CONDUCTION & BREAKDOWN IN GASES

Conduction and Breakdown in Gases

Electrically materials are Classified as:-

1) Conductors:-

- → Carry current easily
- → have Large no. of free elutrons.

2) Insulators:-

- → donot carry Current / show very Low conductivity
- → Electrons are tightly bound to their atoms.

This definition:-

- Applies under ordinary Conditions and at low field.

As the electric field is increased the insulator changes from a purely insulating state to a purely conducting state. This is known as electric breakdown of the insulator.

study of conduction and breakdown phenemenon in insulators is important to design a reliable and economic insulation system.

Electric field:- An electric field is said to exist in a region of space if an electric charge placed anywhere in the region experiences a force.

Electric field Intensity:- Electric field Intensity at a point is the force on a unit positive charge placed at that point. It is a vector (magnitude as well as direction). Its unit is N/C.

Voltage:- workdone in moving a unit positive (test) charge from one point (A) to another point. (B)

$$V = -\int \vec{E} \cdot dx$$

unit is V or J/c

$|\vec{E}| = \frac{dv}{dx}$; voltage gradient, V/m

or kV/cm

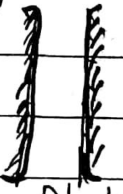
$= 10^5$ V/m.

Uniform field:- An electric field is said to be uniform if the force experienced by a given charge is same (in magnitude & direction) at all points in the region.

Non-uniform field:- An electric field is said to be non-uniform if the force experienced by a given charge is not same at each point in the region.

The field produced, whether uniform or non-uniform, depends upon Electrode Configuration.

Uniform field gap

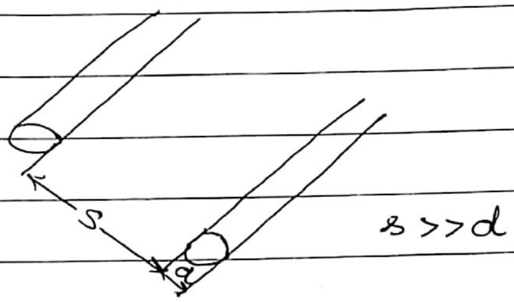


Parallel Plate Electrode arrangement uniform

sphere - sphere
S ≤ 0.5d

Examples of non-uniform field gap

transmission Line



Ionization and Excitation

Ionization in Gases:-
under low fields Conductivity of air ↑ is 10^{-17} to 10^{-16} A/cm²
Collisions occur continuously & are of two types:-

1. Elastic Collisions:- only translational kinetic energy is exchanged.
2. Inelastic Collisions:- Translational kinetic energy as well as internal energy is exchanged. Since it involves exchange of internal energy so it may lead to excitation or ionization.

* ΔW is the energy gained by an electron over the mean free path.
* W_i = Ionization energy

→ If $\Delta W > W_i$ & electron hits a gas molecule it can cause ionization.

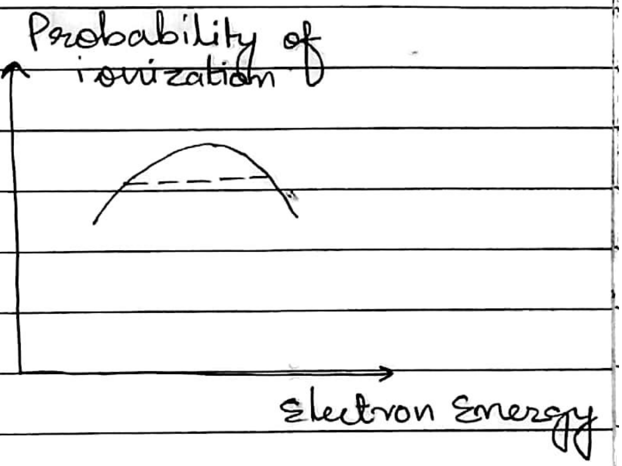
→ If $\Delta W < W_i$, it may cause excitation of gas particles (If this excited particle collides with other excited particle ⊛ then ionization occurs and this ionization is known as

⊛ or electron.

stepped ionization (because ionization occurs indirectly. first excitation occurs & then ionization)

