INFLUENCES OF HIGH VOLTAGE FUSES ON PARTIAL DISCHARGE MEASUREMENT OF ELECTRICAL EQUIPMENT

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Abstract: This contribution deals with the partial discharge (PD) behaviour of sand filled current limiting high voltage fuses (HV-fuses). HV-fuses are often used in combination with switchgear and transformer stations for protection of the equipment against over-currents. HV-fuses are part of those installations and have to meet the corresponding standards and quality requirements. If fuses are exposed to high electrical stress, they may produce PD. When PD measurement is used for quality assessments and monitoring purposes of the switchgear station, the HV-fuse may affect the PD behaviour of the whole installation.

PD are generated in the arc-quenching medium (quartz sand) by the melting elements. The shape of these elements leads to high electrical stress and PD activity. The PD activity was recorded by the help of digital storage oscilloscopes and PD analysis systems.

The source of the PD generation and the influence of parameters like applied voltage, temperature, pressure, and moisture of the arc-quenching medium was investigated on different fuses and on a model reproducing the inhomogeneous field configuration. It was found that ozone generation is one result of the PD activity and an important factor describing the PD behaviour.

PD may also damage the melting elements of the fuse by electrical erosion. A long-time investigation revealed such effects.

To show the important impact of construction parameters on the electrical field inside the fuse and on the PD activity, a computer model based on the finite element method (FEM) was used for optimising the geometry.

Concepts preventing PD generation inside the fuse are discussed in detail. Field grading and modification of the fuse design can reduce the field strength and the PD activity. Special conductive layers for stress relieving may also support the reduction of PD.

The most efficient way to decrease the PD activity of fuses was found to be the application of additives to the arc-quenching medium.

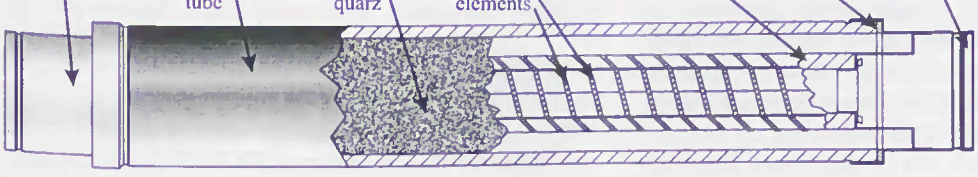

Fig. 1: Schematic view of a HV-fuse (6/12 kV - 40 A)

I. INTRODUCTION

Due to decreasing size of electrical equipments, like switchgears or transformers, PD generation of HV-fuses becomes a problem: Decreasing size of electrical equipment implies reduced distances between the components resulting in higher electrical stress. If the stress exceeds a certain level, PD generation may occur.

Monitoring of electrical equipment becomes an increasingly important issue for achieving high quality in power delivery and to extend the life time of the equipment. If the current state of an electric device is known, maintenance can be scheduled in larger cycles or on demand. Among the multiple parameters that can be evaluated for state estimation, PD behaviour is one of the most important. Because HV-fuses are part of electrical equipment, and often the whole assembly is tested, the influence of the HV-fuses on PD measurements must be known.

This investigation focuses on the widely used sand-filled type of current limiting HV-fuse (Fig. 1).

I.1 Mechanisms of PD generation

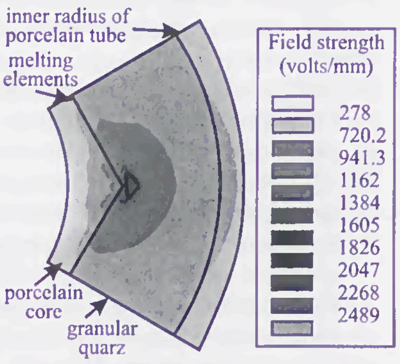

Fig. 2: El. field in HV-fuses (cross section in radial direction)

