Lecture # 1

Insulating Gases

1. Introduction:

Gases have no fixed structure and their atoms and molecules that are free to move in a random fashion. Gas insulators in atomic and molecular form are widely used in high-voltage applications. Air is the most common gas insulation. Besides, many electrical apparatus use other gases such as N_2, CO_2, CCl_2F_2 (Freon) and SF_6 (hexafluoride) are used. Other includes mixture of gases, such as Neon-Argon for special purpose. Gas insulation is commonly used in high-voltage switchgear and in Gas Insulated Substations (GIS). The important characteristic feature is that its dielectric strength is recoverable following a breakdown and therefore, can be used repeatedly in the same or other applications. Amongst the variety of features, the following are of prime importance for a gas to be used as insulator.

1. It must have a high dielectric strength.
2. It must be non-flammable and non-explosive.
3. It must be non-corrosive.
4. It must be non-toxic.
5. It must be environmental friendly.
6. It must be chemically stable (inert).
7. It must not dissociate at working temperatures (thermally stable).

2. Charge Transport and Conduction in Gases

Charge transport and conduction mechanism in gases are subject to different conditions, that is; temperature, pressure, photons (light energy) from external sources and electric field energy in the form of voltage application across the electrodes of a container, which contains the gas. Dielectric gas contains very few free electrons and is generally non-conductive under Standard Temperature and Pressure (STP) and in the absence of electric field. The small conduction current that may results from the ionization of air by the cosmic radiations from outer space and the radioactive substances present in the atmosphere and the earth is of the order of 10^{-10} A/cm^2. In order to conduct electricity in gases, the following two conditions are to be met:

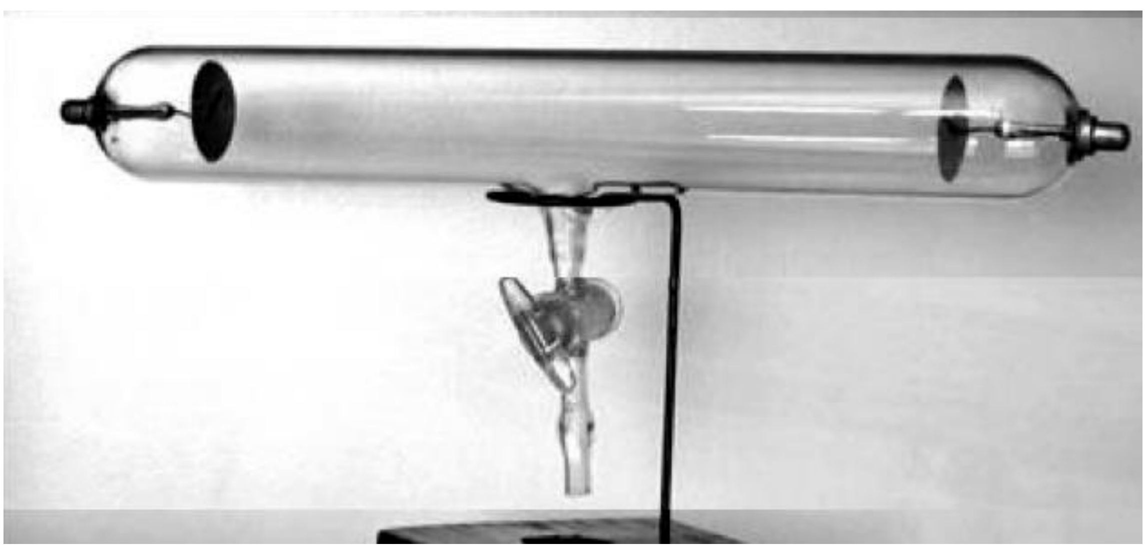
1. The normally neutral gas must create sufficient charges or accept them from external sources, or both.
2. An electric field component should exist to produce the directional motion of the charges.

Practically all dielectric gases contain charge species, though very few, in the form of free electrons and charged atoms or molecules. Charged atoms or molecules are ions, can be either positive or negative which respectively, are produced as a result of ionization and electron attachment. Under the influence of electric field, produced as a result of voltage application between two metal electrodes; anode (positive) and cathode (negative), these charge species can be made to move resulting in electronic and ionic conductivities. Conduction in gases is distinguished from solids and most liquids; that in gases ionic conductivity play an important role in the conduction process. The gas not only permits free charges to pass though, but itself may produce charges. For any gas at a given pressure and temperature there is a certain critical voltage called ionization voltage, that will produce ionization. Application of a voltage above the critical value would initially cause the current to increase due to cumulative ionization that occurs when the original electron and its offspring gain enough energy, so each can produce further electrons. Regions of high electrical stress can cause nearby gas to partially ionize and begin conducting.