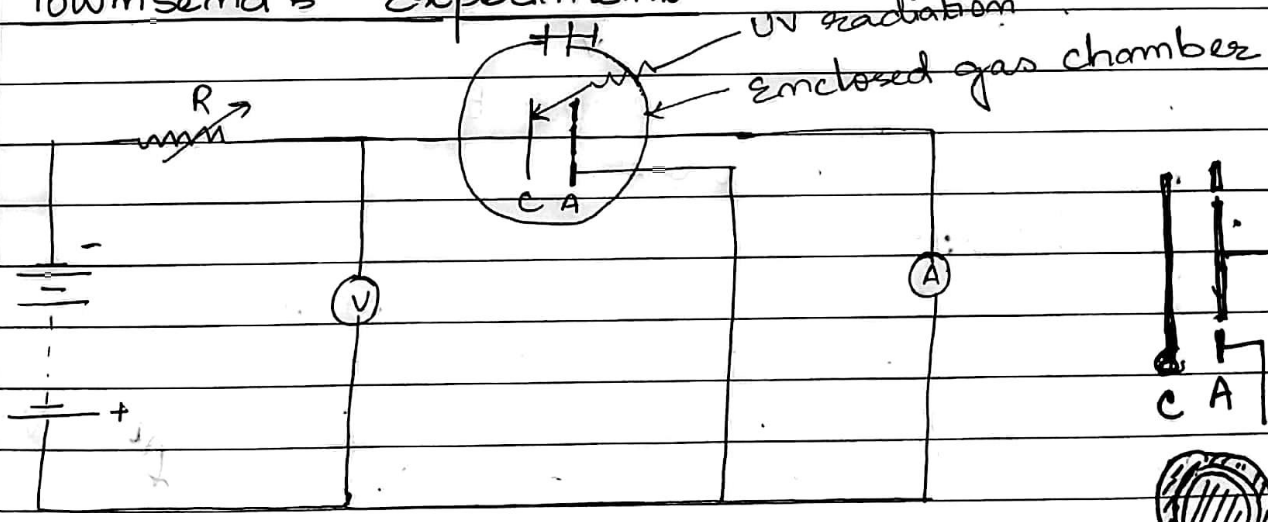
→ Ionization by electron impact is a probabilistic phenomenon, because initially with increase in $\Delta W > W_i$ the probability of ionization increases and after a certain value probability of ionization decreases.

There is an optimum e^- Energy range for ~~where~~ which probability of ionization is maximum.



The decrease of ionization probability is because of reduced collision time at high speeds.

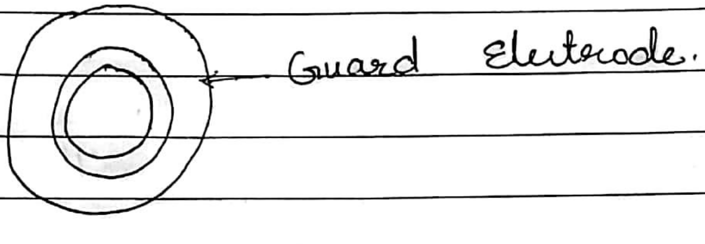
Townsend's Experiment



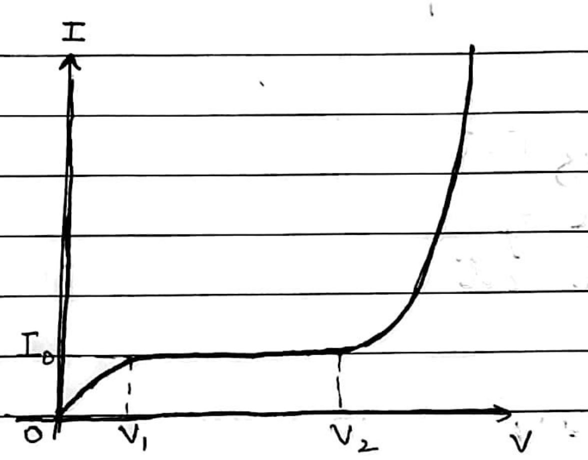
Variation of gas current as a function of the applied voltage for a uniform-field gap.

- parallel plate arrangement
- Enclosed glass chamber at low pressure.
- Anode is guarded Electrode.

Side view of Eletrode



To eliminate the current component due to non-uniform field we use guarded eletrode.



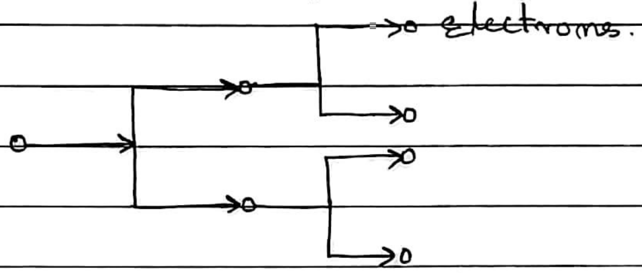
Variation of gas current as a funtion of the applied voltage.

