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Breakdown and Partial Discharge in Dry Air under Non-uniform Electric Field for MVDC Applications

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Abstract—Medium and high voltage gas insulated switchgear (GIS) are key installations in the electrical power transmission and distribution network. The equipment in these substations are insulated with pressurized gas in order to guarantee their proper functioning. This work aims to investigate the performance, in DC, of dry air under non-uniform electric field conditions for medium voltage switchgear applications. Experimental investigations have been carried out to assess the breakdown and the partial discharge inception voltages as function of the electric field non-uniformity and dry air pressures. The experimental work has been compared with numerical study of the breakdown electric field based on streamer criterion using COMSOL Multiphysics numerical software. The results show that the breakdown maximum field decreases as a function of the utilization factor till 0.3, then it stabilizes for weakly non-uniform electric field. The breakdown maximum field is not dependent on the polarity of the DC voltage for utilization factors higher than 0.2. Otherwise, the breakdown maximum field seems to be lower under positive DC voltage for utilization factors under 0.2. Simulation results of the maximum field obtained using the streamer criterion are in good agreement with the experimental partial discharge results.

Keywords—medium voltage switchgear, breakdown, partial discharge, electric field, utilization factor

I. INTRODUCTION

With the spreading of renewable energy sources and the increasing integration of DC grids into existing AC networks, the exploration of insulation breakdown characteristics in MVDC systems assumes critical importance. Medium and high voltage gas insulated switchgear (GIS) are key installations in the electrical power transmission and distribution network [1], [2]. These equipment are insulated with pressurized gas in order to guarantee their proper functioning. Insulation using SF₆ gas is widely used in GIS because of its high dielectric and thermal performance. This solution has made it possible to develop efficient and more compact GIS. However, SF₆ is also responsible for significant environmental impact due to its high global warming potential [3], [4]. Replacing SF₆ with another gas or insulation system would require changing the design of the switchgear or the operating conditions. For example, insulation with air requires about 3 times more inter-electrode distances than with SF₆ if the same pressure value is maintained in the switchgear. Increasing the air pressure improves insulation performance while maintaining the same compactness. The occurrence of electrical breakdown and partial discharge (PD) poses significant risks to the integrity and functionality of MVDC systems [5], [6], [7]. Understanding the underlying mechanisms governing partial discharge initiation, and breakdown of alternative gas is essential for enhancing the reliability and efficiency of MVDC technologies. Moreover, the identification and quantification of PD activity serve as crucial diagnostic tools for assessing insulation health and

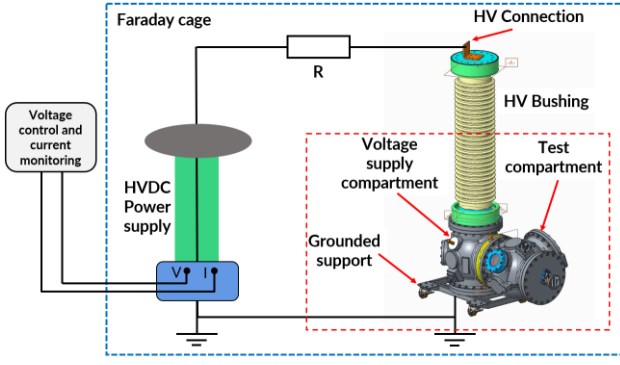
predicting potential system failures. In this context, this work aims to investigate the performance of dry air (80% N₂ + 20% O₂) under non-uniform electric field conditions for medium voltage switchgear applications.

In this work, both experimental and simulation investigations have been carried out to look into the breakdown and partial discharge inception fields in dry air. In contrary to HV GIS where the electric field is nearly uniform, the electric field in medium voltage (MV) GIS can be weakly or even strongly non-uniform. The degree of uniformity of the electric field is usually represented by the utilization factor (η), defined as the ratio between the average and the maximum electric field. Thus, an utilization factor of 1 means uniform electric field. The investigated utilization factors have been chosen with consideration of their values in medium voltage switchgears. They are ranging between 0.053 and 0.512. The breakdown maximum fields of dry air under DC are investigated at different pressures. The experimental work has been compared with the results of the numerical study which is based on the application of streamer criterion using COMSOL Multiphysics® numerical software.

