KLR COLLEGE OF ENGINEERING & TECHNOLOGY
(Affiliated to JNTUH, Approved by AICTE New Delhi, An ISO 9001:2015 Certified)
BCM Road, Paloncha-507115, Bhadradri Kothagudem(Dist.), Telangana.

LECTURE NOTES

ON

HIGH VOLTAGE ENGINEERING

2021 - 2022

III B. Tech I Semester

Estd.2008

ELECTRICAL AND ELECTRONICS ENGINEERING

UNIT -I

BREAKDOWN IN GASES

IONIZATION PROCESSES AND DEIONIZATION PROCESSES

Ionization Process : Ionization process are of two phenomenon that occurs in gas insulation, they areprimary and secondary ionization process. First let us see primary ionization process.

i. Primary ionization process.
ii. Ionization by collision.

DEIONIZATION PROCESS :

Deionization results from the recombination of ions and electrons, their diffusion toward the boundaries of the volume occupied by the gas, and the extraction of the charged particles by an external electrical field applied to the gas.

Townsend's Theory:

Townsend‟s has consider both primary and secondary process which leads breakdown in gas dielectricmedium and proved that increase of electrons in gas medium is not linear but exponential.

Let us assume,

n_o – electrons liberated from cathode due to applied voltagep – primary ionization co-efficient

x – be the distance from cathoden_x – total electron at distance x dx- small distance from x

then total electrons in dx is $p.n_x.dx$

at, $x= 0, n_x = n_o$

$(dn_x / dx) = p.n_x (dn_x / n_x) = p. dx$

Integrating on both sides,

$\ln(n_x) = p.x$

or $n_x = e^{p.x}$

now for a total distance of d and initial electrons of n_o , total electrons liberated in gas medium due toprimary ionization process is,

$n_d = n_o .e^{p.d}$

and in terms of current between electrodes it is given as,

$I_d = I_o .e^{p.d}$

Considering now both criteria-

Let us consider, s- secondary ionization co-efficient considering all secondary Ionization process.n_s – number of secondary electrons liberated due to secondary process

n_c – total electrons released form cathode

there fore, $n_c = n_o + n_s$

the total number of electrons reaching anode are,$n = n_c . e^{p.d}$

$n = (n_o + n_s) . e^{p.d}$

$n_s = s(n-(n_o + n_s))$

by eliminating n_s,

$n = n_o.\ e^{p.d} / 1-s[e^{p.d}$

$- 1]$in terms of

current between the

plates,

$$I = I_o.\ e^{p.d} / 1-s[e^{p.d} - 1]$$

Townsend’s condition of breakdown:

To say that great avalanche is formed between the plates , the denominator of current through the platesmust be zero.

$$1-s[e^{p.d} - 1] = 0$$
$$s[e^{p.d} - 1] = 1$$

this is called as Townsend‟s condition of breakdown in gas insulation medium.

$e^{p.d}$ >>1therefore above condition can be written as ,

$$s.e^{p.d} = 1$$

LIMITATION OF TOWNSEND'S THEORY

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

I. 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

TYPES OF DISCHARGE :

The electrical discharges in gases are of two types;
i) non-sustaining discharges
ii) self-sustaining
The breakdown in a gas (spark breakdown) is the transition of a non-sustaining discharges into a self-sustaining discharge.

i) non-sustaining discharges
This current being dependent on I0 does not represent self sustaining discharge.

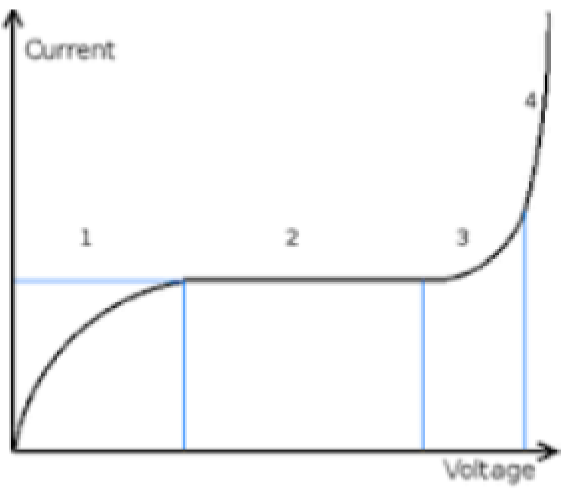
ii) self-sustaining
The breakdown in a gas (spark breakdown) is the transition of a non-sustaining discharges into a self-sustaining discharge.