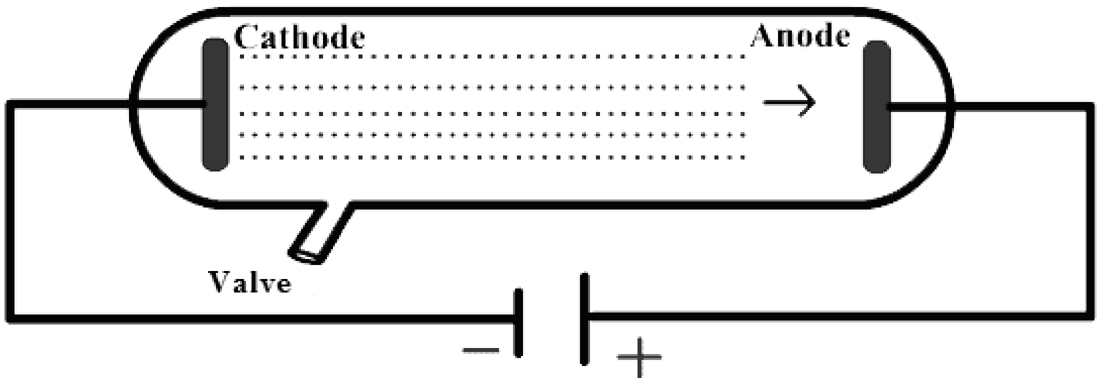
3. Townsend Theory of Breakdown in Gases

Insulation application for a particular purpose cannot be made unless its breakdown mechanism is known and understood. Breakdown is accompanied by the formation of arc. Because of the high temperature and the high current involved, some of the mechanisms of arc formation are complicated and cannot be easily studied. The classical theory, which is still accepted, is the Townsend theory of breakdown of gaseous insulation, named after John Sealy Townsend, who studied the behavior of gases under different conditions with the application of electric field starting in early 1900s.

In his early series of experiments, Townsend enclosed a gas at STP between two metal electrodes implanted in a sealed glass chamber. A photograph of one such typical tube with electrodes is shown in Fig (1a). The external connectors of the electrodes were connected to a variable DC voltage source through a current measuring device. The voltage from the source can be varied steadily from zero to some pre-determined value.



(a)



(b)

Figure 1: Townsend Gas Discharge Tube

The arrangement is shown in Fig (1b). As shown in Fig (1), the setup of the experimental investigations consist of a planar parallel plate electrode arrangement implanted in a glass envelope filled with a gas and a continuous current high voltage DC source connected between its terminals. The arrangement behaves as a gas filled capacitor. The electrode connected to the negative terminal of the voltage source is referred to as cathode while the electrode connected to the positive terminal is referred to as the anode.

Townsend found that the current flowing in the circuit comprising of electrodes, voltage source and the gas medium depends on the electric field between the electrodes in such a way that electrons and gas ions seems to multiply as they moved in the space between the electrodes. Initially very small amount of already present free electrons, accelerated by a sufficiently strong electric field, give rise to electrical conduction through a gas by the process of electron multiplication and avalanche formation. When the electric field weakens, the number of free charges decreases, the phenomena ceases. Initially the process is characterized by very low current densities as in common gas-filled tubes, typical magnitude of currents flowing during this process range from about 10^{-18}A to about 10^{-5}A, while applied voltages are almost constant. Subsequent transition to ionization processes of dark discharge, glow discharge, and finally to arc discharge is resulted by increasing current densities in the gap between the electrodes. In all these discharge regimes, the basic mechanism of conduction is electron multiplication by collision-ionization.

Townsend repeated the same experiment under same laboratory conditions for different gases and found that in all cases, the gap characteristics exhibit a non-linear relationship between voltage and current and nearly assumes the shape as shown in Fig (2). For the purpose of understanding, the characteristics can be divided into three distinct regions; A, B and C referred to as, photo-ionization region, equilibrium or space charge region and avalanche region respectively. These are discussed in the following sub-sections.