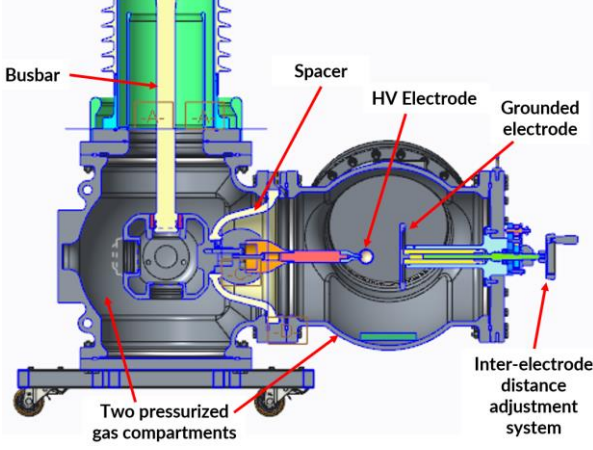
II. EXPERIMENTAL SETUP AND PROTOCOL

The experimental setup used for breakdown and partial discharge experiments is illustrated in Fig 1.a. An HVDC bipolar 400 kV power supply is used for positive and negative voltage application. A protecting resistor of 2 M Ω is connected in series with the device under test (DUT). The breakdown voltage and the discharge current are given by the voltage and current monitoring of the power supply, and measured using a dedicated Labview® acquisition system. The DUT, measuring 2.4 m x 1.5 m x 0.75 m (H x L x W), is presented in Fig.1. It is composed of an HV gas insulated bushing and two pressurized air compartments: the voltage supply compartment and the test compartment. The bushing and the voltage supply compartment are inflated with 1.5 absolute bars pressurized dry air to insure high voltage insulation till 300 kV. The test compartment is the compartment housing the different electrode configurations to obtain different utilization factors. The tests have been carried out under three absolute pressure values: 1.5 bars, 2.5 bars and 3.5 bars. The separation between the test compartment and the voltage supply compartment is achieved using an epoxy resin insulating spacer. A humidity absorber is kept inside the test compartment in order to eliminate and control humidity. A window is placed on the test compartment in order to be able to view the inter-electrode space. The entire metallic part of the compartments are grounded.

After establishing the experimental conditions (electrode configuration, gap and pressure), the applied voltage is increased progressively using multi-steps profile with considering voltage incrementation less than 10% of the expected BDV value. The voltage application protocol is in



(a)



(b)

Fig. 1 Schematic illustration of (a) the experimental setup and (b) the electrodes configurations in the test compartment.

compliance with the IEC 60060-1 standard. 2 kV steps have been considered if the expected BDV value is lower than 50 kV, and 5 kV if the expected BDV value is higher than 50 kV. The plateau duration for each step is 60 s. The power supply current is recorded at the same time with the applied voltage. When a gas breakdown occurs, the power supply measured current highly increases, the applied voltage drops at the same time, and the BDV value is recorded. The partial discharge inception voltage (PDIV) value is measured when the power supply current starts to increase because of the PD activity. For each experimental configuration, ten breakdown experiments have been carried out and the mean values of BDV and PDIV are considered.

Table 1. The characteristics of the investigated configurations.

Tip radius (mm)	Inter-electrodes distance (mm)	Utilization factor
2	15	0.150
	25	0.099
	35	0.073
	50	0.053
5	25	0.206
	35	0.157
	55	0.106
10	30	0.3
	50	0.202
20	25	0.512
	35	0.422

In this work, multiple electrode configurations have been investigated with utilization factors ranging between 0.053 (strongly non-uniform electric field) and 0.512 (weakly non-uniform electric field) for electrodes tip radiuses between 2

mm and 20 mm, and inter-electrode distances between 15 mm and 55 mm. The field utilization factor is defined as the ratio between the average and the maximum electric field (E_{max}) for a given configuration. It can be expressed as:

$$\eta = \frac{V}{d \cdot E_{max}} \quad (1)$$

The investigated electrodes configurations and gaps are summarized in Table 1.

