GOVERNMENT COLLEGE OF ENGINEERING,KALAHANDI

DEPARTMENT OF ELECTRICAL ENGINEERING

Lecture notes on High Voltage Engineering

Submitted By

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HIGH VOLTAGE ENGINEERING

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MODULE-I

Conduction and Breakdown in Gases: Gases as Insulating Media, Collision Processes, Ionization Processes, Townsend's Current Growth Equation, Townsend's Criterion for Breakdown, Experimental Determination of Coefficients a and γ, Breakdown in Electronegative Gases, Time Lags for Breakdown, Streamer Theory of Breakdown in Gases, Paschen's Law, Breakdown in Non-uniform Fields and Corona Discharges, Post-Breakdown Phenomena and Applications, Practical Considerations in using Gases and Gas Mixtures for Insulating Purposes Vacuum Insulation.
(Chapter-2: 2.1 to 2.4 and 2.6 to 2.15)

MODULE-II

Conduction and Breakdown in Liquid Dielectrics: Liquids as Insulators, Pure Liquids and Commercial Liquids, Conduction and Breakdown in Pure Liquids, Conduction and Breakdown in Commercial Liquids.
Breakdown in Solid Dielectrics: Intrinsic Breakdown, Electromechanical Breakdown, Thermal Breakdown, Breakdown of Solid Dielectrics in Practice, Breakdown in Composite Dielectrics, Solid Dielectrics used in Practice.
Generation of High Voltages and Currents: Generation of High Direct Current Voltages, Generation of High Alternating Voltages, Generation of Impulse Voltages, Generation of Impulse Currents.
(Chapter-3: 3.1 to 3.4, Chapter-4: 4.2 to 4.7 and Chapter-6: 6.1 to 6.4)

MODULE-III

Measurement of High Voltages and Currents: Measurement of High Direct Current Voltages, Measurement of High AC and Impulse Voltages, Measurement of High Currents-Direct, Alternating and Impulse.
Non-Destructive Testing of Materials & Electrical Apparatus: Measurement of Direct Current Resistivity, Measurement of Dielectric Constant and Loss Factor, Partial Discharge Measurements.
High Voltage Testing of Electrical Apparatus: Testing of Insulators, Bushings, Isolators, Circuit Breakers, Cables, Transformers and Surge Arresters.
(Chapter-7: 7.1 to 7.3, Chapter-9: 9.2 to 9.4 and Chapter-10: 10.1 to 10.5)

INTRODUCTION

POTENTIAL (V) : Potential at any point in an electric field is defined as the work done in bringing a unit positive charge from infinity to the point of consideration against electric field.

The unit of this potential will depends upon:

i. The unit of charge taken
ii. The unit of work done

V=(W/Q) volt

Work (W) =joule; charge (Q)= coulomb

POTENTIAL DIFFERENCE: Potential difference of one volt exists between two points if 1 joule of work is done by shifting a charge of 1 coulomb from one point to another.

POTENTIAL GRADIENT (Φ): The rate of change of potential with respect to distance is called potential gradient.

Φ = (dv/dx)

ELECTRIC FIELD INTENSITY (E): E=(-dv/dx)

The negative sign indicate the electric field is directed outward and the potential increases inward.

BREAKDOWN VOLTAGE AND DIELECTRIC STRENGTH

i. In high voltage system the important materials used as conductor and insulator.
ii. Conductors carry the current while the insulators resist the flow of current in undesired path.
iii. An insulator or dielectric is a substance in which there are no mobile electrons available for dielectric conduction.
iv. When a voltage is applied to an insulator exceeds a certain value, then it breaks down and allows a heavy electric current to flow through it these voltage is called as the breakdown voltage of that insulator.
v. If the insulator is a solid medium then it get punctured or cracked.
vi. The disruptive or breakdown voltage of an insulator is the minimum voltage required to breakdown.

DIELECTRIC STRENGTH: dielectric strength of an insulator is the maximum potential difference which a unit thickness of the medium can withstand without breaking down.

Unit of breakdown voltage = V and KV.

Unit of dielectric strength = V/m or KV/mm.

Dielectric strength of an insulating material depends upon temperature, pressure, thickness of the insulator, humidity, shape, material of electrodes, surface condition of electrodes, etc.

TYPES OF INSULATORS;

i. Gaseous or vacuum insulator.
ii. Liquid insulator.
iii. Solid insulator.
iv. Composite insulator. (more than one type of insulators are used together in parallel, giving rise to composite dielectrics)

DIFFUSION COEFFICIENT: In electrical discharges, whenever there is a non-uniform concentration of charges there will be migration of charges from region of higher concentration to the region of lower concentration. This process is called diffusion and this causes a deionising effect in the region of lower concentration.

The presence of walls confining a given volume increases the deionisation effect since charge particles lose their charge on hittting the walls.

The diffusion rate is govern by the diffusion passing through unit area in unit time perpendicular to the concentration gradient ad per unit concentration gradient.

$dn/dt= D \nabla^2 n$

n=concentration of particle

d= coefficient of diffusion

According to kinetic theory d=1/3 (lc).

ELECTRON ENERGY DISTRIBUTION—

There are two electron energy distribution function are widely used are-

i. Maxwellian.
ii. Druyesteynian

These two function are generally applicable to elastic condition.

Maxwellian distribution functions applied whenever there is a thermal equilibrium between electron and molecules

$F(\epsilon)=C_1\, \varepsilon^{0.5} e^{(-1.5\epsilon/\epsilon)}$

C_1=constant

$\bar{\varepsilon}$ = mean energy

ε=electron energy

DRUYESTEYNIAN distribution function is applied whenever the electron or ion energy is much greater than the thermal energy. This type of distribution is applicable for Townsends discharges.

$F(\epsilon)=C_2\ \varepsilon^{0.5}e^{(-0.5\epsilon^2/\bar{\epsilon}^2)}$

COLLISION CROSSECTION

Collision of cross section is defined as the area of contact b/w two particles during a collision in other words the total area of impact. This area of contact is different for different type of collision,

EX-the area contact is more in ionisation process. For an excitation it is less

For simultaneously occurring process such as ionisation charge transfer, chemical reaction etc. the effective cross section is obtain by simple addition o all the cross section

$q_t= q_i+q_e+q_c+$…………

q_t=total cross section

The collision cross section is also expressed in terms of the probability of a collision to take place

P=nq

which is the reciprocal of mean free path

MEAN FREE PATH (λ)

The average distance between collisions. It is random quantity and its mean value depends upon the concentration of particles and the density of the gas.

It can be expressed as

$$\lambda=k/p$$

Where k=constant

p=gas pressure in micron

If value of k from nitrogen is 5, at a pressure of 2 torr

1torr=10^3torr

5 =$5/10^3$ =$\lambda X10^{-3}$ cm

$1\propto\lambda/p$

λ is very large at low pressure and very small at high pressure.

Conduction and breakdown in gaseous medium

- Gas as insulating medium:- Air,nitrogen,co2,ccl2f2,sf6,etc.most of electrical products use gas as insulating medium.
- When voltage applied on gaseous dielectric or insulator the following phenomenon occurs.
- When the applied voltage is low small current flows between the electrode and the insulation retains it electrical property.
- On the other hand if the applied voltage is large the current flowing through the insulation between the electrode increasing very sharply and electrical breakdown occurs.
- This electrical breakdown produces a short ckt between the electrode

.