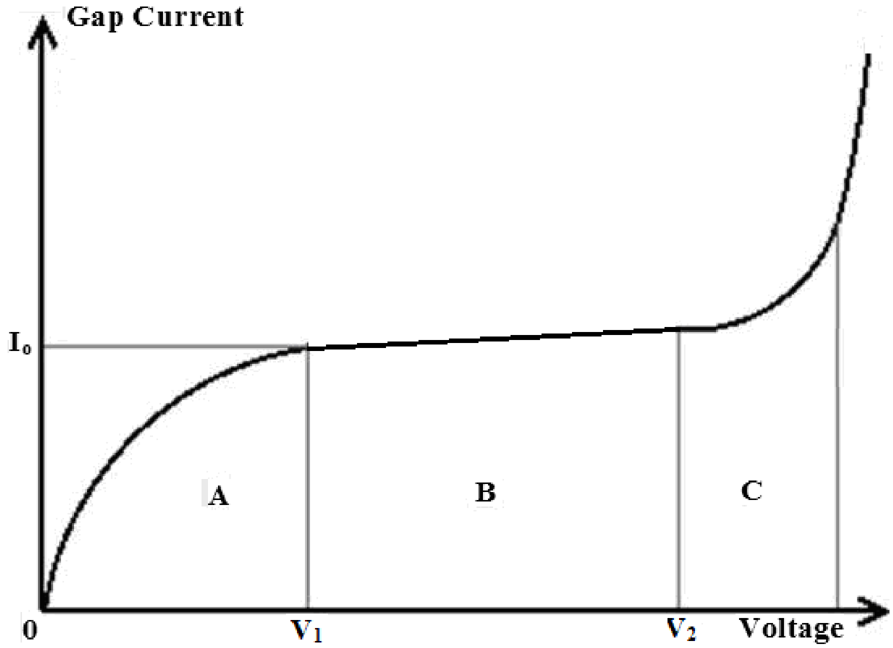


Figure 2: Gap Current Characteristics

3.1. Photo Ionization Region

According to Townsend, the region-A as indicated in Fig (2) is the photo-ionization region. The energy of the field from the applied voltage is not sufficient to produce ionization due to collision on a sizeable scale. The current is due to already present free electrons (although small in number) and these electrons are thought to be produced by one or combination of the following sources:

Cosmic radiations: These consist of high energy Gamma rays and X-rays with wavelengths in the range of about 0.001nm and 10nm. These are radioactive in nature and originate from outer space. When incident on the gas, and under favorable conditions, electrons are liberated and become available for conduction.

Ultraviolet (UV) rays: In the natural form these rays are present in sunlight with wavelength lying between 10 to 100nm. Thus the sunlight consists of swarm of photons with energies that can be estimated to be lying between 10 to 100eV, sufficient to ionize atom of the gas through photo ionization. Thus UV radiations are present in our environment and may have sufficient energy to produce electrons from neutral atoms.

Referring to Fig (2), when the applied voltage is low (below V_1), the electric field in the gap between the electrodes is less. Under low electric field, the energy of the moving free-electron in the gap may not be sufficient to produce electrons by collision-ionization but can result in excitation of gas atoms on collision. These excited atoms emit photons when reverting back to their stable states. A sizable photon activity in the gap may liberate electrons from the atoms, through the process of photo-ionization. The conduction current, however small, is thus due to the presence of electrons mostly produced by photo-ionization. The current increases non-linearly with the applied voltage to I_o. The electrons responsible for this current are also termed as initiatory or primary electrons, which plays a role in liberating further electrons from the gas atoms during the process. Thus in region-A of Fig (2) the electric field due to the applied voltage may not be sufficient to cause ionization by collision. Instead, the atoms of the gas are excited to unstable state, which emit photons on de-excitation to stable state. The photons are absorbed by nearby atoms causes ionization by virtue of absorbed photon energy. The liberation of electrons during photo ionization increases gradually with the applied voltage. This triggers the process of conduction, which ultimately leads to conditions that are favorable for collision-ionization.

3.2. Equilibrium or Space Charge Region

Once the conduction current increases to I_o, further increase in current is very small, represented by region-B in Fig (2). In this region the electric field is sufficient to create ionization activity due to electrons colliding with the atoms. When the voltage is increased beyond V_1 the electrons gain sufficient energy from the field to "knock-off" electrons from the atoms, leaving behind less mobile but positively charged ions. The electron-pair (one incident and one the electron that is being "knocked-off") as a result of collision-ionization, will gain energy from the field to encounter collision course with other atoms of the gas, thus liberating further electrons. It must be noted that the process of collision-ionization produces highly mobile electrons and less mobile positive ions. The electrons are accelerated by the field towards the anode whereas; the positive ions (less mobile) contribute to the formation of positive space charge and their density increases following collision-ionization. Apparently it would be thought that the gap current should increase significantly. However, the gap current exhibits a very small increase with increasing voltage and seems to almost saturate. This small increase in the current in region-B is due to the near-equilibrium being created by the production of free electrons due to collision-ionization and the capturing of free electrons by the positive ions in the path to form neutral atoms. The gap current is due to the flux of electron reaching the anode. The equilibrium persists so long as the positive ions are sufficient in number to capture electrons. Furthermore, the positive ions, being charged particles will drift slowly towards the cathode. The gap current therefore, shows a very small increase or is virtually constant despite the voltage across the electrodes being increased from V_1 to V_2.