GASES AS INSULATING MATERIALS :

The most common dielectrics are gases. Many electrical apparatus use air as the insulating medium, while in a few cases other gases such as N2, CO2, CCl2F2 (freon) and SF6 (hexafluoride) are used. Gases consist of neutral molecules, and are, therefore, good insulators.

GASEOUS BREAKDOWN IN UNIFORM AND NON-UNIFORM FIELDS:

Gases Electrical breakdown occurs within a gas when the dielectric strength of the gas is exceeded. The voltage that leads to electrical breakdown of a gas is approximated by Paschen's Law. Partial discharge in air causes the "fresh air" smell of ozone during thunderstorms or around high-voltage equipment.



UNIFORM FIELD

Electric fields are represented by drawing field lines that represent the direction of the field, as well as the strength of the field. More field lines represent higher field strength. In a non-uniform electric field, the field lines tend to be curved and are more concentrated near the charges. In a uniform electric field, since the field strength does not vary, the field lines are parallel to each other and equally spaced. Uniform fields are created by setting up a potential difference between two conducting plates placed at a certain distance from one another. The field is considered to be uniform at the center of the plates, but varies close to the edge of the plates. The strength of the field depends on the potential difference applied to the plates and the distance by which they are separated. A higher potential difference or voltage results in a stronger electric field. The greater the distance between the plates, the weaker the field becomes. The electric field is therefore calculated as a ratio of the voltage between the plates to the distance they are separated by them.

NON UNIFORM GAPS:

In Breakdown in Non Uniform Fields, such as coaxial cylinders, point-plane and sphere-plane gaps, the applied field varies across the gap. Similarly, Townsend's first ionization coefficient (α) also varies with the gap. Hence αd in Townsend's criterion,
Townsend's criterion for breakdown now becomes

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

Meek and Raether also discussed the non-uniform field breakdown process as applied to their Streamer theory, and the Meek's equation for the radial field at the head of an avalanche when it has crossed a distance x is modified as

$$E_r = \frac{5.27\times10^{-7}\ \alpha_x\ \exp\left(\int_0^x \alpha\, dx\right)}{(x/p)^{1/2}}\ \text{V/cm}$$

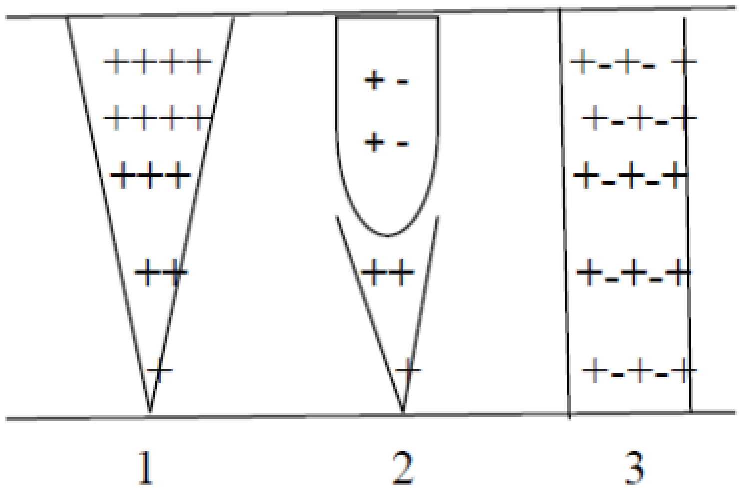
where α_x is the value of α at the head of the avalanche, and p is the gas pressure. The criterion for the formation of the streamer is reached when the space charge field E_r approaches a value equal to the applied field at the head of the avalanche.This equation has been successfully used for determining the corona onset voltages of many non-uniform geometries.

STREAMER MECHANISM:

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.

Townsend"s theory has drawback that it has consider only ionization process as cause of breakdown in gas insulation, but dint consider atmospheric and shape of the medium between the electrodes.

i.Townsend"s criteria says that time lag is approximately 10^{-5} seconds but which actually as small as estimated is 10^{-8} seconds. Townsend"s criteria says that discharge has regular shape but practically discharge
ii. May be irregular and thin path type spark.
Streamer theory says that positive space charges due to ionization process enhances electric field and tends to cathode very rapidly which is called as streamer. This forms an second avalanche between the plates.



