High Voltage Engineering
Module 1
Conduction and Breakdown in Gases

Department of Electrical Engineering

Introduction

What is High Voltage Engineering?

It is the science of planning, operating and testing high-voltage electrical devices and designing the insulation coordination in order to ensure the reliable operation of the power network.

Introduction contd..

•Modern high voltage test laboratories employ voltages upto 6 MV or more.

•The diverse condition under which a high-voltage apparatus is used necessitate careful design of its insulation and the electrostatic field profiles.

•The principal media of insulation used are gases, vacuum, solid, liquid or combination of these.

Introduction contd..

Applications

- Laboratories in nuclear research.
- Particle accelerators.
- Transmission of large bulks of power over long distance.
- X-ray equipments for medical and industrial applications.

Elecrical breakdown or Dielectric breakdown

Electrical breakdown or dielectric breakdown is a process that occurs when an electrical insulating material subjected to a high enough voltage suddenly becomes an electrical conductor and electric current flows through it.

Elecrical breakdown or Dielectric breakdown

Electrical breakdown means failure of insulation.

Case 1

Fig 1

Elecrical breakdown or Dielectric breakdown

Case 2

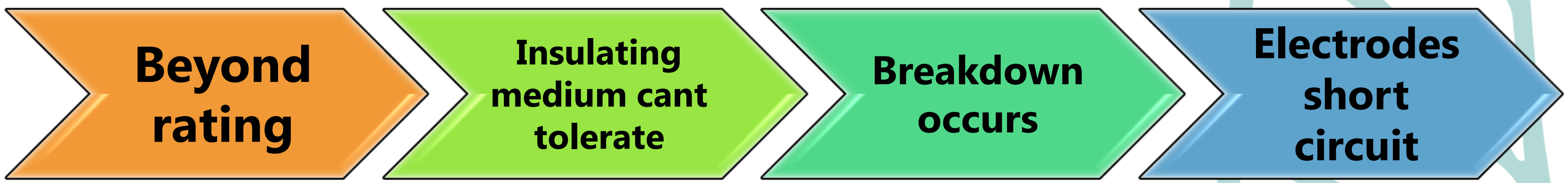


Fig 2

Gases as Insulating Media

- The simplest and the most commonly found dielectric.
- Most of the electrical apparatus use air as the insulating medium.
- In few cases other gases such as nitrogen (N_2), carbon dioxide (CO_2), freon (CCl_2F_2) and sulphur hexafluoride (SF_6).
- The maximum voltage applied to the insulation at the moment of breakdown is called the breakdown voltage.

Gases as Insulating Media

Fig 3: SF_6 gas insulated circuit breaker

Breakdown in gas

- Breakdown occurs within gas when dielectric strength of gas failures.
- The electrical breakdown of a gas is brought about by various process of ionization.
- These are good processes involving the collision of electrons, ions and photons with gas molecules and electrode processes.