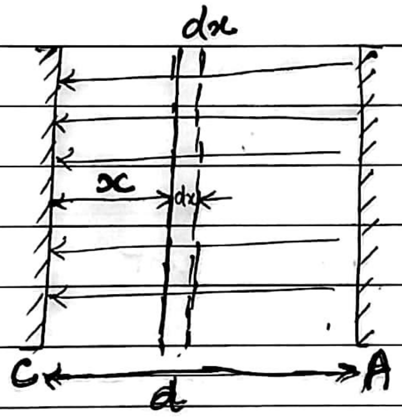
Initially:-

With increase in voltage between the electrodes more no. of electrons reach the anode so current follows applied voltage linearly. Then after V_1, almost all the electrons have reached anode & no further increase in current with increase in voltage. This current is known as saturation current. After V_2, increase in current by ionization of gas molecules by electron impact (because they have gained sufficient energy from field, resulting in collisions, releasing more no. of electrons and further collisions & more electrons & thus rapid increase in current).

Townsend's Ist ionization Coefficient

α = No. of electrons produced by an electron (by impact) per unit length of the path in the direction of the field.





If.
No. of $\bar{e}$s at a distance x from Cathode = n_x
No. of $\bar{e}$s produced over a distance dx

$$dn_x = \alpha n_x dx \quad \text{— ①}$$

$$\frac{dn_x}{n_x} = \alpha dx$$

Integrating from 0 to d

$$\int_{n_0}^{n} \frac{dn_x}{n_x} = \int_{0}^{d} \alpha dx$$

n_0 → No. of $\bar{e}$s starting from cathode
n → No. of $\bar{e}$s reaching anode.

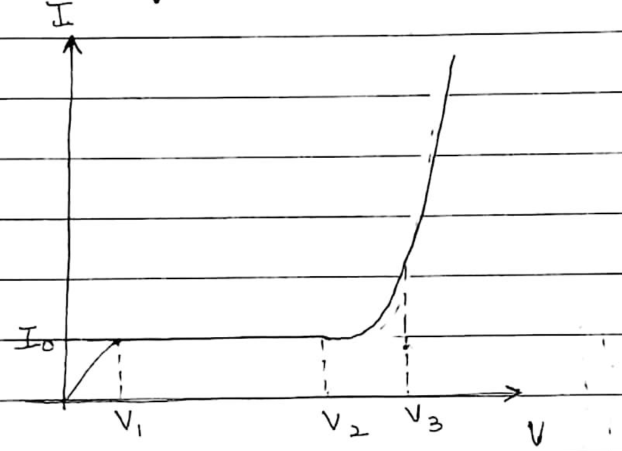
$$\ln \frac{n}{n_0} = \alpha d$$

$$\boxed{n = n_0 e^{\alpha d}} \quad \text{— ②}$$

Where n_0 = no. of $\bar{e}$s at Cathode.

10-05-2019

Townsend's Current - Growth Equation for a Uniform - Field Gaseous Gap



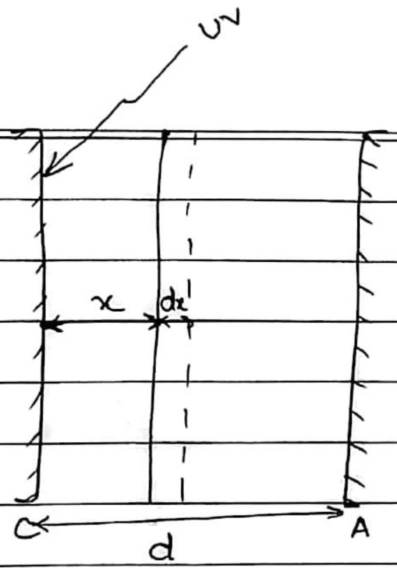
$0 - V_1$:- Emitted photocurrent

$V_1 - V_2$:- I_0, Saturation Current or background current

$> V_2$; increase in Current at a rapid rate

Electrons get sufficient energy from the field i,e $\Delta W \geq W_i$ and result in successive collisions.

$\alpha \rightarrow$ Towsend's first ionization Coefficient



No. of ē's at a distance x from Cathode $= n_x$
No. of ē's produced over a distance dx

$$dn_x = \alpha n_x dx \quad —①$$

$$\frac{dn_x}{n_x} = \alpha dx$$

integrating from 0 to d

$$\int_{n_0}^{n} \frac{dn_x}{n_x} = \int_0^d \alpha dx$$

$$\ln \frac{n}{n_0} = \alpha d$$

$$\boxed{n = n_0 e^{\alpha d}} \quad —②$$ n_0 = no. of ē's at Cathode

For $n_0 = 1$

$$\boxed{n = e^{\alpha d}}$$

This is Called as Electron avalanche (no. of ē's that reach anode when one electron starts from cathode)

In terms of Current

$$\boxed{I = I_0 e^{\alpha d}} \quad \text{— (3)}$$

This is known as Townsend's Current-Growth equation (current beyond V_2) for primary mechanism.

