INSULATION BREAKDOWN

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Insulation System

- The reliability of a High Voltage System depends on the efficacy of the Insulation System.
- Statistics reveal that majority of the power apparatus failures are due to insulation failure.
- The Insulation should withstand the stresses (electrical, mechanical, thermal, environmental) during normal operation and also during a transient condition.

Classification

- Solid : Most widely used are : XLPE, PVC, ceramics, glass, rubber, resins, reinforced plastics, polypropylene, impregnated paper, wood, cotton, mica, pressboards, Bakelite, Perspex, Ebonite, Teflon, etc.
- Liquid: Organic liquids, the mineral insulating oils and impregnating compounds, natural and synthetic, of required physical, chemical and electrical properties are used very widely in transformers, capacitors, cables and circuit breakers.
- Gaseous: Atmospheric air is the cheapest and most widely used dielectric . Other gaseous dielectrics, used as compressed gas at higher pressures than atmospheric pressure in power system, are Nitrogen , Sulphurhexafluoride SF_6(an electro-negative gas) and it's mixtures with CO_2 and N_2 . SF_6 is very widely applied for Gas Insulated Systems (GIS), Circuit Breakers and gas filled installations i.e. sub-stations and cables. It is being now applied for power transformers also.

Classification…

- **Vacuum:** Vacuum of the order of 10^{-5} Torr and lower provides an excellent electrical insulation. Vacuum technology developed and applied for circuit breakers in the last three decades is phenomenon **.**
- **Composite (Solid/Liquid, Solid/Gas) :** A combination of Solid/Liquid ,like Oil /Paper-Pressboard system of a Power Transformer or gas/solid composite insulation system which typically included in gas insulated switchgears (GIS) and a gas insulated transmission line (GIL).

Insulation Breakdown

- Regardless of type all Electrical breakdown is in the gaseous phase
- Breakdown
  - Complete: Continuous conducting path either through the volume or the surface of the insulation causing the insulating gap to be bridged
  - Partial : Local conducting paths due to the presence of voids, conducting particles or absorbed moisture. Partial Discharges, Treeing & Tracking are examples. Lower the ability of the insulation to withstand stresses and can cause complete breakdown eventually.

Gaseous Insulation

- Apart from possessing superior electrical insulating properties other properties, like being easily available at a cheap cost, environmentally harmless and non-flammable are also equally important. The insulation is effective up to the breakdown threshold.
- The maximum voltage applied to the insulation at the moment of breakdown is called the breakdown voltage

Breakdown of Gases

- The electrical discharges in gases are of two types:-

  (i) Non-sustaining discharge.

  (ii) self- sustaining.

  Spark is the transition of non-sustaining discharge into a self-sustaining discharge
- Build-up of high currents in breakdown is due to the process known as ionization in which electrons and ions are created from neutral atoms or molecules' and their migration to the anode and cathode respectively leads to high current.

Theories of Gas Breakdown

- The breakdown voltage depends
  - the field is uniform or non uniform.
  - The Gap distance
  - Temperature
  - Pressure
- At present there are two theories to explain the breakdown

  (i) Townsend theory

  (ii) Streamer theory

Types of Collision

- Electrical discharge is normally created from unionized gas by collision processes between the charged particles and gas atoms or molecules
- Elastic collisions: occur when no change takes place in the internal energy of the particles but only their kinetic energy gets redistributed. These collisions do not occur in practice. When electrons collide with gas molecules, a single electron traces' a zig-zag path during its travel. But in between the collisions it is accelerated by the electric field. Since electrons are very light in weight, they transfer only a part of their kinetic energy to the much heavier ions or gas molecules with which they collide. These result in very little loss of energy by the electrons and therefore electrons gain very high energies and travel at a much higher speed than the ions. Therefore, in all electrical discharges electrons play a leading role.

Collisions….

- Inelastic collisions: are those in which internal changes in energy take place within an atom or a molecule at the expense of the total kinetic energy of the colliding particle. The collision often results in a change in the structure of the atom. Thus all collisions that occur in practice are inelastic collisions. For example ionization, attachment, excitation, recombi-nation are inelastic collisions.

Mobility of Ions

- When an ion moves through a gas under the influence of a static uniform electric field, it gains energy from the field between collisions and loses energy during collisions. Electric force on an electron/ion of charge ***e** is **eE**,* with the resulting acceleration being ***eE/m**.* When the energy gained by the ions from the electric field is small compared with the thermal energy, the drift velocity in the field direction W_i is proportional to the electrical field intensity E and may be expressed as follows:
    - $W_i = \mu_i * E$ (1)
- Where μ_i is called the mobility of ions the mobility is mainly a characteristic of the gas through which the ion moves. At normal temperatures and pressures the mobility μ is of the order of several cm^2/volt-sec.

