker pens was considered, but all inks that were tried did not increase the detection accuracy by much. Other materials or changes to the background or lighting might be able to improve this technique. Additional to the edge detection uncertainty, the contour determined by the scan significantly underestimated the change of the radius around the throat compared with the CMM, as shown in figure 7. This is attributed to the fact that the gap where the two nozzle halves are joined is not perfectly gas-tight. The tests with 800 A and above showed erosion on the mating surface, up to the sealing cord groove, which was likely caused by hot gas entering the gap. This erosion most probably eroded the contour edge as well, which means the assumption of cylindrical symmetry does not hold perfectly.
6. Conclusions

The methods described in section 3 worked with an accuracy as expected. Higher weighing accuracy is hard to achieve since it involves including effects like changes in PMMA density due to humidity, or changes in buoyancy due to changes in air pressure. The scanning method could probably be improved by enhancing the scan quality and the edge detection. The results shown in this paper agree well with previous findings \cite{9}, which indicate that increasing blow pressure is shifting the $u(i)$ curve towards more favourable conditions for passive oscillation breakers. Additionally it can be seen qualitatively that the threshold current above which ablation starts (300 A to 500 A according to figure 3) coincides with the point where the $u(i)$ changes to unfavorable (flat/rising) conditions (see fig. 4). If this is combined with the fact that the share of ablative cooling is increasing in the same region, the onset of significant ablation is directly correlated with the $u(i)$ curve getting flat.

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