

CALCULATION OF POSITIVE STATIC BREAKDOWN VOLTAGE IN ROD GAPS IN SF₆

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ABSTRACT

The peculiar variation of breakdown voltage V_b with pressure p in compressed SF₆ due to corona-stabilization of the applied field is well pronounced in rod to plane gaps, Fig. (1). In this paper, the space-charge modified field has been calculated and a simple criterion based on the gap minimum field is proposed for breakdown in the rising straight part of the V_b - p characteristic. This calls at first for assessment of the corona onset voltage. For pressures greater than the critical pressure breakdown occurs without any preceding corona discharges and the breakdown voltage is theoretically predicted. The calculated corona-onset V_o and breakdown voltages agreed with those measured experimentally within $\pm 10\%$.

INTRODUCTION

Nonuniform fields are found in practical SF₆ insulated equipment which range from moderate nonuniform fields, for example, switchgear contacts, to the highly divergent fields around surface protrusions or free conducting particles.

It has been observed experimentally [1-3] that, in nonuniform field gaps in electronegative gases, corona-onset voltage may be much smaller than the breakdown voltage. Fig.(1) shows a typical breakdown voltage versus pressure characteristic for a nonuniform field gap stressed by a dc voltage[4]. Above the critical pressure p_c , the breakdown occurs immediately unpreceded by corona. This is called direct breakdown. At pressures smaller than p_c , the breakdown is preceded by corona in the so called "corona-stabilized region". The corona-stabilization phenomenon is explained in terms of the reduction of the space charge field in the gap which prevent streamer formation at the anode. Hence, the voltage required to breakdown the gap must exceed the corona onset value.

It has been shown that the field near the plane exceeds a value of about 40 kV/cm bar [5] or minimum field of about 39 to 47 kV/cm.bar [4] or 35

to 45 kV/cm.bar [6] is required for streamer propagation in presence of corona-stabilization. The physical background of the lower limit of electric strength in SF₆ at dc voltage is not clear yet.

This paper is aimed at proposing a simple criterion for calculating the positive static corona-stabilized breakdown voltage in the rising straight part of the V_b - p characteristic. Above the critical pressure the breakdown voltage is directly equal to the corona onset voltage obtained from the streamer criterion.

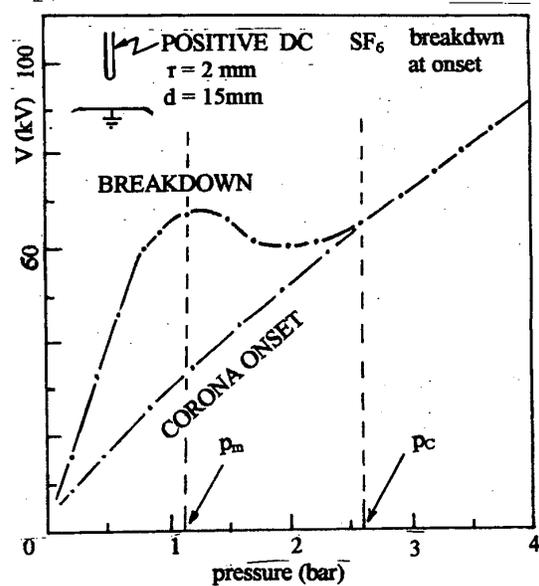


Fig. (1) positive point corona onset and breakdown voltages in SF₆.

METHOD OF ANALYSIS

1- Criterion of Corona Onset Voltage

Assume an electron exists at the border of the ionization zone ($\alpha = \eta$) surrounding the stressed rod, where α (m^{-1}), and η (m^{-1}) [7] are the ionization and attachment coefficients, respectively. This electron generate a primary avalanche by electron collision with SF₆ molecules. The size of the primary

avalanche N_{+1} is calculated. Due to photoionization process, photons produced from the avalanche head ionize the gas molecules in the ionization zone. Due to this process, photoelectrons are produced, and as a result, successor avalanches are produced in the ionization zone, Fig (2). Then, the size of the successor avalanches N_{+2} is calculated. AT the corona-onset voltage N_{+2} just exceed N_{+1} and the discharge process becomes self sustained [8-11].

