Lecture # 2

Role of Ions in Breakdown of Gases

Drawbacks in Townsend Theory

The Townsend theory as discussed in the previous lecture, establishes the growth of charge carriers in an avalanche in a uniform field that is governed by a factor exp(αd), is valid only as long as the influence of the space charge due to positive ions is very small compared to the applied field. In his studies on the effect of space charge on avalanche growth, Raether observed that when charge concentration was between 10^6 and 10^8, the growth of the avalanche became weak. On the other hand, when the charge concentration was greater than 10^8, the avalanche current was followed by a sharp increase in the current in the gap between the electrodes leading to the breakdown of the gap.

Role of Positive Ions

The Townsend original work came under serious objection because of ignoring the role of positive ions in the breakdown process. It must be remembered that positive ion must have kinetic energy (measured as equivalent photon energy) greater than at least twice the work function of the cathode in order to produce electron emission from cathode. Therefore, the threshold condition would be:

$$KE = \frac{1}{2} m_p u^2 = hv \geq 2\phi_k \qquad 1$$

Where m_p is the mass and u is the velocity of positive ion. The difference of energy between the kinetic energy of incident positive ion and twice the work function of the cathode material will be imparted as kinetic energy: $\frac{1}{2} m u_e{}^2$ to that ejected electron. It is obtained from the threshold condition of Eq (1), resulting in:

$$\frac{1}{2} m u_e{}^2 = hv - 2\phi_k \qquad 2$$

From which:

$$u_e = \sqrt{\frac{2(h\nu - 2\phi_k)}{m}} \qquad 3$$

Townsend and his co-workers then put forward an alternative hypothesis, considering emission of electrons from cathode caused by positive ions impact, introducing second ionization coefficient, which was later accounted by Townsend as second ionization coefficient γ, defined as the number of electrons emitted from the cathode material per incident positive-ion impact. Accordingly, the positive ions slowly drift towards the cathode and in doing so they gain energy from the applied field. The massive positive ion when reaches the cathode, suffers a collision course, without being absorbed. In the course of collision, energy is transferred by the positive ion, which is taken by the cathode material. If the energy transferred by the positive ion happens to be greater than the work function ϕ_k of the cathode material (defined as the minimum amount of energy required to eject an electron from metals), then electron is ejected from the cathode. Under a cumulative process, electron emission will result, thereby producing more and more conduction electrons in the gap.

In order to account for the energy gained by the positive ion from the main field that must be at least greater than twice the work function of the cathode material, which means that two electrons will be liberated, one to recombine to form neutral atom and the other to be introduced in the main gap. These electrons, which are being liberated from cathode material, are referred to as secondary electrons. These are not to be confused with those, which are already present in the gap as a result of energy process due to other external agencies. In order to obtain a modified expression for the gap current due to primary and secondary electrons and which incorporates both the Townsend first and the second ionization coefficient, we proceed by supposing that:

n_2 = Number of electrons reaching the anode per sec.
n_o = Number of electrons initially present in the gap.
n_1 = Number of electrons released by cathode through positive ions.
γ = Electrons released from cathode per incident positive ion.

The total electrons in the gap will then be:

$$n_2 = n_1 + n_o \qquad 4$$

Let us consider the dynamics of a single electron moving towards the anode under the influence of electric field. It will produce collision ionization in the gap therefore resulting in the electrons multiplication to form an avalanche. As the distance towards anode decreases, the number of electrons will increase according to the factor exp(αd). So theoretically the number of positive ions formed in the gap by n_2 electron avalanche will be equal to n_2 [exp (αd) – 1]. Using the definition of Townsend second ionization coefficient:

$$\gamma = \frac{n_1}{n_2[\exp(\alpha d) - 1]} \qquad 5$$

Or

$$n_2[\exp(\alpha d) - 1]\gamma = n_1$$

Which, when substituted in Eq (4) will yield:

$$n_2 = n_o + \gamma n_2 [\exp(\alpha d) - 1]$$

Or

$$n_2 = \frac{n_o}{1 - \gamma[\exp(\alpha d) - 1]} \qquad 6$$

Considering secondary emission or the role of positive ions in the breakdown mechanism, the total number of charges reaching the anode will be given by replacing n_2 for n_0, in the original Townsend expression, so that:

$$n = n_2 \exp(\alpha d)$$

Therefore:

$$n = n_o \frac{\exp(\alpha d)}{1 - \gamma[\exp(\alpha d) - 1]} \qquad 7$$

In case when secondary emission or role of positive ion is ignored, then $\gamma = 0$. Therefore, Eq (7) will take the form: $n = n_o \exp(\alpha d)$. The gap current in the formation of breakdown path is then expressed as:

$$I = I_o \frac{\exp(\alpha d)}{1 - \gamma[\exp(\alpha d) - 1]} \qquad 8$$

Example 1: The work function of cesium is 2.14 eV. Determine the maximum kinetic energy and speed of the electrons ejected from the surface of cesium by light of wavelength 546 nm.

Solution:

Given that:

$\phi_k = 2.14$ eV

$\lambda = 546$ nm

Using:

$$KE = h\nu - \phi_k = h\frac{c}{\lambda} - \phi_k$$

Therefore:

$$KE = \frac{6.63\times10^{-34}\times3\times10^{8}}{546\times10^{-9}\times1.6\times10^{-19}} - 2.14$$

$$KE = 2.28 - 2.14 = \mathbf{0.14\ eV}$$

Since:

$$KE = \frac{1}{2} m u_e^{\,2}$$

Then

$$u_e = \sqrt{\frac{2KE}{m}}$$

Therefore:

$$u_e = \sqrt{\frac{2\times0.14\times1.6\times10^{-19}}{9.1\times10^{-31}}} = \mathbf{2.2\ x\ 10^5\ m/s}$$

Example 2: The work function of a material is 2.8eV. Determine the maximum kinetic energy in (eV) and the speed of the electron ejected from the surface of this material by positive having energy of 5.72 eV.

Solution:

Given that:

$\phi_k = 3.17$ eV

$KE = 5.72$ eV (kinetic energy of positive ion)

The difference between the energy of positive ion and $2\phi_k$ will appear as kinetic energy of free electron. Therefore using:

$$\frac{1}{2}mu^2 = 5.72 - 2 \times 2.8 = \mathbf{0.12\ eV}$$

The speed of electron will be:

$$u_e = \sqrt{\frac{2 \times 0.12 \times 1.6 \times 10^{-19}}{9.1 \times 10^{-31}}} = \mathbf{2 \times 10^5\ m/s}$$

Townsend Criterion for Spark

The unstable condition in the gap between the electrodes in Townsend experiment is the rapid rise of current in region-C due to cumulative effects of collision ionization resulting in electron multiplication forming avalanches. Townsend criterion for spark follows from this exponential rise of gap current prior to breakdown. Three interesting cases in this context are discussed below:

Case 1: If exp(αd) = 1, then the number of electron-ion pair produced in the gap by the passage of one electron avalanche is sufficiently large and the resulting positive ions, on bombardment the cathode are able to release secondary electrons.

Case 2: If exp(αd) > 1, then the ionization produced by successive electrons is cumulative. The electrons in the gap multiply due to ionization by collision thus forming avalanche. The spark discharge grows more rapidly and becomes self sustained.

Case 3: If exp(αd) < 1, then the avalanche dies out and the gap current will cease.

Conduction and Breakdown in Electronegative Gases

Some gases are electronegative in nature, the atoms of which have great affinity for electrons. As such these can attach electrons to form negative ions, which can move under the influence of applied field. The electronegativity of gas is governed by attachment coefficient η, which is the measure of the ability of electronegative gas to attach electrons to form negative ions and is defined as the number of attaching collisions made by one electron drifting one centimeter in the direction of the field. Consider an electronegative gas in Townsend experimental set up and considering a small space dx at a distance x from cathode. If electron multiplication by collision-ionization process and negative ion formation by electron absorption takes place simultaneously, then considering that n_i are the electrons produced due to collision ionization in the gap dx, we have:

$$dn_i = n\alpha dx$$

The electron lost by attachment n_a to form negative ions in the gap dx will then be given by:

$$dn_a = -n\eta dx$$

Then the electrons taking part in the two processes within the gap *dx* will be *dn* and is given as:

$$dn = dn_i + dn_a$$

Or

$$dn = n(\alpha - \eta)dx \qquad 9$$

Rearranging and integrating both sides of Eq (9), we obtain:

$$n = n_0 e^{(\alpha-\eta)d} \qquad 10$$

The component of gap current due to negative ions formed can be found out by considering that dn_g are the negative ions formed in gap *dx* by capturing from a share of *n* number of electrons available. Therefore:

$$dn_g = n\eta dx \qquad 11$$

Substituting the expression for *n* for ($d = x$) given in Eq (10) in Eq (11), we obtain:

$$dn_g = n_0 \eta e^{(\alpha-\eta)x} dx$$

Or

$$n_g = n_0 \eta \int e^{(\alpha-\eta)x} dx$$

Or

$$n_g = n_0 \eta \frac{1}{(\alpha-\eta)} e^{(\alpha-\eta)x} + k \qquad 12$$

Where *k* is constant of integration, whose value can be obtained from the boundary conditions for the gap; that is for $x = 0$ at the cathode, $n_g = 0$. Substituting this condition in Eq (12) the value of *k* will be:

$$k = -\left(\frac{n_0\eta}{\alpha-\eta}\right)$$

Substituting the value of *k* in Eq (12), we have:

$$n_g = n_0 \eta \frac{1}{(\alpha-\eta)} e^{(\alpha-\eta)x} - \left(\frac{n_0\eta}{\alpha-\eta}\right)$$

Or

$$n_g = n_0 \eta \frac{1}{(\alpha-\eta)} [e^{(\alpha-\eta)x} - 1] \qquad 13$$

At $x = d$, the total gap current n_T will have two components; one due to electrons and the other due to negative ions. Therefore:

$$n_T = n + n_g \qquad 14$$

Substituting the expression of n from Eq (9) and expression for n_g from Eq (13) for ($x = d$) in Eq (14), we have:

$$n_T = n_0\left[\frac{\alpha e^{(\alpha-\eta)d}}{\alpha-\eta} - \frac{\eta}{\alpha-\eta}\right]$$

The total gap current I_T due to the presence of free electrons and that due to negative ions is then given by:

$$I_T = I_0\left[\frac{\alpha e^{(\alpha-\eta)d}}{\alpha-\eta} - \frac{\eta}{\alpha-\eta}\right] \qquad 15$$

This process gives high breakdown strength to a gas due to the electron attachment in which free electrons get attached to a neutral atoms or molecules to form negative ions. Since both negative and positive ions are too massive to produce direct ionization due to collisions, attachment represents an effective way of removing electrons which otherwise would have led to current growth and breakdown at low voltages. Example of molecular electronegative gas is SF_6 in which sulphur is electronegative.

Applications of Gaseous Insulation

An important characteristic of a gaseous insulation is that it recovers its dielectric strength following breakdown and therefore can be used repeatedly in many high-voltage applications. Over the years, considerable amount of work has been done to select suitable gas insulation or dielectric for practical use. Before selecting a particular gas or gas mixture, it is useful to gain knowledge of what the gas does, what its composition is, and what the factors is that which influence its performance in practice. The greater the versatility of the operating performance demanded from an insulating gas or gas mixture, the more rigorous would be the requirements which it should meet. These requirements needed by a good dielectric do not exist in a majority of the gases. In several cases gas at high pressure is used to make it an effective dielectric or mixture of gases is used in many applications.

Sulphur Hexafluoride (SF_6) has been extensively studied over the years has been found to possess most of the above requirements. Of the above properties, dielectric strength is the most important property of a gaseous dielectric for practical use. SF_6 have excellent arc-quenching properties, therefore it is widely used as an insulating as well as arc-quenching medium in high-voltage circuit breakers. SF_6 is widely used for applications in power system due to its high dielectric strength and good arc interruption properties. However, SF_6 gas has been found to be a greenhouse gas that causes environmental problems.

