STUDIES ON EVAPORATION OF CERAMIC SURFACES IN VACUUM CIRCUIT BREAKERS AND THE EFFECT ON DIELECTRIC PERFORMANCE

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Abstract: Vacuum Interrupters (VIs) have proven over many decades that they are able to fulfill their dielectric tasks even after a large number of switching operations. Switching arcs under vacuum produce substantial masses of metal vapor. This vapor condenses at the inner surface of the components of the VI. Therefore VIs are equipped with shieldings to protect the inner ceramic surface from being evaporated. Alumina ceramics that are covered with a metal film will lose their insulation properties. As a function of layer thickness and size of metalized area on the inside ceramic surface, the dielectric strength of the VI can reduce. Factors of influence are the strength of the switched current and the number of operations.

The test objects were a standard VI with a rated voltage of 12kV, a rated current of 1250A and a short circuit interruption current of 20kA. In order to simulate different operational demands, the VIs were assembled in a switchgear and connected to a high power testfield, where test currents of up to 20kA rms at 50Hz can be generated. Several VIs were switched different times at varying current intensity. By opening the VIs, condensed metal layers on the inner ceramic surface became visible. Current intensities of up to 10kA caused a constant ring-shaped evaporation layer. At currents between 10kA to 20kA more metal vapor was produced per switching operation and the evaporation layers became very non-uniform. Measurement of shield potential during lightning impulse voltage test supports the presumption that breakdowns in the VI with condensed metal layers on inner ceramics run from first contact over shield to second contact.

1 INTRODUCTION

Switching operation of vacuum interrupter (VI) with load or short circuit current generates substantial masses of metal vapor which condenses at the inner surface of the components of VI [1]. Alumina ceramic that is covered with a metal film will lose its insulation properties that can lead to surface flashovers. Even after a large number of switching operations, VIs must be able to withstand the dielectric stress that they have been constructed for. The amount of evaporated contact material depends on the interruption current and the arcing time. Measurement of the influence of evaporation layers on dielectric performance of VI can be done by lightning impulse voltage test.

2 TEST SETUP FOR INTERRUPTION TESTS WITH VIS AND DIELECTRIC INVESTIGATIONS

The subjects of the investigations are standard vacuum interrupters (Fig. 1) with a rated voltage of 12kV, a rated current of 1250A and a short circuit interruption current of 20kA.

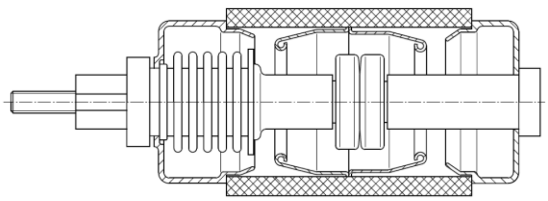

Figure 1: Cross section of vacuum interrupter with a middle shield on floating potential

In order to perform the required interruption operations, it is necessary to use three phase circuit breaker (CB). Standard circuit breakers with permanent magnetic actuators [2] usually operate with the same type of VIs for each phase as they are investigated here. The velocity of the moving contact during opening of contacts is 1,66m/s. For the purposes of this testing, the 3-phase vacuum circuit breaker (VCB) was modified in order to obtain the same conditions that occur in day-to-day operations of the VI. Switching operations with VIs have been performed at the institute’s high power test field. These currents have a 50Hz sine form, so that the evaporation process inside the VI is the same as under daily operational demands [3].

Dielectric investigations have been performed with 1,2/50µs lightning impulse voltage provided by Marx generator. During lightning impulse voltage tests, the VIs had to be placed into an insulating oil bath to avoid external flashovers. A test vessel holds the VI and adjusts the contact gap, which is chosen at 7mm. In addition the main shield of the VI that is placed into the vessel can be connected in order to measure shield potential during dielectric tests[3].