Ionisation process

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

- Ionisation by collision

In this process a free electron collide with a neutral gas molecule and gives rise to a new electron and a positive ion.

Let us take two electrode cathode and anode under low pressure and applied an electric field 'E' across two parallel plate electrodes then any electron liberated at cathode will be accelerated more between collision.
If energy gained during this travel exceeds ionization potential then ionization take place.

- Photo-ionisation process

This process occurs when radiation energy absorbed by atom or molecule exceeds its ionization potential.
Several processes by which radiation can be absorbed by atoms are

1.Excitation of atom to higher energy state

2.Continuous absorption of the atom or dissociation of diatomic molecule or direct ionization

Collision process

The collision process are mainly gas processes which occurs due to the collision between the charge particle and gas molecule on electrical discharges as normally created from the collision process.There are two types of collision .

1.Elastic collision.

2.Inelastic collision.

Elastic collision

- It is the collision which occurs in no change in internal energy but only the kinetic energy redistributed.Elastic collision in practice does not occurs.
- When electron collide with gas molecule a single molecule traces a zigzag path during this travel it ia accelerated by electric field.
- Since electron are very light in weight they transfers a little amount of kinetic energy with the much heavier atom which result in little loss of energy and travels a t a greater speed than ion.

In elastic collision

- Inelastic collision are those in which internal change in energy takes place within an atom or an molecule with the expence of the total kinetic energy of the colliding particle.
- The collision often result in change in shape of the particle.
- E.g ionization, attachment and excitation are inelastic collision.

Mobility of ions and electron

When the energy gained by the ion in electric field is small as compared with thermal energy.The drift velocity of ion in the field direction may be expressed as

$$W=uE$$

- The mobility is mainly isa characteristics of gas through which ion moves at normal temp. and pr.
- Elctric force on an electron of charge on e

$$F=eE$$

Diffusion coefficient

In electrical discharges when there is non uniform concentration of charge there will be migration of charge from higher conc. to lower conc. And then causes a deionising effect in the rigion of lower conc.

- The prescribed wall containg a given vol. increasing the deionization effect.Charge particle loss their charge on heating the wall.
- The diffusion rate is governed by the diffusion passing through unit area in unit time perpendicular to the conc.and for unit conc. Gradient.
  dn/dt=Dv2n
- According to privacy theory
  D=1/3(lc)
  L=mean free path
  C=avg velocity

Secondary Ionization process

Secondary ionization processes by which secondary electrons are produced at sustain a discharge after it is established due to ionization by collision and photoio

(a) Electron Emission due to Positive Ion Impact

Positive ions are formed due to ionization by collision or by photo ionizat positively charged they travel towards the cathode. A positive ion approaching a m can cause emission of electrons from the cathode by giving up its kinetic energy or total energy of the positive ion, namely, the sum of its kinetic energy and the ioniz greater than twice the work function of the metal then one electron will be ejecte electron will neutralize the ion. The probability of this process is measured as γ_i the Townsend's secondary ionization coefficient due to positive ions and is defi yield of electrons per incident positive ion. γ_i increases with ion velocity and depe of gas and electrode material used.

(b) Electron Emission due to Photons

To cause an electron to escape from a metal, it should be given enough energy to surface potential barrier. The energy can also be supplied in the form of a photon light of suitable frequency. Electron emission from a metal surface occurs condition.

$$h \, . \, \upsilon \leq \varphi$$

Where φ is the work function of the metallic electrode. The frequency (υ) is relationship.

$$\upsilon = \frac{\varphi}{h}$$

is known as the threshold frequency. For a clean nickel surface with $\varphi = 4.5\,eV$ frequency will be that corresponding to a wavelength λ=2755 Å. If the incident greater frequency than the threshold frequency, then the excess energy goes partly energy of the emitted electron and partly to hit the surface of the electron. Since few electrons volts, the threshold frequency lies in the far ultraviolet electromagnetic radiation spectrum.

(c) Electron Emission due to Metastable and Neutral Atoms

lifetime of other excited states is too short for them to reach the cathode and cause electron emission, unless they originate very near to the cathode surface. Therefore, the yields can also be large nearly 100%, for the interactions of excited He atom with a clean surface of Molybdenum, nickel or magnesium. Neutral atoms in the ground state also give rise to secondary electron emission if their kinetic energy is high (≅ 1000 eV). At low energies the yield is considerably

IONIZATION PROCESS

A gas in its normal state is almost a perfect insulator. When a high voltage is applied between the electrodes immersed in a gaseous medium, the gas act as conductor and breakdown occurs.

There are several process responsible for breakdown of gas such as:-

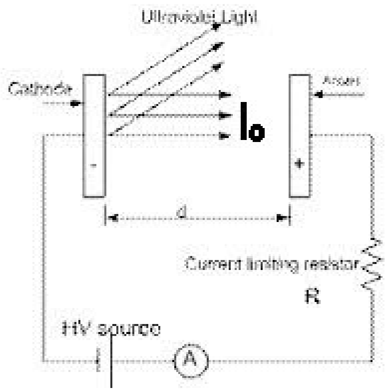
1- Ionization by collision

2- Photo ionization

3-Secondary ionization

1. IONIZATION BY COLLISION

In the process of ionization by collision, a free electron collide with a neutral gas molecule and gives rise to new electron and positive ion.



I_0 – Initial current at cathode

Let us consider a low pressure gas column in which an electric field 'E' is applied across the two plane parallel electrode. Then any electron produce at the cathode by the falling of UV ray on cathode, ionizes the neutral gas molecule or atom producing positive ion and additional electron.

The additional electron themselves makes the ionizing collision and process repeat itself. This represent an increase in electron current; since number of electron reaching anode per unit time is greater than those of cathode.

Similarly the positive ions move towards the cathode and on bombardment with cathode create secondary electron.

If the energy gain by the electron is more than the ionization energy of the electron then ionization takes place.

$\varepsilon > V_i$

Where;

ε :- energy gain by electron

V_i:- ionization energy of electron

The process can be represented as

$\varepsilon > V_i$

$e^- + A$ -----------------------→ $e^- + A^+ + e^-$

Where;

A :- neutral atom molecule

A^+ :- positive ion

e^- :- electron

2. PHOTO IONIZATION

The phenomena associate with ionization by radiation, involves interaction of radiation and atom.

Photo ionization occurs when energy of the photon received by the electron is more than the ionization energy.

The process can be represented

$$A^{+} + h\surd \xrightarrow{h\surd > V_i} A^{+} + e^{-}$$

There are several process by which radiation can be absorbed by atom. Such as

(a) Excitation of atom to a higher energy state

$$A^{+} + e^{-} \text{--------------------->} A^{*} + e^{-}$$

Where;

A^{*} :- excited state of atom

(b) Continuous absorption by direct excitation of atom or direct ionization.

As excited atom emits radiation, when the electron returns to the ground state

The reverse process takes place when an atom absorb radiation.

$$h\surd + A \text{ <------------------> } A^{*} \qquad eq^{n}(1)$$

photo ionization occurs when

$\lambda \leq c.h / V_i$ $eq^{n}(2)$

where;

h -> Plank's constant=$6.6*10^{-34}$ Js

c-> velocity of light

λ->wavelength of incident radiation

√->threshold frequency/ frequency of radiation

Now, substitute the value of h & c in eq^n(2)

$\lambda \leq (1.27 / V_i)$ µcm

Where;

V_i is in eV (electron volt)

The higher the ionization energy the shorter will be the wavelength of the radiation which is capable of causing ionization.

