SI streamer initiation and breakdown in pressurized technical air in sphere-plane geometries

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Abstract

The breakdown properties of air are well studied at ambient pressure. For higher pressures, less information can be found in the literature. In this paper, switching impulse breakdown properties in technical air as a function of pressure are investigated. The study focus on a spherical electrodes with 30 mm and 10 mm diameter with a distance to a ground plane of 100 mm. From pre-breakdown photomultiplier signals and photographs taken with an ultrahigh-speed camera also the initiation voltages are measured. From the analysis of the results, streamer initiation fields as well as propagation fields are extracted. As expected, the breakdown voltages as well as the initiation voltages increases with pressure, for both positive and negative polarity. Streamer integrals are used to evaluate the initiation fields. The observed streamer initiation voltage agrees well with streamer integral theory in the studied pressure range 1 Bar to 6 Bar. The pressure dependence of streamer propagation is also analyzed and is found to approximately scale linear with the pressure for both polarities.

1. Introduction

Air is frequently used as an insulation media for high voltage equipment at ambient pressure. At ambient pressure the initiation as well as breakdown properties are accordingly well studied [1-7].

Pressurized gases are known to have improved electrical withstand properties compared to gases at 1 Bar, and are therefore frequently used in high voltage equipment such as GIS, bushings, cable terminations etc. One of the most frequently used pressurized insulation gas is SF_6 that is therefore carefully studied [8]. For pressurized Air, much less information can be found in the literature. The aim of the work presented in this article is to gain additional understanding of the breakdown properties of pressurized air.

2. Streamer initiation and propagation criteria

In order to fulfill an electrical breakdown in an insulation gas the two following criteria have to be fulfilled [2]: 1) a streamer has to be initiated. 2) The streamer has to propagate from one electrode to the opposite electrode. Below, these criteria are discussed in the light of information found in the scientific literature. In the relatively short electrode gaps used in this study, no streamer to leader transition is expected to occur during the breakdown.

Streamer Initiation

Free electrons always occur in a gas due to the background radiation (such as cosmic and terrestrial radiation) that can ionize the gas. If a free electron is exposed to a large enough electrical field it will gain energy large enough for causing secondary impact ionization. If the secondary electrons in turn also are accelerated to cause impact ionization, an electron avalanche may occur. Based on avalanche theory a criterion for streamer initiation can be formulated:

$$I = \int_{r_0}^{r_c} \alpha_{eff}(E)dr > C_{crit} \qquad (1)$$

Where α_{eff} is the field dependent effective ionization parameter, r_0 to r_c are the interval in which the field are above the critical field for impact ionization. The critical number C_{crit} is known for air to be in the range 9-20. Several parametrizations of the effective ionization parameters are found in the literature. One of them [1] is:

$$\alpha_{eff}(E) = p\left[k\left(\frac{E}{p} - \Lambda\right)^2 - A\right] \qquad (2)$$

Where p is the pressure in Bar, k=1.6 mm·Bar/kV^2, Λ= 2.2 kV/mm·Bar and A=0.3 1/mm·Bar. According to this formulation the critical field for impact ionization onset is 2.6 kV/mm at 1 Bar.

The streamer integral criterion is known to give good estimates of the streamer initiation voltages for both positive and negative polarity. At pressures around 1 Bar this type of streamer integral criterion is extensively studied and validated. At pressures > 1 Bar, the information in the literature is much more limited.

In the present article the electrical fields under a switching impulse surge, SI, are simulated for the studied geometries with the software package COMSOL

Multiphysics [9]. From the simulated field the streamer integral is calculated from the above formulas (equation 1 and 2).

Streamer propagation voltages at positive polarity

If the field is large enough, an initiated streamer will propagate to the opposite electrode. For positive polarity at 1 Bar and a gap larger than 40-50 mm, a simple empirical formula is found to give a good estimate of the positive streamer propagation voltage [2]:

$$U_p = U_0 + d \cdot E_{st} \qquad (3)$$

Where d is the gas gap distance in mm, E_{st} ~0.5 kV/mm and U_0 = 20-30 kV.

