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ON THE CALCULATION OF ELECTRICAL BREAKDOWN VOLTAGE IN SHORT GAS-GAPS AT VARYING PRESSURES

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This paper is concerned with the calculation of electrical breakdown voltage in uniform-field short gas-gaps at varying pressures. The oxygen is chosen being the main gas component in the atmospheric air, which poses the electronegativity character to the air. The calculation is based on the criterion of self-recurrence of single electron avalanche growing in the gap. This ensures sustenance of gas discharge for gap breakdown to occur. The calculated breakdown voltage and current-growth values agreed reasonably with those measured experimentally in oxygen at varying pressure values.

Keywords: breakdown, avalanche, oxygen, short gaps, uniform-field

1. INTRODUCTION

The air breakdown received the interest of many applications in industry including electrostatic precipitation of suspended particles for control of air pollution, electrostatic spraying of pesticide in agricultural farms, electrostatic painting of frames in automobile industry, electrostatic separation of raw materials in mining, ozone generation for killing viruses and dangerous odors in the atmosphere and for use in medical therapy, etc.

The studies of electrical discharges and the growth of ionization in uniform field gas gaps have been presented for different values of E/p, where E is the electric field strength in V.cm^{-1} and p is the pressure in Torr. In oxygen, the current growth was studied over the ranges 25 < E/p < 70 V.cm^{-1}.Torr^{-1} and 10 < p < 400 Torr [1]; 35 < E/p < 50 V.cm^{-1}.Torr^{-1} and 60 < p < 600 Torr [2]; 35 < E/p < 70 V.cm^{-1}.Torr^{-1} and 25 < p < 300 Torr [3].

In the range E/p > 30 V.cm^{-1}.Torr^{-1}, the electron attachment $e + O_2 \rightarrow O^- + O$ and the electron detachment $O^- + O_2 \rightarrow O_2 + O + e$ occur along with the ionization multiplication $e + O_2 \rightarrow O_2^+ + e + e$, and charge transfer $O^- + O_2 \rightarrow O_2^- + O$. The formation of three body collision O_3^- was assumed to be negligible for p < 1000 Torr [4]. Two detachment reactions were suggested, $O^- + O_2 \rightarrow O_2 + O + e$ and $O^- + O_2 + O_2 \rightarrow O_2 + O_3^-$ but only O^- and O_2^- are important for E/p > 30 V.cm^{-1}.Torr^{-1} [1].

In the literature, the breakdown voltage is assist empirically as it crossbones to the applied voltage when the avalanche reaches a critical size [5]–[7]. However, the critical size depends on the gap geometry [8] and no single value can be assigned to this size. This motives the authors to calculate the breakdown voltage in uniform-field short gaps in oxygen at varying pressure.

This paper is aimed at calculating the breakdown voltage in short oxygen gaps at varying pressures. The calculation is based on the criterion of self-recurring avalanche growing in the gap. The calculated breakdown voltage values are compared with those measured experimentally.

The paper is organized as follows: the methodology of the calculation is described in section two. The obtained results and their correlation to experimental findings reported in the literature are given in section three. The main conclusions of the paperwork are summarized in section four. The Arabic summary is written in section five.

2. METHODOLOGY:

In a uniform-field oxygen-gap, let a primary avalanche starts by one electron i.e., $n_0 = 1$ at the cathode as shown in Fig. 1. The size of the avalanche is equal to the total number of electrons existing at its head $N_e(z)$ at distance z from its starting point as expressed as

$$N_e(z) = n_0 \exp\left(\int_0^z (\alpha - \eta)dz\right) \quad (1)$$

where α and η are the Townsend's first ionization and attachment coefficients [2]. The coefficients α and η depends on the oxygen pressure and the applied electric field.

The space-charge field E_s due to positive ions N_+ left in the avalanche wake is expressed as [9]:

$$E_s(z) = \frac{e}{4\pi\varepsilon_0}\sum_{j=1}^{m}\frac{\Delta N_{+j}}{((m-j+1)\Delta z)^2} \quad (2)$$

This is based on dividing the avalanche wake into m divisions along the z-axis, so j = 1, 2, ….m. e is electron charge, ε_0 is the oxygen permittivity, $\Delta N_{+j} = \Delta N_{ej}$ and Δz is the incremental distance along the z-axis within the avalanche wake.