Layout of gas breakdown process

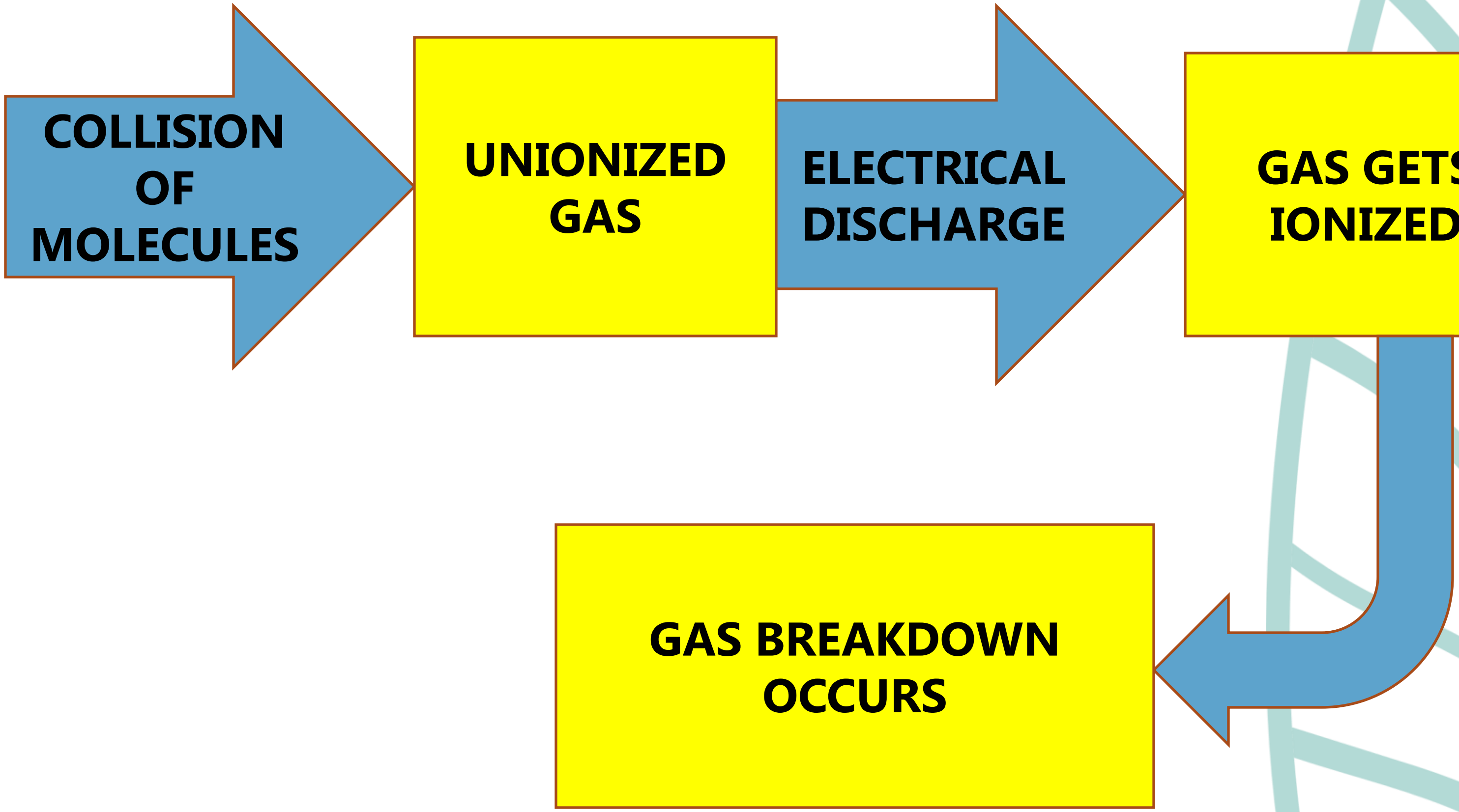


Figure 4

Ionization by Collision

- The process of liberating an electron from a gas molecule with the simultaneous production of a positive ion is called ionization.

- In this process free electron collides with a neutral gas molecule and give rise to a new electron and a positive ion.

Ionization by Collision contd..

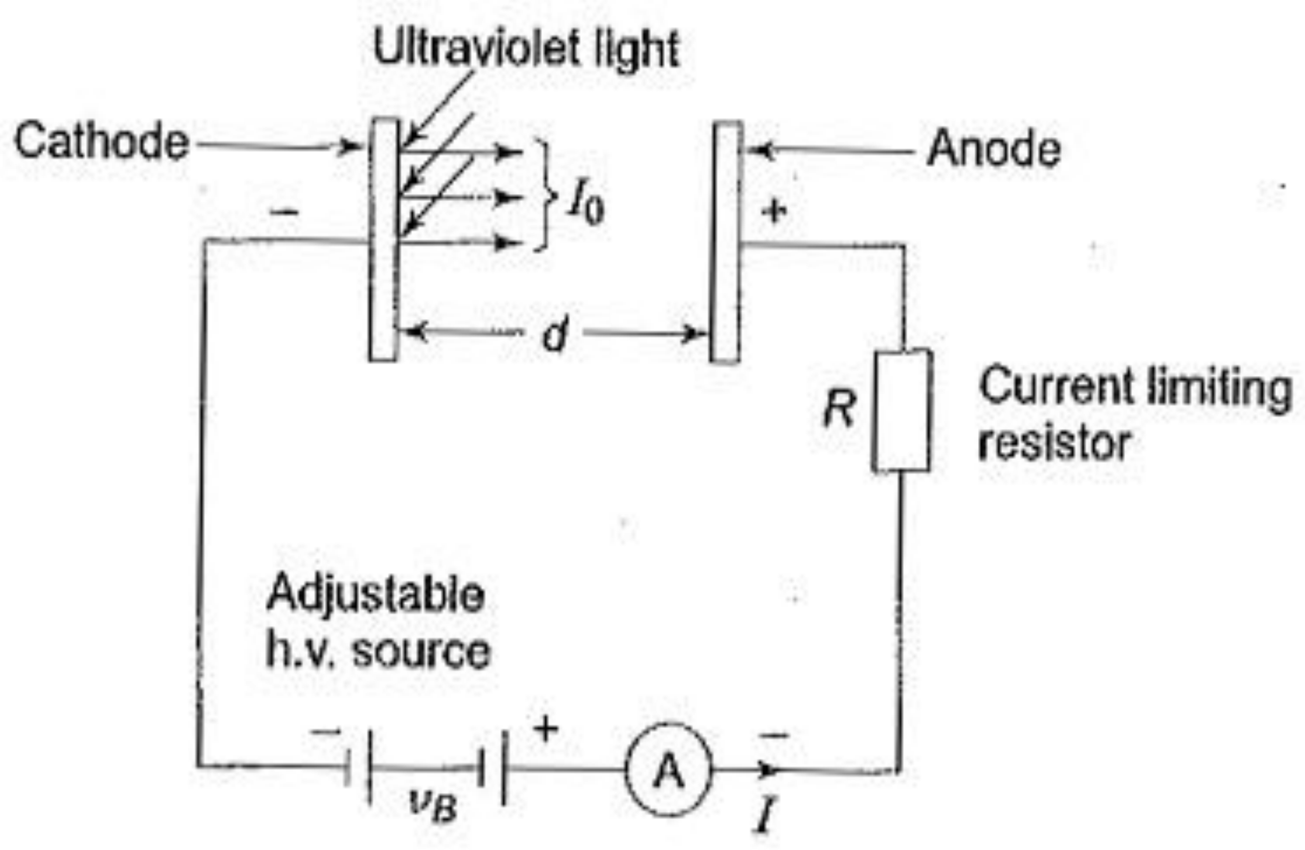


Figure 5: Arrangement for a study of Townsend discharge

Ionization by Collision contd..