The main reason for PD generation inside fuses is the inhomogeneous electrode arrangement formed by the thin fusible elements and surrounding components on earth or high-voltage potential. Because melting elements are shaped matching the fuses' purpose [1, 2] they form a sharp electrode: Commonly used silver bands only have a thickness of some dozens of micrometers. To resist the recovery voltage, they are often notched, leading to extreme electrical stress. For arc - quenching purpose, the melting elements are embedded in sand. Sand forms a porous dielectric filled with air, which is a weak dielectric in terms of high - voltage engineering. If this

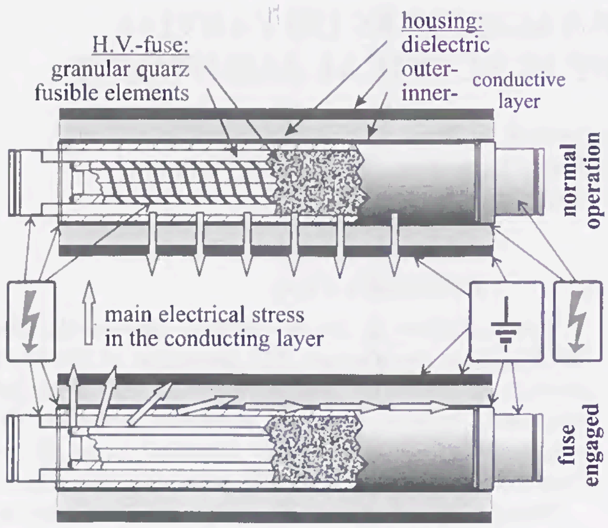

Fig. 3: Fuse housing with field grading

dielectric is exposed to high electrical stress, electrical breakdown in the air gaps between the sand grains occurs. The breakdown begins near the fusible elements, because the electrical stress is more than 50 times higher than in the rest of the fuse (Fig. 2).

If the electrical stress is high enough, discharge channels can propagate until the inner border of the porcelain tube. The role of the sand grains is ambivalent in this case, because they can stop the propagation of the discharge channel mechanically, or sustain it by surface effects.

I.2 Concepts preventing PD generation

PD activity of H.V.-fuses can be decreased in several ways:

1. Field grading, such that critical el. field strength for PD generation is not exceeded.
2. Insertion of metallic shields (shielding).
3. El. filtering, to prevent that generated PD impulses propagate into the switchgear installation.
4. Modification of material properties, to reduce the electrical stress in the sand.
5. Constructional changes in the design of the fuses.

Field grading can be implemented by fuse housings with conductive layers (Fig. 3). The layer must be capable to feed the capacitance of the dielectric during normal operation but must prevent current flow after the fuse has opened. This can be accomplished with materials having a voltage dependent non-linear conductivity [3, 4, 5, 6].

Insertion of metallic shields is disadvantageous because the fuses operation is inhibited.

Filtering implies additional components added in the current path and is not cost-efficient.

Modification of the arc-quenching medium can affect the switching behaviour. If the supplement to the sand is gas evolving, care must be taken not to overstress the fuses' enclosing tube. Gas evolving additives tend to support the arc interruption [7].

Constructional changes can be performed on nearly all parts of the fuse, with respect to existing standards. Impacts on the electrical stress can be obtained by changing the melting elements' shape, enlarging the clearances of the inhomogeneous "electrode setup" etc. Often these changes are disadvantageous with respect to the fuses' switching behaviour or costs.

II. INVESTIGATIONS, TEST SET-UP, AND SAMPLES

Preliminary measurements showed that the highest electrical field occurs in fuses employed under oil. Here the distance between melting elements and grounded environment (for example the transformer tank) is very small. In gas-insulated switchgears clearances are larger and therefore electrical stress is less critical. The lowest electrical stress can be found in air-insulated switchgear stations, because clearances are even larger.