ELECTRON ATTACHMENT PROCESS

- **The types of collision in which electron may be attached to atoms or molecules to form negative ions are called attachment collision.**
- **Electron attachment process depends on the energy of the electron and the nature of the gas.**
  Ex- O_2, CO_2, CL_2, F_2, C_2F_6, C_3F_8, CCL_2F_2, and SF_6
- **An electron-attachment process can be represented as**

$$\text{Atom}+e^{-}+k \rightarrow \text{negative atomic ion} + (E_a+K)$$

- **The energy liberated in this process is kinetic energy (k) + electron affinity E_a.**
- **In this attachment process the atom or molecules have vacancies in their outermost shells and, therefore, have an affinity called electrode.**
- **The attachment process plays a very important role in the removal of free electrons from an ionised gas when arc interruption occurs in gas-insulated system.**

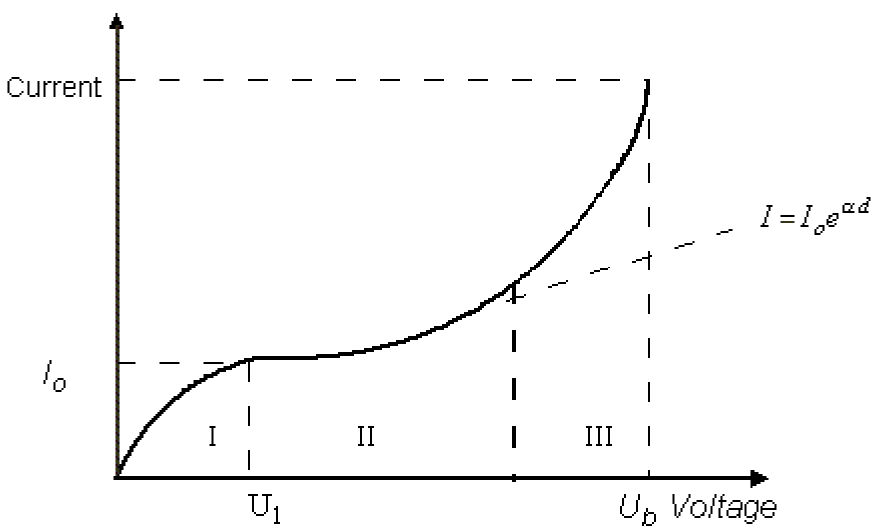
NOTE

Electron attachment decreases the no of electron, where the ionisation process decreases the no of electron.

TOWNSEND'S CURRENT GROWTH EQUATION:

Townsend's first ionisation co-efficient(α):

- Consider a parallel plate capacitor having gas as an insulating medium and separated by distance'd'.
- When no electric field is set up between the plate a state of equilibrium exist between the state of electron and positive ion generation due to the decay process, This state of equilibrium will be distributed at the moment a high electric field is applied.
- (a)The variation of current as a function of voltage was shown by Townsend.
- (b)He found that the current at first increase proportionally as the voltage is increase and then remains constant I_0 which corresponds to the saturation current at still higher voltages the current increase exponentially.



- (c)The exponential increase in current is due to ionisation of gas by electron collision.
- (d)As the voltage increase (V/d) increases and hence the electrons are accelerated more and more and between collisions this acquire higher kinetic energy and therefore procedure more and more electrons.
- To explain the exponential rise in current Townsend introduce a co-efficient α known as Townsend first ionisation co-efficient and is defined as the number of electrons produced by an electron per unit length of path in the direction of field.
- α is a function of gas pressure p and E/p.
- Referring to the figure 2.1

  Let n_0 be the number of electrons leaving the cathode and when these have moved through a distance x from the cathode these becomes n.

Now when ‘n’ electron move through a distance dx produce additional dn electrons due to collision

Therefore

$$dn = \alpha n dx$$

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

At $x = 0, n = n_0$

Therefore $\ln n_0 ¿ A$

$\ln n = \alpha x + \ln n_0$

$$\ln \frac{n}{n0} = \alpha x$$

$$\frac{n}{n0} = e^{\alpha x}$$

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

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

$n = n_0 e^{\alpha d}$

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

$e^{\alpha d} - 1 = ¿_0 ¿ / n_0$

Therefore the average current in the gap

$I = I_0 e^{\alpha d}$

This equation called as Townsend’s current growth equation.

where I_0 initial current at the cathode

The term $e^{\alpha d}$ is called electron avalanche and it represents the number of electron produced by one electron in travelling from cathode to anode.

NOTE:

ELECTRON AVALANCHE:

It is a process in which a number of free electrons in a gaseous medium are subjected to strong acceleration by an electric field, ionising the medium's atoms by collision (impact ionisation) releasing additional electrons which are themselves accelerated and collides with further atoms, releasing more electrons in a chain reaction. The result is the affected region of gas becomes plasma making it electrically conductive.

Current growth in the presence of secondary process:

- The single avalanche process described in the previous section becomes complete when the initial set of electrons reaches the anode.
- However, since the amplification of electrons (e^{ad}) is occurring in the field, the probability of additional new electrons being liberated in the gap by other mechanism increases and these new electrons create further avalanches.

The other mechanisms are

1. The positive ions liberated may have sufficient energy to cause liberation of electrons from the cathode when they collide each other.
2. The excited atoms or molecules in the avalanches may emit photons and this will lead to emission of electrons due to photon emission.
3. The metastable particles may diffuse back causing electron emission. The electrons produced by this process are called secondary electrons. The process is called secondary process.

The secondary ionisation coefficient or the Townsend's secondary ionisation coefficient (γ) is depends as the net number of secondary electrons produced per incident positive ion, photon, excited atom, and metastable particle.

- The total value of γ is the sum of the individual coefficients due to the three different process.

$$\gamma = \gamma_1 + \gamma_2 + \gamma_3$$

$\gamma =$ ¿ Townsend's secondary ionisation coefficient

Townsend's procedure for current growth:

→Let $n_0' =$ ¿number of secondary electrons produced due to secondary process

n_0 "¿total number of electrons leaving the cathode

Then $n_0 = {}_0 + n_0'$

The total number of electrons n reaching the anode becomes,

$n = n_0 e^{\alpha d}$

$n = ¿_0 + n_0')e^{\alpha d}$ (1)

And $n_0 = \gamma\, [n - ¿_0 + n_0')]$

$n_0' = \gamma\, (n - n_0) / (1+\gamma)$

Putting the value of n_0' in equation (1)

$n = n_0 e^{\alpha d} / 1 - \gamma\, [e^{\alpha d} - 1]$

$I = I_0 e^{\alpha d} / 1 - \gamma [e^{\alpha d} - 1]$ (2)

Townsend's criterion for breakdown

Equation (2) gives the total average current in a gap (cathode to anode) before the occurrence of breakdown as the distance between the electrodes is increased. The denominator of the equation tends to zero or the current becomes ∞, and at some critical distance the denominator is zero.

