Effect of Secondary Ionization Coefficient on the Breakdown Voltage in Nitrogen Gas

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Abstract. A theoretical investigation of the secondary ionization coefficients that responsible for the ionization current growth in uniform electric field studied. Nitrogen gas was from the range of \(E/p\) various 60 to 392 V/cm Torr, which corresponding to low values of pressures (0.05 < \(p\) <0.684 Torr). The secondary ionization coefficients have been calculated using the breakdown criterion condition for a discharge gap in a uniform electric field. Using theoretical values of the primary ionization coefficient determined from numerically solving Boltzmann equation together with the values of the sparking distance (ds) obtained from present work. The program provided all cross-sections data from nitrogen. Experimentally, the measurement of breakdown voltage was taken after fixing sparking distance at ds= 69 cm. The results of the present work showed that, the value of breakdown voltage decreased during the increase of the secondary ionization coefficient value. Furthermore, under very low-pressure range, and within the studied sparking distance ds, the value of secondary ionization coefficient was negligible. During pressure increase, the value of secondary ionization coefficient becomes a saturation value.

Keywords: Breakdown Voltage, Ionization Coefficient.

1. Introduction

Many of the previous studies included the study of the primary ionization coefficient of most gases due to the great importance in the occurrence of the electrical breakdown process. For example, theoretical studies \[1-5\] concerned nitrogen gas with a mixture of gases such as SF\(_6\), CC\(_{12}\)F\(_2\), etc., where the basis for the selection of gases was as much as the value of the insulation intensity. These studies based mainly on the calculation of the numerical Boltzmann equation and for different ranges of \(E/p\) after including all cross-sections of the studied gas. The practical studies \[6\] were based mainly on the application of Townsend’s relationship to current growth, after measuring the current as a function of the distance between the electrodes \[7\].

In the present research, the value of the secondary ionization factor at which the electric breakdown of nitrogen gas occurs is extracted. It is known that the breakdown voltage is a function of the product of multiplying both the pressure \(p\) and the distance \(d\), which is called the Paschen's law:

\[
V_B = f \left( pd \right)
\]  

(1)

The lowest value of the breakdown voltage at which the electrical breakdown occurs called \(V_B(\text{min})\), which corresponds to a given value of the product for both distance and pressure (pd). In the present
paper, this study conducted under very low pressures, while the distance between the electrodes was used as a constant value and considered the value at which the electrical breakdown occurs \((d_s = 69\text{ cm})\). Therefore, the results obtained from the research are beyond the value of \((P_d)\) which corresponds to \(V_{B(\text{min})}\) in Paschen curved.

The primary ionization coefficient \((\alpha/p)\) is a function of \(E/p\), where the relationship between them \([8]\):

\[
\frac{\alpha}{p} = A \exp \left( - \frac{B}{(E/p)} \right) \quad \text{for} \quad 50 \leq \frac{E}{p} \leq 260 \text{ V (cm. Torr)} \quad (2)
\]

Where \(A, B\) are constants.

Equation (1) can take the following relation \([9]\):

\[
V_B = \frac{Bp^d}{\ln \left( \frac{A}{\ln \left( 1 + \frac{1}{\alpha (W/\alpha)} \right)} + \ln(p) \right)} \quad (3)
\]

Where \(A, B\) are constants, and \(\bar{\alpha}\) is the ionization coefficient which is equal to \((\bar{\alpha} = \alpha - \eta)\), where \(\alpha\) is the primary ionization coefficient and \(\eta\) contact coefficient, and \(W/\alpha\) is the total secondary ionization coefficient. The pressure unit \(p\) is Torr, the distance \(d\) is centimeters, and \(V_B\) is kV.

For electronegative gases such as nitrogen, \(\eta = 0\), so the relation (3) becomes:

\[
V_B = \frac{Bp^d}{\ln \left( \frac{A}{\ln \left( 1 + \frac{1}{\alpha} \right)} + \ln(p) \right)} \quad (4)
\]

The relationship (4) is experimental, and it is clear that the voltage of the breakdown is affected by the value of the secondary ionization coefficient, so in this research has been studied this effect of nitrogen gas.

On the other hand, Townsend's relationship to current growth is \([10]\):

\[
I = I_0 e^{\frac{\bar{\alpha}d}{\bar{\alpha} - 1}} \quad (5)
\]

\(I_0\) is the initial current that occurs as a result of the radiation falling on the cathode surface.

The condition of electrical breakdown is that the denominator in relationship (5) is zero, i.e. \(I = \infty\) \([10]\):

\[
1 - \frac{W}{\bar{\alpha}} (e^{\bar{\alpha}d_s} - 1) = 0 \quad (6)
\]

In equation (5), \(d\) converted to \(d_s\), that the distance at which the breakdown occurs. Practically, changing the distance is not easy, so the distance has been fixed. It is known from equation (1) that the voltage breakdown is a function of both the distance product and pressure, so the pressure is introduced into the relationship (6) to become:

\[
1 - \frac{W}{\bar{\alpha}} (e^{\bar{\alpha}d_s} - 1) = 0 \quad (7)
\]
The total secondary ionization coefficient \((w/α)\) is the number of secondary electrons produced for each positive ion collision, photon or semi-stable or irritating atom \([11]\). When the positive ion collision is dominant, the relationship (7) becomes:

\[
1 - γ \left( e^\infty_ρ ds - 1 \right) = 0
\]

\[
∴ γ = \left( e^\infty_ρ ds - 1 \right)^{-1} \tag{8}
\]

Accordingly, the resulting secondary electrons were due to only positive ion collisions \((w/α=γ)\).

