Electrical Strength of Air Containing Ozone and Nitric Oxides Produced by Intensive Partial Discharges

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ABSTRACT

Internal arcing test results of gapped SiC arresters are presented. During a test in which the arrester is exposed to internal arcing, the positive impulse breakdown voltage increases. Measurements made with a model arrangement indicate that the increase in the electrical strength of gas is higher for positive than for negative impulse polarity. When the internal discharges extinguish, recovery processes occur. Additional phenomena that can cause changes in the electrical strength are discussed.

1 INTRODUCTION

PARTIAL discharges can occur under polluted conditions inside of HV arresters. As a result of these discharges, the chemical constitution of the gas inside the arrester also is altered. The concentrations of ozone and nitrogen oxides increase, while the oxygen concentration decreases [1, 2]. Intensive internal discharges can also initiate degradation of zinc oxide varistors [3]. The above-mentioned phenomena, together with thermal processes, contribute to the most severe aging of gapless metal oxide surge arresters. The electrical strength of the gas inside the gapped arrester determines its sparkover voltage. In the case of gapless arresters, the inner gas strength influences the ignition or extinction of internal partial discharge (PD), and also determines if breakdown of the internal channel occurs.

The electrical strength of air that changes as a result of PD occurring in a closed or open volume is of basic importance for the aging of HV insulation and for the efficiency of ozone generation in ozonizers [4]. It is clear that a great deal of work has been published on the chemical reactions created by PD in both dry and humid atmospheres [5]. However, there are few reports that deal directly with the electrical strength of gases produced as by-products of PD [6–9]. This paper therefore provides a more general insight into the electrical strength of air exposed to the influence of PD. Possible causes of the observed changes in breakdown voltage are discussed. Ultimately this information can be applied not only to HV arresters, but also to electrical insulation that is stressed by PD.

2 EXPERIMENTAL METHODS AND PROCEDURE

A gapped arrester, model XAA106T, manufactured by ASEA, with 72 air gaps with resistive grading (height 100 cm, inside diameter 11.5 cm) was chosen for the experiments. The air gaps were grouped alternately with five SiC varistors (Figure 1). A semiconducting film with surface conductivity of $\sim$ 200 μS was sprayed on the porcelain housing using Graphite 33. A clean band of $\sim$ 10% of the creepage length was formed at the upper flange. An additional toroidal electrode was mounted at the end of the pollution layer to prevent external corona (Figure 2). A voltage of 50 kV (rms) at a frequency of 50 Hz was applied to the arrester. Subsequently, intensive discharges within the arrester ignited due to the high radial field between the semiconducting layer and the air gaps. The applied voltage was switched off after a fixed stress time of 30 min, and the lightning sparkover voltage (1.2/50 μs) of positive polarity was measured according to the up and down method. The ac voltage was applied again. Additionally, at the conclusion of the test, the arrester was dismounted, and the maximum temperature inside the arrester (recorded by thermo strips) was read.

The temperature increase inside the non-uniformly polluted gapped arrester was observed during the test. The temperature increase was measured earlier during similar experiments with a gapless arrester (metal oxide surge arrester) and also with a gapped arrester [1]. It was confirmed experimentally that the temperature increase was caused mainly by capacitive current injection into the varistor blocks rather than by PD, also referred to as 'cool discharges' [1]. Therefore, a sim-

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pler model arrangement was used to avoid the phenomena described above, as well as other 'disturbing' effects.

The model setup consisted of a hermetic glass vessel and the test air gap (sphere-plane or rod-plane) for measurement of the electrical strength of the gas (Figure 3). After application of an ac voltage to the exterior toroidal electrode, internal discharges started to burn between the glass wall (thickness 4 mm) and the grounded aluminum rod inside the vessel (air gap 25 mm). The gas temperature inside the vessel was measured using a mercury thermometer. After a fixed stress time, the 50% breakdown voltage of the test air gap was measured using a standard lightning impulse voltage.

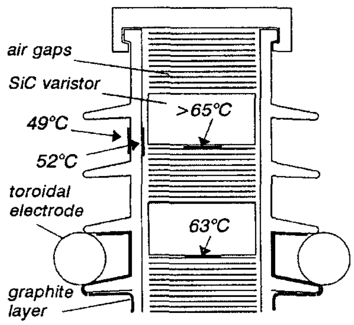

Figure 1. The arrester's longitudinal section.

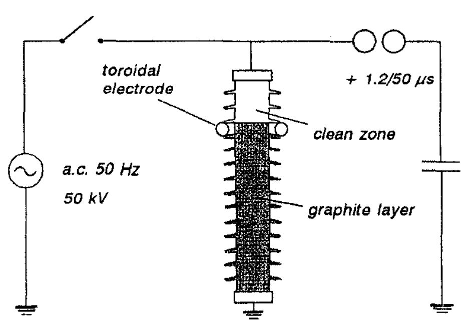

Figure 2. The arrester under internal arcing test.