3.3. Avalanche Region

When most of the positive ions have been reverted back to neutral atoms in region-B and with voltage increased beyond V_2, the field is sufficient to impart high energies to the already present electrons. These electrons gain sufficient energies and when collides with the gas atoms, will knock further electrons. The liberated electrons also gain energy from the field, thereby producing further ionization by collision giving rise to more electrons reaching the anode and as a consequence the gap current increases sharply in region-C as shown in Fig (2). Thus when the voltage is increased further from

V_2 the current increases at a much greater rate than the rate at which the voltage is increased. This sharp increase in the gap current is attributed to the electron multiplication caused by enormous collision-ionization activity, forming avalanche that results in steep rise in gap current leading to breakdown. This process is illustrated in Fig (3). The increase in voltage beyond V_2 will result in high electric field between the electrodes. Very high electric fields (>10^8 V/m) can free electrons from atoms, and accelerate them to significantly high energies that they can, in turn, free other electrons in collision-ionization process. In the process, electron accelerates in the electric field, gaining sufficient energy such that it frees another electron upon collision with atom and molecule of the medium.

The two free electrons as a result of single collision-ionization travel some distance (mean-free path) before another collision occur. The number of electrons traveling towards the anode is multiplied by a factor of two for each collision, so that after n effective collisions, there are 2^n free electrons. The process will therefore result in electron multiplication on a massive scale forming electron avalanche. An avalanche is a cascaded "reaction" involving electrons with a sufficiently high electric field. The positive ion drifts towards the cathode, while the free electrons move with very high velocities towards the anode. The electron avalanche produces a large current accompanied by a conductive "plasma" formation. The "plasma" forms a luminous path referred to as an arc, resulting in the increased conductivity of gas between the electrodes with temperature somewhat between 1000 to 2500ºK. The result is dielectric breakdown and the field necessary to cause this is called the breakdown field, more commonly called dielectric strength or breakdown strength, and the voltage necessary to cause breakdown is referred to as breakdown voltage or spark-over voltage. The arc is in the form of luminous channel that follows the least distance path between the two electrodes. The arc, accompanied with very high temperatures and the high thermal energies are sufficient to melt metals.

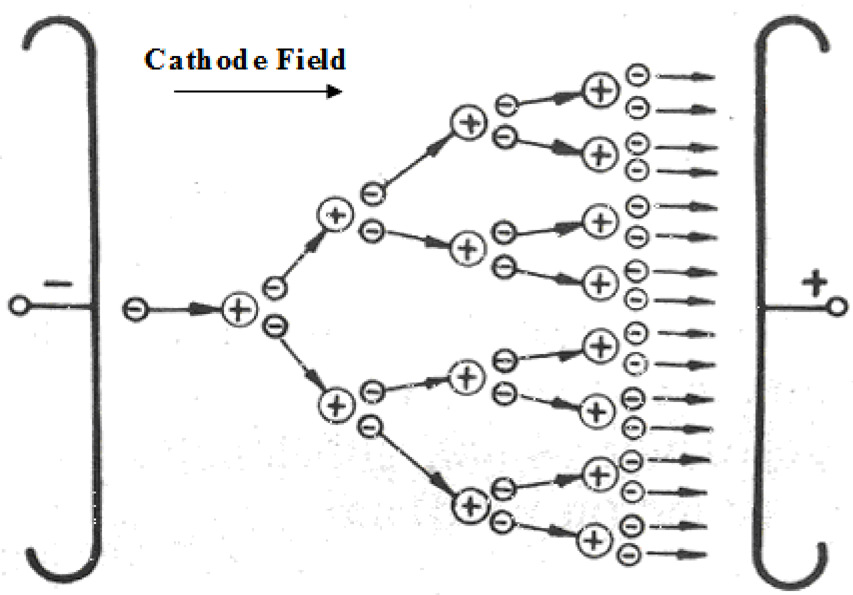


Figure 3: Process of Electron Multiplication and Avalanche Formation

Once breakdown occurs, the gap current is independent of voltage. The breakdown path is conducting and places a short circuit across the electrodes. An arc can be initiated without a preliminary Townsend discharge; for example when electrodes touch and are then separated as in the case of contacts of a circuit breaker.

4. Mathematical Model of Gap Current

Townsend theory can be mathematically modeled for the growth of gap current resulting form electron avalanche starting from the initial photo-ionization current I_o by considering Fig (4).