If $\alpha = 0$. (⇒ no electrons produced due to collisions)

$$\boxed{I = I_0}$$

Townsend's Second Ionization Coefficient (γ)

→ Beyond V_3, Current grows at a much rapid rate than described by =n ③

⇒ Second mechanism must be responsible for current growth beyond V_3.

→ Second mechanism proposed by Townsend was the liberation of electrons from the cathode due to positive ion bombardment. So, this mechanism is known as Secondary mechanism.

γ = No. of secondary electrons released from Cathode per incident positive ion (small fraction of the order of 10^{-3})

γ depends upon Cathode material.

n_0 = number of $\bar{e}$s released from Cathode due to primary process (e.g UV radiation)

n_+ = No. of $\bar{e}$s released from Cathode due to positive ion impact.

= γ x No. of incident +ve ions — ①

Total no. of $\bar{e}$s released from Cathode = $n_0 + n_+$

No. of $\bar{e}$s reaching anode, $n = (n_0 + n_+) e^{\alpha d}$ — ②

No. of $\bar{e}$s produced within the gap = No. of +ve ions produced within the gap.

$= n - (n_0 + n_+)$ — ③

from $\Rightarrow$ ① & ③

$$n_+ = \gamma \{ n - (n_0 + n_+) \} \text{ — ④}$$

multiply $\Rightarrow$ ④ by $e^{\alpha d}$ on b/s

$$n_+ e^{\alpha d} = \gamma [n e^{\alpha d} - (n_0 + n_+) e^{\alpha d}] \text{ — ⑤}$$

From $\Rightarrow$ ②

$$n_+ e^{\alpha d} = n - n_0 e^{\alpha d}$$

$\Rightarrow$ ⑤ becomes.

$$n - n_0 e^{\alpha d} = \gamma [n e^{\alpha d} - n]$$

$$n - n_0 e^{\alpha d} = \gamma n (e^{\alpha d} - 1)$$

$$n \{ 1 - \gamma (e^{\alpha d} - 1) \} = n_0 e^{\alpha d}$$

$$\boxed{n = \frac{n_0 \, e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)}} \quad — ⑥$$

In terms of current

$$\boxed{I = \frac{I_0 \, e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)}} \quad — ⑦$$

Townsend's current growth equation in presence of secondary processes.

Equation ⑦ is applicable beyond V_2

At a certain voltage;

If $1 - \gamma(e^{\alpha d} - 1) = 0$ — ⑧

denom. of Eq. (7) → 0.

$I \rightarrow \infty$, unless limited by the external circuitry.

So, this is a case of short circuit or we say that breakdown of the gap has occured.

Equation ⑧ is also referred to as Townsend's breakdown criteria.

Eqn ⑧ can be rewritten as

$$\gamma(e^{\alpha d} - 1) = 1 \quad — ⑨$$

$e^{\alpha d}$ is no. of ēs reaching the anode when one electron starts from the Cathode.

$(e^{\alpha d} - 1)$ is the no. of ēs Created in the gap.
= no. of +ve ions created in the gap.

from =n ⑨
The no. of positive ions created within the gap due to an electron avalanche is sufficiently Large enough to release one secondary electron from the Cathode upon bombardment so that every electron avalanche will have a successor

⇛ Discharge is self-sustaining.
So, equation ⑨ is known as Townsend's Criterion for self sustained discharge i.e the discharge can continue even if the source that produces the primary electrons is removed.

If $\gamma(e^{\alpha d} - 1) > 1$ it will lead to rapid breakdown

If $\gamma(e^{\alpha d} - 1) < 1$ Discharge is not self-sustaining.

Paschen's Law

Energy gained by an electron over the mean free path in the direction of the field,

$$\Delta W = e E \lambda_e \quad - ①$$ (λ_e is the mean free path in the direction of field)

$$\lambda_e \propto \frac{1}{p}$$, $p \rightarrow$ gas pressure.

$$\Delta W = f_1 \left(\frac{E}{p} \right) \quad - ②$$

For a given energy distribution ΔW, α will depend upon the no. of collisions made.

No. of collisions made $\propto p$

$\Rightarrow$

$$\alpha = p f_2 \left(\frac{E}{p} \right) \quad - ③$$

$$\boxed{\frac{\alpha}{p} = f_2 \left(\frac{E}{p} \right)} \quad - ④$$ has been verified experimentally.

Assuming that all the $\bar{e}$s with energy $\Delta W \geq W_i$ can cause ionisation, it can be shown that

$$\frac{\alpha}{p} = A e^{-B/(E/p)} \quad - ⑤$$

where $A = \frac{\sigma_i}{KT}$, $B = AV_i$

σ_i = ionisation cross-section of gas
k = Boltzmann's constant
T = Temperature
V_i = ionisation potential.