For d=ds, $1 - \gamma\, [e^{\alpha d} - 1]\, ¿\, 0$ (3)

For d<ds, $I = I_0$

For d=ds, $I \rightarrow \infty$

And if the external source for the supply I_0 is removed, I becomes zero.

- The current is limited only by the resistance of power supply and the external circuit. This condition is called Townsend's breakdown criteria.

And it can be written as,

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

Or $\gamma\, [e^{\alpha d} - 1] = 1$

Normally, $e^{\alpha d}$ is very large and hence the above equation reduces to

$\gamma e^{\alpha d}=1$ (4)

Townsend's criteria for spark formation or Townsend's breakdown criteria:

Spark breakdown voltage (v):

The voltage at which sparking occurs. and the corresponding distance d_s is called sparking distance.

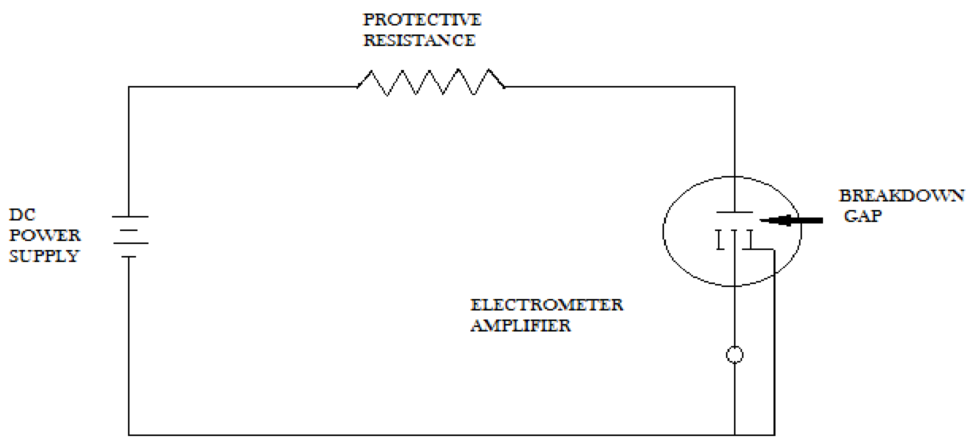
Note

The Townsend's mechanism explain the phenomena of breakdown only at no pressure, corresponding to

$P \times d \rightarrow$ (Gas pressure × Gap distance) of 1000 torr-cm and below.

EXPERIMENTAL DETERMINATIION OF COEFFICIENTS α AND γ

The experimental arrangement is shown in fig. 2.2.The electrode system consists of two uniform field electrodes. The high voltage electrode is connected to a variable high voltage dc source. The low voltage electrode consists of a central electrode and a guard electrode. The central electrode is connected to the ground through the high resistance of an electrometer amplifier having an input resistance of 10^9 to 10^13 Ω.The guard electrode is directly earthed. The electrometer amplifier measures currents in the range 10^-14 to 10^-8 A.

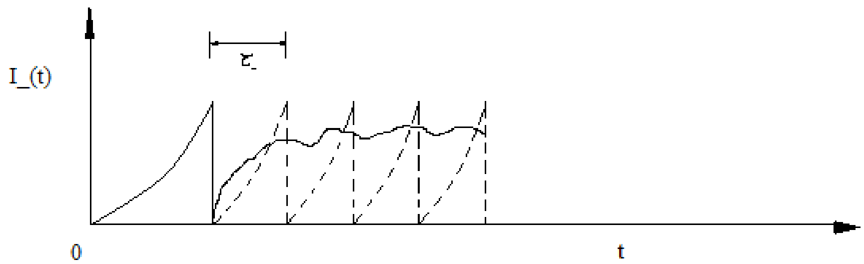


Experimental arrangement to measure ionisation coefficients α and γ .

The electrode system is placed in n ionization chamber which either a metal chamber made up of chromium plated mild steel or stainless steel or glass chamber. The electrodes are usually made of brass or stainless steel. The chamber is evacuated to a very high vacuum of the order of 10^-4 to 10^-6 torr.Then it is filled with the desired gas and flushed several times till all the residual gases and air is removed. The pressure inside the chamber is adjusted to few torr depending on the gap separation and left for about half an hour for the gas to fill the chamber uniformly.

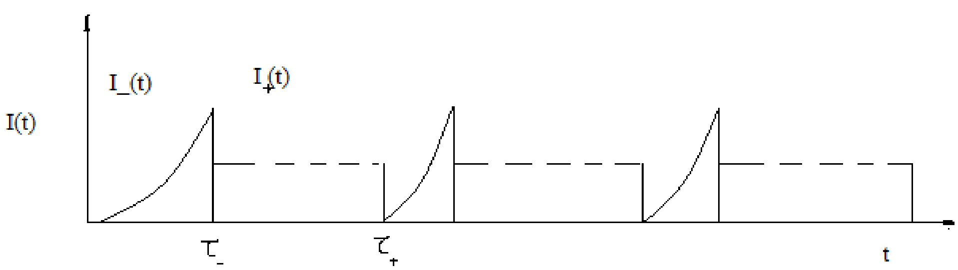
The chamber is irradiated using an UV lamp kept outside the chamber. The UV radiation produces the initiatory electrons by photo electric emission.

When the dc voltage is applied and when the voltage is low, the current pulses start appearing due to the electrons and positive ions as shown in figs 2.3a and 2.3b.These records are obtained when the current is measured using a cathode ray oscilloscope.



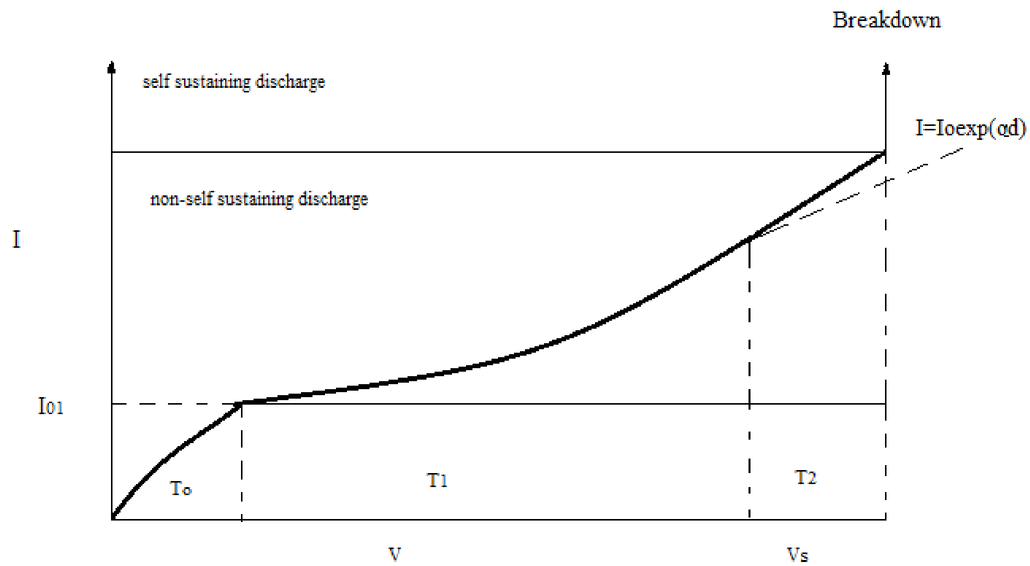
(b) When secondary electrons are produced by photons at the cathode _______ ideal,
______ actual.
I(t) is the total current and I_(t) and $I_+(t)$ are electron-ion currents. τ_- and τ_+ are the electron and ion-transit times.