III. NUMERICAL SIMULATION

For electronegative gases such as air and SF₆, electrons can attach to gas molecules to form negative ions, the streamer breakdown criterion can be expressed mathematically as follows [8], [9]:

$$\int_0^{x_c} \alpha_{eff}(E(x)) dx = \ln N_c = K_s \quad \text{with, } \alpha_{eff} = \alpha - \bar{\eta} \quad (2)$$

In this equation, α_{eff} the effective ionization coefficient, α the Townsend ionization coefficient, that depends on the electric field, E . $\bar{\eta}$ is the attachment coefficient, x_c is the distance along the field line, N_c is the critical number of electrons at the head of the avalanche and K_s is a dimensionless parameter. There is still some uncertainty about the K_s value. There are many indications that K_s may be a constant or may depend on discharge conditions such as field non-uniformities, pressure, gas type or voltage polarity. According to Zaengl et al. [9], [10], $K_s = 9.15$ in dry air, this value is considered in this work.

The effective ionization coefficients can be given by the following equations [11]:

In the domain $2.588 < \frac{E}{p} < 7.943$ kV/(mm. bar):

$$\frac{\alpha_{eff}}{p} = C_0 \left[\frac{E}{p} - \left(\frac{E}{p} \right)_M \right]^2 - A_0 \quad (3)$$

With, $C_0 = 1.6053$ mm. bar. kV⁻², $A_0 = 0.2873$ (mm. bar)⁻¹, $\left(\frac{E}{p} \right)_M = 2.165$ kV/(mm. bar)

In the domain $7.943 \leq \frac{E}{p} < 14$ kV/(mm. bar):

$$\frac{\alpha_{eff}}{p} = C_1 \frac{E}{p} - A_1 \quad (4)$$

With, $C_1 = 16.7766$ kV⁻¹, $A_1 = 80.006$ (mm. bar)⁻¹

The breakdown criterion in dry air is given by the following equations:

In the domain $2.588 < \frac{E}{p} < 7.943$ kV/(mm. bar):

$$\int_0^{x_c} \left(\frac{1.6053}{p} \cdot (E(x))^2 - 6.951 \cdot E(x) + 7.237 \cdot p \right) dx = K_s \quad (5)$$

In the domain $7.943 \leq \frac{E}{p} < 14$ kV/(mm. bar):

$$\int_0^{x_c} (16.7766 \cdot E(x) - 80.0006 \cdot p) dx = K_s \quad (6)$$

Fig. 2 presents the 3D electrostatic electric field distribution in needle-plane configuration for a needle's tip of 5 mm, and the electric field at the axis of symmetry for different utilization factors. We can see clearly the enhancement of the electric field value at the tip of the needle. The electric field maximum value is inversely proportional to the field utilization factor. Fig. 3 presents the effective ionization coefficient variation through the axis of symmetry.

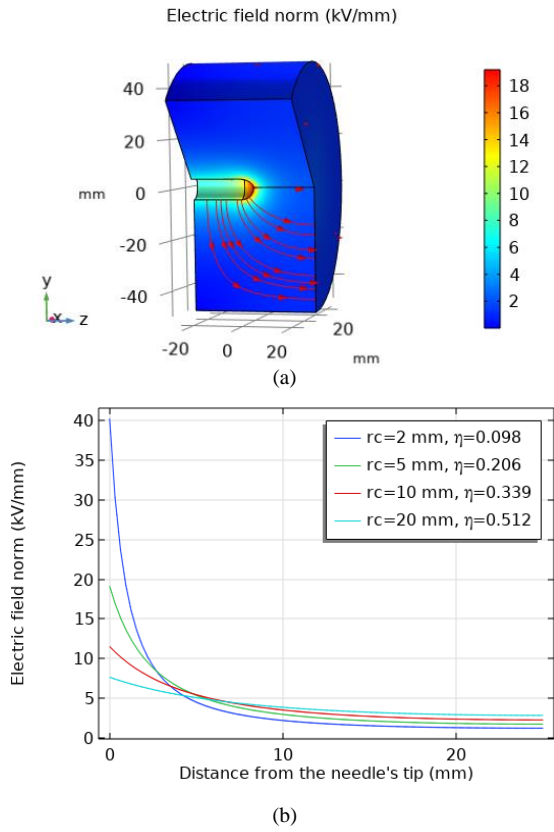


Fig. 2 Numerical simulation of the electric field (a) 2D and (b) on the axis of symmetry under 100 kV for different utilization factor values.