Townsend's breakdown criteria,

$$\gamma(e^{\alpha d} - 1) = 1 \quad \text{— ⑥}$$

or

$$e^{\alpha d} - 1 = \frac{1}{\gamma}$$

$$e^{\alpha d} = 1 + \frac{1}{\gamma}$$

$$\alpha d = \ln\left(1 + \frac{1}{\gamma}\right) \quad \text{— ⑦}$$

Substituting for α from eqn ⑤, we have

$$Apd\, e^{-B/(E_b/p)} = \ln\left(1 + \frac{1}{\gamma}\right) \quad \text{— ⑧}$$

Where E_b is the electric field intensity at breakdown

For a uniform field gap

$$E_b = \frac{V_b}{d} \quad \text{— ⑨}$$

where V_b = breakdown voltage
d = Electrode spacing

Substitute value of E_b in eqn ⑧

$$Apd\, e^{\frac{-Bpd}{V_b}} = \ln\left(1 + \frac{1}{\gamma}\right)$$

$$\frac{Apd}{\ln\left(1+\frac{1}{\gamma}\right)} = e^{\frac{Bpd}{V_b}}$$

$$\ln \frac{Apd}{\ln\left(1+\frac{1}{\gamma}\right)} = \frac{Bpd}{V_b}$$

$$\boxed{V_b = \frac{Bpd}{\ln\left(\frac{Apd}{\ln\left(1+\frac{1}{\gamma}\right)}\right)}} \quad - ⑩$$

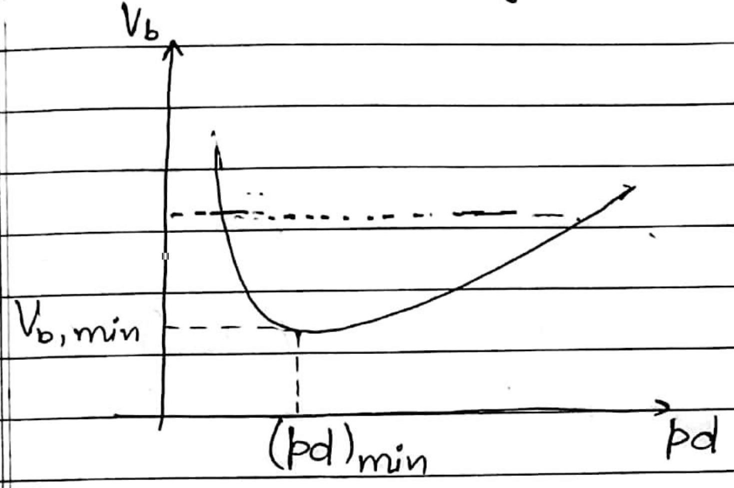
Paschen's Law was first experimentally established in 1805 before it was mathematically derived.

Paschen's Law:- "For a given gas & Cathode material, the breakdown voltage of a uniform field gap is a unique function of the product of gas pressure and electrode separation."

$$V_b = f(pd) \quad - ⑪$$

{A, B and γ are included in given gas and Cathode material}.

V_b vs pd gives Paschen's Curve



→ $V_{b,min}$ is the value below which breakdown Cannot occur.

→ At $(pd)_{min}$, the no. of ionising Collisions is maximum.

→ At two values of pd, there is one value of V_b at which breakdown Can occur (one is low value of (pd) and another is high value of pd).

To find $N_{b,min}$ & $(pd)_{min}$

$$\frac{dV_b}{d(pd)} = 0$$

$$\ln \frac{Apd}{\ln\left(1+\frac{1}{\gamma}\right)} B - B\cancel{pd} \cdot \frac{1}{\frac{\cancel{A}\cancel{pd}}{\cancel{\ln\left(1+\frac{1}{\gamma}\right)}}} \cdot \frac{\cancel{A}}{\cancel{\ln\left(1+\frac{1}{\gamma}\right)}} = 0$$

$$\ln \frac{Apd}{\ln\left(1+\frac{1}{\gamma}\right)} B = B$$

$$\ln \frac{Apd}{\ln\left(1+\frac{1}{\gamma}\right)} = 1$$

$$\frac{Apd}{\ln\left(1+\frac{1}{\gamma}\right)} = e$$

$$\boxed{(pd)_{min} = \frac{e}{A} \ln\left(1+\frac{1}{\gamma}\right)} \quad — ⑫$$

$$V_{b,min} = \frac{B\cdot(pd)_{\cancel{min}}}{\ln\left(\frac{Apd}{\ln\left(1+\frac{1}{\gamma}\right)}\right)}\Bigg|_{(pd)_{min}} = \frac{B\cdot(pd)_{min}}{1}$$

$$\boxed{V_{b,min} = \frac{eB}{A} \ln\left(1+\frac{1}{\gamma}\right)} \quad — ⑬$$

At $(pd) > (pd)_{min}$.

