Determination of Waiting Times between Successive Breakdown Experiments

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Abstract- A common duty in high voltage engineering is the experimental determination of the breakdown voltage probability distribution of gaseous insulated electrode configurations. Due to electron detachment from negative ions in the case of electron attaching gases, the breakdown probability does not only depend on the gas and its density, but also on the ion density in the gas. If a disruptive discharge occurs in a gas gap, the number of ions in the gap is significantly increased compared to the equilibrium state at zero voltage. If the time until the next voltage application is too short, the statistical time lag will be decreased and, as a consequence, the probability of breakdown will be increased. To perform statistical independent breakdown experiments it is necessary to ensure identical ion densities in the gas gap before every new voltage application. In the literature waiting times mostly around six minutes are proposed as sufficient for ion density equalization in sulfur hexafluoride (SF$_6$). However, simulations of the behavior of SF$_6$ performed for the present contribution reveal that six minutes are not always sufficient to achieve statistical independent results. Especially at higher pressures longer waiting times are necessary. To investigate this problem, measurements of the natural ion pair generation in SF$_6$ were performed at different laboratories. Based on this data the temporal development of the ion distribution in the gas is calculated. Two cases are of interest: the changes in ion density after a disruptive discharge and in case the gap withstood the applied voltage and therefore all ions are swept out. After transformation of the temporal ion density into breakdown probability curves it is possible to estimate the necessary waiting time.

I. INTRODUCTION

Breakdown processes are statistical processes. Depending on field configuration, electrode surfaces, insulation material, location of the test site and applied voltage level and waveform the results are varying over the number of voltage applications.

Especially in experiments with very inhomogeneous electrode arrangements in electronegative gases several random processes affect the breakdown [1]. Predominantly the statistical time lag and the formative time lag determine the time to breakdown. The former is connected to the question how long it takes that an electron starting the breakdown process is detached within the critical volume (i.e. the volume with positive effective ionization coefficient) [2].

The main process for delivering start electrons in gases at low electric field strength is ionization by extraterrestrial radiation consisting of high energetic particles. Over several steps those particles ionize SF$_6$ molecules [1,2,3].

Within very short time the free electrons attach to SF$_6$ molecules forming negative ions. This does not reduce the number of charged particles but the number of free electrons. The free electrons are essential for the collisional ionization process in gases and thus for the gas breakdown [1].

Only if the electrical field accelerating the negative ions is high enough, their kinetic energy is sufficient for electron detachment. The detached electrons then may start electron avalanches. For the development of an avalanche the effective ionization coefficient $\alpha^* = \alpha - \eta$ has to be positive [1,3].

This electron detachment is the dominant process for first electron production. With the detachment rate coefficient $k_d$ and the number density of negative ions $n^-$ the number of detached electrons per unit time and unit volume can be described [4]:

$$\frac{dn_e}{dt} = k_d \cdot n^-.$$  \hspace{1cm} (1)

For the dimensioning of gaseous insulation it is of interest to be able to determine the breakdown probability distribution. Normally a large number of experiments has to be carried out. This gives a statistical description of the breakdown probability as a function of the applied voltage [5].

Every applied voltage changes the ambient conditions. In the case of a breakdown, a large number of the molecules is ionized. The contrary is the case, if the insulation withstands the applied voltage. Then the ions are, at least partly, swept out. After the voltage application the ion density will relax to an equilibrium ion density with a certain time constant. In literature several different waiting times to sufficiently approximate equilibrium ion densities are given. Wiegart et al. [2] suggest a time between successive voltage applications of 6 minutes at 0.1 MPa and 7 minutes at 0.4 MPa. According to Kindersberger et al. [6] periods in the range of 10 minutes would ensure the zero field equilibrium number of ions in the test gap. In [7] 350 s for 0.1 MPa and 440 s for 0.4 MPa are reported for the time needed to reach 90% of the equilibrium state. Experimental investigations at the authors’ institute showed that these waiting times are not always sufficient to achieve statistical independent series [8,9].

The presented paper is aimed to get a deeper insight into the necessary waiting times and the processes connected to it. Therefore simulations were performed which will be presented in the following. In section II the theory and the measurement setup for the ionization current are presented. Subsequent, the ion production rate and the temporal ion density development are calculated. The calculation of breakdown
probability curves based on the ion density depending on the waiting time is presented in Section III.

II. ION PAIR GENERATION

As seen above the dominant mechanism for first electron generation is the detachment from negative ions. Therefore the density of negative ions in the critical volume in the moment of voltage application is crucial to calculate the breakdown probability. Wiegart et al. [2] describe great variations in the ionization rates depending on the location of the test device. For an accurate basis for the following calculations the ion production rate was measured at different locations at the authors’ institute.