Mobility of Electrons

- The concept of ionic mobility cannot be directly applied to electrons because of their extremely low mass. Any externally applied electric field will cause the electrons to gain energies much higher than their mean thermal energy. So the electron drift velocity, which has been defined as the average velocity, with which the centre of mass of the electron swarm moves in the direction of the field, is not a simple function of ***E/p***, but is determined from the energy distribution function. From the kinetic theory the electron drift velocity W_e is given in microscopic terms as follows:

- $W_e = E_e / 3ma^2\, d/dc\, (\lambda c^2)$ (2)

  Where λ is an equivalent mean free path of an electron with speed c

Diffusion Coefficient

- When particles possessing energy, which is exhibited as a random motion, are distributed unevenly throughout a space, then they tend to redistribute themselves uniformly throughout the space. This process is known as diffusion and the, rate at which this occurrence is governed by the diffusion passing through unit area in unit time perpendicular to the concentration gradient and for unit concentration gradient. In three dimensions this may be written as

$$\frac{\delta n}{\delta t} = -D\nabla^2 n$$

Where ***n*** *is* the concentration of particles. Kinetic theory gives ***D*** in microscopic terms as follows

$$D = 1/3\ (\boldsymbol{\lambda}\ \boldsymbol{c})$$

Where ***λ*** is the mean free path and ***c*** the random velocity, the average being taken over ***c***

Diffusion Coefficient…

- In electrical discharges, whenever there is a non-uniform concentration of charges there will be migration of these charges from regions of higher concentration to regions of lower concentration. This process is called diffusion and this causes a de-ionising effect in the regions of lower concentration. The presence of walls confining a given volume increases the de-ionization effect since charged particles lose their charge on hitting the wall. Both diffusion and mobility result in mass motion described by a drift velocity caused either by unbalanced collision forces (concentration gradient) or by the electric field itself.

Electron Energy Distributions

- For the development of a complete theory giving the relationship between the data concerning single collisions of electrons with gas molecules, and the experimentally obtained average properties of discharges, a knowledge of the electron energy distribution functions is essential.
- The most widely used distribution functions are the Maxwellian and Druyesteynian distributions which apply specifically to elastic conditions.The Maxwellian distribution has been found to apply where there is thermal equilibrium between the electrons and molecules.
- The distribution takes the form

Electron Energy Distributions…

$$F(\varepsilon) = C_1 \varepsilon^{0.5} \,.\, e^{\left(-1.5 \frac{\varepsilon}{\varepsilon^{-}}\right)}$$

Where $\boldsymbol{C_l}$ is the constant and is the mean energy. Druyesteynian distribution applies when the electron or ion energy is much greater than the thermal energy and is therefore expected to be more of application in transcends discharges. This distribution takes the form

$$F(\varepsilon) = C_2 \varepsilon^{0.5} \,.\, e^{\left(-1.5 \frac{\varepsilon^2}{\varepsilon^{-2}}\right)}$$

Where $\boldsymbol{C_2}$ is another constant

Collision Cross Section

- Collision cross section is defined as the area of contact between two particles during a collision. In other words, the total area of impact of this area of contact is different for each type of collision. For example, the area of impact is more for ionisation while for an excitation it is less. For simultaneously, occurring processes such as ionization, excitation, charge transfer, chemical reactions, etc., the effective cross section is obtained by simple a addition of all the cross sections. If ***q**,* is the total cross section, and if q_i, q_e, q_c ... etc., are the cross sections for ionization, excitation, charge transfer, etc, respectively, then

$$q_t = q_i + q_e + q_c + \ldots\ldots.$$

- Thus the use of collision cross sections instead of mean free paths has often proved to be advantageous. The collision cross section is also expressed in terms of the probability of a collision to take place, i.e.,

$$P = nq \qquad (7)$$

which is the reciprocal of the mean free path.