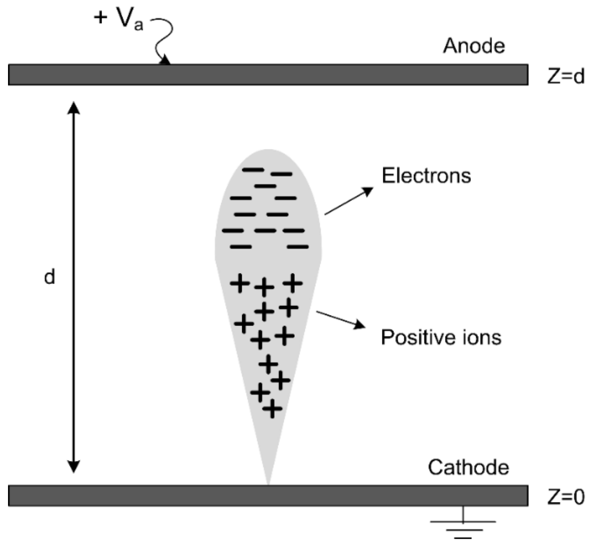

Fig. 1 Growth of avalanche in uniform-field gap

The number of photo-emitted electrons from the cathode by the end of avalanche growth (Z=d) is expressed as:

$$N_{eph} = \gamma_{ph} \int_0^d [\alpha(z) - \eta(z)] N_e(z) g(z)\, e^{-\mu z} dz \tag{3}$$

where γ_{ph} is Townsend's second ionization coefficient due to the action of photons at the cathode, μ is the photon absorption coefficient [10] in the gas, g(z) is a geometry factor to account for the photons received at the cathode from the primary avalanche during its growth at distance z along the gap axis and d is the gap spacing [9].

The condition for breakdown to occur is expressed as:

$$N_{eph} \geq n_0 \tag{4}$$

The breakdown voltage V_{BD} is the minimum applied-voltage V_a value which satisfies the equality (4). This ensures that the avalanche is self-recurring and the discharge in the gap is sustained for breakdown to occur.

The gap current I is mainly determined by the number of electrons at avalanche head, which reaches its peak $N_e(d)$ at the anode.

$$I(t) = e\, N_e(d) v_e E/V_a \qquad (5)$$

where v_e is the electron drift velocity [11].

To check the proposed methodology in its prediction of breakdown voltage of oxygen in uniform-field gaps, the calculated breakdown voltages are compared with available measured values reported in the literature.

3. RESULTS AND DISCUSSION

Figure 2 shows the calculated breakdown voltage for different gap spacing 0.5 to 3 cm at oxygen pressure of 100, 200 and 250 Torr. The breakdown voltage increases with the increase of oxygen pressure for the same gap spacing. With the increase of gas pressure at the same gap spacing, the mean free path of electrons accelerating between the gap electrodes decreases with a subsequent decrease of the energy acquired by the electrons from the applied field. This reduces the capability of electrons to multiply during their acceleration. To counterbalance such decrease of electron multiplication, the applied voltage and hence the electric field has to increase in order to materialize the gap breakdown. The breakdown occurs when the electron multiplication exceeds a critical value [5], [12]. This is why the breakdown voltage increases with the gas pressure for the same gap spacing as shown in Fig. 2.

The breakdown voltage increases with the increase of the gap spacing for the same oxygen pressure as shown in Fig. 2. With the increase of the gap spacing at the same gas pressure, the applied electric field decreases with a subsequent decrease of the energy acquired by the electrons from the applied field. This also reduces the capability of electron to multiply during their acceleration between the gap electrodes. To counterbalance such decrease of electron multiplication, the applied field and hence the voltage has to increase so the resulting multiplication reaches the critical value for breakdown to occur. This is why the breakdown voltage increases with the increase of gap spacing at the same gas pressure as shown in Fig. 2.