The ion density \( n^\pm \) is affected by ion pair generation with the ionization rate \( \dot{n}_{rad} \), by ion-ion recombination with the ion recombination constant \( k_r \), and by ion drift with the flow of charge carrier density of positive and negative ions \( j^\pm \), respectively. It is assumed that electrons are attached to \( \text{SF}_6 \) molecules immediately to form negative ions. The production rate for negative and positive ions is thus identical. The term “ion pair production rate” is thus justified. The ion density can be described according to following differential equation [2,4]:

\[
\frac{dn^\pm}{dt} = \dot{n}_{rad} - k_r \cdot n^- \cdot n^+ - dW j^\pm. \tag{2}
\]

For the determination of the ionization rate \( \dot{n}_{rad} \) the stationary solution is needed and the time derivative can be neglected. The resulting stationary flow of charge carrier density \( j^\pm \) depends on the applied electric field:

\[
j^\pm = \mp n^\pm \cdot \mu^\pm \cdot \nabla \Phi, \tag{3}
\]

Where \( \mu^\pm \) is the ion mobility and \( \nabla \Phi = -E \). Diffusion can be neglected compared to the drift. For a coaxial arrangement the electric field \( E \) can be expressed by analytical solution depending on the applied voltage and the radii of the cylindrical capacitor [1].

In equilibrium the concentration of negative and positive ions is equal \( n^+ = n^- = n \). The ion density is then calculated from (2):

\[
n = \frac{\dot{n}_{rad}}{k_r} \tanh \left( \frac{1}{2} \frac{\mu^\pm}{\mu^1} V \ln \frac{r_a}{r_i} \sqrt{\dot{n}_{rad} k_r (r_a^2 - r_i^2)} \right). \tag{4}
\]

where \( V \) is the applied voltage and \( r_a \) and \( r_i \) the outer and inner conductor radii.

![Fig. 1: Setup for ion current measurement](image)

To determine the voltage to achieve stationary currents the argument of the hyperbolic tangent has to be much larger than one. This equals the consideration that with increasing voltages the loss of ions by recombination decreases until recombination can be totally neglected [7].

With the values for \( k_r \) and \( \mu \) as given in Table I and the average ionization \( \dot{n}_{rad} \) according to [2] it can be calculated that a voltage of 100 V is sufficient to reach the saturation current.

The setup used for the measurement is depicted in Fig. 1. The test vessel was built of the coaxial part of a gas insulated switchgear. The inner conductor was connected to ground via a dumping resistor \( R_D = 1 \text{ M} \Omega \) and a pico ampere meter (Electrometer Keithley 617). The damping resistor is needed to achieve a stable signal. The outer conductor was connected to the internal DC voltage source of the electrometer. The output was adjusted to 100 V. The coaxial arrangement was filled with sulfur hexafluoride gas with a pressure up to 0.6 MPa. First, a large polarization current was measured after voltage application. This polarization current decayed with a time constant of approx. 2.2 min and after 120 min a steady state current was observed. As the resistivity of the solid disc insulators is very large, this current is the desired steady state total ion current \( I_{ion} \). The ionization rate was then calculated with the elementary charge \( e \) and the gas volume \( V \):

\[
\dot{n}_{rad} = \frac{I_{ion}}{e \cdot V}. \tag{5}
\]

The ion production rate was measured at three different locations: outside, and at two laboratories at the institute. Lab 1 is one level below ground and with five floors above and Lab 2 is two levels below ground with eight levels above.

Table II summarizes the results at 0.6 MPa. It can be seen that outside the ion production rate was highest with 46.0 \( \text{IP}/(\text{s} \cdot \text{cm}^3) \) and the deep laboratory had lowest ion production rate.

Based on the measurements of the ion production rate the development of the ion density over the time is calculated according to (2). The result of the calculation is shown in Fig. 2. The full line shows the development beginning with zero ion density. This is equivalent to an experiment where the gas gap withstand the applied voltage. In this case it is assumed that all ions in the gas gap are swept out because of the applied electric field. There is an exponential grow of the number of ion pairs in the gas gap according to the measured

| Table I: Parameters for estimation of voltage level for ionization rate measurement |
|------------------|------------------|------------------|
| Ion-ion recombination constant \( k_r \) | \( 1.7 \cdot 10^{-14} \left( \frac{\text{m}^3}{\text{s}} \right) \) | \( 1.25 \cdot 10^{-13} \left( \frac{\text{m}^3}{\text{s}} \right) \) |
| Low field ion mobility \( \mu \) | \( 0.36 \cdot 10^{-4} \left( \frac{\text{m}^2}{\text{Vs}} \right) \) | \( 1.25 \cdot 10^{-13} \left( \frac{\text{m}^2}{\text{Vs}} \right) \) |

| Table II: Ion production rate for 0.6 MPa \( \text{SF}_6 \) depending on experiment location |
|------------------|------------------|------------------|
| Location | Outside | Lab 1 | Lab 2 |
| Ion production rate \( \text{IP}/(\text{s} \cdot \text{cm}^3) \) | 46.0 | 37.5 | 30.8 |
ion generation rate. After 14 to 18 minutes the equilibrium state is reached.