$$N_{+2} \geq N_{+1} \quad (1)$$

$$N_{+1} = \exp\left[\int_{zi}^H (\alpha(\bar{z}) - \eta(\bar{z}))d\bar{z}\right] \quad (2)$$

$$N_{+2} = \int_{r_1}^R g_1 f_1 f_2 N_{+1} \mu \exp[-\mu \rho] + \int_{\rho}^{r_1} \alpha(z, \bar{\rho}) - \eta(z, \bar{\rho} d\bar{\rho}) d\bar{\rho} \quad (3)$$

$$r_1 = \sqrt{6 \int_{zi}^H D_e \frac{dz}{V_e}} \quad (4)$$

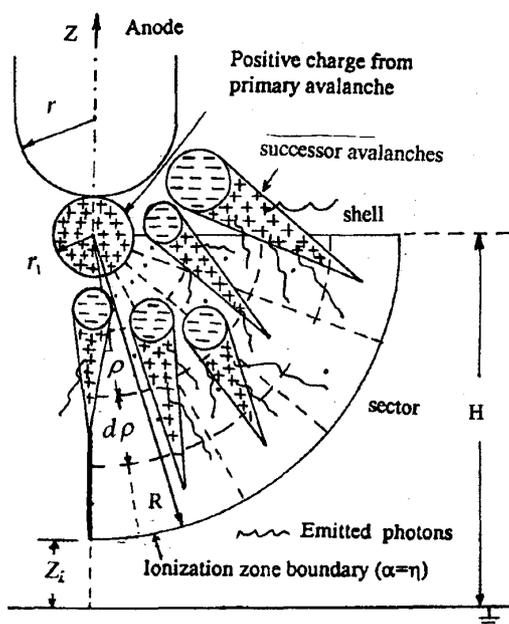


Fig. (2) Growth of successor avalanches starting from the centers of sectors and ending at the positive space charge sphere or the rod tip .

where, r^* equals the rod radius r , or the radius r_1 of the space charge left by the primary avalanche depending on the direction of avalanche growth, f_1 is the number of photo electrons released by absorption of one photon, f_2 is the number of excited states production

per ionizing collision, μ is the photon absorption coefficient ;($\mu = 600 \text{ p} / 760 \text{ m}^{-1}$ [12]), r_1 is the radius of positive ions sphere produced from the primary avalanche at ($z = H - r_1$) being started at the border of the ionization zone Z_i , $f_1 f_2 = 6 \times 10^{-6}$ [12], g_1 is the geometry factor ($g_1 = 0.25$ [11]), V_e , and D_e are the electron drift velocity and the diffusion coefficient [13] expressed in terms of the electric field and SF_6 pressure. The field along the gap axis due to the applied voltage was obtained by the charge simulation technique [14].

2 - Proposed Criterion for Breakdown in the Rising Straight Part

The electric field in the interelectrode spacing is governed by the ion space-charge in it while the ion-flow itself is a function of the electric field [15,16]. The equations describing the electric field and the ion-flow are

$$\nabla \cdot E = \rho / \epsilon_0 \quad (5)$$

$$J = k \rho E \quad (6)$$

$$\nabla \cdot J = 0 \quad (7)$$

where, E is the space charge modified electric field, ρ is the charge density, j is the current density, k is the mobility of ions, and ϵ_0 is the permittivity of gas. The first is Poisson's equation for the electric field, the second is the equation of current density and the third is the equation of current continuity. Some simplifying assumptions [15,16] were taken into account to solve the equations (5-7). Among these assumptions, the space charge affects only the magnitude but not the direction of the electric field, and the electric field at the surface of stressed electrode (where corona occurs) remains constant at the onset value corresponding to the onset voltage (V_0). The mobility of the positive ions is assumed constant, the thermal diffusion of ions is neglected.

Fig. (3) shows the calculated values of E/p along the gap axis for voltages starting from corona onset to breakdown. As the voltage increases above the onset value, the field at the plane rises faster than elsewhere in the gap and a more uniform field distribution is obtained.

In the rising part of the V-p curve the breakdown voltage corresponds to limiting minimum value of E/p in the gap necessary for streamer propagation. This limiting value is proposed to be 50 % of the critical value 89 kV/cm.bar.

3 - Breakdown Voltage Above the Critical Pressure

The breakdown voltage occurs without any preceding corona and it is equal to the corona onset voltage obtained by the streamer criterion.

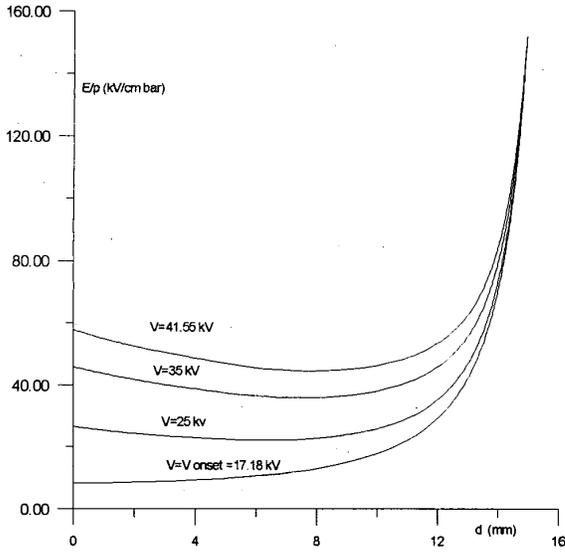


Fig. (3) The calculated values of E/p along the gap axis for voltages starting from corona onset to breakdown ($p = 0.5$ bar, $r = 2$ mm, & $d = 15$ mm).