The Mean Free Path

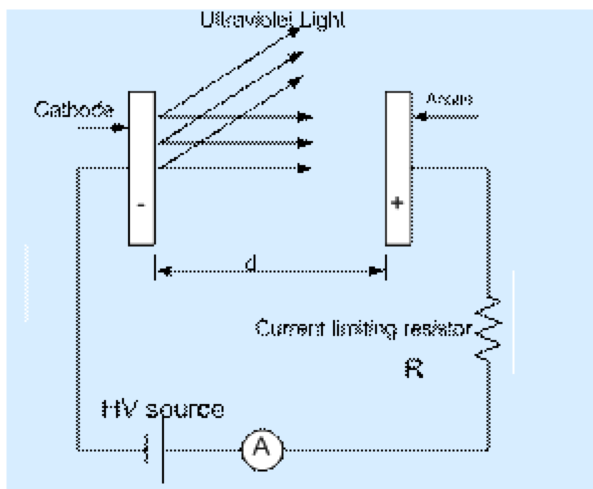
- The mean free path is defined as the average distance between collisions. When a discharge occurs large number of collisions occurs between the electrons and the gas molecules. Depending on the initial energy of the colliding electron, the distance between the two collisions vary The average of this is the mean free path. The free path is a random quantity and its mean value depends upon the concentration of particles or the density of the gas.
- The mean free path can be expressed as
- $\lambda = k / p$ **(8)**
- Where ***k*** is a constant and p is the gas pressure in microns.
- The value of k for nitrogen is 5. From this equation it is seen that at a pressure of 1 torr, **λ** is 5×10^{-3} cm. If the pressure is 10^{-6} ton, then **λ** = $5 \times 10^{+3}$ cm. From this it is seen that mean free path is very large at very low pressures and is very small at high pressures.

Ionization by Collision

- The process of liberating an electron from a gas molecule with the simultaneous production of a positive ion is called ionization.
- a free electron collides with a neutral gas molecule and gives rise to a new electron and a positive ion.

Ionization by Collision …

- If we consider a low pressure gas column in which an electric field ***E*** is applied across two plane parallel electrodes, as shown in Fig. 1 then, any electron starting at the cathode will be accelerated more and more between collisions with other gas molecules during its travel towards the anode.



Ionization by Collision…

- If he energy **(ε)** gained during this travel between collisions exceeds the ionization potential, V_i, which is the energy required to dislodge an electron from its atomic shell, then ionization takes place. This process can be represented as

$$e^- + A \rightarrow e^- + A^+ + e^-$$

Where, A is the atom, A^+ is the positive ion and e- is the electron.

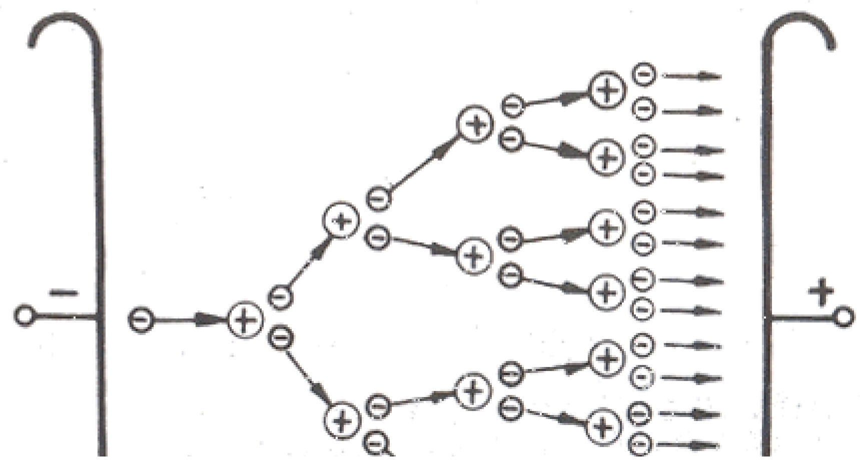
Townsend's Theory

- Initially the electrons are originated in a gaseous dielectric gap space between two electrodes either by ionization of neutral molecules by photons from cosmic rays, or by ultraviolet illumination of cathode, or at a later stage by photons from the discharge itself when electric field is applied.
- The electrons thus generated accelerate towards the anode, gaining kinetic energy of movement from the applied electric field between the electrodes.
- The kinetic energy thus acquired by the electrons can be so high that on collision with neutral molecules it may ionize them (elastic collision) or render them to a higher excited or vibrational state (inelastic collision).

Townsend’s Theory….