Keeping d constant, if we increase p then the gas molecules will come closer and mean free path will decrease. Since Energy $\propto$ mean free path, so energy will decrease. Thus to cause breakdown higher voltage will be required.

Keeping p constant, if we increase d, Energy gained by electrons over the mean free path decreases. Thus to cause breakdown higher voltage will be required.

At $(pd) < (pd)_{min}$.

Keeping d constant, if we decrease p, mean free path will increase but no. of ionizing collisions decreases, so we need higher voltage to cause breakdown.

Same is for if we keep p constant & decreas d, ~~mean free path will increase but~~ no. of ionizing collisions decrease. So to cause breakdown we need high breakdown voltage.

breakdown of of gaseous gap depends upon the "no." of "ionizing" collisions made over the gap.

For $(pd) > (pd)_{min}$, "no." of collisions ↑es but their "ionizing capability" ↓es.

For $(pd) < (pd)_{min}$, "ionizing capability" of the collisions ↑es but the "no." of such collisions ↓es.

Measured Values

Gas	(pd) min (torr-cm)	$V_{b,min}$ (Volts)
Air	0.55	352 ←
N_2	0.65	240
H_2	1.05	230
O_2	0.7	450
SF_6	0.26	507
CO_2	0.57	420
Ne	4.00	245 ←
He	4.00	155 ←

→ Ne and He are used in gas discharge tubes because we need a low breakdown voltage.

→ Paschen's Law applies over a wide range of (pd) values upto about 1000 - 2000 torr-cm

Deviations observed at too high & too low pd values

At a higher pd value, for the constant pd, V_b is lower at large gap spacing; this is because of transition from Townsend breakdown mechanism to streamer breakdown mechanism as pd is increased above a certain value.

At low pd values, deviation is observed because the breakdown mechanism ceases to be influenced by gas particles & becomes electrode dominated (Vacuum breakdown)

Practical applications

1. Gas discharge tubes are operated near (pd) min so that breakdown occurs at low voltage.
2. Air and SF_6 at high pressure is used in gas circuit breakers, because breakdown voltage is high, so high insulation property.
3. Air at low pressure is used in vacuum circuit breakers.

Effect of Temperature on Breakdown Voltage

$$\frac{\alpha}{p} = f\left(\frac{E}{p}\right) \quad -(1)$$

→ Used in derivation of $V_b = f(pd)$.

p affects the mean free path and hence the no. of ionising collisions.

It is often convenient to use gas density ρ instead of pressure p and mean free path and hence the ionizing collisions are actually dependent on ρ as such the effect of temperature is also taken into account. Therefore paschen's Law should be generally stated as:

$$V_b = g(\rho d) = g_1\left(\frac{pd}{T}\right) \quad -(2)$$

$\because \rho \propto \frac{p}{T}$

Since the atmospheric conditions (p & T) vary considerably in time and locations, the breakdown characteristics of various apparatus will be affected accordingly. For practical purposes, therefore, the breakdown characteristic under given atmospheric conditions are compared with those under standard atmospheric conditions. These are

$p = 760$ mm Hg , $T = 20°$c

For small changes in gas density around standard conditions, eq. ② is practically linear.

Hence, $$\frac{V_{b,amb}}{V_{b,N}} = \frac{p}{760} \times \frac{(273+20)}{273+T}$$

$$\frac{V_{b,amb}}{V_{b,N}} = \frac{0.386p}{273+t} = d \quad — ③$$

Air density correction factor $d = \frac{0.386p}{273+T}$

$$\boxed{V_{b,amb} = d\, V_{b,N}} \quad — ④$$

Electronegative Gases

Certain atoms or molecules in their gaseous state can readily acquire a free electron to form a stable negative ion. Such gases lack one or two electrons in their outermost shell and are known as electronegative gases.

examples F, Cl, Br, I, At lack one $\bar{e}$
O, S, Se lack two $\bar{e}$s

For the negative ions to remain stable for some time, the total energy* must be less than that of the atom or molecule in ground state. This energy is released as a quantum or K.E upon attachment and is called electron affinity (Wa)

* of the -ve ion

There are several mechanisms of negative ion formation e.g

1) Radiative attachment

$$A + \bar{e} \rightleftharpoons \bar{A} + h\nu; \quad W_a = h\nu$$

2) Third body collision Attachment

$$A + B + \bar{e} \rightleftharpoons A^- + (B + W_K)$$

3) Dissociative attachment

$$AB + \bar{e} \rightleftharpoons \underset{\text{meta stable state}}{(AB^-)^*} \rightleftharpoons A^- + B$$

→ There is a range of electron energy for which the probability of attachment is maximum.