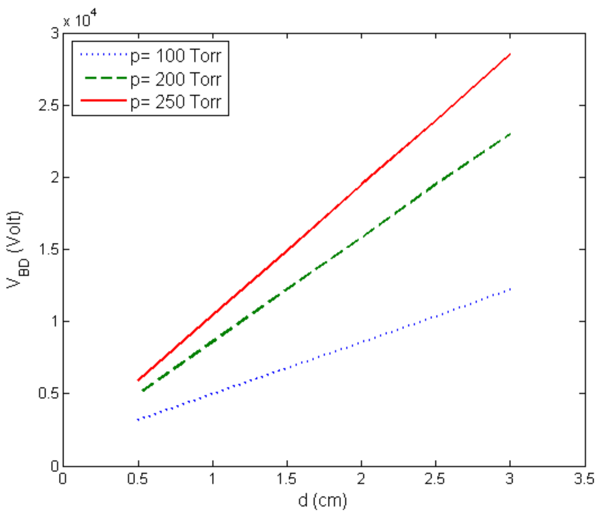

Fig. 2 Calculated breakdown voltage versus gap spacing at oxygen pressure p of 100, 200 and 250 Torr

Figure 3 shows how the breakdown voltage of oxygen increases with the increase of product pd over the range 100 to 760 Torr.cm in agreement with previous calculations and measurements using platinum electrodes [2]. The increase of the product pd can be achieved by increasing either the gas pressure p at constant gap spacing d or the gap spacing d at constant gas pressure p. As stated above, the breakdown voltage V_{BD} increases with the increase of p at constant d as shown in Fig. 2. Also, V_{BD} increases with the increase of d at constant p, Fig. 2. This is why the breakdown voltage increases with the increase of the product pd as shown in Fig. 3.

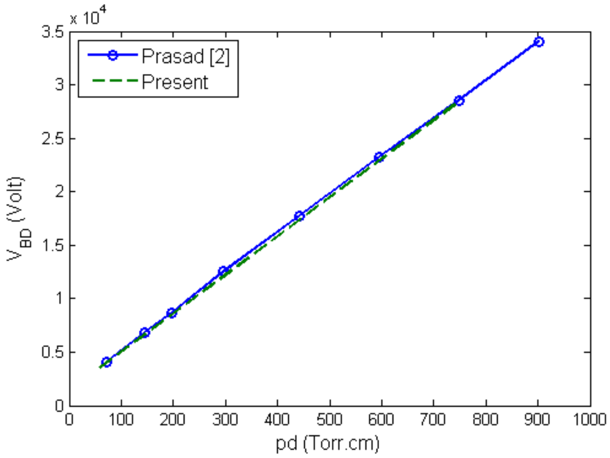

Fig. 3 Calculated and measured [2] breakdown voltage values versus product pd at oxygen pressure p in the range 100 < p < 760 Torr

Figure 4 shows how the breakdown field normalized to oxygen pressure E/p decreases with the increase of product pd over the range 100 to 760 Torr.cm in agreement with previous calculations and measurements using platinum [2] and nickel [3] electrodes. The increase of the product pd can also be achieved by increasing both the gas pressure p and the gap spacing d. Even the breakdown voltage V_{BD} increase with the increase of the product pd as shown in Fig. 3, the normalized electric field E/p (=(V_{BD}/d)/p) at breakdown has an opposite trend as both p and d increase simultaneously. This is why E/p at breakdown decreases with the increase of pd as shown in Fig. 4. The electrode material has insignificant impact on the breakdown voltage because of its slight effect on γ_{ph}, the Townsend's second ionization coefficient due to the action of photons at the cathode.

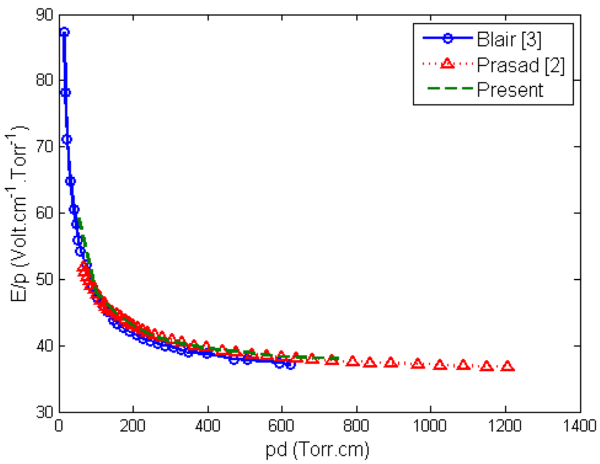

Fig. 4 Calculated and measured [2], [3] breakdown field E_{BD} normalized to oxygen pressure p versus product pd