The production and use of SF_6 gas has increased steadily and today it is about 10,000 metric tons due to leakages into the atmosphere from the electrical equipment. The concentration of SF_6 in the environment has been steadily increasing. The release of SF_6 into the atmosphere leads to concentration of large volumes of SF_6 gas in the upper atmosphere. SF_6 molecules absorb energy from the sun and radiate it into the atmosphere for long duration of time. There has, however, been a large concern for these environmental effects and therefore it is essential to look for an alternate gas or gas mixture to be used in electrical equipment, which presently uses SF_6 gas as an insulating and arc interruption medium. Mixing two or more gases in proper proportions can reduce its breakdown voltage.

The large amount of experimental data that is presently available suggest that 40% SF_6 and 60% N_2 mixtures have all the dielectric characteristics that make it suitable for use as insulation in high voltage equipment.

Effect of Gas Pressure on Breakdown (Paschen's Law)

In practice, breakdown voltages were found to depend on the gas pressure and the geometry of the gap. If Townsend experiment is performed at different electrode separations and gas pressures inside the chamber, different values of breakdown voltages will be obtained. In actuality, the pressure is generally replaced by the gas density. It is important to know that Friedrich Paschen initially worked at high pressures and gap separations of several millimeters. Later from series of experiments with different pressures and gap separations the familiar "Paschen curve" with the minima was created and given the shape in the form of Paschen's Law. The law essentially states that the breakdown characteristics of a gap are a function (generally not linear) of the product of the gas pressure and the gap length, usually written as $V_b = f(pd)$, where p is the pressure and d is the gap distance.

This behavior generally follows a pattern of the curve as shown in Fig (1), referred to as Paschen's curve. Townsend experiment was carried out at different pressures. Pressure plays an important role in the breakdown mechanism of gases. Increased pressure is the result of densely packing of atoms and molecules of a gas. The electrons, which are present in the gap, are under the influence of the closely packed neighboring atoms and molecules, which restrict their movement. In other words, in the presence of external field, these electrons wound not gain enough energy to produce effective collision-ionization because their means free path will be restricted or small enough to gain sufficient energy form their field. Thus, for favorable conditions the following two criterions must be met:

1. Either very high field must exit.
2. Electrons playing major role in the breakdown must be increased.

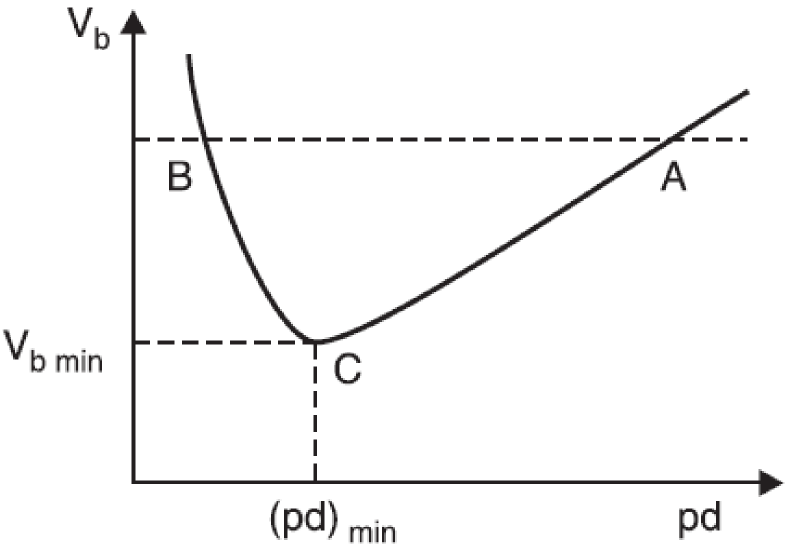

Figure 1

By reducing the pressure below Paschen minimum, the breakdown will take place at higher voltage as evident from Fig (1). This is because at low pressures, the atoms and molecules of the gas are far apart from each other. The mean free path is thus greater due to the atoms and molecules of the gas being widely apart. Under these conditions, there is a good chance of missing a collision with the gas by an electron moving towards the anode. The chances of collision-ionization leading to avalanches are therefore less. However, in the presence of very high electric field, electrons are introduced in the main gap by the electrodes material because as an increase in the field will lower the potential barrier, thereby overcoming the work function of the cathode resulting in the liberation of electrons from the cathode material. When the numbers of electrons are increased in the gap, chances of the collision-ionization will increase.