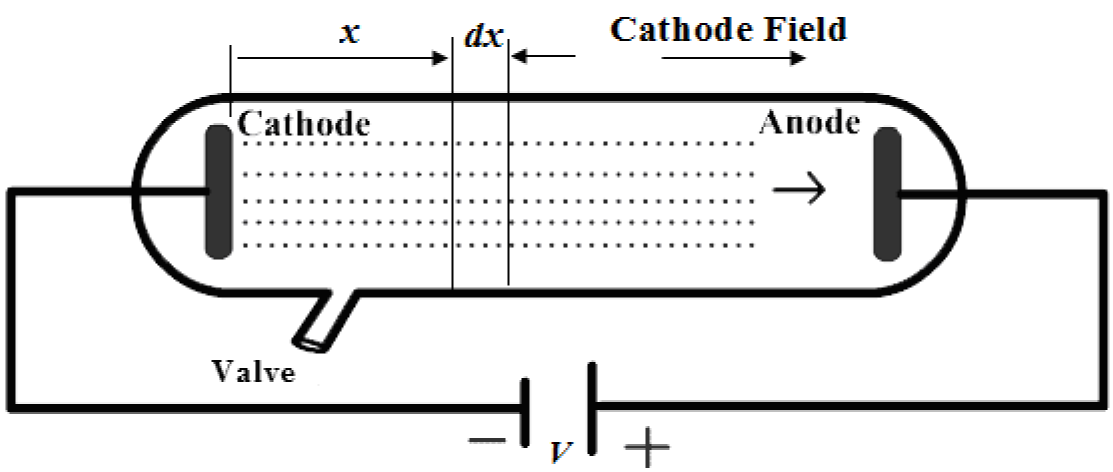


Figure 4

Consider the gap between two electrodes implanted in a Townsend discharge tube as shown in Fig (4). The distance between the two electrodes is *d* and the voltage applied is *V*, resulting in an electric field. Consider a distance *x* from the cathode and an infinitesimal length *dx* towards the anode. Let us suppose that there are n_o numbers of initiatory electrons present in the gap by one or more of the processes already discussed. These electrons gain energy from the field and are accelerated towards the anode in the direction of cathode field. In the incremental length *dx* the electrons suffer collision with the atoms in their path, resulting in ionization process that produces free electrons and positive ions. The number of electrons produced in the length *dx* will be *dn*. According to Townsend theory:

$$dn \propto n dx$$

Or

$$dn = \alpha \, n dx \qquad 1$$

Where α is the Townsend's first ionization coefficient, defined as the number of electrons produced by collision-ionization per incident electron. The Townsend coefficient α, also known as first Townsend coefficient or primary ionization coefficient is a term used where ionization occurs because the primary ionizing electrons gain sufficient energy from the electric field to initiate the process leading towards breakdown. The coefficient gives the number of electrons produced by primary electron per unit path length. From Eq (1):

$$\frac{dn}{n} = \alpha\, dx$$

Integrating both sides:

$$\int_{n_o}^{n} \frac{dn}{n} = \alpha \int_{0}^{d} dx$$

This yield: $\ln\left(\frac{n}{n_o}\right) = \alpha d$

Or $n = n_0 \exp(\alpha d)$ 2

Since the conduction current is due to electrons, therefore Eq (2) can be expressed in the form of:

$$I = I_0 \exp(\alpha d) \qquad 3$$

Example 1: Calculate the arc current in a gas having first ionization coefficient of 400 m^{-1} enclosed in a protector gas discharge tube with electrode separation of 5cm. The conduction current in the gas under normal working conditions is 0.01 mA.

Solution:

Given that:

I_o = 0.01 mA
α = 400 m^{-1}
d = 5 cm = 0.05 m

Using Eq (3):

$I = 0.01x10^{-3}$ exp(400 x 0.05) **= 4.85 kA**

Example 2: Calculate the ionization coefficient of a gas enclosed in a gas discharge tube with electrode separation of 10 cm. The conduction current in the gas under normal working conditions is 0.01 mA and the maximum breakdown current is 10 kA.

Solution:

Given that:

d = 10 cm = 0.1 m
I_o = 0.01 mA
I = 10 kA

By rearranging Eq (3), to determine α that is:

$$\alpha = \frac{1}{d}\ln\left(\frac{I}{I_0}\right)$$

Substituting the required values, we obtain:

$$\alpha = \frac{1}{0.1}\ln\left(\frac{10000}{0.01\times10^{-3}}\right) = \mathbf{207.23\ m^{-1}}$$