Streamer propagation criteria above 1 Bar is much less studied in the literature. In most of the studies on breakdown in pressurized air the results are not analyzed in terms of initiation and propagation criteria. In Ref. [7] breakdown voltages in a rod-plane geometry with a 0.5 mm rod tip radius and an air gap of 50 to 80 mm are studied in the pressure interval 1 to 2.5 Bar. Due to the inhomogeneous field in their geometry the maximal fields are far above the initiating field (> 10 times) at the observed breakdown voltages. Therefore this data can be used to extract information on the propagation criterion. From our analysis of the measured results presented in Ref. [7] it is found that for each gap distance the average propagation field, E_{prop}, scales with the simple formula:

$$E_{prop} = E_{prop}^{1\,Bar} \cdot k^{\frac{P}{P_0}} \qquad (4)$$

Where P_0 =1 Bar, $E_{prop}^{1\,Bar}$ is the propagation field at 1 Bar and k is a parameter found to be in the range 0.8 to 0.95 for the studied gap distances and with an k value that increase with gap distance (i.e. k=0.95 for 80 mm gap)

Streamer propagation voltages at negative polarity

Information on the streamer propagation field for negative polarity is much less reported in the literature. In [2] a typical value of 1.2 kV/mm propagation field at 1 Bar is given. No information regarding the propagation field is found in the literature for negative polarity at pressures > 1 Bar.

3. Experimental set up

Initiation and breakdown voltages, for an SI surge, were recorded as a function of pressure for two different sphere-plane geometries, referred to as geometry A and B. The grounded plane in both geometries have a diameter of 400 mm. Geometry A have a sphere diameter of 30 mm and Geometry B have a diameter of 10 mm. In geometry B a rod with a 10 mm dimeter spherical cap is used. Both geometries have a 100 mm air gap between the sphere electrode and the grounded plane. The pressure was varied in the interval 1 to 6 Bar and technical air was used in all cases.

SI surges were generated with an impulse generator (Haefely SGS 600/30) with a maximal peak Voltage of ~550 KV. The SI had a rise time of 250 µs and a 50 % decay time of 2500 µs. A Photomultiplier (Hammatsu H9305-1) was used to detect initiation. In addition to the photomultiplier a high-speed camera was sometimes used to secure that the interpretation of the photomultiplier signal was correct. The test objects were mounted inside a pressure chamber with an inner diameter of 650 mm. In Figure 1 a picture of a test object inside the test chamber is show together with a simulation of the electrical field.

Both the initiation voltages and breakdown voltages were, separately, studied with the so called up-and-down method [10]. If an initiation/breakdown is recorded the voltage is reduced by one step in the next SI surge. If no initiation/breakdown is observed the voltage is increased by one step in the next SI surge. As a result, the 50% probability voltages for streamer initiation and disruptive discharge can be determined, respectively. The voltage step used was 5 kV.

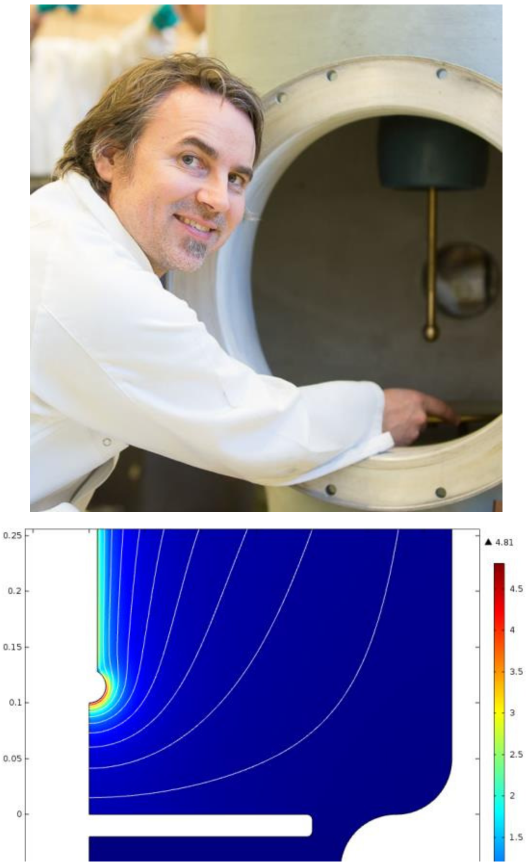

Figure 1 –Upper panel: picture of the test object mounted inside and the test chamber [11]. Lower panel: simulation of the electrical field 8kV/mm) at an 75 kV SI surge in a 100 mm long air gap and 30 mm sphere radius (Geometry A)