- When an electron gains more energy than required for ionization of the gas molecules ,then it is capable of ionizing, that is, ejecting an electron from the neutral molecule, and leaving behind a positive ion.
- The new electron thus ejected along with the primary one repeat the process of ionization.
- Since a molecule is much heavier compared to an electron, it can be considered relatively stationary, making no contribution to the ionization process.
- On the contrary, the electrons move very fast under the influence of applied electric field and continue to release further electrons from the gas molecules.
- An 'avalanche' of electrons finally reaches the anode as shown in Fig. 2

Electron Avalanche



At the field intensities at which impact ionization occurs, the value of drift velocity of electrons in air is usually ~10^7 cm/s, while of positive ions it is about 150 times lower ~10^5 cm/s. Accordingly, the transit time required by electrons and ions to cross a gap differ about 150 times.

Townsend’s Theory …

- The process of avalanche form of charge carrier multiplication was first described by Townsend(1901). Later he also gave its mathematical formulation.
- If only the process of electron multiplication by electron collision is considered in uniform field between two plates, then neglecting other processes (recombination and diffusion), the number of electrons produced by collision at an element dx, at distance x from the cathode is,

$$dn_x = n_x \alpha \, dx$$

where *x* is the distance form the cathode, α the Townsend's primary ionization coefficient, and n_x the number of electrons at distance *x* from the cathode.

Townsend’s Theory …

- In a uniform field where the field intensity *E* is constant, the ionization coefficient α can be considered constant. By integrating Equation and applying the initial condition $n_x = n_0$ at x = 0, the following equation is derived for a uniform field,

$$n_x = n_0 e^{\alpha x}$$

- For weakly non-uniform fields, where α is not constant, the above equation is re-written as,

$$n_x = n_0 \exp\left[\int_0^x \alpha \, dx\right]$$

where n_0 is the number of electrons emitted per second from the cathode, also known as the initial number of electrons.

Townsend's Theory …

- Therefore, in case of very small gap distances, the number of electrons striking the anode per second (at x = d) are,
- This means that on an average $n_d = n_0 e^{\alpha d}$:ron leaving the cathode produces ($e^{\alpha d}$ - 1) new electrons and the same number of positive ions in traversing the distance d.
- The expressions show distinctly the exponential or avalanche form of growth of the number of charge carriers by primary or α process.
- The Townsend's first ionization coefficient α is a function of the electric field intensity E, and at constant temperature it is dependent upon the gas pressure p. It can be proved that,

Townsend's Theory …

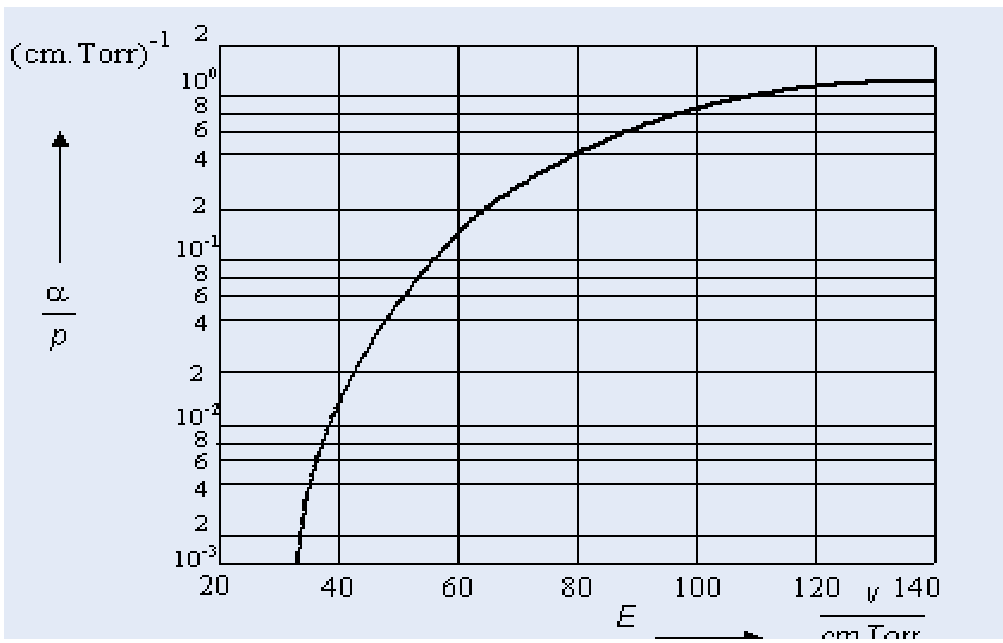
$$\frac{\alpha}{p} = f\left(\frac{E}{p}\right)$$