- Consider a low-pressure gas column in which an electric field *E* is applied across two plane parallel electrodes.
- Any electron starting at the cathode will be accelerated more and more between collisions with other gas molecules during its travel toward the anode.
- If the energy (ε) gained during this travel between collisions exceeds the ionization potential V_i then ionization takes place.

Ionization by Collision contd..

This process can be represented as:

$$e^{-} + A \xrightarrow{\varepsilon > Vi} e^{-} + A^{+} + e- \quad \text{........ (1)}$$

Where, A is atom

A^{+} is positive ion and

e^{-} is the electron

Ionization by Collision contd..

Few of the electrons produced at the cathode by some external means.

- Ultra-violet light falling on the cathode, ionize neutral gas particles producing positive ions and additional electrons.
- The additional electrons then, themselves make ‘ionizing collisions’, thus the process repeats itself.
- This represents increase in electron current.
- Positive ions also reach the cathode.
- On bombardment on the cathode gives rise to secondary electrons.

Townsend's Current Growth Equation

- Let us assume that n_o electrons are emitted from the cathode.
- When one electron collides with a neutral particle, a positive ion and an electron are formed.
- Let **α** be the average number of ionizing collisions made by an electron per centimeter travel in the direction of the field

A depends on gas pressure p and E/p, and is called the Townsend's first ionization coefficient.

- At any distance x from the cathode, let the no. of electrons be n_x.

Townsend's Current Growth Equation

- When these n_x electrons travel a further distance of dx they give rise to (α n_x dx) electrons.

At $$x = 0, n_x = n_0 \qquad (2)$$

Also, $$\frac{dn_x}{dx} = \alpha n_x; \text{ or } n_x = n_0 \exp(\alpha x) \qquad (3)$$

Then, the number of electrons reaching the anode ($x = d$) will be

$$n_d = n_0 \exp(\alpha d) \qquad (4)$$

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

$$\exp(\alpha d) - 1 = \frac{n_d - n_0}{n_0} \qquad (5)$$

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

$$I = I_0 \exp(\alpha d) \qquad (6)$$

where I_0 is the initial current at the cathode.

CURRENT GROWTH IN THE PRESENCE OF SECONDARY PROCESSES

•The primary process becomes complete when the initial set of electrons reaches the anode.

•The secondary ionization process follow resulting in the final breakdown of gases.

•These processes are:

I. Ionization due to positive ions.

II. Photo ionization

III. The metastable particles may diffuse back causing electron emission.

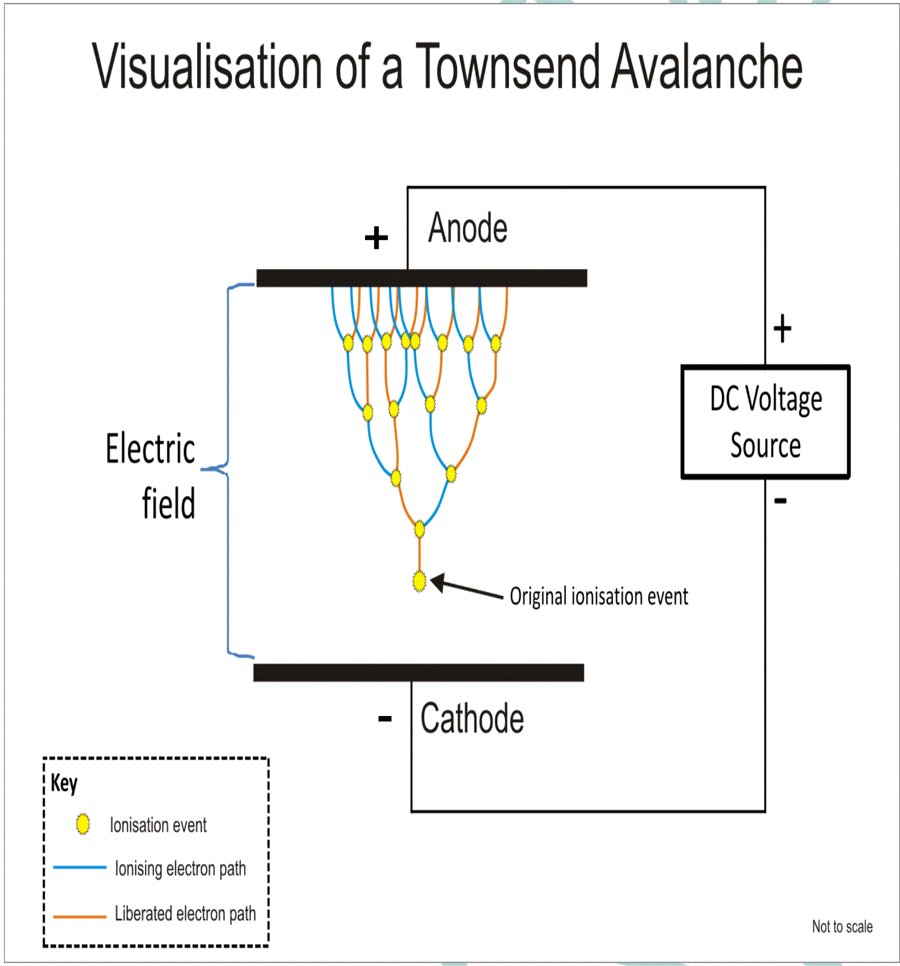
CURRENT GROWTH IN THE PRESENCE OF SECONDARY PROCESSES contd..

❖The electrons produced by these processes are called secondary electrons.