4. Experimental results and discussion

To start with Geometry A (30 mm sphere and 100 mm air gap distance) was tested with positive SI voltage. For positive polarity, no initiations were observed for voltages below the breakdown voltages, for any pressure. This show that in this case the breakdown voltage are determined by the inception voltage. Once an initiation occurs, the discharge can propagate across the air gap, causing a breakdown. The average breakdown voltage as a function of pressure is presented in Figure 2. In the same graph, the initiation voltages predicted by the streamer integrals are shown. We notice that the predicted initiation voltages coincide with the observed breakdown voltages.

Geometry A was also tested with negative SI voltage. In this case initiation voltages below the breakdown voltages were observed. The measured results are plotted in Figure 3 Notice the very good agreement between the theoretically predicted initiation voltages and the measured initiation voltages. The agreement is good for all studied pressures (1 to 6 Bar). At 1 Bar an average breakdown voltage of 140 kV was observed. This gives an average field at breakdown of 1.4 kV/mm that is slightly higher but nearby the previously reported values ~ 1.2 kV/mm [2]. At 3 Bar the average breakdown was increased to 450 kV indicating a close to linear scaling with pressure (i.e. k ~1 in equation 4 above). Unfortunately, no breakdown values were observed for 4.5 and 6 Bar due to the limitation in peak voltage of the impulse generator.

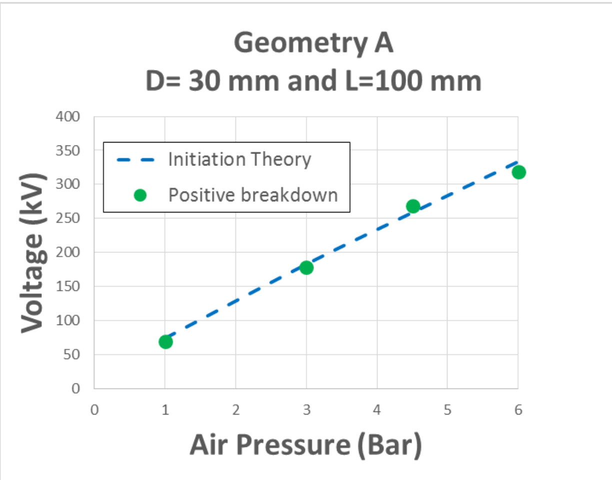

Figure 2: Measured breakdown voltages in Geometry A at positive polarity as a function of air pressure are shown with green circles. Theoretical prediction of the initiation voltage, from Streamer integral theory, is shown with the dotted line.

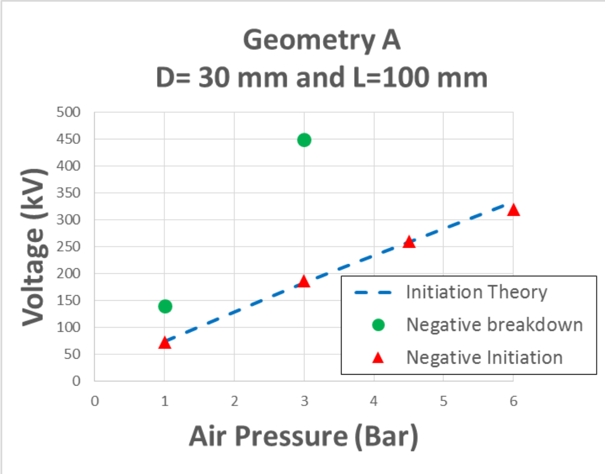

Figure 3: Measured initiation and breakdown voltages in Geometry A at negative polarity as a function of air pressure are shown with red triangles and green circles, respectively. Theoretical prediction of the initiation voltage, from Streamer integral theory, is shown with the dotted line

As presented above, the initiation voltage and breakdown voltage coincide at positive polarity for geometry A. Therefore, in order to separate the initiation and propagation voltage, the 30 mm diameter sphere was replaced by a 10 mm diameter sphere (Geometry B). The higher maximal field at the electrode tip of Geometry B reduces the initiation voltage. The measured initiation and breakdown voltages for positive polarity are presented in Figure 4. As seen in the graph, distinct initiation and breakdown value are now observed, as expected. The agreement between the predicted and measured initiation voltage is very good also for this geometry. The measured average breakdown voltage at 1 Bar is 57 KV giving an average field of 0.57 kV/mm which is in good agreement with values reported in the literature [2]. At 3 Bar, an average breakdown voltage of 185 kV is measured. This was slightly higher but close to a linear scaling with P (i.e. k ~1 in equation 4 above).