- The coefficient α can be calculated with the help of molecular parameters. However, α is usually obtained experimentally by measuring the multiplication of electrons in high electric fields. For air, the following equation is approximated

$$\frac{\alpha}{p} \approx 1.11 \times 10^{-4} \left(\frac{E}{p} - 25.1\right)^2$$

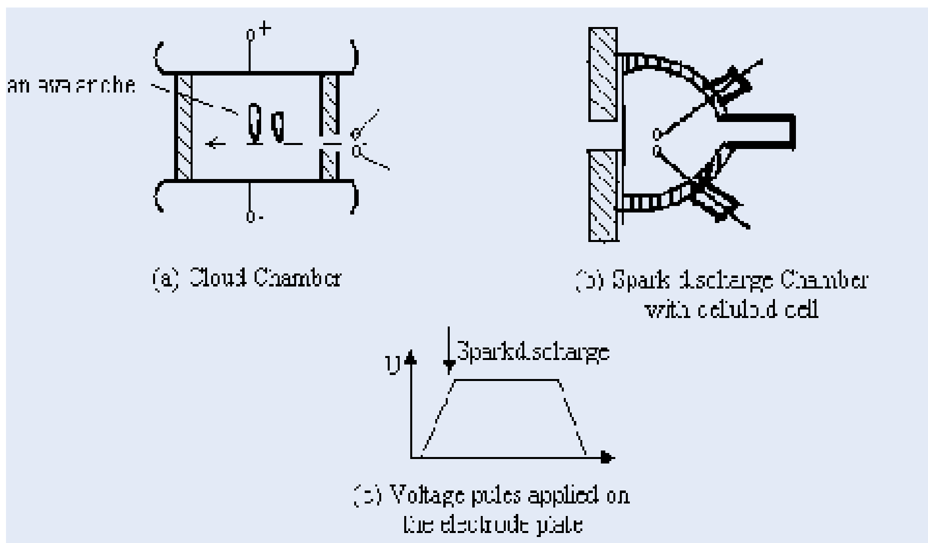
Townsend's Theory …

where E is in V/cm, p in Torr and α in $cm^{-1.}$ Plotted for α/p and E/p at constant temperature is shown below..



Townsend's Theory …

- Raether used the 'Wilson Cloud Chamber', which caused condensation of water vapour droplets on the charge carriers of an avalanche at appropriate gas pressure



Townsend’s Theory …

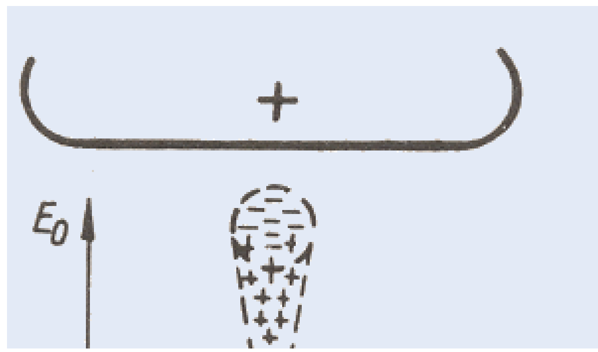
- In his experiment, a short duration voltage pulse was applied on the electrode system .
- When the voltage applied reached its desired peak value, just sufficient to develop an avalanche, it was maintained at this magnitude, but was not allowed to lead to a breakdown.
- Just at this stage, primary electrons were produced in the electrode system with the help of an external spark discharge source .
- This gave rise to the development of an electron avalanche.
- In order to avoid a breakdown, the process was controlled by a steep reduction in the applied voltage to zero after the duration of a few tens of nanoseconds.

Townsend’s Theory …

- Since the drift velocity of electrons is about 150 times more than that of the ions, hence as soon as an avalanche is formed, the positive ions remain practically stationary where they are produced, i.e, at the tail of the avalanche.
- The head of the avalanche is consequently built-up by electrons.
- The form of the track is wedge shaped, apparently due to the thermal diffusion of the drifting electron swarm having acceleration in the direction of electric field.
- The head of the avalanche is rounded since the diffusion of electrons takes place in all directions.