3 MEASUREMENT RESULTS

As can be seen in Figure 4, the arrester's sparkover voltage increased from 76 kV to ~ 90 kV over a 4 h period as a result of internal discharges. Concurrently, the temperature of the interior of the arrester increased unevenly, reaching values >65°C. This phenomenon was due to the capacitive coupling between the pollution layer and the stack of air gaps connected to the SiC varistors. The highest temperature occurred opposite the clean zone (Figure 1). Although the pressure was not directly measured, given the fact that the unit was closed, an increase in temperature of the gas would cause a corresponding increase in pressure.

When experiments with the model setup were conducted, the gas temperature (measured ~ 4 cm from the silent cold discharges) increased by ~ 1 to ~ 2°C from an initial temperature of 20°C. The positive impulse breakdown voltages of the two test air gaps increased by $\lesssim$ 45% (Figures 5 and 6).

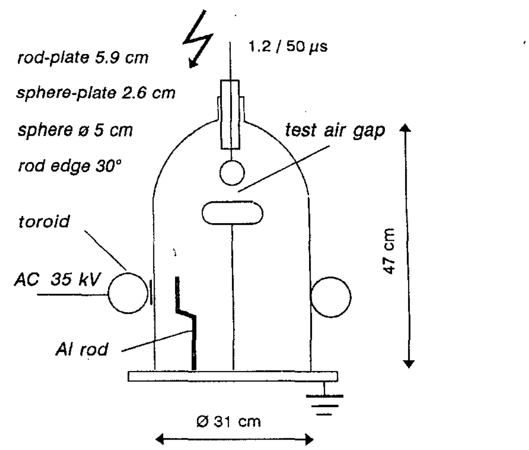

Figure 3. Model test setup.

Under negative impulse the electrical strength of the gas measured by means of a sphere-plane gap increased ~ 10% (Figure 7) during arcing. On the contrary, at the rod-plane gap the breakdown voltage increased by an insignificant amount at the onset of arcing. After 3 h, a decrease in the breakdown voltage was observed (Figure 8). The voltage spread had increased considerably. Small liquid drops were also detected at the rod tip when the test with impulse voltage was finished. It seems that the small temperature increase of the gas, combined with the attraction of water dipoles to the high electric field region, may have caused condensation to appear on the rod electrode.

Previous results [10] indicate that if there is water on the rod tip in the rod-plane gap experiments, then the negative breakdown voltage will decrease considerably as compared to the gap without a drop. Under positive voltage, the same air gap with a drop on the tip showed only small changes in electrical strength compared to the gap without a drop. This phenomenon is caused by different discharges formed under negative or positive voltage polarity.

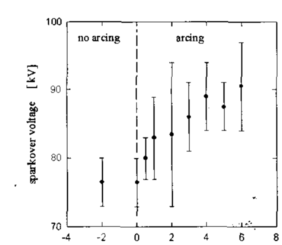

Figure 4. Increase of arrester sparkover voltage during internal arcing test.

When the voltage is switched off, and the PD extinguished, the electrical strength gradually decreases to the initial value of the electrical strength. This phenomenon usually occurs on a time scale from ~ 2 to ~ 8 h. Measurement of the rate of decrease in electrical strength is not

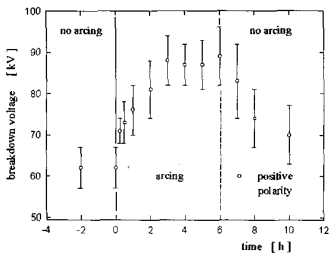

Figure 5. Electrical strength changes at the sphere-plane gap, positive polarity.

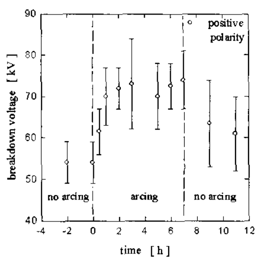

Figure 6. Electrical strength changes at the rod-plane gap, positive polarity.

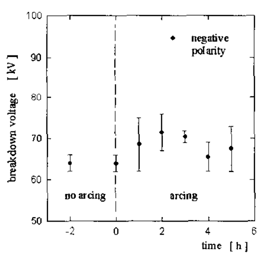

Figure 7. Electrical strength changes at the sphere-plane gap, negative polarity.

a simple task. Even small amounts of air byproducts formed during the test procedure according to the up and down method, cause noticeable changes in the electrical strength of the gas mixture.