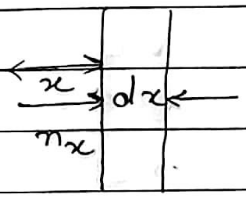
Current Growth in an Electronegative Gas

When an Electronegative gas is subjected to an electric field, the process of electron multiplication by collision will be accompanied by electron loss due to attachment.

Attachment Coefficient = η = No. of ēs lost due to attachment per unit length of the path of an electron in the direction of the field.

$$dn_x = (\alpha - \eta)\, n_x\, dx$$

$\Downarrow$ effective no. of ēs remained



$$\int_{n_0}^{n_x} \frac{dn_x}{n_x} = \int_0^x (\alpha - \eta)\, dx$$

$$\boxed{n_x = n_0\, e^{(\alpha - \eta)x}}$$

$\alpha - \eta$ is known as effective ionisation Coefficient

$$\bar{\alpha} = \alpha - \eta$$

$$n = n_0\, e^{(\alpha - \eta)d}.$$

In an electronegative gas, as the electrons are lost due to attachment, negative ions are formed, the anode current will therefore have two Components

1. Due to the flow of electrons.
2. Due to the flow of negative ions.

Negative ions behave differently from electrons in carrying current. while electrons produce further ionisation due to collisions, negative ions donot. The result is a reduction in the no. of charge carriers in the gap with a consequent reduction in anode current. As electron attachment reduces electron amplification in a gas, gases with high attachment coefficients such as SF_6, Freon (CCl_2F_2) (Dichloro-di-Fluro methane) have much dielectric strength than air or nitrogen. These gases are technically important and are widely used as insulating media in compact HV equipment including gas insulated substation (GIS) or HV cables.

Ionization processes in a Gas

i) Ionization by Collision.
ii) Photoionization.
iii) By interaction of metastables with atoms
iv) Thermal ionization.

Deionization Processes

i) By attachment
ii) Recombination
iii) Diffusion

Cathode Processes

i) Photoelectric emission
ii) By positive ion & excited atom impact
iii) Thermionic emission.
iv) Field emission.

Streamer or Kanal Breakdown Mechanism

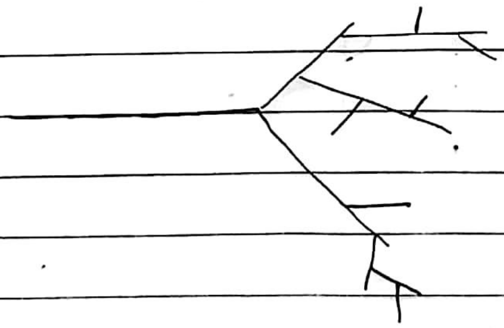
In the Townsend breakdown mechanism, the gap current grows as a result of

i) ionisation of gas molecules by electron impact

ii) Electron emission from the Cathode by positive ion impact.

The time required for the formation of a breakdown channel after the appearance of an electron at the Cathode is Called Formative time lag (t_f). The Townsend mechanism predicts a formative time lag which Can at best be as short as electron transit time (t_i). However, in Long gaps and pd values greater than 1000 torr cm, the actually measured formative time lags (10^{-8} sec) are much shorter than electron transit time.

Also while the Townsend mechanism predicts straight breakdown channels. Under static field, the cloud chamber photographs of the avalanche development in ~~the~~ long gaps show filamentary, branched, Zig zag breakdown channels Called streamers.



The observed short time lags together with the observations of discharge development led to the advancement of streamer or Kanal breakdown mechanism. This mechanism was proposed by Raether and independently by Meek & Loeb.

The models developed take into account the effect of the electric field of the space charge of the electrons and ions of an avalanche. Also the secondary mechanism is considered as photoionisation of gas molecules.