Current as a fuction of time



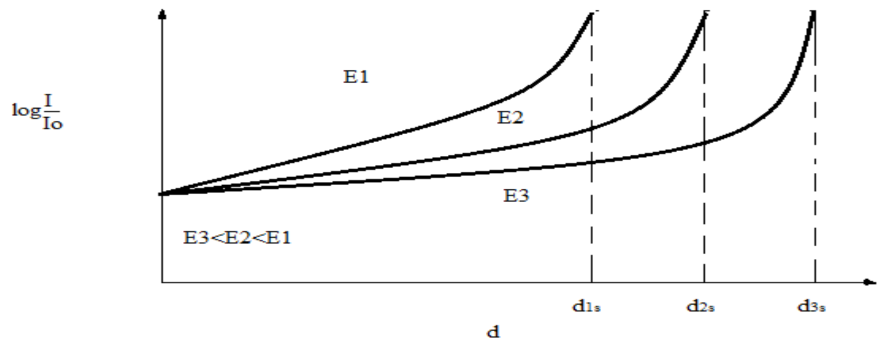
(a) When secondary electrons are produced at the cathode by positive ions

When the applied voltage is increased, the pulses disappear and an average dc current is obtained as shown in fig 2.4.In the initial portion (To) the current increases slowly but unsteadily with the voltage applied. In the regions T1 and T2 current increases steadily due to the Townsendmechanism. Beyond T2 the current rises very sharply and a spark occurs.



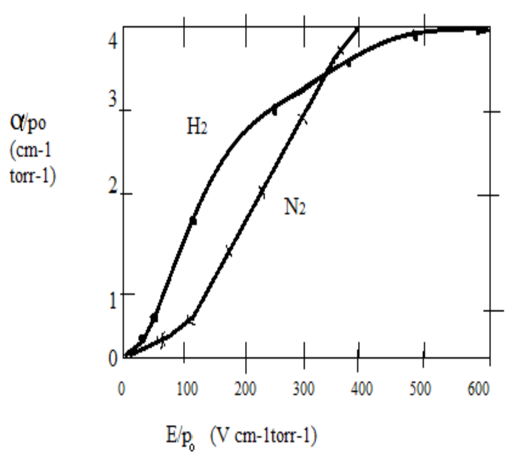
Typical current growth curve in a Townsend discharge.

For determining α and ¥ coefficients, the voltage-current characteristics for different gap settings are obtained. From these results, a log I/Io versus gap distance plot is obtained under constant field (E) conditions as shown in fig 2.5.The slope of the initial portion of the curves gives the value of α.Knowing α,¥ can be found from Eq.(2.20) using points on the later upturn portion of graphs. The experiment can be repeated for different pressures.



Townsend type log(I/Io) vs. d plot

It can be easily seen that α/p and ¥ are the functions of E/p.The spark over voltage for any gap length ds is vs=Eds where ds is the critical gap length for that field strength as obtained from the graph.It may be noted that if Io the initial current is more the average anode current I will be more, but the relation log I/Io versus d plot remains the same. Typical variation of α is shown in fig. 2.6.



The variation of α/p with E/p in hydrogen and nitrogen, Po in both x and y axes refers to values of pressure reduced to 0^0C.

BREAKDOWN IN ELECTRONEGATIVE GASES

The gases in which electron attachment process occur is called as electronegative gases.

The most common attachment process encounter in gasses are

1. Direct attachment

2. Dissociative attachment

DIRECT ATTACHMENT

An electron directly attaches to form a negative ion.

Symbolically,

AB + e -------AB- +hv ----1

DISSOCIATIVE ATTACHMENT

The gas molecules splits into their constituent atom and the

Symbolically,

AB + e----------A + B+ +e -------2

Example:

Simple gas – O_2 , SF_6 , CO_2 , Fluorocarbon.

In this gases A = Sulphur or carbon atoms

B = Oxygen atom or one of the halogen atom

----with such gases, the Townsends current growth is modified to include ionization and attachment process.

----an attachment coefficient(n) is defined as the number of attaching collisions made by one electron drifting 1cm in the direction of field.

-----under this condition, the current reaching the anode

The average current growth in a uniform field can be written as

$$I = I.\ \frac{\left(\left(a/a-n\right)e^{(a-n)d}\right)-\left(n/a-n\right)}{1-\{v\ (a/(a-n))[e^{(a-n)d}-1]\}}$$

-The Townsend criteria’s for attaching gases can also be obtained by equating the denominator of the above equation to zero.

$$v * a/(a-n)\ [e^{(a-n)d}-1] = 1 \qquad ....(4)$$

For spark breakdown

-For a>n, breakdown is always possible irrespective of the value of a ,n and v.

-For n>a, equation (4) approaches an asymptotic form with increase value of d, and the equation becomes

v *(a/a-n)=1

or a=n/1-r …….(5)

-If v is very small (< 10^4), The above equation(5) becomes

a=v

STREAMER THEORY OF BREAKDOWN IN GASES

Townsend mechanism when applied to breakdown at atmospheric pressure was found to have certain drawbacks. Firstly, according to the Townsend theory, current growth occurs as a result of ionization processes only. But in practice, breakdown voltages were found to depend on the gas pressure and the geometry of the gap. Secondly, the Sphere gap Transformer Impulse voltage mechanism predicts time lags of the order of 1(T5S, while in actual practice breakdown was observed to occur at very short times of the order of 1(T8S. Also, while the Townsend mechanism predicts a very diffused form of discharge, in actual practice, discharges were found to be filamentary and irregular. The Townsend mechanism failed to explain all these observed phenomena and as a result, around 1940, Raetherand, Meek and Loeb independently proposed the Streamer theory.

The theories predict the development of a spark discharge directly from a singleavalanche in which the space charge developed by the avalanche itself is said to transform the avalanche into a plasma streamer. Consider Fig. 2.12. A single electron starting at the cathode by + Anode ionization builds up an avalanche that crosses the gap. The electrons in the avalanche move very fast comparedwith the positive ions. By the time the electrons reach the anode the positive ions are virtually in their original positions and form a positive space charge at the anode. This enhances the field, and the secondary avalanches are formed from the few electrons produced due to photo- Cathode ionization in the space charge region. This occurs first near the anode where Fig. 2.12 Effect of space charge the space charge is maximum. This produced by an avalanche results in a further increase in the on the applied electric field space charge. This

process is very fast and the positive space charge extends to the cathode very rapidly resulting in the formation of a streamer. Comparatively narrow luminous tracks occurring at breakdown at high pressures are called streamers. As soon as the streamer tip approaches the cathode, a cathode spot is formed and a stream of electrons rush from the cathode to neutralize the positive space charge in the streamer; the result is a spark, and the spark breakdown has occurred. The three successive stages in the development of the streamer are shown diagrammatically in Fig. 2.13 in which *(a)* shows the stage when avalanche has crossed the gap, *(b)* shows that the streamer has crossed half the gap length, and *(c)* shows that the gap has been bridged by a conducting channel.
Meek proposed a simple quantitative criterion to estimate the electric field that transforms an avalanche into a streamer. The field *Er*produced by the space charge, at the radius r, is given by
Er=5.27xl0-7<*2^v/cm (2.20) *(x/p)*where a 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. According to Meek, the minimum breakdown voltage is obtained when *Er*= *E* and *x* = *d* in the above equation.
Fig. 2.13 Cathode directed streamer.