II.1 Switching behaviour

The switching behaviour of the fuses was tested according to IEC 282-1. To determine the post-arcing behaviour, a shunt was connected in series to the fuse (Fig. 4). The shunt was shortened by a switch that was opened after arcing to allow sensitive current measurement.

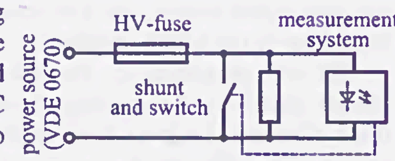

Fig. 4: Extension to IEC 282 test circuit

II.2 PD measurements

For long-time observations, the fuses were equipped with an earth electrode located in the middle of the porcelain tube and were connected to earth via an automatic PD-measurement system (Fig. 5). The fuses were supplied with 20 kV AC voltage. The electrode was glued directly on the surface of the porcelain tube and graded with semi-conducting material. The test set-up contained 10 fuses in parallel. The PD activity was

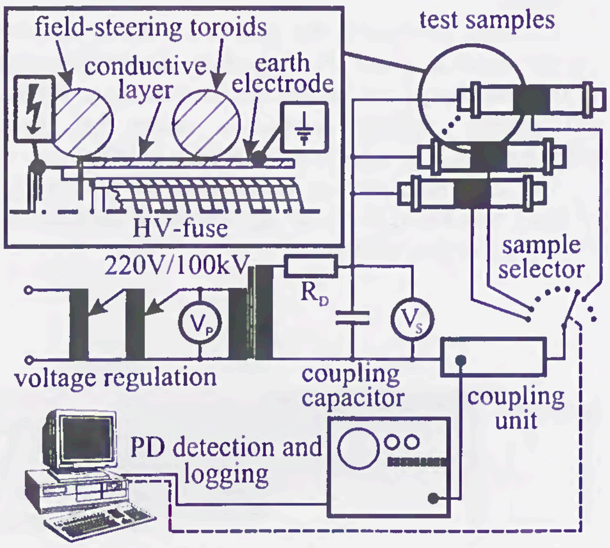

Fig. 5: Test set-up for long-time investigations

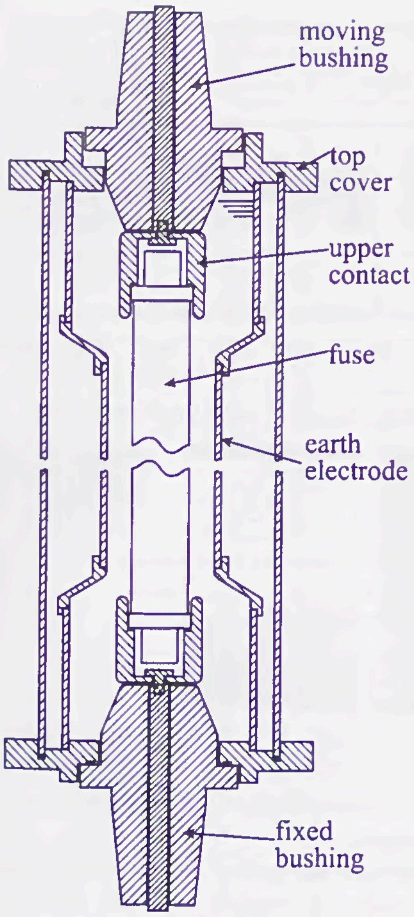

Fig. 6: PD measurement tank

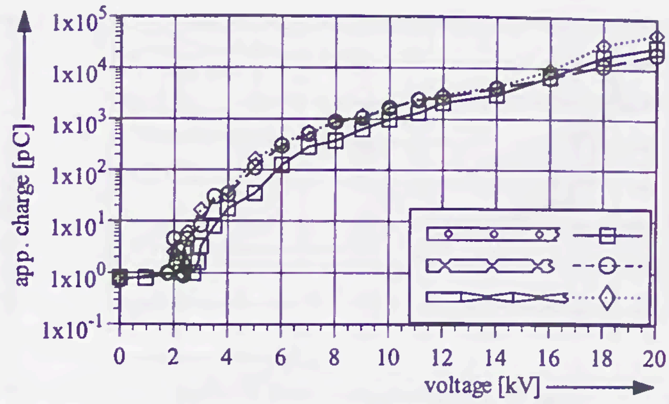

Fig. 7: PD behaviour over voltage with different elements' shapes

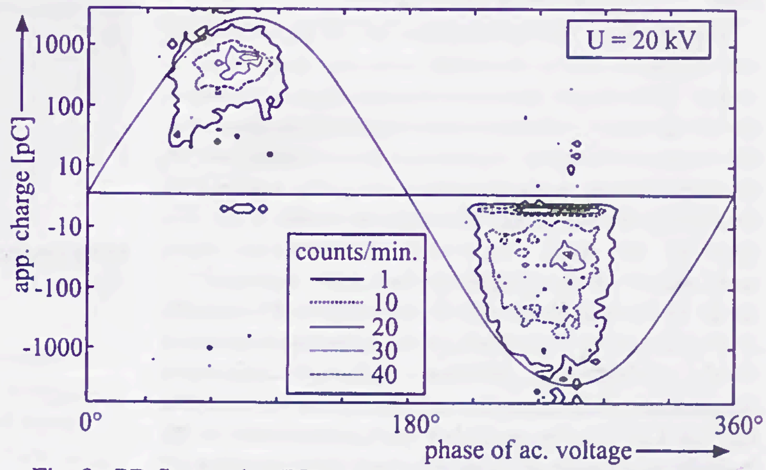

Fig. 8: PD fingerprint (PD number vs. phase and apparent charge)

recorded for 1000 hours. The samples were cyclically selected for a measurement time of one minute.

Fig. 6 shows the PD measurement tank used to test the short-time PD behaviour of HV-fuses. It consists of an outer cylindrical oil-filled tank, embedding the fuse to prevent from PD generated on the fuses' surface. At a distance of 10 mm around the porcelain tube of the fuse, a cylindrical earth electrode was placed and connected to the PD detector.

II.3 FEM model

For the field-computation, a three dimensional model was used and calculated by means of FEM. The calculation was run on a workstation cluster in the university's calculation centre.

III. RESULTS