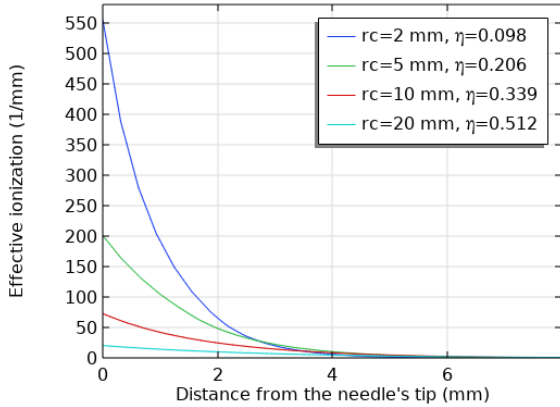


Fig. 3 Numerical simulation of the effective ionization under 100 kV.

The effective ionization is higher at the needle's tip when the utilization factor is lower, because of the enhancement of the electric field. The critical distance where the effective ionization becomes negative increases with the increase of the utilization factor.

IV. RESULTS AND DISCUSSION

A. Effect of gas pressure and voltage polarity

Fig. 4 presents the evolution of the breakdown maximum field of dry air as a function of the electric field utilization factor for different gas pressures and different applied voltage polarities. Each point in the curves is the average of 10 breakdown tests. When the utilization factor increases, the breakdown maximum field decreases, then, it stabilizes when the utilization factor is equal or higher than 0.3 with values of about 5.7 kV/mm, 8.75 kV/mm, 12.05 kV/mm for gas pressures of 1.5, 2.5 and 3.5 bars respectively. The increase of

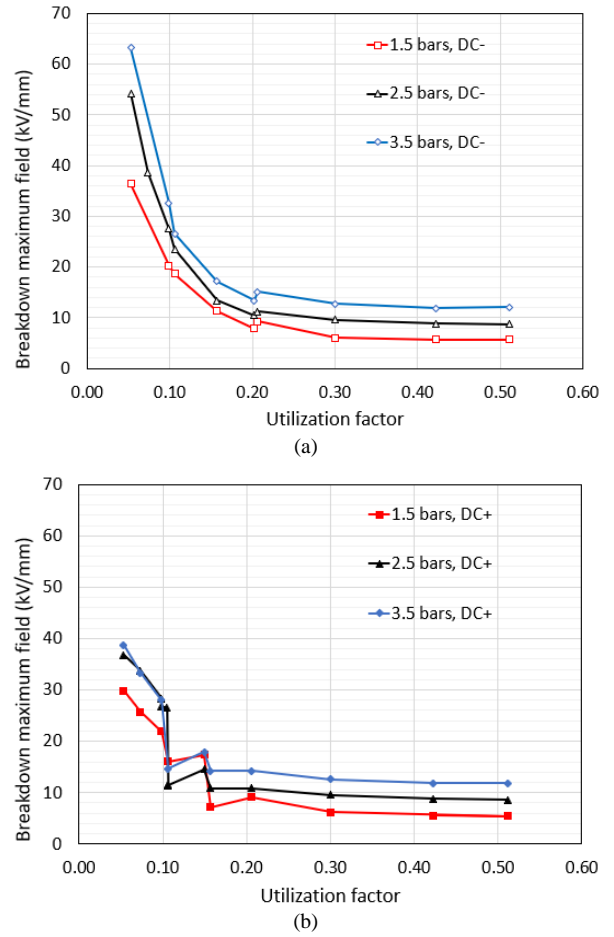


Fig. 4 Evolution of the breakdown maximum field as a function of the utilization factor for different gas pressures and DC voltage polarities with (a) negative polarity and (b) positive polarity.

the breakdown maximum field at strongly non-uniform electric field can be related to the contribution of the space charge in the reduction of the local electric field at the vicinity of the electrode's tip. We can observe also that the breakdown field increases as a function of the pressure according to Paschen law.

Fig.5 presents the ratio between the breakdown field under negative polarity and positive polarity as a function of the utilization factor for the three tested pressures. For utilization factors higher than 0.2 (weakly non-uniform electric field), the results show that the breakdown maximum field is not affected by the voltage polarity, the same breakdown field has been obtained for both positive and negative polarities. For utilization factors lower than 0.2 (strongly non-uniform electric field), the ratio is higher than 1 which means that the breakdown field under positive DC voltage is lower than that of negative DC voltage in most cases. As a consequence, the positive DC voltage is most relevant to consider for MVDC equipment sizing.