The equation simplifies into, arfflnf*(-P^)* V 14.5+l*(*n*P*f -*J*X *2^* lnf*(-p))* (2.21) This equation is solved between *ajp*and *EIp*at which a given *p* and *d* satisfy the equation. The breakdown voltage is given by the corresponding product of £ and *d.*The above simple criterion enabled an agreement between the calculated and the measured breakdown voltages. This theory also neatly fits in with the observed filamentary, crooked channels and the branching of the spark channels, and cleared up many ambiguities of the Townsend mechanism when applied to breakdown in ahigh pressure gas across a long gap.It is still controversial as to which mechanism operates in uniform field conditions over a given range of *pd*values. It is generally assumed that *torpd*values below 1000 torr-cm and gas pressures varying from 0.01 to 300 torr, the Townsend mechanism operates, while at higher pressures and *pd* values the Streamer mechanism plays the dominant role in explaining the breakdown phenomena. However, controversies still exist on these statements.

PASCHEN'S LAW

It has been shown earlier (refer Sec. 2.5) that the breakdown criterion in gases is
given as

Y [exp (ad)-I]=I (2.22)

where the coefficients a and y are functions of *EIp,* i.e
a- *f (E*p- y, and Y= /J^
Also E= *%d*

Cathode

Anode

Substituting for *E* in the expressions for a and y and rewriting Eq. (2.18) we have
/2[^][exp{p^|-l]=l (2.23)
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 functions /i and/2 we can rewrite Eq. (2.22) as, *V= flpd)* (2.24)

This equation is known as Paschen's law and has been experimentally established for many gases, and it is a very important law in high voltage engineering. The Paschen's curve, the relationship between *V* and *pd*is shown in Fig. 2.14 for three gases CC>2, air and H2. It is seen that the relationship between *V* and *pd*is not linear and has a minimum value for any gas. The minimum breakdown voltages for various gases are given in Table 2.1

Table 2.1 Minimum Sparking Potential For Various Gases

Gas	*Vs* min	*pd*at *V5* min
	(V)	(torr-cm)
Air	327	0.567
Argon	137	0.9
H_2	273	1.15
Helium	156	4.0
CO_2	420	0.51
N_2	251	0.67
N_2O	418	0.5
O_2	450	0.7
SO_2	457	0.33
H_2S	414	06

The existence of a minimum sparking potential in Paschen's curve may be explained as follows:
For values of pd >*(pd)m^,* electrons crossing the gap make more frequent collisions with gas molecules than at *(pd)m^,* but the energy gained between collisions is lower. Hence, to maintain the desired ionization more voltage has to be applied. For *pd*<(pOmin, electron may cross the gap without even making a collision or making only less number of collisions. Hence, more voltage has to be applied for breakdown to occur.
However, in some gases Paschen's law is not strictly obeyed, and sparking potentials at larger spacings for a given value *ofpd*are higher than at lower spacingsfor the same *pd* value. This is attributed to the loss of electrons fro^i the gap due to diffusion.
The sparking potentials for uniform field gaps in air, CO2 and H2 at 2O0C are shown in Fig. 2.14. It has been observed that the cathode materials also affect the breakdown values. This is shown in Fig. 2.15 for cathodes made of barium, magnesiumand aluminium.pj(torr-cm)
Fig. 2.14 Breakdown voltage-pdcharacteristics for air, CO andhydrogen
pd(torr-cm)
FIg. 2.15 Dependence of breakdown voltage on the cathode materials Air
Breakdown voltage, *y* Breakdown Voltage, volts
In order to account for the effect of temperature, the Paschen's law is generally stated as *V =f(Nd)* where *N* is the density of the gas molecules. This is necessary, because the pressure of the gas changes with temperature according to the gas law *pv*= NRT, where v is the volume of the gas, *T* is the temperature, and *R* is a constant.
Based on the experimental results, the breakdown potential of air is expressed as a power function in *pd*as *-*»psgM^f It may be noted from the above formula that the breakdown voltage at constant pressure and temperature is not constant.
At 760 ton and 2930AT.
E =Vld= 24.22 + fe=H kV/cm (2.26) LVdJ

This equation yields a limiting value for E of 24 kV/cm for long gaps and a value of 30 kV/cm for J^* = 1, which means a pressure of 760 torr at 2O0C with 1 cm gap. i /Ov./ I This is the usually quoted breakdown strength of air at room temperature and at atmospheric pressure.

BREAKDOWN IN NON_UNIFORM FIELD AND

CORONA DISCHARGE

- **BREAKDOWN IN NON UNIFORM FIELD**
- **CORONA DISCHARGES**

BREAKDOWN IN NON_UNIFORM FIELD

- IN NON UNIFORM FIELD,SUCH AS COAXIAL CYLINDERS,POINT_PLANE AND SPHERE_PLANEGAPS,THE APPLIED FIELD VARIES ACROSS THE GAP.
- SIMILARLY ,TOWNSEND'S FIRST IONIZATION COEFFICIENT **(α)**ALSO VARIES WITH THE GAP.
- TOWNSEND'S CRITERION FOR BREKDOWN NOW BECOMES

$$\Upsilon\left\{\exp\left[\int_0^d \alpha\, dx\right] - 1\right\} = 1$$

- MEEK EQUATION FOR THE RADIAL FIELD AT THE HEAD OF AN AVALENCHE WHEN IT HAS ACROSSED DISTANCE **X** IS MODIFIED AS

$$Er = \frac{5.27\times10^{-7}\,\alpha_x \exp\left[\int_0^x \alpha\, dx\right]}{\left(\frac{x}{p}\right)^{\frac{1}{2}}}$$

WHERE **αx**IS THE VALUE OF **α**AT THE HEAD OF THE AVALANCHE AND **P** IS THE GAS PRESSURE.

- THE CRITERION FOR THE FORMATION OF THE STREAMER IS REACHED WHEN THE SPACE CHARGE FIELD Er APPROACHES A VALUE EQUAL TO THE APPLIED FIELD AT THE HEAD OF THE AVALANCHE.

- THIS EQUATION HAS BEEN SUCCESSFULLY USED FOR DETERMINIG THE CORONA ONSET VOLTAGES OF MANY NONUNIFORM GEOMATRIES.