Effect of space charge of Electrons and positive ions in the gap

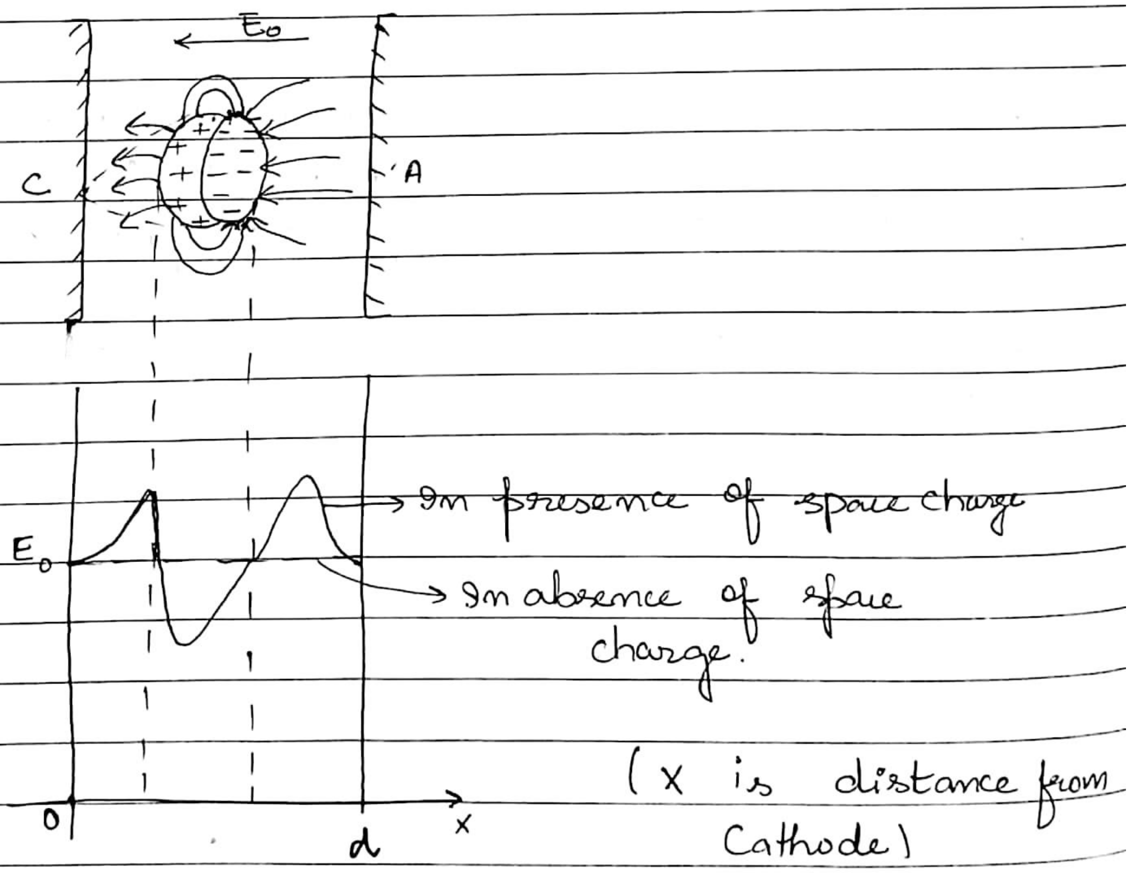


Figure 1

Figure 1 shows the electric field around an avalanche as it progresses along the gap and the resulting field modification in the gap. For simplicity, the space charge at the head of the avalanche is assumed concentrated within a spherical volume with the negative charge ahead. The field is enhanced in front of the avalanche head with the field lines from anode terminating at the head. Further back in the avalanche the field between electrons and the positive ions reduces the field in the gap. still further back, the field between the Cathode and the positive ions is enhanced again. The field distortion becomes noticable with a Carrier no. $n_x > 10^6$. However, the distortion is only significant in the immediate vicinity of the avalanche head. It has been found that as the Carrier no. in the avalanche n_x reaches to about 10^8, the space charge field becomes of the same magnitude as the applied field and may lead to rapid breakdown.

For the charge within the avalanche head to reach this critical value $n_x = n_0 e^{\alpha x_c} \approx 10^8$

For $n_0 = 1$

$e^{\alpha x_c} \approx 10^8$

$\alpha x_c \approx 18-20$

Where x_c is the length of avalanche path in the gap when it reaches the critical size. If $x_c > d$, the initiation of streamer is unlikely (d is total spacing).

In the models developed by Raether and Meek, it has been proposed that when the avalanche in the gap reaches critical size, the resultant field in the gap leads to intense ionization and excitation of gap particles in front of the avalanche head. Recombination between positive ions and electrons releases photons which inturn generate secondary electrons by photoionization process. These electrons under the influence of electric field in the gap develop into secondary avalanches as shown in figure 2. Since photons travel with the velocity of light, the process leads to a rapid development of the Conduction channel across the gap.

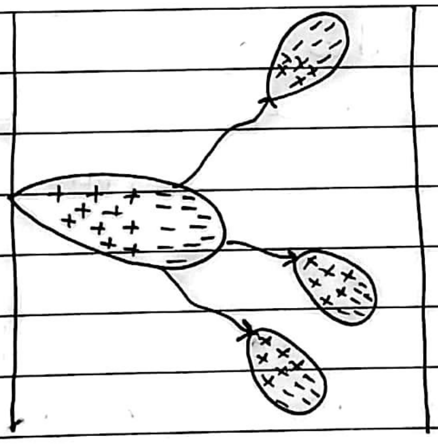


Figure 2.