B. Partial discharge and streamer criterion

Fig. 6 presents the evolution of the breakdown and the partial discharge inception fields obtained numerically and experimentally as a function of the utilization factor for both negative and positive polarities at 3.5 absolute bars. For utilization factors higher than 0.2, no partial discharge has been observed and the gas breaks down directly. For utilization factors lower than 0.2, the partial discharge activity is observed at lower field values than the dielectric

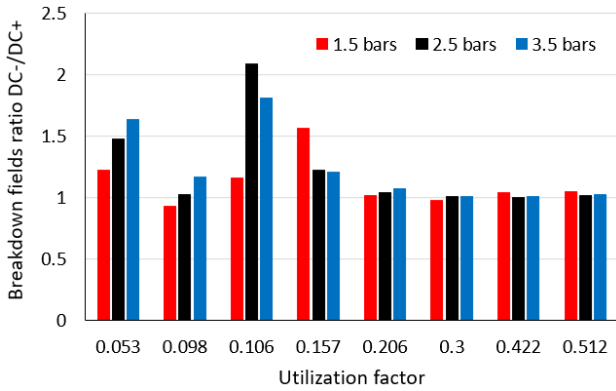


Fig. 5 The evolution of the ratio between the breakdown fields under negative polarity and positive polarity as a function of the utilization factor.

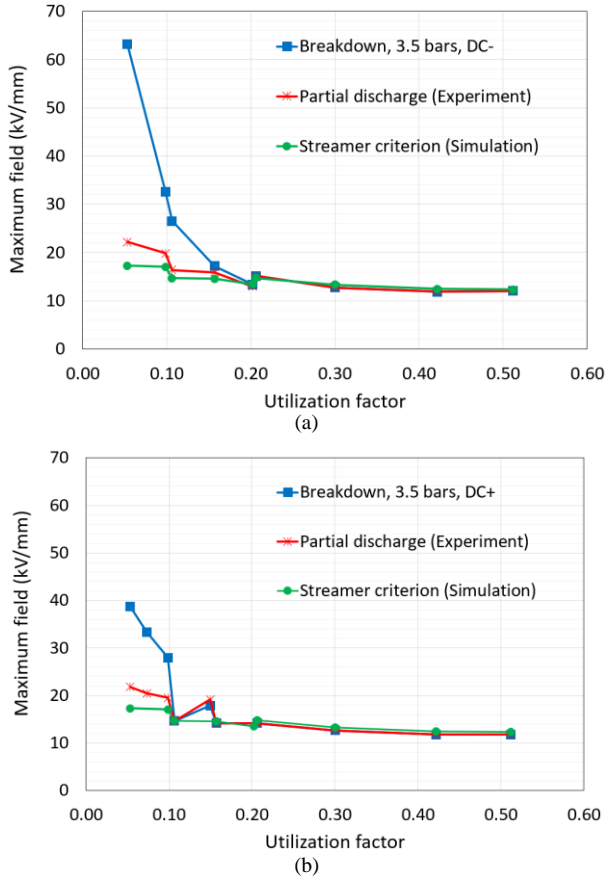


Fig. 6 Evolution of the breakdown and partial discharge inception fields, from experiments and simulations, as a function of the electric field utilization factor under 3.5 bars gas pressure with (a) negative polarity and (b) positive polarity.

breakdown. The results show that the numerical results obtained by the application of streamer criterion are in good agreement with the experimental results of the partial discharge inception field. As a consequence, the streamer criterion can be used to predict the breakdown maximum field of dry air for weakly non-uniform and uniform electric fields. However, it is a good indicator of partial discharge inception field for strongly non-uniform electric field.

V. CONCLUSION

In this paper, the breakdown and the partial discharge inception fields have been investigated numerically and experimentally in dry air under non-uniform field conditions

for MVDC equipment applications. The breakdown electric field of dry air under both positive and negative polarities is investigated at different pressures and for various field utilization factors. The results show that the breakdown maximum field decreases as a function of the utilization factor for strongly non-uniform electric field (utilization factors less than 0.3), then it stabilizes for weakly non-uniform electric field (utilization factor higher than 0.3). The dielectric breakdown is not dependent on the polarity of the DC voltage for utilization factors higher than 0.2. Otherwise, the maximum field seems to be lower under positive DC voltage for field utilization factors under 0.2. The simulation results of the maximum field obtained using the streamer criterion are in good agreement with the experimental results of partial discharge inception field for low utilization factor. The streamer criterion can also be used to predict the dielectric breakdown of dry air for weakly non-uniform and uniform electric fields.

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