3 DIELECTRIC INVESTIGATIONS BY LIGHTNING IMPULSE VOLTAGE TESTS

Previous studies showed that the dielectric strength of VIs can be reduced by interrupting load or short circuit currents several times [3]. The criterion to pass lightning impulse voltage tests was to withstand 50 lightning impulses of 125kV without any flashovers. If several flashovers occurred during increasing voltage, up and down method was applied. Fig. 2 shows the dielectric test of a VI after 10 switching operations with 15kA. VI didn't pass the test. The values given in the following lightning impulse voltage test charts are the peak values of measured voltage at VI.

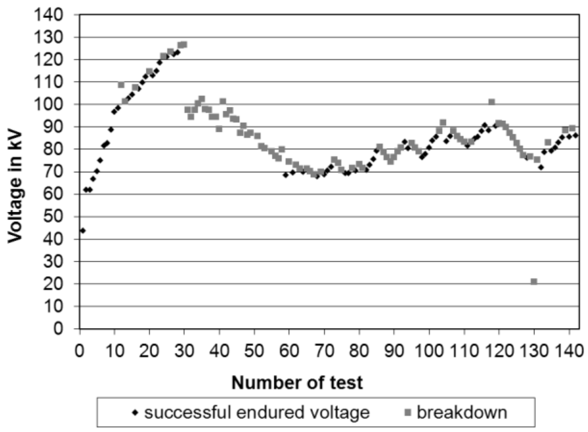

Figure 2: lightning impulse voltage test (1,2/50) of VI after 10 interruption operations with 15kA

This lightning impulse voltage tests showed that dielectric strength becomes reduced when VIs are switched several times with short circuit current or many times with load currents. But these results suggest no specific conclusion about the influence of different dimensions of condensed metal layers on dielectric strength. Inside of VI, there are two vacuum gaps where flashovers can take place. One is the gap between open contacts at a length of 7mm. The second gap consists of two series connected gaps between contact shields and main shield. The total length of these gaps is around 14mm. They are located near the surface of ceramics where the ceramic evaporation takes place during switching operations.

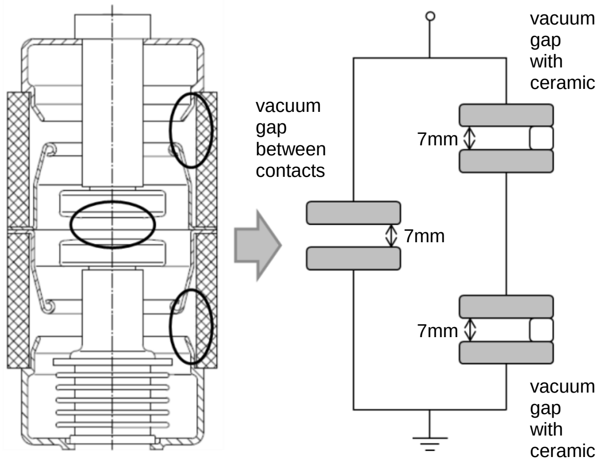

Figure 3: Concerning flashover, the inner parts of VI can be reduced to a single gap in parallel to two series connected gaps with ceramic

It is known from previous investigations [4] that vacuum gaps with dielectric always have a lower dielectric strength than gaps without these. Especially the triple junction of vacuum- dielectric-electrode is a critical area of vacuum insulation, because primary electrons can emit at lower electric field strength [5]. Furthermore, between these gaps there are not only bare ceramic surfaces but ceramics that are contaminated with CuCr vapor. Theses surfaces will have a lower dielectric strength than bare ceramics, so they should have a big influence on total dielectric strength of VI. Related to lightning impulse voltage test, both gaps are connected in parallel. A simplified representation of these connections is shown in Fig. 3. In order to determine if the contact gap or the series connected shield gaps have the bigger influence on VI's dielectric strength, shield potential measurements during lightning impulse voltage tests were taken. The VI test vessel allows to connect a voltage divider to main shield of VI from outside and therefore to the transient recorder. The plan is to measure whether flashovers take place from contact to contact or from first contact shield over main shield to second contact shield. Flashovers over main shield should be measurable, because the shield will be connected to test voltage by flashover during voltage breakdown. Fig. 4 shows lightning impulse voltage test of VI after having carried out 30 interruption operations with 5kA. Test routine was the same as described before. On the left side of Fig. 4 the test- and breakdown voltage is plotted in kV. On the right side the ratio between applied test voltage and measured shield potential is given. This ratio x is calculated as follows:

$$x = \frac{U_{test}}{U_{shield}}$$

When the ratio between test voltage and shield potential is around x=1, the shield potential has the same amplitude as the test voltage. This means, that there is a conductive connection between contact shield and main shield. This connection can only build up during flashover. When no flashover took place, shield potential is around 1/6 of applied test voltage. This potential results from capacitive coupling.

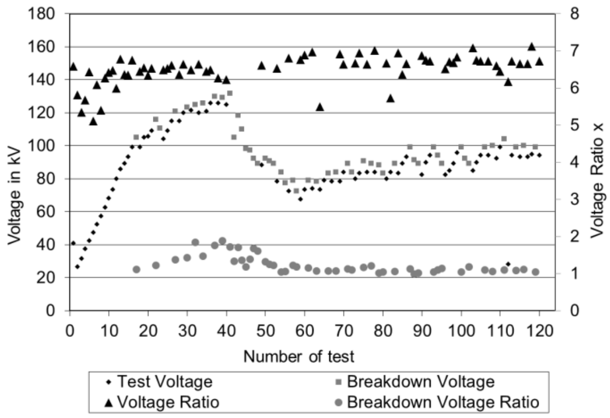

Figure 4: Lightning impulse voltage test of VI with shield potential measurement. Shield potential is plotted as ratio between applied test voltage and measured shield potential

Another lightning impulse voltage test with the same type of VI was performed at 2mm contact gap. The reduction of the contact gap leads to a lower dielectric strength between contacts. This guaranteed that breakdowns would not happen between contact shields and main shield. When breakdown occurred in VI with 2mm contact gap, the ratio x was measured around 1/6. This test showed, that breakdowns in VI not always cause a ratio x=1, but only when breakdowns happens over main shield.

Lightning impulse voltage tests between both contacts and main shield were done by connecting ground potential during lightning impulse voltage tests from outside of VI test vessel to shield connection. It was proven, that dielectric strength of these gaps becomes reduced when ceramics are contaminated with metal layers.

4 EVAPORATION LAYERS ON INNER CERAMIC SURFACE OF VI

After performing switching operations and dielectric tests, the VIs were opened so that the evaporation layers could be investigated. Previously, all parts of VIs were labeled, so that the exact position of each part to the others could be reconstructed later again. Then the caps of VI with contacts were removed from a metal working lathe. The two cylindrical ceramic parts were detached from each other by sawing the brazed weld, which holds both parts and the main shield together. In order to investigate not only small segments but the complete shape of evaporation layers, it was very important not to damage or contaminate the cylindrical ceramic parts during detaching. A digital endoscope camera with 2MP resolution was used to take pictures of evaporated parts of ceramics. These pictures were put together, so that panoramic pictures of evaporation layers were generated. In order to give a general idea of the entire evaporation of VI, the panoramic evaporation pictures were placed beside a sectional view of a VI (Fig. 5 to 9). The sectional view of VI is placed on the left side of the ceramic pictures, where the fixed contact is always on top and the movable contact on the bottom of the picture.

Investigation into the evaporation layers of VIs showed that there are two different sources of melted material. When switched VIs were tested with lightning impulse voltage, a mechanism of evaporation could be traced that is different from evaporation as a result of switching operations. This mechanism is explained down below in connection with pictures of evaporation profiles. Furthermore, the shapes of evaporation layers around ceramics varied as a function of current intensity and number of switching operations. Evaporation layers that were caused by interruption of currents around 5kA to 10kA were always more or less uniformly ring shaped (Fig. 5). The shapes became more and more irregular with increasing current intensity.