Equation (8) is the relationship adopted in the current research to study the effect of secondary ionization coefficient on the voltage breakdown. The equation (4) is the product of equations (2) and (8).

2. **The experimental part**

The discharge system is a thick cylindrical tube, made of quartz material and has anode and cathode poles on both ends of which are flat planes to form the electric field between them uniformly, was employed. The tube was 76.5 cm long, 5.1 cm in diameter, and the distance between the poles was 69 cm, where the electrodes were made of aluminum. The ROBINAIR rotary pump, which can reduce the pressure inside the discharge tube to 20.52 millimeters, and also uses horsepower of a 1/3 HP and rotates at 1425 PPM, was utilized. Moreover, a pressure Pirani gauge which is a digital gauge that measures in millibars was used.

The electrical breakdown occurs when there is a large increase in the external current, so the value of the voltage breakdown is adopted through observing the large increase in current and pressure variables \((p = 0.05, 0.102, 0.243, 0.41, 0.684)\) Torr.

3. **Calculation**

In the present research, the secondary ionization coefficient in nitrogen gas calculated in a range of \(E/p < 392 < 60 \text{ vol}./\text{(cm.Torr)}\). This range considered outside the range of equation (2), through using values \((A=8.68, B=282.89)\) \([8]\). Therefore, the computer program that solved the Boltzmann equation for \(N_2\) gas instead of SF6 \([12]\) was generalized after all the nitrogen gas cross-sections taken from the source \([13]\) were used.

Nitrogen gas did not possess contact cross sections, unlike SF6 gas that had these cross sections. Therefore, when using the program, cross sections of contact for nitrogen gas were neglected. The program extracts the distribution function, which is the solution of the Boltzmann equation; the primary ionization coefficient can then be determined by the following equation:

\[
\frac{\infty}{ρ} = \frac{1}{W} \int_{-\infty}^{\infty} q_1(ε)ε^{0.5} F(ε) dε \tag{9}
\]

\[
W = \frac{1}{3} \int_{-\infty}^{\infty} F_1(ε) dε \tag{10}
\]

Where \(W\) is the drift velocity, \(q_1(ε)\) is the ionization cross-sections as a function of energy, \(F(ε)\) is the distribution function, \(F_1(ε)\) is the distribution function which is a solution to the Boltzmann equation of two edits, and \(ε\) is the ionization energy.

By incorporating the results of equation (2) and equation (9) into equation (8), the secondary ionization coefficient was calculated at different breakdown voltages and for certain pressures.

4. **Results and discussion**

Figure (1) showed the primary ionization coefficient for nitrogen gas as a \((E/p)\) function. Figure (1) also illustrated that there was agreement in the results of equation (2) and equation (9) in the few ranges of \(E/p\), but in the long ranges there is disagreement between the two equations. The values of
the primary ionization coefficient for equations (2) and (9) were taken and then included in equation (8) to calculate the secondary ionization coefficient.

Figure 1. Primary Ionization Coefficient as a function of E/p (Volt.Torr⁻¹.cm⁻¹).

Figure (2) showed the secondary ionization coefficient as a function of (E/p)b. (E/p)b represented the value of E/p at which the electrical breakdown occurs and equals (V_b/p_d), figure (2) also illustrated the results of equation (2) and (9). The ionization coefficient reduced by increasing the value of (E/p)b for equations (2) and (9) results.

Figure 2. Secondary Ionization Coefficient as a function of (E/p)b.

Figure (3) illustrated the secondary ionization coefficient as a function of voltage breakdown. The value of voltage breakdown (which is beyond the minimum voltage breakdown in the Paschen curve) was either low (which means that both the pressure and the distance between the electrodes were low), or high (which means that all the distance and pressure were large). Figure (3) also showed the number of low voltage breakdowns when the secondary ionization coefficient neglected, while the number of high-voltage breakdown becomes an invaluable value in the occurrence of electrical breakdown.
Figure 3. Secondary Coefficient of Ionization as a function of Breakdown Voltage.

Figure (4) shows the voltage breakdown as a function of pd (Paschen curve), where pd values are beyond the value of \((pd)_{\text{min}}\).

Figure 4. Breakdown Voltage as a function of pd (Paschen curve).

Figure (5) illustrates the relationship between the coefficient of secondary ionization and pressure when the distance constant, it also shows that at low values of pressure, the secondary ionization coefficient is neglected and begins to increase the pressure, but to take stability and becomes constant.
Figure 5. Secondary Ionization Coefficient as a function of Pressure.

Note: The results of the present study did not include any comparison with previous studies, because the previous studies used low values of the product of the distance multiplied with pressure, on the contrary the current research where the values were relatively high.

5. Conclusion
The effect of secondary ionization coefficient on the voltage breakdown for pressures of \((p = 0.05, 0.102, 0.243, 0.41, 0.684)\) Torr, was studied after making the distance constant. From the results of the current search, it was found that the values of \(\gamma\) were sensitive to \((E/p)\) and \(p\) where \(\gamma\) was stable the increase of both \((E/p)\) and \(p\).

This method can be generalized to include other gases, especially some gases that have an electrical negative, where the connection coefficient included in the calculations and the breakdown condition is Townsend.

The present study, adopted studying the relationship of the secondary ionization coefficient with the voltage breakdown beyond the minimum value of the voltage breakdown; this study can be generalized to extract the relationship before the minimum value of the voltage breakdown.

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