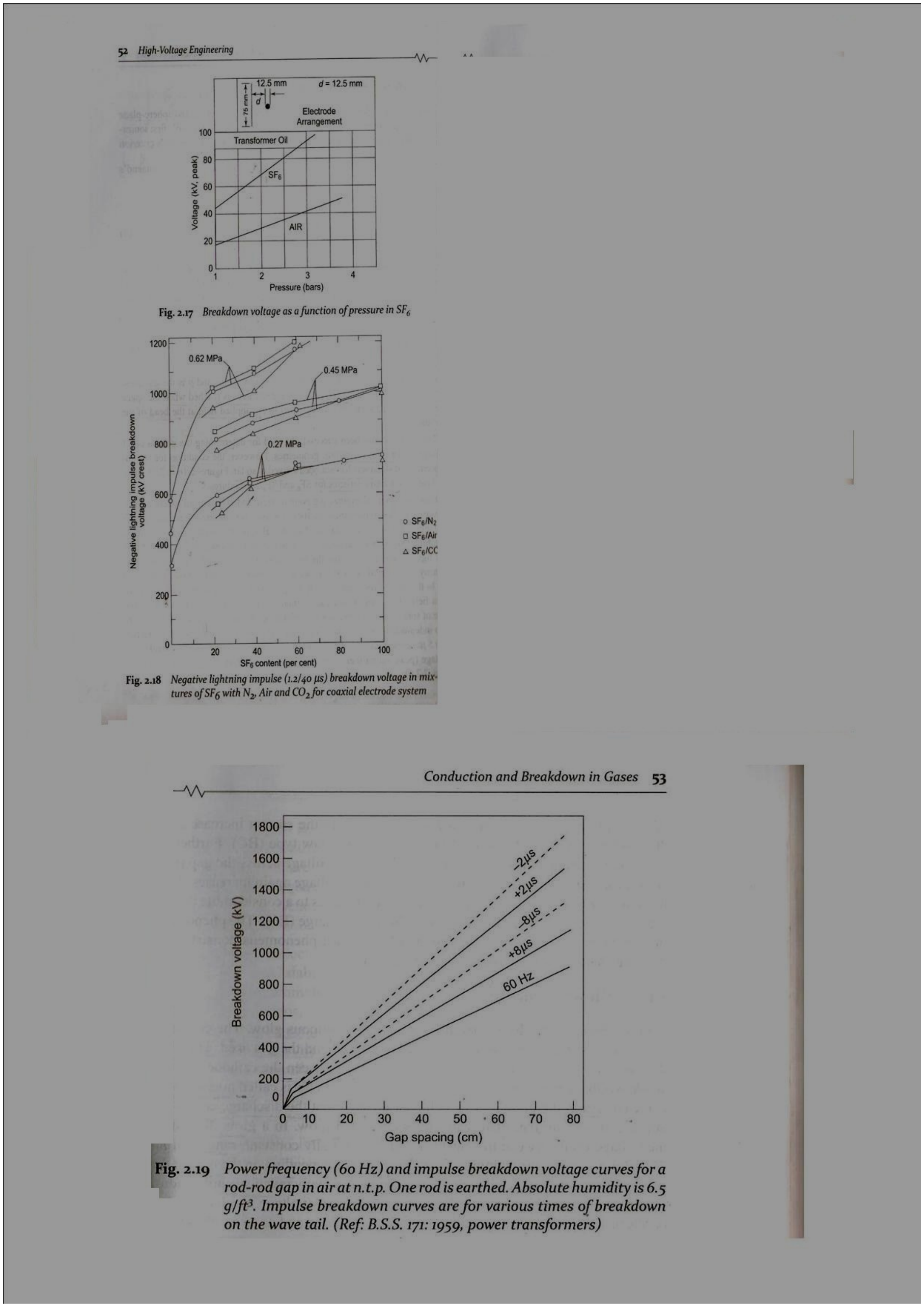

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Fig. 2.17 Breakdown voltage as a function of pressure in SF_6

Fig. 2.18 Negative lightning impulse (1.2/40 μs) breakdown voltage in mixtures of SF_6 with N_2, Air and CO_2 for coaxial electrode system

Conduction and Breakdown in Gases 53

Fig. 2.19 Power frequency (60 Hz) and impulse breakdown voltage curves for a rod-rod gap in air at n.t.p. One rod is earthed. Absolute humidity is 6.5 g/ft³. Impulse breakdown curves are for various times of breakdown on the wave tail. (Ref: B.S.S. 171: 1959, power transformers)

CORONA DISCHARGES

- IF THE ELECTRIC FIELD IS UNIFORM, A GRADUAL INCREASE IN VOLTAGE ACROS A GAP PRODUCES A BREAKDOWN OF THE GAP IN THE FORM OF A SPARK WITHOUT ANY PRILIMINARY DISCGARGES.
- IF THE FIELD IS NON UNIFORM,AN INCREASE IN VOLTAGE WILL FIRST CAUSE A DISCHARGE IN TH GAS TO APPER AT POINTS WITH HIGHEST ELECTRICFIELD INTENSITY,NAMELY A SHARP POINTS OR WHERE THE ELECTRODES ARE CURVED OR ON TRANSMISSION LINES.THIS FORM OF DISCHARGE IS CALLED A CORONA DISCHARGE
- CORONA DISCHAGE CAN BE OBSERVED AS A BLUISH LUMINSCENSE.IT PRODUCES A HISSING NOISE AND THE AIR SURROUNDING THE CORONA REGION BECOMES CONVERTED INTO OZONE.CORONA ALSO GIVE RISE TO RADIO INTERFERENCE.
- THE VOLTAGE GRADIENT REQUIRED TO PRODUCE VISUAL AC CORONA IN AIR AT A CONDUCTOR SURFACE,CALLED THE CORONA INCEPTION FIELD ,CAN BE APPROXIMATELY GIVEN FOR THE CASE OF PARALLEL WIRES OF RADIOUS **r**AS

$$E_W = 30md\left[1+\frac{0.031}{\sqrt{dr}}\right]$$

- FOR THE CASE OF COXIAL CYLINDERS,WHOSE INNER CYLINDER HAS A RADIUS **r** THE EQUATION BECOMES

$$E_C = 31md\left[1+\frac{0.308}{\sqrt{dr}}\right]$$

d IS THE RELATIVE AIR DENSITY CORRECTION FACTOR GIVEN BY,

$$d=\frac{0.392b}{(273+T)}$$

- WHERE B IS THE ATMOSPHERIC PRESSURE IN TORR,**T** IS THE TEMPRETURE IN ^{o}C,d=1 AT 760 TORR AND 25^{o}C.
- WHEN THE VOLTAGE IS POSITIVE,CORONA APPEARS AS A UNIFORM BLUISH WHITE SHEATH OVER THE ENTIRE SURFACE OF THE CONDUCTOR .

- ON THE OTHER HAND, WHEN THE VOLTAGE IS NEGATIVE,THE CORONA WILL APPEAR LIKE REDDISH GLOWING SPOTS DISTRIBUTED ALONG THE LENTH OF THE WIRE.
- WHEN POINT IS NEGATIVE,CORONA APPEARS AS CURRENT PULSES CALLED **TRICHELS PULSES,**AND THE REPITITION FREQUENCY OF THESE PULSES INCREASES AS THE APPLIED VOLTAGE IS INCREASED AND DECREASES WITH DECREASE IN PRESSURE.
- AT SUFFICIENTLY HIGH VOLTAGE,CURRENT AMPLIFICATION INCREASES RAPIDLY WITH VOLTAGE,UP TO A CURRENT OF ABOUT 10 A,AFTER WHICH THE CURRENT BECOMES PULSED WITH REPITITION FREQUENCY OF ABOUT **1KHZ** COMPOSED OF SMALL BURSTS.**THIS FORM OF CORONA IS CALLED BURST CORONA.**

Vacuum Insulation

A vacuum system in which the pressure is maintained at a value much below the atmospheric pressure. In a vacuum the pressure is always measured in terms of millimeter of mercury () and 1mmHg=1torr.