The PD behaviour of HV-fuses over the voltage is shown in Fig. 7. The values of the apparent charge rise fast up to levels inhibiting sensitive PD measurement of other components in the switchgear assembly.

The influence of the melting elements' shapes is negligible. The PD inception voltage varies within 2.0 kV between individual fuses of the same series. Fuses can even change their PD behaviour between distinct measurements if they are physically moved. This is related to the displacement of sand grains inside of the fuse, resulting in differently shaped air gouges in the sand. Therefore PD conditions may change unpredictable. At high voltages, the apparent charge remains constant, because further propagation of the PD arcs is inhibited by the porcelain tube. The position of PD impulses relative to the phase of the supplying voltage is similar to corona impulses in air [8, 9]. The number of PD impulses rises very fast from individual impulses near inception voltage to more than thousand pulses per second at 10 kV.

In Fig. 8 a "fingerprint" of a 12/20 kV fuse at 20 kV is shown. The number of PD impulses with a specific level is mapped over the phase of the supplying voltage and the corresponding PD charge. Darker shading indicates a higher amount of counts. As can be seen, PD arise most frequently in the interval between the zero-crossings and the maximum of the half-waves. At lower voltages, the impulses occur in the negative half-wave only. With increasing voltage the impulses rise and affect also the positive phase. At high voltages, strong pulses in the negative phase combined with a high impulse rate in the positive phase are dominant.

The characteristic feature of the fuses' PD behaviour is the occurrence of impulse clusters instead of single impulses. This can be explained with the inhomogeneous configuration of the melting elements. The PD are generated along longer parts of the wire, not only at discrete sites.