❖Secondary ionization coefficient is γ.

❖The net number of secondary electrons produced per incident positive ion, photon, excited particles, or metastable particle and the total vale of γ is the sum of the individual coefficients due to the three different processes, i.e. $\gamma=\gamma_1+\gamma_2+\gamma_3$.

❖ γ is called Townsend's secondary ionization coefficient and is a function of the gas pressure *p* and *E/p*



CURRENT GROWTH IN THE PRESENCE OF SECONDARY PROCESSES contd..

Following Townsend's procedure for current growth, let us assume

n_0' = number of secondary electrons produced due to secondary (γ) processes.

Let n_0'' = total number of electrons leaving the cathode.

Then
$$n_0'' = n_0 + n_0' \qquad (7)$$

The total number of electrons n reaching the anode becomes,

$$n = n_0'' \exp(\alpha d) = (n_0 + n_0') \exp(\alpha d);$$

and
$$n_0' = \gamma[n - (n_0 + n_0')]$$

Eliminating n_0',
$$n = \frac{n_0 \exp(\alpha d)}{1 - \gamma[\exp(\alpha d) - 1]}$$

or
$$I = \frac{I_0 \exp(\alpha d)}{1 - \gamma[\exp(\alpha d) - 1]} \qquad (8)$$

Eqn 8 gives the total average current in a gap before the occurrence of breakdown.

TOWNSEND'S CRITERION FOR BREAKDOWN

❖As the distance between electrodes d is increased, the denominator of eqn 8 tends to zero and at some critical distance $d=d_s$.

$$1-\gamma[\exp(\alpha d)-1]=0 \quad ....(9)$$

For values of $d<d_s$, $I = I_0$, if external source of I_0 is removed, I becomes zero.

If $d=d_s$, $I \rightarrow \infty$ and the current will be limited only by the resistance of the power supply and the external circuit.

TOWNSEND'S CRITERION FOR BREAKDOWN

This condition is called Townsend's breakdown criterion and can be written as,

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

Normally, exp(αd) is very large, and hence the above equation reduces to

$$\gamma \exp(\alpha d)=1 \quad \ldots\ldots\ldots(10)$$

TOWNSEND'S CRITERION FOR BREAKDOWN

- A given gap spacing and at a given pressure the value of the voltage V which gives the values of α and γ satisfying the breakdown criterion is called the spark breakdown voltage V_s and

The corresponding distance d_s is called the sparking distance

BREAKDOWN IN ELECTROMAGNETIVE GASES

- One process that gives high breakdown strength to a gas is the electron attachment in which free electrons get attached to neutral atoms or molecules to form negative ions.
- Since negative ions like positive ions are too massive to produce ionization due to collisions, attachment presents an effective way of removing electrons which otherwise would have let to current growth and breakdown at low voltage.
- The gases in which attachment plays an active role are called electronegative gases.

BREAKDOWN IN ELECTROMAGNETIVE GASES

- The most common attachment processes encountered in gases are:

(a) Direct attachment

$$AB + e \rightarrow AB^{-} + h\nu$$

(b) Dissociative attachment

$$AB + e \rightarrow A + B^{-} + e$$

BREAKDOWN IN ELECTROMAGNETIVE GASES

- In this gases, ‘A’ is usually sulphur or carbon atom, and ‘B’ is oxygen atom or one of the halogen atoms or molecules.
- Townsend’s current growth equation is modified to include ionization and attachment.
- An attachment coefficient (η) is defined similar to α, as the no. of attaching collisions made by one electron drifting one centimeter in the direction of the field.

BREAKDOWN IN ELECTROMAGNETIVE GASES

- Under this condition, the current reaching the anode, can be written as:

$$I = I_0 \frac{[\{\alpha/(\alpha-\eta)\}\exp(\alpha-\eta)d]-[\eta/(\alpha-\eta)]}{1-\left\{\gamma \frac{\alpha}{(\alpha-\eta)}[\{\exp(\alpha-\eta)d\}-1]\right\}} \qquad (11)$$

The Townsend breakdown criterion for attaching gases can also be deduced by equating the denominator in Eq. (5) to zero, i.e.,

$$\gamma \frac{\alpha}{(\alpha-\eta)}[\exp(\alpha-n)d-1]=1 \qquad (12)$$

This shows that for $\alpha > \eta$, breakdown is always possible irrespective of the values of α, η, and γ. If on the other hand, $\eta > \alpha$ Eq. (12) approaches an asymptotic form with increasing value of d, and

$$\gamma \frac{\alpha}{(\alpha-\eta)} = 1; \text{ or } \alpha = \frac{\eta}{(1-\gamma)} \qquad (13)$$

BREAKDOWN IN ELECTROMAGNETIVE GASES

- γ is very small ($\leq 10^{-4}$) and the above equation can be written as $\alpha = \eta$.
- The condition puts a limit of E/p below which no breakdown is possible irrespective of the value of d and the limit value is called critical E/p.

LIMITATION OF TOWNSEND'S THEORY

- ❖ Townsend mechanism when applied to breakdown at atmospheric pressure was found to have certain drawbacks:

I. Current growth occurs as a result of ionization process only, but in practice breakdown voltage were found to depend on the gas pressure and the geometry of the gap.

II. The mechanism predicts time lags of the order of 10^{-5} ,while in actual practice breakdown was observed to occur at very short times of the order of 10^{-8} s.