The dashed curve is calculated for the case breakdown occurred. In this case the number of ions in the gas gap is increased. At maximum all molecules are ionized, which is assumed in the calculations. A sensitivity study of the number of initial ions revealed that even a significantly smaller number of ions (only 100 times the equilibrium state density) results in a shift of less than 5 s. In a real experiment not all ions will be ionized but due to low sensitivity it is a good approximation. After breakdown the number of ion pairs decreases exponentially and reaches an equilibrium state as well after 14 to 18 minutes.

With this calculated temporal distribution of the ion density inside the gas gap it is possible to estimate the breakdown probability curves depending on the waiting times between succeeding voltage applications.

III. BREAKDOWN PROBABILITY CURVES

All simulations concerning the breakdown probability are based on a rod-plane electrode arrangement as depicted in Fig. 3. The distance between the electrodes is 30 mm. It is assumed that the electrode arrangement is installed in an environment with sulfur hexafluoride (SF₆) at an absolute pressure of 0.6 MPa.

The electric field of the electrode arrangement is calculated with the FEM program Comsol. For the simulation the voltage shape of a standard lightning impulse (1.2/50 μs) is taken with a positive rod. Constant voltage levels are used for the calculations of succeeding experiments as during constant voltage tests.

The probability of streamer discharge inception is calculated by the volume-time law [2,4,10]

$$P = 1 - \exp \left[-\int_0^t \left( \int_{v_{cr}} \frac{\partial n_e}{\partial t} \left(1 - \frac{\eta}{\alpha} \right) dv \right) dt \right]. \quad (6)$$

The term \((1 - \eta/\alpha)\) is the probability that an electron contributes to the growth of an avalanche. \(\partial n_e/\partial t\) is the electron production rate and can be calculated by (1). For the negative ion density \(n^-\) the values according to Fig. 2 are taken. The density depends on the waiting time between the voltage applications. In the volume \(v_{cr}\) the electrical field strength exceeds the critical field strength. The distance from the electrode has to be sufficiently large so that avalanches reach the critical amount of charge carriers to form a streamer [4]. The values of \(k_d\) as a function of \(E/E_{cr}\) are taken from [4].

With the results of the ion density development over time the breakdown probability was calculated. Fig. 4 shows the probability curves for 0.6 MPa and waiting times of 2, 3, 6 and 15 minutes.

At short waiting times the curves for an experiment following a successful execution (gap withstanded the applied voltage) and for an experiment following an unsuccessful execution (gap breakdown) differ. For a waiting time of two minutes between the succeeding experiments the difference in the probability curves is relatively large. For a constant applied voltage of 750 kV the probability of a breakdown after a breakdown is about 90%, but after a successful experiment only about 20%. Towards longer waiting times the two curves are approaching each other.
IV. DISCUSSION

The measurements of the ion production rate at different laboratories confirm the variations depending on the experiment location although the values are lower than reported in [2]. The calculation of the ion density development over time reveals that at a pressure of 0.6 MPa a time of 14 to 18 minutes is necessary to reach an equilibrium state in sulfur hexafluoride (Fig. 2).

This result directly affects the breakdown probability curves shown in Fig. 4, because the ion density is a strong factor in the calculation of the volume-time law. For waiting times from two to six minutes the probability for a breakdown after withstand is much lower than the probability after a preceding breakdown. In this case the breakdown probability of the actual experiment depends on the result of the former stress of the gap. The experiments are not independent and no conclusion can be extracted. For a waiting time of 15 minutes the probability curves are almost matching. In this case the successive experiment executions are no more depending on each other.

V. CONCLUSION

The results shown in this paper indicate that the waiting time between successive breakdown experiments has to be chosen longer than the generally mentioned 6 minutes to get to statistical independent experiments at 0.6 MPa in a sulfur hexafluoride environment. According to the simulations performed a waiting time of 15 minutes or longer (at 0.6 MPa SF₆) will be necessary for independent experiment executions.

VI. OUTLOOK

Further investigations will focus on the waiting times at other pressures and also under negative rod-plane arrangements. Especially in negative configurations field emission has to be taken into account because it is an effective mechanism to lower the breakdown voltage. Additionally, further surface effects, such as roughnesses, have to be investigated. The simulations of the dependences of the results on waiting time have to be proven in an experimental setup.

REFERENCES