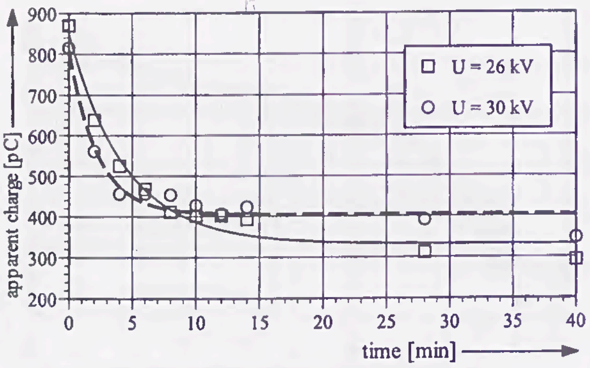

Fig. 9: PD behaviour of 6/12 kV fuse

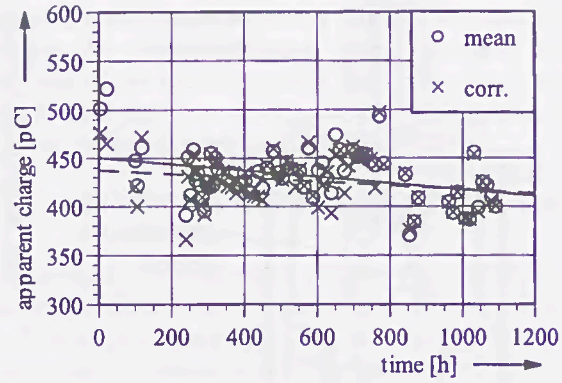

Fig. 11: App. charge in long-time observation

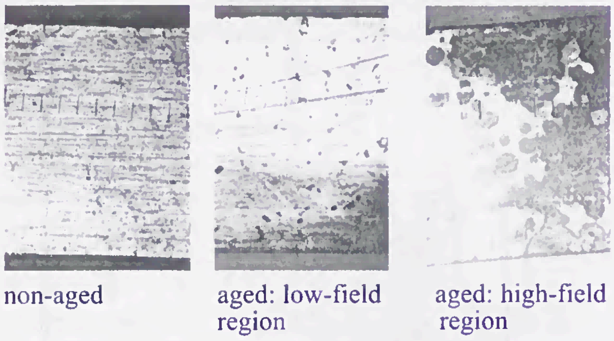

Fig. 12: Erosion effect on melting elements

III.1 PD behaviour over the time

Fig. 9 shows the development of PD over the time. The apparent charge decreases with the stress time as well as the impulse rate (not shown). This is related to the development of ozone in the high-field region, near the fusible elements [10, 11]. The results of an investigation on a needle-plane electrode set-up [10] correspond to the ones obtained on fuses (Fig. 10), although the fuses were only measured at room temperature. When temperature increases above 60 °C, ozone is not generated and no decrease of PD activity can be observed. This is related to ozone disintegration, which depends on different parameters: pressure, temperature, field-strength, and chemical reactions [10, 12, 13, 14]. The ensemble of parameters leads to an equilibrium in ozone generation and disintegration. If ozone generation is stopped, disintegration continues by chemical reactions. Therefore, after 24 hours without electrical stress, the PD activity of HV-fuses rises to initial values.

When voltage is applied for longer time (1000 hours), apparent charge and impulse rate still decrease (Fig. 11). This can be explained by electrical erosion [15]: After the ageing process the fusible elements show erosion effects (Fig. 12). The excavated material moves to the enclosing sand. If the material excavated from the fusible elements is deposited around the sharp edges of the wires, electrical stress and PD generation decrease.