III. Also , while the Townsend mechanism predicts a very diffused form of discharge, in actual practice, discharges were found to be filamentary and irregular.

STREAMER THEORY

STREAMER THEORY of breakdown mainly arises due to the added effect of the space- charge field of an avalanche and photo-electric ionization in the gas volume.

But in practice, breakdown voltages were found to depend on the gas pressure and the geometry of the gap.

STREAMER THEORY

- The growth of charge carriers in an avalanche is uniform field described by $e^{\alpha d}$.
- This is valid only as long as the influence of the space charge due to ions is very small compared to the applied filed.
- On the effect of space charge on avalanche growth when the charge concentration was between 10^6 and 10^8, the growth of avalanche became weak.

STREAMER THEORY

- When the charge concentration was higher than 10^8, the avalanche current was followed by a steep rise in the current between the electrodes, leading to the breakdown of the gap.

- Both slow growth at low charge concentration and fast growth at high charge concentration have been attributed to the modification to the originally applied uniform field E by the space charge P.

STREAMER THEORY

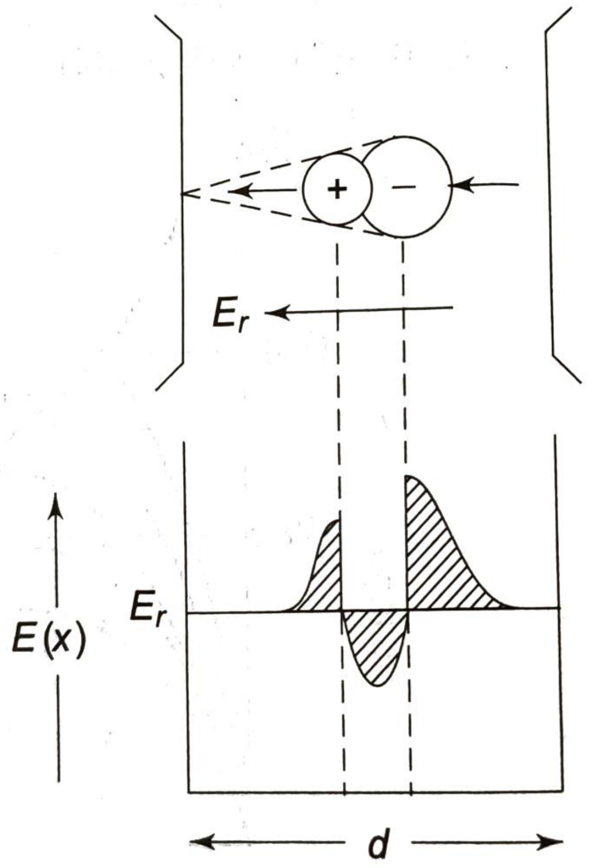


Fig. 7 *Field distortion in a gap due to space charge*

STREAMER THEORY

- The space charge at the head of the avalanche is assumed to have a spherical volume containing negative charge at top because of the higher electron mobility.
- The field gets enhanced at the top of the avalanche.
- At the bottom of the avalanche the field between the electrons and ions reduces the applied field (E).
- Further the field between cathode and positive ions gets enhanced.

STREAMER THEORY

- Thus the field distortion occurs and it becomes noticeable with charge carrier number $n>10^6$.

- If the charge density in the avalanche approaches $n=10^8$ the space charge filled field and the applied field will have the same magnitude and this leads to the initiation of a streamer.

STREAMER THEORY

- When the avalanche in the gap reaches a critical size, the combined applied field and the space charge field causes
  - Intense ionization and
  - Excitation of the gas particles in front of the avalanche.

STREAMER THEORY

- ❖ Instantaneous recombination between positive ions and electrons releases photons which produces secondary electrons by photo-ionization.
- ❖ The secondary electrons under the influence of the field in the gab develop into secondary avalanche as shown in fig. 8