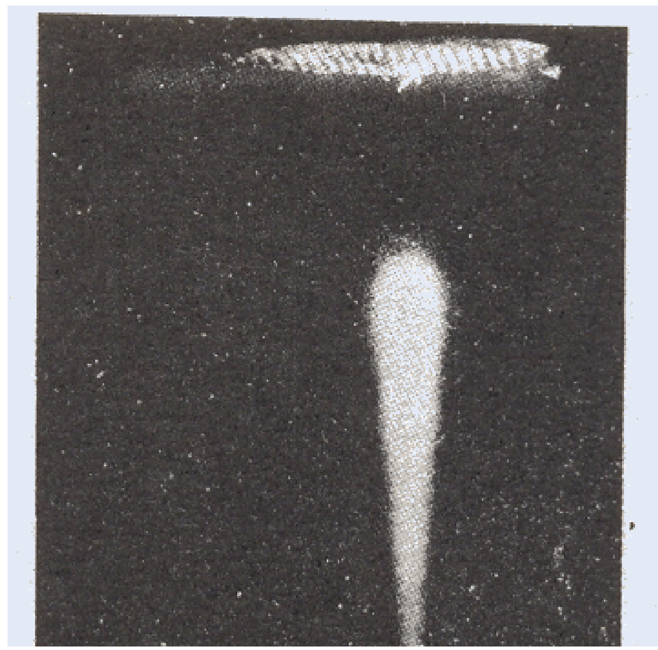
Townsend’s Theory …

- Distribution of charge carriers



Townsend's Theory …

- Actual photographs of avalanche



Townsend’s Theory …

- The experiments conducted by Wagner in 1966 were on slightly longer gap distances in uniform field. He also photographed the electron avalanche in a cloud chamber.
- It was revealed that when the light was first detected in the chamber, the number of charge carriers in the avalanche, that is the space charge was insufficient to cause any distortion in the applied electric field E_0.
- The center of the electron cloud moved at the electron drift velocity corresponding to the field E_0.
- This light first detected is known as 'primary avalanche'
- Through these experiments it was concluded that only after further development, when the total number of electrons reach ~10^7 to $l0^8$, the space charges of ions and electrons in the avalanche become strong enough to distort the applied field E_0.

Breakdown by Avalanche Discharge (Townsend Mechanism)

- When the distance *d* between two electrodes in a uniform field is very small, α the Townsend's first ionization coefficient which is a function of field intensity *E,* may still have quite a low value even at the breakdown field intensity.
- Under these conditions, the avalanche space charge concentration is not able to acquire its critical amplification (the total number of electrons ≈ 10^8).
- Production of sufficient number of charge carriers in the gap under such conditions is possible only by secondary ionization process, also known as - process.
- These secondary processes are ionization of the gas 'by positIve ions and photons from the excited molecules, and ejection of electrons from the cathode by following effects:

Townsend's Theory …

- Positive ion effect ' $_{ion}$': While the positive ions, produced in the primary avalanche, cannot gain enough kinetic energy in the electric field to ionize molecules, they may have sufficient potential energy to cause ejection of electrons upon striking the cathode.
- Photon effect ' $_{p}$': Excited molecules in the avalanche may emit photons on returning to their ground state. This radiation falling on cathode may produce photo-emission of electrons.
- Metastable effect ' $_{m}$': Metastable molecules may diffuse back to the cathode and cause electron emission on striking it.

Townsend's Theory …

- The three processes of cathode effect are described quantitatively by a coefficient γ as follows,

$$\gamma = \gamma_{ion} + \gamma_p + \gamma_m$$

- γ ' is known as Townsend's secondary ionization coefficient. It is defined as the number of secondary electrons on an average produced at the cathode per electron generated by the primary process, that is, per ionizing collision in the gap. ' γ ' strongly depends upon the cathode material and is a function of field intensity and pressure of the gas."
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$$\gamma = f\left(\frac{E}{p}\right)$$

Townsend's Theory

- Like α, γ also represents a probability process. If the mean number of secondary electrons per avalanche produced are μ, then