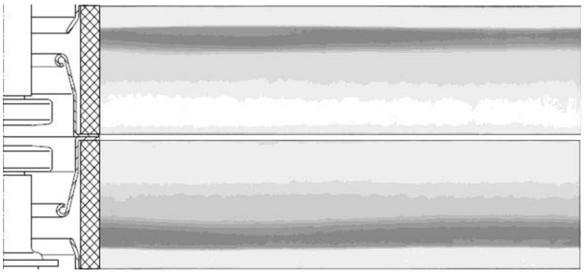

Figure 5: VI after 100 times of interrupting 5kA, polarity of current was changed after every switching operation

Figure 6: VI after 30 times of interrupting 5kA, polarity of current was changed after every switching operation

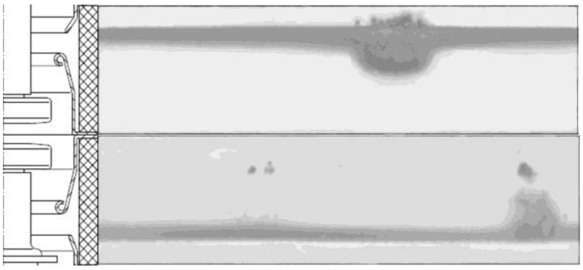

Figure 7: VI after 30 times of interrupting 10kA, polarity of current was changed after every switching operation

Fig. 5 shows a ring shaped evaporation layer on both sides of the VI ceramics. These layers were caused by 100 interruption operations with 5kA. Fig. 6 shows that interrupting 5kA can produce some irregularities in evaporation shape as well. Fig. 7 shows the same kind of irregularities, this VI was used for 30 interruption operations of 10kA. Beside the evaporation layers that were caused by switching operations, could also be observed punctual vapor spots. These spots were caused by lightning impulse voltage tests, they can be seen in Fig. 6 and Fig. 7. The VI shown in Fig. 5 wasn’t tested by lightning impulses and therefore the punctual evaporation spots are missing. The formation of vapor deposition by lightning impulse voltage tests will be subject of chapter 5.
Switching operations with 15kA and 20kA produced very non uniform evaporation spots. Even three to five switching operations produced substantial masses of metal vapor that condensed on ceramic surface (Fig. 8 to 9).

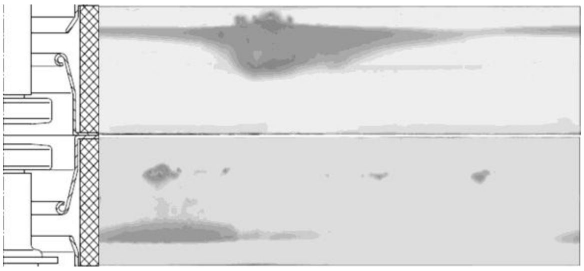

Figure 8: VI after 10 times of interrupting 15kA, polarity of current was chosen from fixed to movable contact

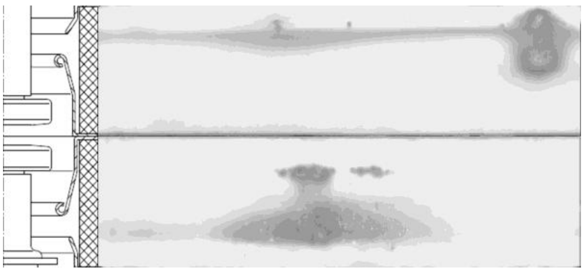

Figure 9: VI after 3 times of interrupting 20kA, polarity of current was chosen from fixed to movable contact