STREAMER THEORY

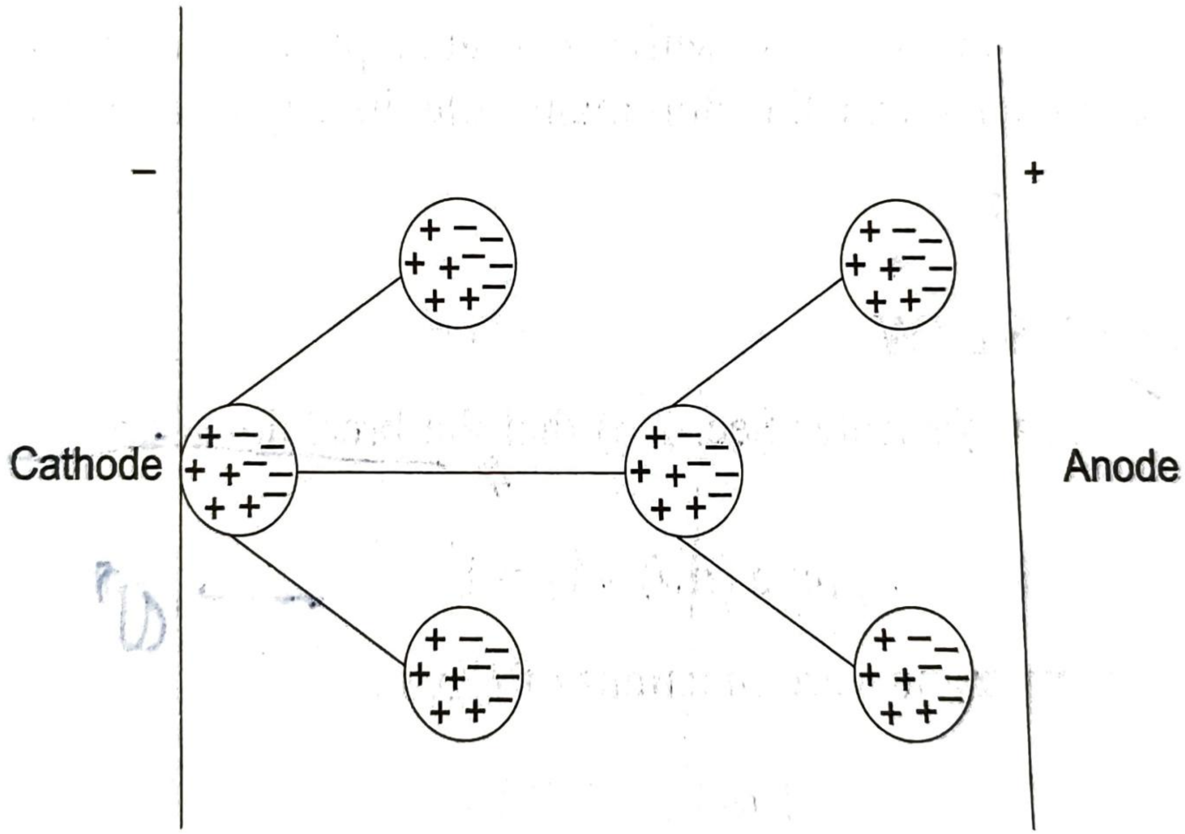


Fig. 8 *Formation of secondary avalanches due to photo-ionization*

STREAMER THEORY

On the basis of experimental observation for the streamer spark criterion of the form

$$\alpha x_c = 17.7 + \ln x_c + \ln (E_r/E) \qquad (14)$$

Where x_c is the length of the avalanche in which secondary electrons are produced

E_r is the space charged field directed radially at the head of the avalanche and E is the applied field.

STREAMER THEORY

The conditions for the transition from the avalanche to streamer assumes that the space charged field ***E***, approaches the externally applied field ***(E=Er)*** and hence the breakdown criterion (eqn 14) becomes

$$\alpha x_c = 17.7 + \ln x_c \qquad \textbf{(15)}$$

- ❖ The transition from an avalanche to a streamer occurs when the avalanche has just crossed a gap, ***d.***
- ❖ The minimum breakdown voltage by streamer mechanism occurs only when a critical length $x_c = d$.
- ❖ The field E_r produced by the space charge at the radius ***r***, is given by

STREAMER THEORY

$$E_r = 5.27*10^{-7} \frac{\alpha exp\,(\alpha x)}{(x/p)^{1/2}} \ V/cm \qquad (16)$$

Taking in

$$ln\,E = -14.5 + ln\,\alpha + ln e^{\alpha d} - \frac{1}{2} ln(\frac{d}{p})$$

$$ln\,E = -14.5 + ln\,\alpha + \alpha d - \frac{1}{2} ln(\frac{d}{p})$$

$$ln\,E - ln\,p = -14.5 + ln\,\alpha - ln\,p + \alpha d - \frac{1}{2} ln(\frac{d}{p})$$

$$ln\,E - ln\,p = -14.5 + ln\,\alpha/p + \alpha d - \frac{1}{2} ln(\frac{d}{p})$$

STREAMER THEORY

Where *α* is Townsend's first ionization coefficient,

- *p* is the gas pressure in torr, and
- *x* is the distance to which the streamer has extended in the gap.

The minimum breakdown voltage is obtained when $E_r = E$ and $x = d$ in (eqn.17)

STREAMER THEORY

The equation simplifies into

$$\alpha d + \ln\left(\frac{\alpha}{p}\right) = 14.5 + \ln\left(\frac{E}{p}\right) + \frac{1}{2} ln(\frac{d}{p}) \qquad \textbf{(17)}$$

Experimental values of α/p and E/p are used to solve the equation using trial and error method.

PASCHEN'S LAW

The breakdown criterion in gases is given as

$$\gamma[\exp(\alpha d)-1]=1 \qquad (18)$$

Where the coefficients α and γ are the function of E/p, i.e,

$$(\alpha/p)= f_1 (E/p)$$

$$\alpha= p * f_1 (E/p) \text{ and}$$

$$\gamma= f_2 (E/p) \text{ also}$$

$$E=V/d$$

PASCHEN'S LAW

Substituting for E in the expressions for α and γ and rewriting eqn. 12

$$f2\left(\frac{V}{pd}\right)\left[\exp\left\{pd\, f1\left(\frac{V}{pd}\right)\right\} - 1\right] = 1 \quad \textbf{(19)}$$

This equation shows a relationship between V and pd, and implies that the breakdown voltage varies as the product pd varies.

Knowing the nature of f_1 and f_2 we can rewrite eqn.18 as

$$V=f(pd) \qquad (20)$$

This equation is known as Paschen's Law

PASCHEN'S CURVE

It is seen that the relationship between V and pd is not linear and has a minimum value for any gas.