In the above diagram figure 1 indicate formation positive space charge tending towards cathode. Figure indicates how field of positive space charge ionizes the gas. Figure indicates formation of avalanche between plates.

Field developed by space charge is , $E = \frac{5.27 \times 10^{-7} \times p \times e^{p.x}}{(x/b)^{1/2}}$

Where, E- electric field due to space charge
b- gas pressure.
Above equation can further simplified as , $Pd + \ln(p/b) = 14.5 + \ln(E/b) + 0.5\ln(d/b)$

Paschen's Law:
From the breakdown criteria of Townsend"s, $1 - s[e^{p.d} - 1] = 0$
$s[e^{p.d} - 1] = 1$ where the co-efficient p and s are functions of E/b i.e
$p/b = g_1(E/b)$ $s = g_2(E/b)$ $E = V/d$
Substituting above equations in townsend"s criteria, $g_2(E/b)[e^{g_1(E/b).d} - 1] = 1$ $g_2(V/d.b)[e^{g_1(V/d.b).d} - 1] = 1$
hence from above equation we can say that applied voltage is the function of produce of pressure and distance.

V = g(d.b)

CORONA DISCHARGE:

Definition: The phenomenon of ionisation of surrounding air around the conductor due to which luminous glow with hissing noise is rise is known as the corona effect .Corona Discharge (also known as the Corona Effect) is an electrical discharge caused by the ionization of a fluid such as air surrounding a conductor that is electrically charged. The corona effect will occur in high voltage systems unless sufficient care is taken to limit the strength of the surrounding electric field. Corona discharge can cause an audible hissingor cracking noise as it ionizes the air around the conductors. This is common in high voltage electric power transmission lines. The corona effect can also produce a violet glow, production of ozone gas aroundthe conductor, radio interference, and electrical power loss .The corona effect occurs naturally due to the fact that air is not a perfect insulator – containing many free electrons and ions under normal conditions. When an electric field is established in the air between two conductors, the free ions and electrons in the airwill experience a force. Due to this effect, the ions and free electrons get accelerated and moved in the opposite direction. The charged particles during their motion collide with one another and also with slow- moving uncharged molecules. Thus the number of charged particles increases rapidly. If the electric field isstrong enough, a dielectric breakdown of air will occur and an arc will form between the conductors.

Two factors are important for corona discharge to occur:

i. Alternating electrical potential difference must be supplied across the line.
ii. The spacing of the conductors, must be large enough compared to the line diameter.

When an alternating current is made to flow across two conductors of a transmission line whose spacing is large compared to their diameters, the air surrounding the conductors (composed of ions) is subjected to dielectric stress.

At low values of the supply voltage, nothing occurs as the stress is too small to ionize the air outside. But when the potential difference increases beyond some threshold value (known as the critical disruptive voltage), the field strength becomes strong enough for the air surrounding the conductors to dissociated intoions – making it conductive. This critical disruptive voltage occurs at approximately 30 kV.

The ionized air results in electric discharge around the conductors (due to the flow of these ions). This gives rise to a faint luminescent glow, along with the hissing sound accompanied by the liberation of ozone.

This phenomenon of electric discharge occurring in high voltage transmission lines is known as the corona effect. If the voltage across the lines continues to increase, the glow and hissing noise becomes more and more intense – inducing a high power loss into the system.

Factors Affecting Corona Loss

The line voltage of the conductor is the main determining factor for corona discharge in transmission lines. At low values of voltage (lesser than the critical disruptive voltage) the stress on the air is not high enough to cause dielectric breakdown – and hence no electrical discharge occurs.

With increasing voltage, the corona effect in a transmission line occurs due to the ionization of atmosphericair surrounding the conductors – it is mainly affected by the conditions of the cable as well as the physical state of the atmosphere. The main factors affecting corona discharge are:

i. Atmospheric Conditions
ii. Condition of Conductors
iii. Spacing Between Conductors

Atmospheric Conditions:

We have proved that the voltage gradient for dielectric breakdown of air is directly proportional to the density ofair. Hence in a stormy day, due to continuous air flow, the number of ions present surrounding the conductor is far more than normal, and hence it‟s more likely to have electrical discharge in transmission lines on such a day, compared to a day with the fairly clear weather. The system has to be designed considering those extreme situations.