Measurement of evaporation layer thickness and composition was done on several VIs. Electron probe micro analyses (EPMA) was used for surface investigations. With EPMA, surface thickness and composition of layers in a range of some nanometer thickness can be measured. During EPMA measurement, the surface to be examined is shot by a focused electron beam. X-ray is emitted from an excited volume, captured by wavelength dispersive spectroscopy detectors and gives information about the probe. EPMA was done for every investigated VI at a predetermined number of measurement points in a row. These measurement lines always went along the longitudinal axis of VIs. Fig. 10 shows a sample thickness measurement. The x-axis represents the line of measurement points. This evaporation layer was measured at 40 single points along a line of 8mm length. The y-axis gives information about the layer thickness measured at each point. Fig. 11 shows the measured composition in atom percentage.

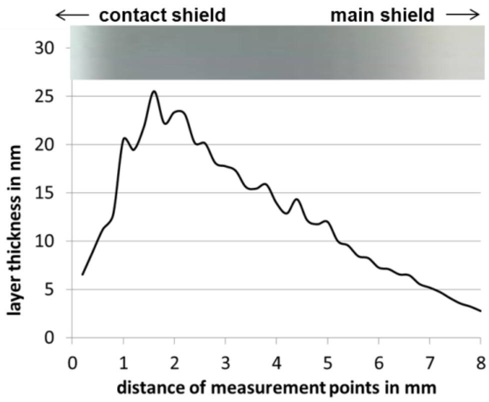

Figure 10: EPMA measurement of evaporation layer thickness on ceramic of a VI

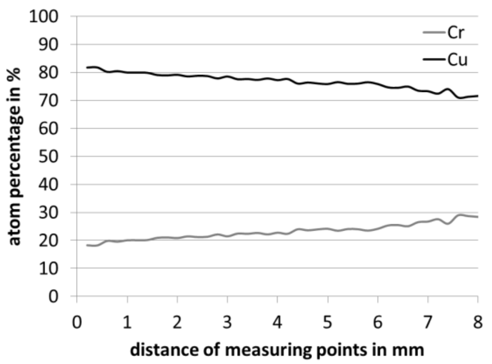

Figure 11: EPMA measurement of evaporation layer composition on ceramic of a VI

While the shielding of VI consists of copper, the contacts are made of CuCr (75/25). The measurements showed that the composition of evaporation layers generated during switching operations matches approximately the composition of contacts. Furthermore, the results showed that the development of layer thickness matches the color gradient along evaporation layers. This is demonstrated on top of Fig. 10, where the development of color gradient can be seen in connection to EPMA measurement. Near contact shields (left side of Fig. 10), the color of evaporation layers went fast from white (no evaporation) to dark (thickest layer). From thickest layer to main shield, the colour went more slowly from dark to white. Evaporation layers on ceramics at fixed contact side were compared to evaporation layers on ceramics at movable contact side. This revealed that the evaporation is always stronger near fixed contacts. Evaporation layers of investigated VIs were always approximately two times thicker on fixed contact sides than on movable contact sides.

The measurement of evaporation layer composition generated by lightning impulse voltage test is shown in Fig. 12. This surface investigation revealed that these punctual spots consist of pure copper. This in turn leads to the conclusion that the sources of these spots have to be vapor shields, because they are consisting of pure copper and not of copper- chrome like contacts.

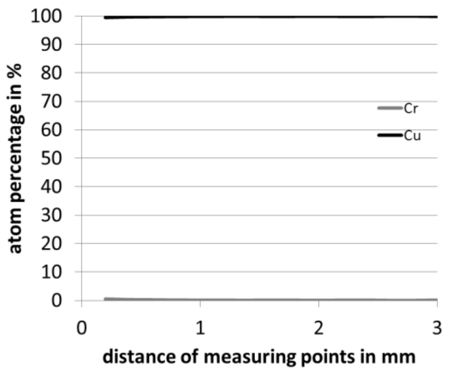

Figure 12: EPMA measurement of evaporation layer composition of punctual spot near main shield

5 CORRELATION BETWEEN EVAPORATION LAYERS AND DIELECTRIC STRENGTH

The dielectric investigations revealed that the gaps between main shield and contact shields have a great influence on flashover in VIs during lightning impulse voltage tests.