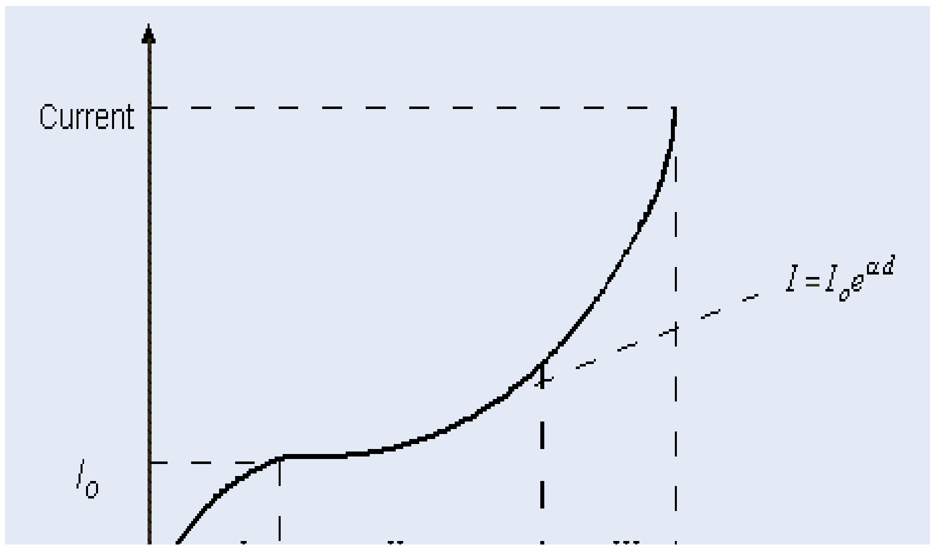
$$\mu = \gamma(e^{\alpha d} - 1)$$

If the primary electron generation process begins with *n0* number of electrons, the second generation begins with μ*n0*number of electrons.

- Average current growth with respect to the applied voltage and time shown in next few slides

Townsend’s Theory

- current growth with respect to the applied voltage



Townsend's Theory…

- In order to measure the U-I characteristic, Townsend's original experimental arrangement had uniform field electrodes enclosed in a glass vessel. This vessel was provided with a quartz window for irradiating the cathode with ultra violet light to emit photo electrons.
- As the voltage applied is raised, the initial current through the gap increases slowly to a value I_o
- The magnitude of this current depends upon the ultra violet illumination level of the cathode, region I, shown in Fig. 8.1.
- The electrons emitted from the cathode move through the gas with an average velocity determined by their mobility at the field intensity in the gap.
- The initial increase in current is followed by an approach to saturation because some of the electrons emitted from the cathode return to it by diffusion.

Townsend's Theory…

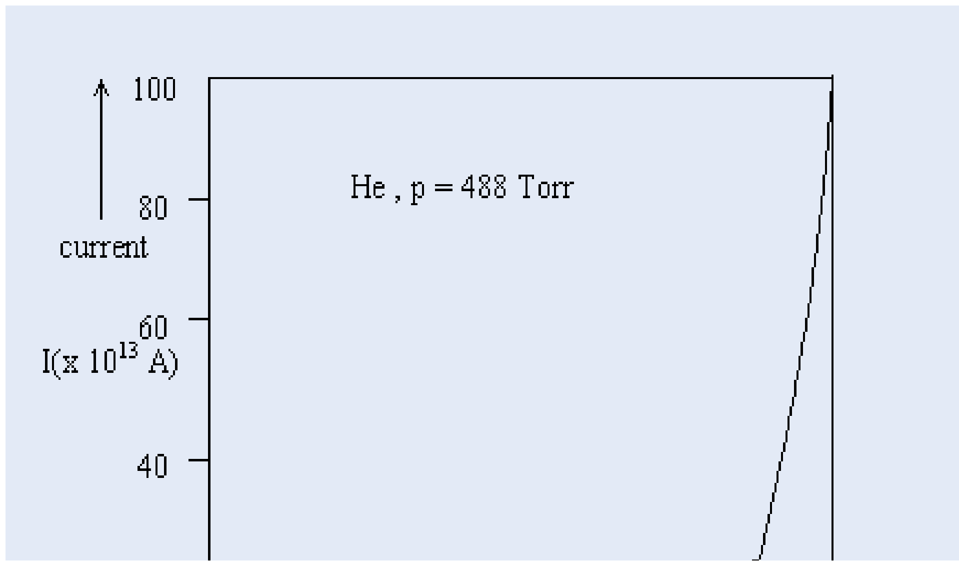
- The proportion of electrons which diffuse back decreases as the voltage is increased, but not all the electrons emitted reach the anode, even at the voltages at which ionization in the gas begins to occur.
- Thus, in general, there is no well defined plateau in the U-I characteristic, and the current eventually increases rapidly through the regions II and III with increasing voltage until a breakdown occurs at some well defined voltage $U = U_b$.
- Whatever may be the level of initial illumination of cathode, the voltage $U_b$at which the breakdown occurs remains unaltered.

Townsend's Theory…

- The increase in current in region II is derived from the process of field intensified ionization by primary or α - process. The secondary or γ - process accounts for the sharper increase in current in region III and for an eventual spark breakdown of the gap. Next Figure shows the U-I characteristic in helium at a pressure of 488 Torr, measured by Rees . It is evident from the Figures that the characteristics measured by Townsend and Rees are very similar.