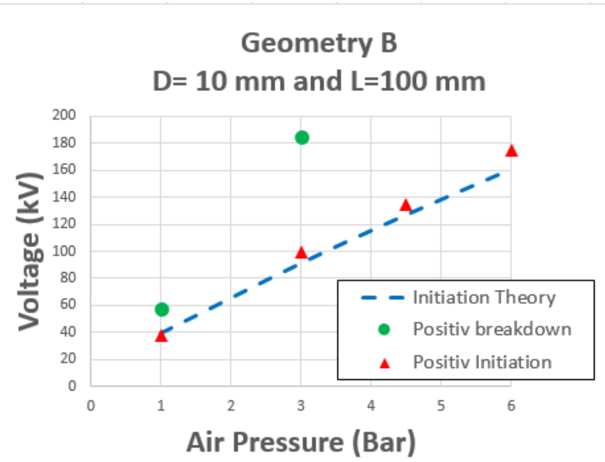

Figure 4: Measured initiation and breakdown voltages in Geometry B at negative polarity as a function of air pressure are shown with red triangles and green circles, respectively. Theoretical prediction of the initiation voltage, from streamer integral theory, is shown with the dotted line

In general, the statistical scattering of the measured initiation and breakdown voltages are small. Each average value is calculated from 10 initiations/breakdowns and the standard deviation is found to be in the range 1 to 6 % of the average value.

6. Conclusion

Sphere-plane geometries were used to study initiation as well as propagation fields for both positive and negative voltages, in the pressure range 1 to 6 Bar.

It was found that the used streamer inception criteria (Streamer integral) predicts the streamer initiation voltage in the pressure range 1 to 6 Bar with an good accuracy for both positive and negative polarity.

Furthermore, streamer propagation fields in the pressure intervals 1-3 Bar are established for positive and negative polarity respectively. In both cases they are found to scale linearly with P, within the uncertainty of the measurements. These findings are in line with the limited information on this topic available in the literature. Further studies for different distances is called for in order to validate this finding further.

References

[1] K. Petcharaks, "Applicability of the streamer breakdown criterion to inhomogeneous gas gaps",Ph.D. Thesis No. 1192 ETH Zurich 1995

[2] A. Pederssen, T. Christen, A Blaszczyk and H. Boehme, "Streamer inseption and propagation models for designing air insulated power devices", p 604, CEIDP 2009,

[3] N.L. Allen and A. Ghaffar, "The condition required for the propagation of a cathode-directed positive streamer in air", Journal of Physics D: Applied Physics, 28:331, 1995

[4] R.F. Griffiths and C.T Phelps "The effect of air pressure and water vapour content on the propagation of positive corona streamers and their implications to lightning initiation", Quaterly Journal of the Royal Meteorological Society, 102:419-426, 1976

[5] L. Niemayer "A generalized approach to partial discharge modeling" IEEE Transaction on Dielectrics and Electrical Insulation, Vol.2 No 4, p 510, 1995

[6] IEC 60052:2002, "Voltage measurement by means of standard air gaps"

[7] M.S. Kamarudin et al, "Experimental Investigation on Air Breakdown under Lightning Impulse with various Electrode Configurations", conf. puplication at Clean Energy and Technology, Kuching, Malaysia, Nov 2014

[8] "Optimized Gas-Insulated Systems by Advanced Insulation Techniques", CIGRE TB-571, Working group D1.28, April 2014

[9] Comsol Multiphysics V5.2a, www.comsol.com

[10] IEC 60060-1, "High voltage testing techniques – Part1: General definitions and test requirements"

[11] Photo by Kim Norman, Kim Norman AB