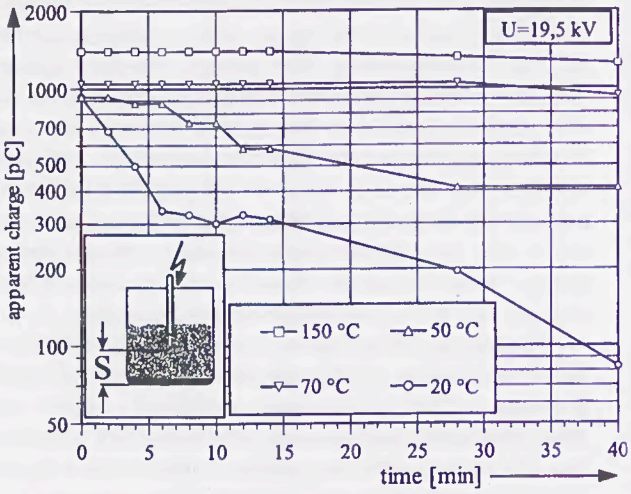

Fig. 10: PD behaviour of needle-plane set-up in sand

Other fuses from the ageing test have been tested to show the impact of erosion on the current-time characteristic (Fig. 13). The influence is negligible. This may also be related to the material excavated by electrical erosion, because it "glues" the sand to the melting elements, resulting in better heat transfer to the sand and by filling the air gaps to a higher thermal capacitance.

III.2 Results from field-computation

Figures 2 and 14 show results obtained from field-computations. Because FEM cannot calculate the exact results at the edges of the fusible elements, the mean of 5 % from the most charged finite elements was used as "maximum" electrical field-strength. Starting from a set of global constraints, only one single parameter was

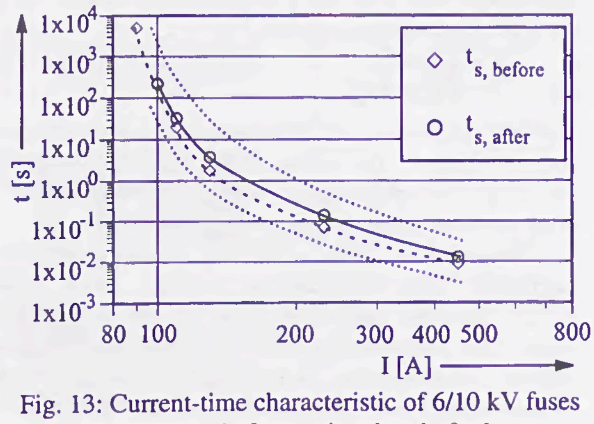

Fig. 13: Current-time characteristic of 6/10 kV fuses before and after ageing, band of tolerance