Condition of Conductors:

This particular phenomenon depends highly on the conductors and its physical condition. It has an inverse proportionality relationship with the diameter of the conductors. i.e., with the increase in diameter, the effect ofcorona on power system reduces considerably. Also, the presence of dirt or roughness of the conductor reduces the critical breakdown voltage, making the conductors more prone to corona losses. Hence in most cities and industrial areas having high pollution, this factor is of reasonable importance to counter the ill effects it has on the system.

Spacing Between Conductors:

As already mentioned, for corona to occur in the spacing between the lines effectively should be much higher compared to its diameter, but if the length gets increased beyond a certain limit, the dielectric stress on the air reduces, and consequently, the effect of corona reduces as well. If the spacing is made too large, then corona forthat region of the transmission line might not occur at all.

Reducing Corona Discharge:

Corona discharge always results in power loss. Energy is lost in the form of light, sound, heat, and chemical reactions. Although these losses are individually small, over time they can add up to significant power loss inhigh voltage networks.

Corona discharge can be reduced by:

i. Increasing the conductor size**:** A larger conductor diameter results in a decrease in the corona effect.
ii. Increasing the distance between conductors**:** Increasing conductor spacing decreases the corona effect.
iii. Using bundled conductors**:** Bundled conductors increase the effective diameter of the conductor – hencereducing the corona effect.
iv. Using corona rings: The electric field is stronger where there is a sharp conductor curvature. Because of this corona discharge occurs first at the sharp points, edges, and corners. Corona rings reduce the corona effect by „rounding out‟ conductors (i.e. making them less sharp). They are used at the terminals of veryhigh voltage equipment (such as at the bushings of high voltage transformers). A corona ring is electrically connected to the high voltage conductor, encircling the points where the corona effect is mostlikely to occur. This encircling significantly reduces the sharpness of the surface of the conductor – distributing the charge across a wider area. This in turn reduces corona discharge.

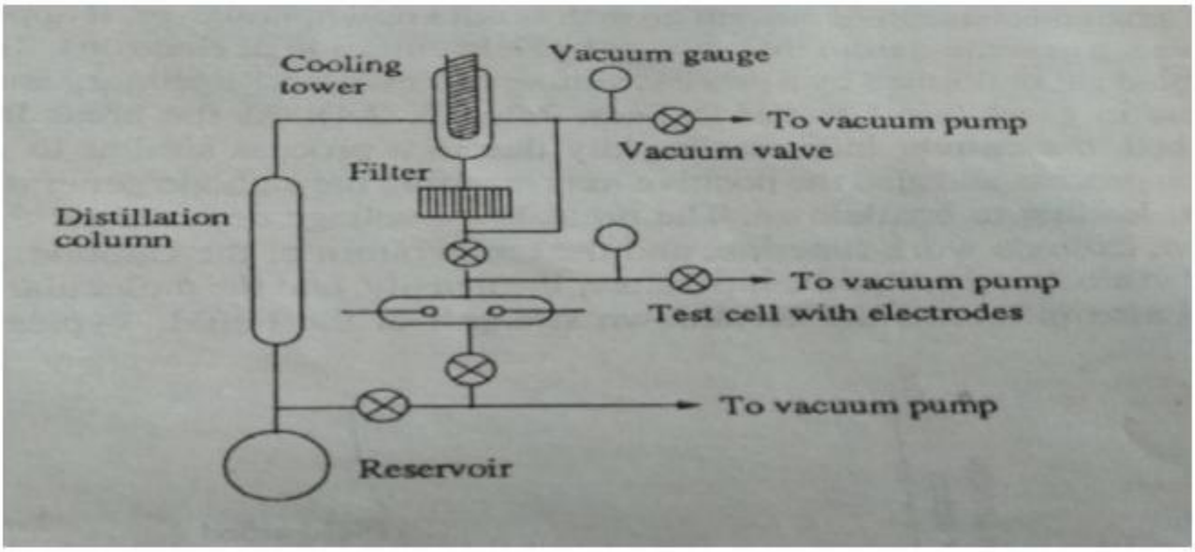
Disadvantages of corona discharge:

- **i)** The undesirable effects of the corona are:
- **ii)** The glow appear across the conductor which shows the power loss occur on it. .
- **iii)** The vibration of conductor occurs because of corona effect.
- **iv)** The corona effect generates the ozone because of which the conductor becomes corrosive.
- **v)** The corona effect produces the non-sinusoidal signal thus the non-sinusoidal voltage drops occur inthe line.
- **vi)** The corona power loss reduces the efficiency of the line

BREAKDOWN IN LIQUID AND SOLID INSULATING MATERIALS:

Pure And Commercial Liquid:

Pure liquids are the one which has no contaminants in the traces of 1 in 10^9 . commercial liquids are the one which contains impurities like sand particles, gas pockets, air bubbles, dust etc. before taking any liquid insulation into service once purification process is recommendable.