Townsend's Theory…

- V-I characteristic in helium as measured by Rees



Townsend's Theory

- It is a distinguishing feature of breakdown that the voltage across the gap drops in the process which produces a high conductivity between the electrodes. This takes place in a very short time (in μsecs). If α is the primary ionization coefficient for the applied uniform field E_0 ,the amplification of ionizing collisions of the electrons is given by $e^{\alpha x}$. In the event of positive ion space charge distorting the field, the amplification of α which increases with distance and time is given as,

$$\exp\left[\int_0^d \alpha(x,t)\,dx\right]$$

Townsend’s Theory

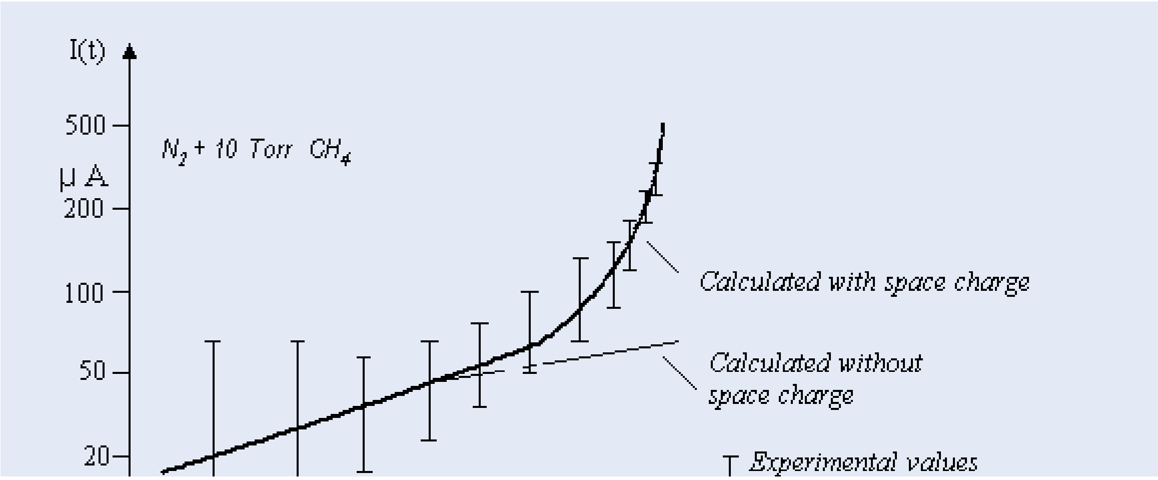
- For this case, μ(t) can be written as,
- $$\mu(t) = \gamma \left\{ \exp\left[\int_0^d \alpha(x,t)\,dx \right] - 1 \right\}$$
- which grows continuously, till breakdown occurs.
- Experiments have been performed to study the current growth in uniform fields in air and other gases initiated by a single electron *(n_0* =1) with the help of a light flash. The process with higher number of electrons *(n_0* » 1) is achieved by illuminating the cathode with constant intense light
- Hoger developed one such method of measurement in nitrogen.

Townsend's Theory…

- With the help of theoretical considerations confirmed with experimental results, he computed the current growth started by a single and more number of electrons shown in next figure. The measured values are indicated by the vertical lines. At lower values of current, the statistical distribution scatters more compared to the distribution at higher current values.

Townsend's Theory…

- Current growth initiated by a single electron



Townsend's Current Growth Equation

- Assuming n_0 electrons are emitted from the cathode and when one electron collides with a neutral particle, a positive atom and electron formed. This is called an ionization collision. Let α be the average number of ionizing collisions made by an electron per centimeter travel in the direction of the field where it depends on gas pressure *p* and *E/p*, and is called the Townsend's first ionization coefficient. At any distance *x* from the cathode when the number of electrons, n_x , travel a distance of *dx* they give rise to $\alpha n_x dx$ electrons. Then, the number of electrons reaching the anode at *x=d*, n_d will be $n_0 = n_x$ at x = d
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- $$\frac{dn_x}{dx} = \alpha n_x$$ or $$n_x = n_0 e^{\alpha x}$$ At x= d $$n_d = n_0 e^{\alpha x}$$

Townsend's Current Growth Equation...

- The number of new electrons created, on the average, by each electron is

- Therefore the average current in the gap, which is equal to the number of electrons traveling per second will be