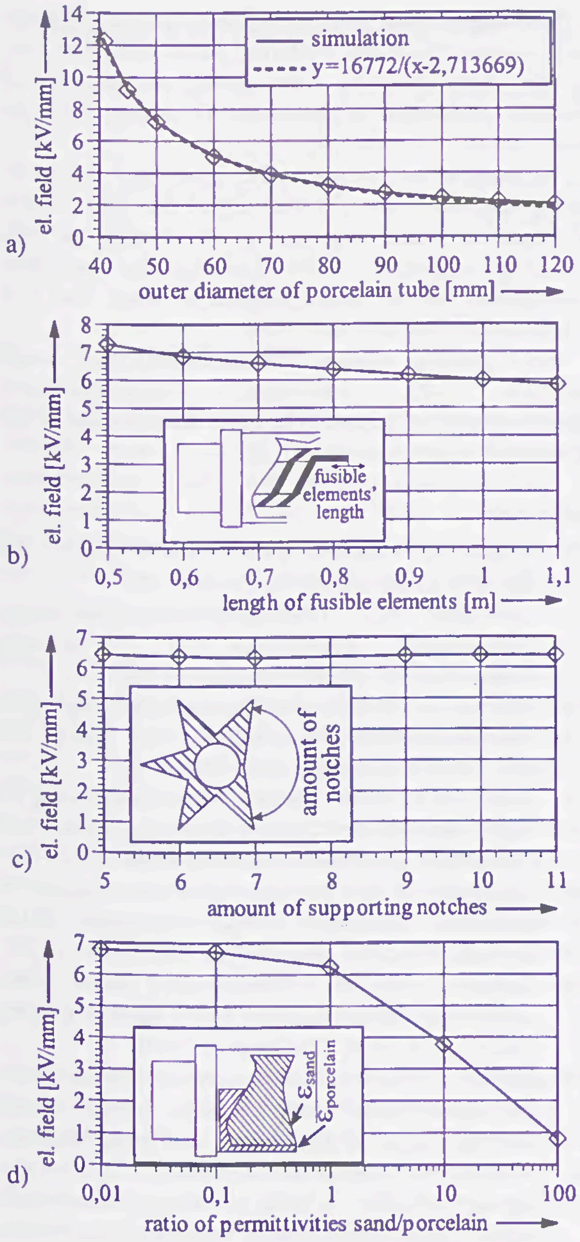

Fig. 14: Results from field-computation

varied on each calculation as described below.

As proof of reliability for the calculations the variation of the porcelain tubes' diameter can be interpreted (Fig. 14a): It follows the 1/r-ratio known from cylindrical electrode set-ups. The diameter has the strongest impact on the maximum electrical field, but enlargement leads to higher weight and costs of the fuse.

The enlargement of the fusible elements' length (Fig. 14b) yields to better field behaviour, because the windings of fusible elements are approaching. The total length of the fuse was held constant. Longer fusible elements reduce the maximum electrical field. However, a minimal distance between distinct windings must be respected, because of switching behaviour.

The variation of the number of supporting notches (Fig. 14c) does not affect the field strength at all,

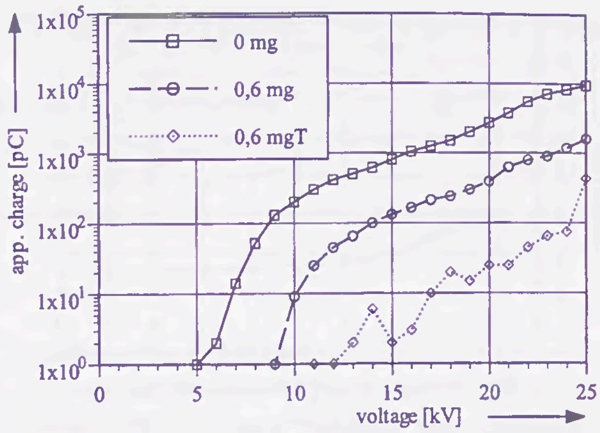

Fig. 15: Influence of adding water to the filler (12/20 kV fuse)

although with growing amount of notches the support becomes rounder. The non-homogeneity of the field depends on the thickness of the fusible elements compared to the grain size of the sand. This corresponds to Fig. 7 where differently shaped melting elements show comparable PD behaviour.

Variation of the permittivity ratio (sand to porcelain, Fig 14d) can be used to boost the field strength in the porcelain and therefore reducing it in the sand. Increasing of sand's permittivity is possible by adding additives based on elements like titanium to the sand, but it is unknown how this may affect the switching behaviour of the fuse. At least the fuse becomes more expensive, because large amounts of additives have to be added to the sand to achieve relevant changes in the permittivity ratio.

If the electro-conductive analogy is taken into consideration, the results of Fig. 14d can be interpreted in a second way: A high ratio of conductivity (sand to porcelain) also leads to lower electrical stress in the sand. As porcelain is a very good insulator, only a small amount of additives in the sand needs to be employed.