The general impurities in liquid dielectrics are dust particles which cane removed by the process of filtration, gas bubbles and moisture are other impurities which can be eliminated by distillation and degassing, ionic impurities leads increase in conductivity of liquid. Water content can be removed by drying agents. Sometimes liquids are shaked with some chemicals agents to purify the liquid dielectric.

The above figure indicates the process of purification of the commercial liquids.

i. Firstly liquid insulation stored in the reservoir.
ii. Liquid dielectric first undergo distillation process where gas bubbles, moisture contentcan be removed.
iii. Then it undergoes drying agents where unwanted water contents can be eliminated.
iv. Then undergoes filtration where dust particles are removed.

v. Then an sample of liquid is sent into test cell where it is tested for withstand voltage.

SOLID DIELECTRICS AND COMPOSITE DIELECTRIC:

Solid dielectric materials are used in all kinds of electrical circuits and devices to insulate one current carrying part from another when they operate at different voltages. A good dielectric should have low dielectric loss, high mechanical strength, should be free from gaseous inclusion, and moisture, and be resistant to thermal and chemical deterioration. Solid dielectrics have higher breakdown strength compared to liquids and gases. Studied of the breakdown of solid dielectrics are of extreme importance in insulation studies. When breakdown occurs, solids get permanently damaged while gases fully and liquids partly recover their dielectric strength after the applied electric field removed. The mechanism of breakdown is a complex phenomenon in the case of solids, and varies depending on the time of application of voltage.

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BREAKDOWN INTRINSIC

When voltages are applied only for short durations of the order of 8 10 s the dielectric strength of a solid dielectric increases very rapidly to an upper limit called the intrinsic electric strength. Experimentally, this highest dielectric strength can be obtained only under the best experimental conditions when all extraneous influences have been isolated and the value depends only on the structure of the material and the temperature. The maximum electrical strength recorder is 15 MV/cm for polyvinyl-alcohol at -1960 C. Themaximum strength usually obtainable ranges from 5 MV/cm. Intrinsic breakdown depends upon the presence of free electrons which are capable of migration through the lattice of the dielectric. Usually, a small number of conduction electrons are present in solid dielectrics, along with some structural imperfections and small amounts of impurities. The impurity atoms, or molecules or both act as traps for the conduction electrons up to certain ranges of electric fields and temperatures. When these ranges are exceeded, additional electrons in addition to trapped electrons are released, and these electrons participate in the conduction process. Based on this principle, two types of intrinsic breakdown mechanisms have beenproposed.

ii) Electronic Breakdown

Intrinsic breakdown occurs in time of the order of 10-8 s and therefore is assumed to be electronic in nature. The initial density of conduction (free) electrons is also assumed to be large, and electron-electron collisionsoccur. When an electric field is applied, electrons gain energy from the electric field and cross the forbidden

energy gap from the valence band to the conduction band. When this process is repeated, more and more electrons become available in the conduction band, eventually leading to breakdown.

2.Avalanche or Streamer Breakdown

This is similar to breakdown in gases due to cumulative ionization. Conduction electrons gain sufficient energy above a certain critical electric field and cause liberation of electrons from the lattice atoms by collision. Under uniform field conditions, if the electrodes are embedded in the specimen, breakdown will occur when an electron avalanche bridges the electrode gap. An electron within the dielectric, starting from the cathode will drift towards the anode and during this motion gains energy from the field and loses it during collisions. When the energy gained by an electron exceeds the lattice ionization potential, an additional electron will be liberated due to collision of the first electron.

ELECTROMECHANICAL BREAKDOWN AND THERMAL BREAKDOWN

Electro mechanical breakdown:

If high voltage is applied to solid insulation the electro static forces may experience

by high stress whichmay exceed mechanical stress of the specimen.