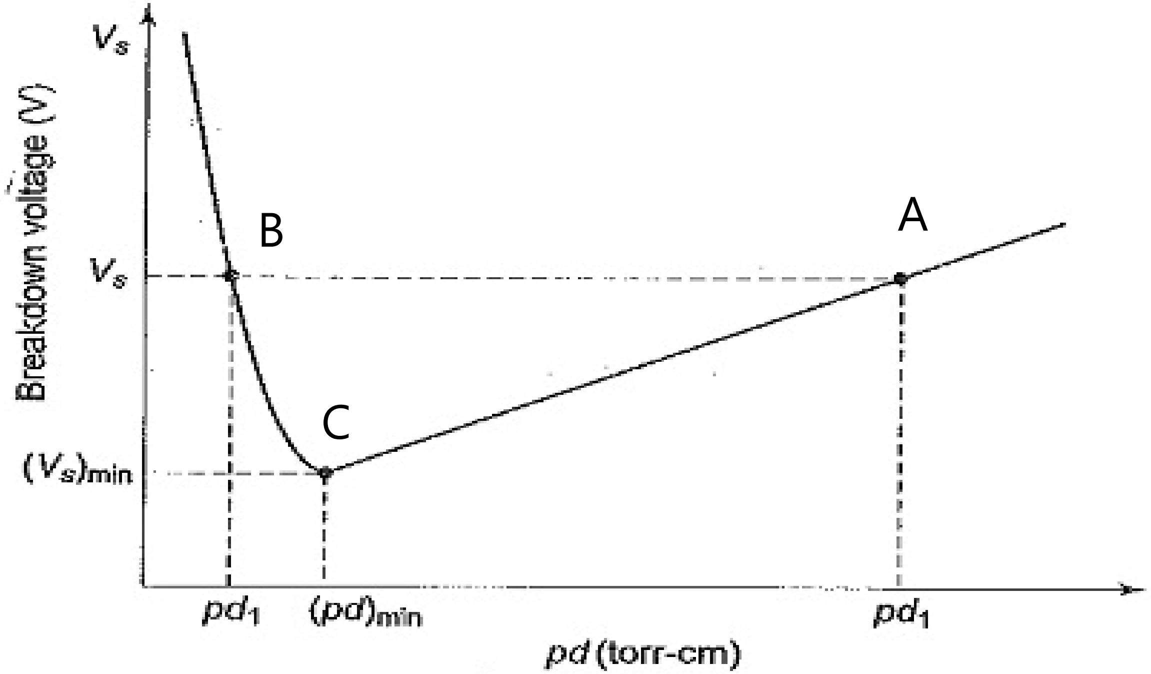


Fig. 9 *Breakdown voltage-pd curve (Paschen's law)*

PASCHEN'S CURVE

- This means that a breakdown voltage of a uniform field gap is a unique function of the product p, the gas pressure and d, the electrode gap for a particular gas and for a given electrode material.
- From Paschen’s law, the breakdown voltage of a spark gap can be obtained in terms of α and γ by rewriting eqn.18 and substituting for α and γ in terms of ‘pd’ product.

PASCHEN'S CURVE

- This gives rise to 'd', the gap distance as

$$d = \frac{1}{\alpha}[ln(1 + \frac{1}{\gamma})]$$

$$= \frac{1}{pf1(\frac{v}{pd})} ln [1 + \frac{1}{f2(\frac{v}{pd})}]$$ where

$$\frac{\alpha}{p} = f1\frac{E}{p} \qquad \text{and} \qquad \gamma = f2(\frac{E}{p})$$

f_1 and f_2 being some functions and $E = V/d$ 'α' may be assumed to follow an exponential function and may be written as

PASCHEN'S CURVE

$$\frac{\alpha}{p} = Ae^{Bp/E} \quad \text{or} \quad \alpha = pAe^{-Bpd/V_b}$$

or $$e^{-Bpd/V_b} = \frac{pA}{\alpha} \quad \text{or} \quad \frac{1}{\alpha} = \frac{e^{Bpd/V_b}}{pA}$$

or $$d \cdot \frac{1}{\alpha d} = \frac{e^{Bpd/V_b}}{pA}$$

We know that $$\alpha d = \ln\left(1 + \frac{1}{\nu}\right)$$

Therefore, $$d = \frac{e^{Bpd/V_b}}{pA} \ln\left(1 + \frac{1}{\nu}\right)$$

Assuming ν to be constant, let $\ln\left(1 + \frac{1}{\nu}\right) = k$

Then $$d = \frac{e^{Bpd/V_b}}{pA} K$$

PASCHEN'S CURVE

In order to obtain minimum sparking potential, we rearrange the above expression as

$$V_b = f(pd)$$

Taking ln on both sides, we have

$$\frac{Bpd}{V_b} = \ln \frac{Apd}{K}$$

or $$V_b = \frac{Bpd}{\ln Apd/k}$$

Differentiating V_b w.r. to pd and equating the derivative to zero

$$\frac{dV_b}{d\,(pd)} = \frac{\ln \frac{Apd}{K} \,.\, B - Bpd \,.\, \frac{K}{Apd} \,.\, \frac{A}{K}}{\left(\ln \frac{Apd}{K}\right)^2} = \frac{B \ln \frac{Apd}{K}}{\left(\ln \frac{Apd}{K}\right)^2} - \frac{B}{\left(\ln \frac{Apd}{K}\right)^2} = 0$$

or $$\frac{1}{\ln \frac{Apd}{K}} = \frac{1}{\left(\ln \frac{Apd}{K}\right)^2}$$

PASCHEN'S CURVE

or $$\ln \frac{Apd}{K} = 1$$

or $$\frac{Apd}{K} = e$$

or $$(pd)_{min} = \frac{e}{A} K$$

or $$V_{b\,min} = \frac{B\,e^{K/A}}{1} = \frac{B}{A} . eK$$

$$V_{bmin} = 2.718 \frac{B}{A} \ln\left(1 + \frac{1}{\nu}\right)$$

If values of A, B and ν are known both the (pd) min and V_{bmin} can be obtained.