When evaporation layer reaches a length of about 21mm, the VIs weren't able to pass lightning impulse voltage tests any more. Punctual evaporation spots were always observed near the longest switching- evaporation layers. This indicates that the longest evaporation layers were always the place where the flashovers during lightning impulse voltage tests happened. Therefore these areas are responsible for reduction of dielectric performance of VI. The punctual evaporation spots could only be found on one side of both VI ceramic parts. This can be explained by triple junction effect during lightning impulse voltage test. Triple junction is the most critical part of vacuum insulation with dielectric [5]. Primary electrons will be emitted in or near this region, this can lead to voltage breakdown. Fig. 13 shows parts of a cross section of a VI with section of the ceramics. The area marked with "a" shows the triple junction at cathode during dielectric test. When a flashover takes place in this area, the main shield is connected to the cathode by a plasma channel. Main shield will have nearly the same electrical potential as fixed contact and therefore a new cathode triple junction can build up. This triple junction is marked with b in Fig. 13. Flashover of this second vacuum gap will lead to total voltage breakdown of VI.

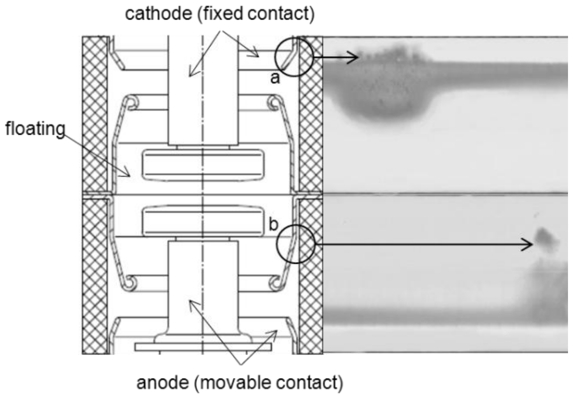

Figure 13: Triple junctions in VI at fixed contact (a) and at main shield (b), evaporation spots on ceramics caused by lightning impulse voltage tests near triple junctions.

Investigations of evaporation layers led to the conclusion, that the biggest evaporation layers on VI ceramics do have a big influence on dielectric performance. Small triple junction evaporation spots were always observed directly at the vertically longest evaporation layers. These spots are always placed near triple junctions of lightning impulse voltage test. These spots can be seen in Fig. 13 on the right hand side of VI cross section, they are pointed by an arrow.

6 CONCLUSIONS

Investigations on switched VIs showed that evaporation layers on ceramics are responsible for reduction of dielectric performance. This was confirmed by the following results:

- During voltage breakdown of lightning impulse voltage test, shield potential had the same value as applied test voltage. This indicates that flashovers didn't happen between contact gaps but on the main shield.
- Besides the evaporation layers caused by switching operations, there were evaporation spots caused by lightning impulses. These spots consist of pure copper, therefore the source has to be shield material.
- Punctual evaporation spots were always placed at parts of VI that served as

cathode during the lightning impulse voltage test. This fits into the theory of a breakdown initiated at triple junction in vacuum.

- Punctual evaporation spots caused by lightning impulse voltage tests were always observed in direct connection to the vertically longest evaporation layers. Flashovers in VI must have been initiated in this region. This leads to the conclusion, that the longest evaporation layers are responsible for reduction of dielectric performance.

Irregular evaporation layers caused by switching operations of currents near maximum of VI's rated short circuit current were found to be most critical. These switching operations generated evaporation spots of more than 20mm length. Switching operations of currents lower than half of maximum rated short circuit current generated ring shaped layers on ceramic surfaces. Thickness of these layers increased with higher number of switching operations, but dielectric performance was not influenced very strongly when layers didn't grow much in vertically length.

7 REFERENCES

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