Let us consider d_0 – initial thickness of specimen.

Let us consider d0 – initial thickness of specimen.

d – compressed thickness due to static forces. E – applied voltage.

Under equilibrium

$\varepsilon_0 \varepsilon_r E^2/2d^2 = Y \ln (d_0 / d)$ $E^2 =(Y^2 d^2 / \varepsilon_0 \varepsilon_r) \ln (d_0 / d)$

Where, Y – youngs modulus.

The mechanical breakdown may occurs if:

$d / d_0 = 0.6$ $d_0 / d = 1.67$

with above failure conditions the maximum field experienced by solid insulation is. $E_{max} = 0.6(Y/ \varepsilon_0 \varepsilon_r)^{1/2}$

Thermal or Over heat breakdown:

When the DC high voltage is applied the heat experienced by solid insulation is : $W_{dc} = E^2 \zeta$.

When the AC high voltage is applied the heat experienced by solid insulation is : Wac = E2 fεr tan β / 1.8 * 1012

Where, f – frequency

β – power factor of insulation

E – RMS value of applied voltage. ζ – Dc conductivity.

The heat lost form the material is:

W = Cv dT/dt + ▼ (K grad T)

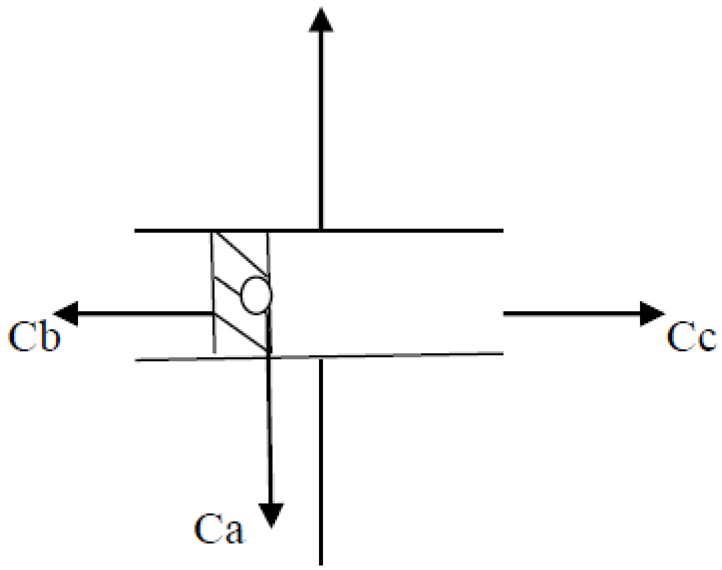
Where , Cv – material specific heat

T – temperature of specimen.

K – thermal conductivity of the material. t – time taken to leave the heat.

Under normal working condition heat generated must be equal to heat lost. Otherwise over heat of specimen may takes place thereby causing breakdown of insulation.

Partial discharge:



This type of discharge mainly occurs due to presence of internal voice or cavities. If solid insulation consist of voids which may be considered as gas pockets, when the high voltage is applied to such a insulation ionization process occurs in the gas pockets which may leads to internal discharge. This internal discharge may be treated as partial discharge. If the structure of solid insulation consists of multiple voids then possible multiple partial discharge may occur.

These partial discharges decrease the dielectric strength of solid insulation. If the applied voltage to the insulation is V, the voltage across the void which leads to breakdownis

$V_1= Vd_1 / d_1+(\varepsilon_0 / \varepsilon_1) d_2$.

Where d_1: thickness of void.

d_2: thickness of insulation.

We know that d1 is very much less than d2. Then voltage across void can be written as: $V_1 = V\varepsilon_r (d_1/d_2)$.

APPLICATIONS OF INSULATING MATERIALS:

The applications of insulating material are

2 Cable and transmission lines
3 Electronic systems
4 Power systems
5 Domestic portable appliances
6 Electrical cable insulating tape
7 Personal protective equipment
8 Electrical rubber mats

UNIT II

GENERATION OF HIGH VOLTAGES

Introduction:

Once the study of insulation technology is completed , next important part of high voltage engineering isgeneration of high voltages and high currents. The generation of several voltages and currents, they are

i. High DC voltage
ii. High AC voltage
iii. High direct current
iv. High alternating current
v. High impulse voltage
vi. High impulse currents.

In this unit we are going to study different arrangements to generate high voltage currents.