PASCHEN'S CURVE

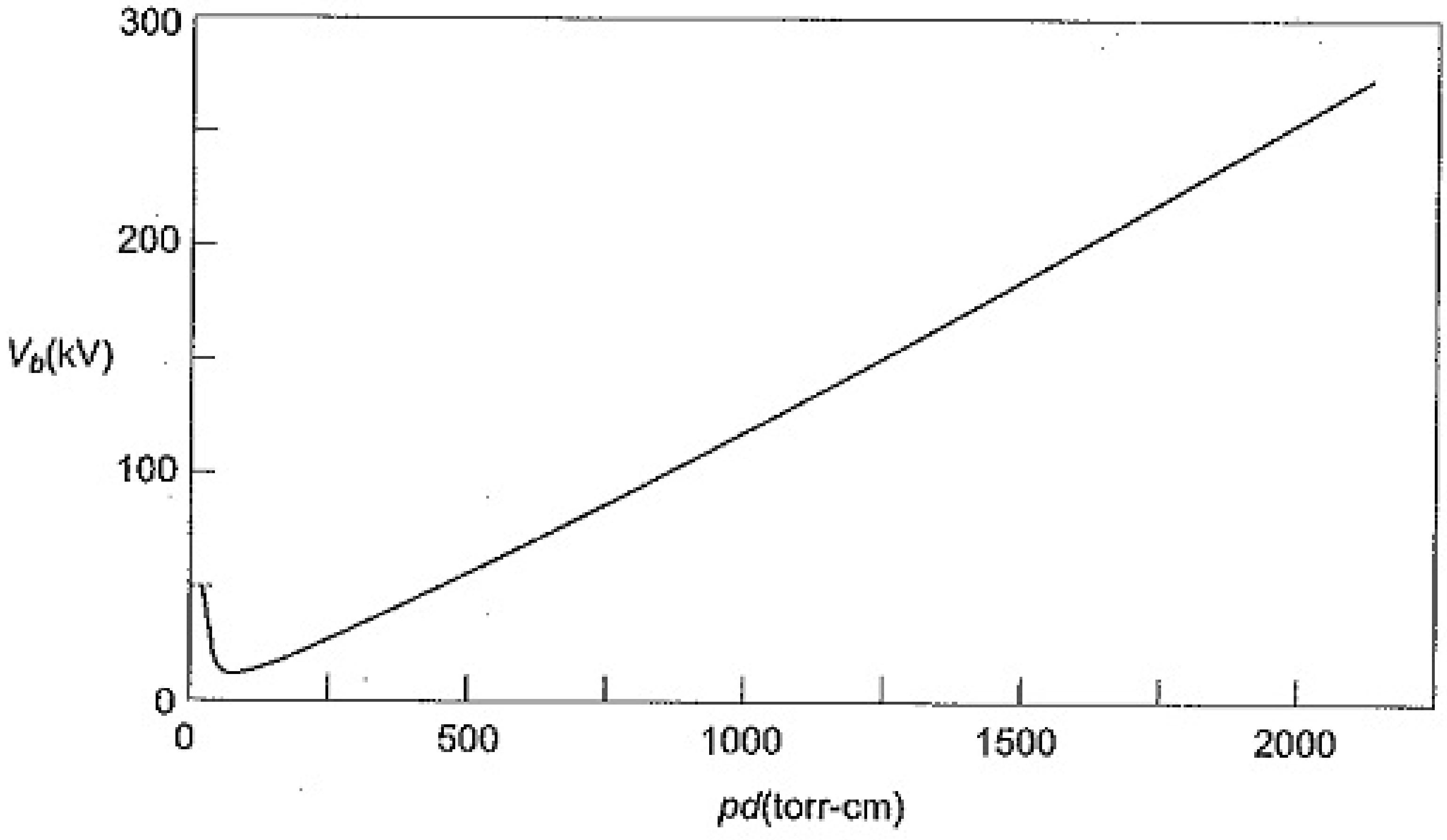


Fig 10 *Breakdown voltage (V_b) as a function of pd in SF6. (Electrical Breakdown of Gases, edited by J.M. Meek and J.D.Craggs, John Wiley, New York, 1978)*

PASCHEN'S CURVE

Based on the experimental results, the breakdown potential of air is expressed as a power function in *pd* as

$$V = 24.22\left[\frac{293pd}{760T}\right] + 6.08\left[\frac{293pd}{760T}\right]^{1/2}$$

It may be noted from the above formula that the breakdown voltage at constant pressure and temperature is not constant.

At 760 torr and 293 K.

$$E = V/d = 24.22 + \left[\frac{6.08}{\sqrt{d}}\right] \text{kV/cm}$$

This equation yields a limiting value for E of 24 kV/cm for long gaps and a value of 30 kV/cm for $\left(\frac{293pd}{760T}\right) = 1$, which means a pressure of 760 torr at 20°C with 1 cm gap. This is the usually quoted breakdown strength of air at room temperature and at atmospheric pressure.

Thank You