Additionally, traces of corrosion were observed on the brass electrodes in both the arrester and in the model arrangements. Several locations on the electrodes changed from a dark yellow to a rose color. In addition, the surface smoothness was altered. Investigations of the electrode sediments in other arresters that suffered internal discharges in the field also have indicated a distinct acidity [11].

4 DISCUSSION

The electrical strength of air in both the surge arrester and model system containing chemical byproducts produced by PD has been shown to increase. However, when the corona in the closed volume is extinguished, the breakdown voltage decreases over the time span of ~ 5 h to a value close to the initial voltage. The latter phenomenon is primarily due to the continuation of chemical reactions within the system [7].

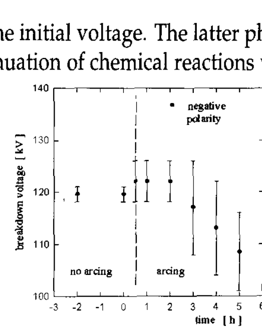

Figure 8. Electrical strength changes at the rod-plane gap, negative polarity.

However, in the model arrangement, a decrease in the negative impulse breakdown voltage can be observed due to other effects. The types of different factors that influence the electrical strength of a gas mixture are discussed below.

4.1 FACTORS WITH WEAK OR NO INFLUENCE

In a closed volume, an increase in gas temperature causes a corresponding pressure increase. In the model vessel, the temperature increased by ~ 1 to 2°C. However, temperature increases in the tiny gas cavities embedded in HV insulation are more pronounced. The air density correction factor k_1, for the breakdown voltage under pressure p, and temperature T, is defined as

$$k_1 = \frac{p}{p_o}\frac{T_o}{T} \tag{1}$$

where p_o is the standard pressure of 101.3 kPa, and T_o the standard temperature of 293 K. However, an ideal gas contained in a closed volume obeys the following condition

$$\begin{aligned} \frac{pV}{T} &= \text{constant} \\ &= \frac{p_o V}{T_o} \end{aligned} \tag{2}$$

and therefore k_1=1. Based on the above equations we can say that in a closed volume filled by an ideal gas, the electrical strength does not depend on the temperature. In other words, the strength depends strictly on the number density of the gas molecules in the fixed volume.

In the arrester exposed to non-uniform pollution (*e.g.* the internal arcing test) the higher temperature additionally decreases the voltage non-uniformity along the air gap stack. At the beginning of the test, the temperature of arrester elements equals the ambient temperature. The voltage distribution along the air gap stack is non-uniform due to a very non-uniform pollution layer on the porcelain housing [1]. The grading resistors in the air gap warm up more rapidly than other arrester parts. Because of the negative temperature coefficient of grading resistors, their resistance decreases, which in turn improves the voltage distribution. Therefore, under the internal arcing test, the increase in sparkover voltage is a result of gas composition changes and decreasing non-uniformity in voltage.

4.2 FACTORS THAT INCREASE THE STRENGTH

Ryzko measured an increase of $\leqslant 50\%$ in the impulse breakdown voltage after sparking in a closed chamber [7]. In open air (under atmospheric pressure), a gaseous mixture containing 3.1% ($\sim$ 60 g O_3/m^3) ozone causes a 16% increase in electrical strength [8]. Ryzko attributed the increase in breakdown voltage to an increase in the electron attachment coefficient or the reduced availability of free electrons. The free electrons were likely absorbed by a strongly electronegative and highly reactive oxidant such as ozone. See the discussion on chemical reactions and recovery processes below.

A temperature increase within an arrester can cause water evaporation from surfaces or from the bulk of construction materials and varistors. The resulting pressure increase, together with the known electronegative properties of water vapor can cause an increase in the sparkover voltage [12]. Corona burning on the polymer insulators in our vessel can produce moisture by the reaction of atmospheric oxygen with hydrogen that is released from the polymer [13].

4.3 FACTORS THAT DECREASE THE ELECTRICAL STRENGTH

During arcing, gases are produced which are heavier than gases in the atmospheric air. O_2 diminishes, ozone O_3 increases, and nitrogen oxides NO_x are formed

$$O + O_2 + M \rightarrow O_3 + M \quad (3)$$

$$N_2 + O_2 \rightarrow 2NO \quad (4)$$

$$2NO + O_2 \rightarrow 2NO_2 \quad (5)$$

$$NO_3 + NO_2 \rightarrow N_2O_5 \quad (6)$$

When the system temperature returns to ambient temperature, the above processes can be responsible for a pressure decrease. A decrease in pressure due to a reduction in number density is related to a decrease in electrical strength. The phenomenon of pressure decrease was found in the arresters returned from substations because of excessively low sparkover voltages [11].