Classification of vacuum

- High vacuum()
- Very high vacuum()
- Ultra high vacuum()

Vacuum break down

- Partial exchange mechanism
- Field emission mechanism
- clump theory

Partial exchange mechanism

it involves electrons ,positive ions, photons and the absorbed gases at the electrode surfaces. Quantitatively an electron present in the vacuum gas is accelerated towards anode and on impact releases a positive ion and c photon.

These positive ions are accelerated towards cathode and on impact each positive ion liberated B electrons and each photon liberates D electrons.

The breakdown will occur if the coefficient of production of secondary electron exceeds unit mathematically condition for breakdown is AB+CD>1. ………….(1)

Later Trump and vandal gaff measured this coefficient and showed that they are too small for this process to take place. Accordingly this theory modified for allow for the presence of positive ion and the criteria for breakdown than becomes.

AB+EF>1 …………….. (2).

> E and F represent the coefficients for negative and positive ion liberation by positive and negative ion.

It was experimentally found that the values of product of EF is closed enough to unity for Cu, Al, stainless steel electrode to make this mechanism at voltage above 250w.

Field emission theory

(i) Anode heating mechanism:- This theory postulates that electrons produced at small micro projections anode causing a local rise in temperature and release gases and vapors into the vacuum gap. These electrons ionize the atoms of the gas and produce positive ions. These positive ions arrive at the cathode increase the primary electron emission due to space charge formation and produce secondary electrons by bombarding the surface. The process continues until a sufficient number of electrons are produced to give rise to breakdown as m the cose of low pressure Townsend type gas discharge.

(ii) Cathode heating emission:- This mechanism postulates that near the breakdown voltage of the gap sharp points on the cathode surface are responsible for the existence of the pre-breakdown current which is generated according to field emission process. This current causes resistive heating at the tip of a point and when a critical current density is reached the tip melts and explodes thus intia vacuum discharge. The mechanism is called field emission the intiation of emission depends upon the nature of cathode surface. Experimentally this type of emission takes place when the electrode surface field is of order 10^6 to 10^7 v/cm.

Clump mechanism

A loosely bound particle exists on one of the electrode surface.

On the application of high voltage, this particles get changed subsequently get deched from the mother electrode and accelerated across the gap.The breakdown occurs due to discharge on the vapor or gas released by the impact of the particles at the target electrode.

Cranberry was the first to propose this theory. He initially assumed that breakdown will occur when the energy pet unit area was delivered to the target electrode by clump exceeds a value $c^{'}$

$$VE=c^{'}$$

In case of parallel plane electrode the electric E=v/d

Where d is the distance between $v= (cd)^{1/2}$

Conduction and Breakdown in Liquid Dielectrics

LIQUIDS AS INSULATORS :

Liquid dielectrics, because of their inherent properties, appear as though they wouldbe more useful as insulating materials than either solids or gases. This is because bothliquids and solids are usually 103 times denser than gases and hence, from Paschen'slaw it should follow that they possess much higher dielectric strength of the order of107 V/cm. Also, liquids, like gases, fill the complete volume to be insulated andsimultaneously will dissipate heat by convection. Oil is about 10 times more efficientthan air or nitrogen in its heat transfer capability when used in transformers. Althoughliquids are expected to give very high dielectric strength of the order of 10 MV/cm,in actual practice the strengths obtained are only of the order of 100 kV/cm.Liquid dielectrics are used mainly as impregnants in high voltage cables andcapacitors, and for filling up of transformers, circuit breakers etc. Liquid dielectricsalso act as heat transfer agents in transformers and as arc quenching media in circuitbreakers. Petroleum oils (Transformer oil) are the most commonly used liquiddielectrics. Synthetic hydrocarbons and halogenated hydrocarbons are also used forcertain applications. For very high temperature application, silicone oils andfluorinated hydrocarbons are also employed. In recent times, certain vegetable oilsand esters are also being tried. However, it may be mentioned that some of the isomersof poly-chlorinated diphenyls (generally called askerels) have been found to be verytoxic and poisonous, and hence, their use has been almost stopped. In recent years, asynthetic ester fluid with the trade name 'Midel' has been developed as a replacementfor askerels.

Liquid dielectrics normally are mixtures of hydrocarbons and are weakly polarised. When used for electrical insulation purposes they should be free frommoisture, products of oxidation and other contaminants. The most important factorthat affects the electrical strength of an insulating oil is the presence of water in theform of fine droplets suspended in the oil. The presence of even 0.01% water intransformer oil reduces its electrical strength to 20% of the dry oil value. Thedielectric strength of oil reduces more sharply, if it contains fibrous impurities inaddition to water.

Transformer oils are the cheapest andthe most commonly used. The electrical properties of transformer oil are given in theabove table. Oils used in the capacitors are similar to transformer oil but they are subjected to a very high degree of purification. Various kinds of oils are used in cablesas impregnants for paper insulation and to improve their heat transfer capability.

In practice, the choice of a liquid dielectric for a given application is made mainlyon the basis of its chemical stability. Other factors such as saving of space, cost,previous usage, and susceptibility to the environmental influences are also considered.

Classification of Liquid Dielectrics :

In the the recent year ,a substitute to mineral oils other polyester oils have been developed which are extensively used in transformer in Europe and other countries one such oil is the halogen- free penta- ethythrite –tetra fatty acid polyester oil which has very good electrical,physical , and thermal properties .it is also biodegradable,i.e. when decomposed has almost negligible toxicity .

a) Transformer Oil

Transformer oil is the most commonly used liquid dielectric in power apparatus. It is all most colourless liquid consisting of a mixture of hydrocarbons which includes paraffines ,iso-paraffinesnaphthalenes and aromatics. When in service ,the liquid in a transformer is subjected to prolonged heating at high temperature of about 95 degree C, and consequently it undergoes a gradual ageing process. With time the oil becomes dark due to the formation of acid and resins or sludge in the liquid.

b) Synthetic Hydrocarbon

Among synthetic liquids dielectrics , polyolefin's are the dielectrics of choice for applications in power cables .Over 55% of synthetic hydrocarbons produced worldwide today are polyolefin's .

c) Chlorinated Hydrocarbons

Two aromatics hydrocarbons , benzene and diphenyl are chlorinated to produce chlorinated aromatics compounds called askarels or simply polychlorinated biphenyl(PCB).

d) Silicone Oils

Silicon oils represent an alternative to PCBs but they are expensive .even at temperature of 150% C, they exhibit high long-term thermal stability.
Silicone oils are resistance to most chemicals, and are oxidation resistant, even at higher temperatures. They can be used at higher temperature than mineral oils. Silicon oils are an acceptable substute for PCBs in transformer despite their slightly inferior non-flammable properties.

e) Esters

Nature ester such as castor oil has been used as a capacitor impregnent for many years, but currently two types of synthetic esters are being used ,viz., organic esters and phosphate esters.

The phosphate esters have high boiling point and low flammability amnd marketed and therefore are used in transformer that are to be installed in hazardous areas.

f) Latest Developments

Some new oils have been introduced in recent years. These are being marketed under different commercial names, such as high-temperature hydrocarbons oil, tetrachloroethylene and perfluoropolyether.

High Temperature Hydrocarbons (HTH) oils have good electrical insulating and adequate heat transfer properties. They are chemically similar to regular mineral transformer oils, but possess higher boiling points and higher fire points. However , they have viscosity which reduces heat transfer capability.