III.3 Reduction of PD activity

The effect of increasing the conductivity of the sand is shown in Fig. 15: If a small amount of water is added to the fuses' sand, the PD inception voltage rises and the increase of PD over voltage becomes smaller. If the fuse

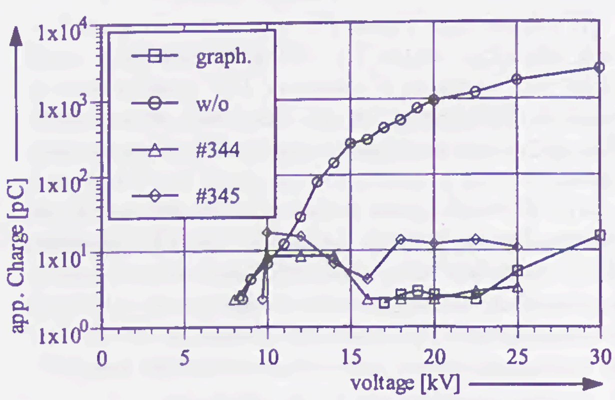

Fig. 16: PD behaviour of fuses with field grading layer

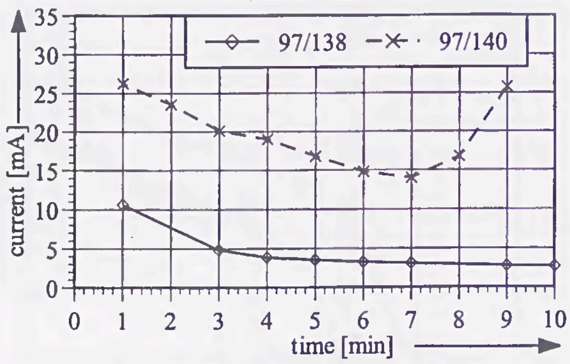

Fig. 17: Post-arcing behaviour of fuses

is tempered after applying water, the PD activity decreases even more (Fig. 15: "0,6 mgT").

Another attempt to reduce PD generation of the fuses is field grading. Based on coatings elaborated in [6], test fuses were made and tested for switching behaviour. The SiC based coating was applied to the surface of the porcelain tube and a 10 kV fuse inlet was mounted. Fig. 16 shows the results of PD measurement. Contrary to a fuse without coating (Fig. 16: "w/o"), PD activity shows a significant decrease for all samples. Samples 344 and 345 were graded using a ceramic overglaze. Most fuses successfully fulfilled the switching test. Fuses with graphitized surface show the best PD behaviour (Fig. 16: "graph") but are unable to switch.

To explore the post-arcing behaviour of the conducting layers, the recovery voltage was applied for 10 minutes. The remaining current in this period is shown in Fig. 17. Nearly all samples manifest decreasing currents.

The high initial current (t = 1 min. in Fig. 17) results from the conductivity of the fuses' fulgurite. After cool-down of the fulgurite, the remaining current is dominated by the conductive layer. In case of 97/140, the conductivity was chosen too high, leading to self-heating of the layer and finally destruction of the fuse due to over-heat. The turn-around point at seven minutes results from the heat produced during the arcing phase, which propagates slowly from the inner of the fuse (arcing channel) to the surface.

IV. CONCLUSION

HV-fuses may create PD impulses, if exposed to high electrical stress. The PD generated may reach levels not tolerable if sensitive PD measurement is required. The impact on the fuse itself is negligible, although electrical erosion of the fusible elements takes place.

The PD mechanisms are complicated, because of the inhomogeneous sand-air dielectric. The PD behaviour of HV-fuses depends on different parameters:

- the electrical field the fuse is exposed to,
- temperature, pressure inside the fuse,
- moisture and properties of sand inside the fuse,
- ozone generation and electrical erosion.

Shielding of the fuses is difficult, because metallic shields impair the fuses' switching behaviour. However, shielded fuses may be used during on-site tests of electrical equipment to eliminate PD coming from the fuse.

The easiest way to reduce PD generation inside the fuse is to enhance the conductivity of the filler. In this investigation water was used. Its impact on the switching behaviour of the fuse has not yet been investigated, but the small amount of water that was added does not seem to be critical.

Field grading reduces PD generation. SiC based materials with non-linear voltage-resistance characteristics can be used. However the selection of the appropriate resistances is difficult.

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