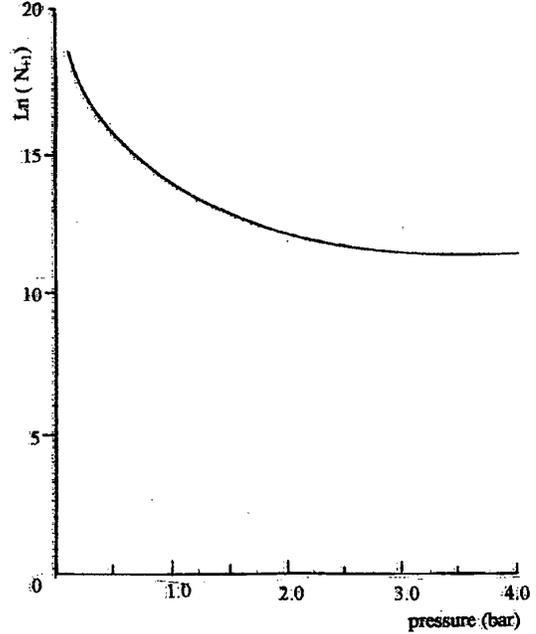


Fig. (4) The size of the primary avalanche (N_{+1}) size at corona onset versus pressure for rod gap ($r = 2$ mm, $d = 20$ mm).

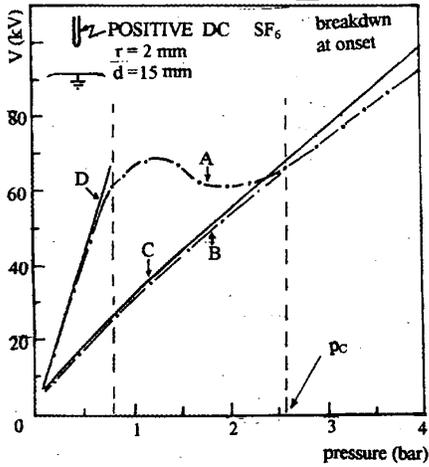


Fig. (5-a) Positive point corona onset and breakdown voltages in SF₆. A - measured V_b , B- measured V_o . [5] & C- calculated V_o , D - calculated V_b for rising part

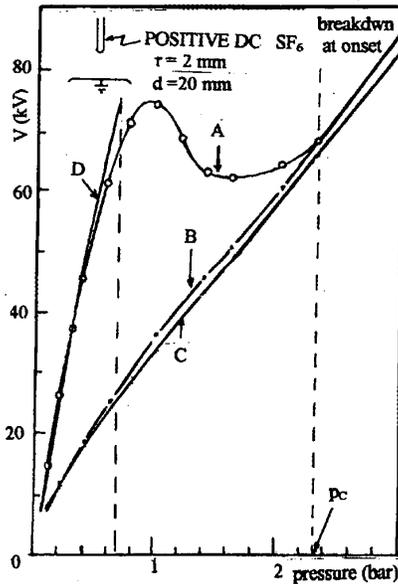


Fig. (5-b) Positive point corona onset and breakdown voltages in SF₆. A - measured V_b , B- measured V_o . [4] & C- calculated V_o , D - calculated V_b for rising part.

RESULTS AND DISCUSSION :

Fig. (4) shows how the size of the primary avalanche (N_{+1}) at corona-onset decreases with the increase of pressure which is different from Reather suggestion who assumed 10^8 independent of pressure[17]. This size of the primary avalanche was found to change from 10^8 at 0.1 bar to 0.5×10^5 at 4 bar, approximately.

Fig. (5-a & 5-b) shows the measured [4,5], and the calculated values of corona onset and

breakdown voltages in the rising part of V_b - p characteristic in addition to the breakdown voltages above p_c .

The maximum pressure is calculated according to reference [18] to determine the rising breakdown voltage zone.

CONCLUSION

1 - The onset criterion is formulated for corona in SF₆ rod gaps. The size of the primary avalanche depends on the SF₆ pressure, different from the value which was reported in the literature.

2 - A simple criterion based on the minimum gap field is proposed for calculating the breakdown voltage in the corona stabilized-region.

3 - The calculated breakdown voltage agreed with those measured experimentally within $\pm 10\%$ however the corona onset voltages agreed with the experimental values within $\pm 7\%$. The deviation may be partly ascribed to the experimental error ($\pm 5\%$) which was reported [5] in repeated tests.

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