Water drops can be formed on the electrodes [10], thus decreasing the electrical strength of the system.

Electrode surfaces can become contaminated with corrosion that is induced by the discharges [14–16]. The crust can decrease the electrode distances significantly (which are in the range of 1 mm), thus decreasing the electrical strength. It is worth noting that even stainless steel is not totally resistant to corona induced corrosion [16].

The nonlinear voltage distribution along the air gap stack can be increased by non-uniform pollution on the housing or by different degradation rates of grading resistors. This nonlinear distribution can cause a decrease in the electrical strength.

When the arrester is warm, part of the inner gas can escape from the enclosure when the arrester is not airtight. Thus, the pressure inside the arrester will be lowered, and the electrical strength will decrease.

4.4 CHEMICAL REACTIONS AND RECOVERY PROCESSES

The gases present in the interior of both the arrester and the model system are comprised of typical air components. However, due to high temperature experienced during arcing, molecular oxygen and molecular nitrogen are broken down according to the Zeldovich mechanism [17]

$$O_2 + M = 2O + M \quad (7)$$

$$O + N_2 = NO + N \quad (8)$$

$$N + O_2 = NO + O \quad (9)$$

where M is any other species, to ultimately yield nitric oxide (NO). In addition, ozone is formed due to the reaction of atomic and molecular oxygen

$$O_2 + O + M = O_3 + M \quad (10)$$

Thus, the atmospheric components within both the arrester and the model system change over time. This resulting change in the chemical nature of the air within the arrester and the model systems results in a change in the measured breakdown voltage. Clearly, if a highly electronegative compound is present in the air, the observed breakdown voltage generally will be larger. The opposite is equally true. Using the simple Mulliken method for determining electronegativity, one can determine that ozone is more electronegative than molecular oxygen [18, 19]. Thus, as ozone is formed in the presence of arcing, the breakdown voltage increases.

However, after arcing ceases and the system returns to ambient temperature, the breakdown voltage returns to the voltage seen at time zero. This observed variation in voltages can be explained quite easily from a chemical perspective by considering reactions that are believed to occur in the polluted troposphere and in the ionosphere. In the absence of arcing, the ozone that is present in the system diminishes according to the following mechanism

$$O_3 + NO \rightarrow NO_2 + O_2 \quad (11)$$

$$O_3 + NO_2 \rightarrow NO_3 + O_2 \quad (12)$$

It is important to note that reactions (11) and (12) are well-established pathways for the decrease in the concentration of tropospheric ozone during night conditions [20]. The products that are formed in each of the two reactions are less electronegative than ozone. Thus, as the concentrations of products in reactions (11) and (12) increase, the breakdown voltage is expected to decrease. Indeed, the breakdown voltage does decrease, as can be seen in Figures 5 and 6.

Ozone may also be destroyed through low energy electron impact dissociative attachment [21]. The pertinent reactions are

$$e + O_3 \rightarrow O^- + O_2 \quad (13)$$

$$e + O_3 \rightarrow O + O_2^- \quad (14)$$

The anions that are formed subsequently can continue to react to form products that will contribute to a decrease in the breakdown voltage. If NO_2 is present, one of the products that may form is NO_3^- [21].

The presence of water vapor can lead to the formation of nitric acid according to the following mechanism [20]

$$NO_3 + NO_2 \rightarrow N_2O_5 \quad (15)$$

$$N_2O_5 + H_2O \rightarrow HNO_3 \tag{16}$$

Reaction (16) is facilitated by the presence of a surface. Thus, the discoloration seen on the electrodes is most likely due to the formation of nitric acid (HNO_3). In using the Mulliken scale to asses the relative electronegativity of nitric acid as compared to ozone [18, 19], it is clear that nitric acid is less electronegative than ozone. Once again, a species that is less electronegative than ozone is formed as the arcing ceases. Thus, the formation of nitric acid can also lead to a decrease in the breakdown voltage once the discharges end.

5 CONCLUSIONS

1. The electrical strength of air containing ozone and nitric oxides produced by PD was found to increase substantially for gapped arrester and model systems. Increases of $\leqslant$ 50% occurred for positive impulse voltages on sphere-plane electrodes. When the discharges extinguish, the recovery processes decrease the breakdown voltage to the initial value.
2. The increase in sparkover voltage is attributed to the formation of electronegative compounds such as ozone [7, 8].
3. The decrease in electrical strength to a value below the initial value in the negative rod-plane model arrangement (or in arresters from the field [11]) probably is caused by additional phenomena like corona induced corrosion, water condensation, lack of tightness, or nonlinear voltage distribution.

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