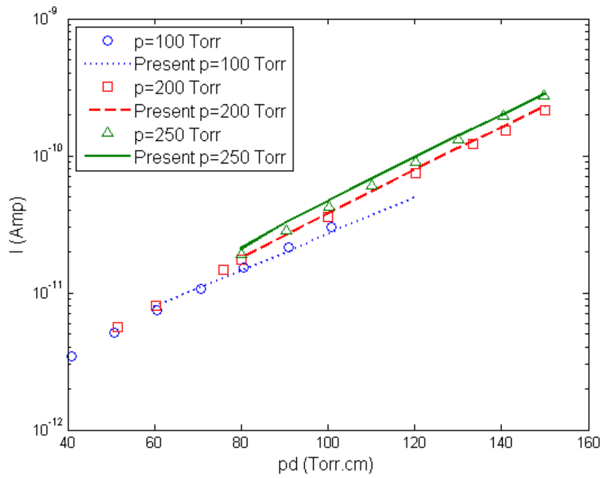

Fig. 5 Calculated and measured [1] gap current I at E/p of 40 $V.cm^{-1}.Torr^{-1}$ at oxygen pressure p of 100, 200 and 250 Torr.

Figure 5 shows that the pre-breakdown gap current in oxygen increases with the increase of product pd over range 50 to 150 Torr.cm at different oxygen pressure of 100, 200 and 250 Torr in agreement with experimental values [1]. The current increases with the increase of oxygen pressure at the same value of the product pd in agreement with previous calculations and measurements [1]. Reference is made to Fig. 3, where the breakdown voltage V_{BD} increases linearly with the product pd. With the increase of V_{BD}, the electric field increases with a subsequent increase of the velocity of electrons, the carriers of the current in the gap and hence the increase of the gap current. This is why the gap current increases linearly with the product pd as shown in Fig.5. For the same value of pd, the higher the gas pressure p, the smaller is the gap spacing d with a subsequent increase of the electric field driving the current carriers in the gap. This results in increase of the gap current with the increase of the gas pressure at the same value of pd as shown in Fig.5.

It is worthy to mention that the proposed method is applicable for calculating the breakdown voltage of oxygen in uniform-field gaps irrespective of the oxygen pressure or gap spacing pending that the avalanche can cross the gap to materialize its breakdown.

The proposed method for calculating the breakdown voltage is also applicable for any gas provided that the physical parameters of the gas including Townsend's ionization coefficient α, attachment coefficient η, absorption coefficient μ, .. etc., are available as functions of gas pressure and gap spacing.

4. CONCLUSIONS

1- A method is proposed for calculating the breakdown voltage of oxygen in uniform field gaps. The method is applicable for any oxygen pressure or gap spacing provided that the avalanche can cross the gap to materialize its breakdown.

2- The breakdown voltage increases with the increase of oxygen pressure for the same gap spacing.
3- The breakdown voltage increases with the increase of gap spacing for the same oxygen pressure.
4- The breakdown voltage of oxygen increases with the increase of product pd for the same oxygen pressure.
5- The breakdown field normalized to oxygen pressure increases with the decrease of product pd.
6- The discharge current just before breakdown increases with the increase of the product pd for the same oxygen pressure.
7- The discharge current just before breakdown increases with the increase of oxygen pressure for the same value of pd.

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الملخص العربى

يهتم هذا البحث بحساب جهد الانهيار الكهربائي في فجوات غازية قصيرة عند ضغوط مختلفة. يتم اختيار الأكسجين باعتباره مكون الغاز الرئيسي في الهواء الجوي ، حيث انه يشكل خاصية التصاق الالكترونات لجزيئات الهواء. يعتمد الحساب على التكرار الذاتي لإنهمار الكتروني الذي ينمو في الفجوة. هذا يضمن استدامة التفريغ الكهربي للغاز لحدوث انهيار الفجوة. اتفقت القيم المحسوبة لجهود الانهيار و لتيار الفجوة قبل الانهيار بدرجة مرضية لنظيرتها المقاسة معمليا في الأكسجين و المحسوبة بواسطة اخرين بقيم ضغط متغيرة.