High Voltages Course

Fourth year level (Elective course)

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(1) In this lecture you will learn the following:

Levels of voltages, Electrical Insulation and Dielectrics

Levels of high voltage:

- LOW
- MEDIUM
- HIGH
- EXTRA and
- ULTRA HIGH Voltages

- However, the exact magnitude of these levels varies from country to country. Hence this system of technical terms for the voltage levels is inappropriate.
- In most part of the world even 440 V is considered to be high voltage since it is dangerous for the living being.
- Hence it would be more appropriate to always mention the level of voltage being referred without any set nomenclature

VOLTAGE LEVELS Consumer

- **AC power frequency** :
  110 V, 220 V- single phase
  440 V, 3.3 kV ,6.6 kV, 11 kV-three phase (3.3 & 6.6 kV are being phased out)

Advance countries like US, Canada and Japan have their single phase ac power consumption level at 110 V. Rest of the whole world consumes single phase ac power at 220 V.

The only advantage of 110 V single phase consumer voltages is that it is safer over 220 V. However, the disadvantages are many.

Disadvantages:

- It requires double the magnitude of current to deliver the same amount of power as at 220 V
- Hence for the same magnitude of I^2R losses to limit the conductor or the insulation temperature to 70° C (for PVC), the resistance of the distribution cable should be 4 times lower. Therefore, the cable cross-section area has to be increased four folds.
- Four times more copper requirement, dumped in the building walls is an expensive venture.
- Due to higher magnitude of current, higher magnetic field in the buildings. Not good for health.
- With the installation of modern inexpensive protective devices (earth fault relays), 220 V is equally safe as 110 V

Rated maximum temperature of cables:

- It is important to understand the current and voltage carrying capacities of a conductor separately. While the current carrying capability is determined by the conductivity of the conductors, directly proportional to the area of conductor cross-section, the voltage bearing capacity depends upon the level of insulation provided to the conductor.

- The current carrying capability in turn is determined by maximum permissible temperature of the insulation or that of the conductor.
- The real power loss, I^2R and the rate of cooling determine the temperature rise of the conductor which should not be more than the maximum permissible temperature of the type of insulation provided on the conductor.
- Hence, not only electrical but thermal and mechanical properties of insulation are important in power system.

Electrical Insulation and Dielectrics

Gaseous Dielectrics:

- Atmospheric air is the cheapest and most widely used dielectric. Other gaseous dielectrics, used as compressed gas at higher pressures than atmospheric in power system, are Nitrogen, Sulphurhexafluoride SF_6 (an electro-negative gas) and it's mixtures with CO_2 and N_2. SF_6 is very widely applied for Gas Insulated Systems (GIS), Circuit Breakers and gas filled installations i.e. sub-stations and cables. It is being now applied for power transformers also.

Vacuum as Dielectric:

- Vacuum of the order of 10^{-5} Torr and lower provides an excellent electrical insulation**. V**acuum technology developed and applied for circuit breakers in the last three decades is phenomenon.

Liquid Dielectrics:

- Organic liquids, the mineral insulating oils and impregnating compounds, natural and synthetic, of required physical, chemical and electrical properties are used very widely in transformers, capacitors, cables and circuit breakers.

Solid Dielectrics:

- Very large in number.
- Most widely used are : XLPE, PVC, ceramics, glass, rubber, resins, reinforced plastics, polypropylene, impregnated paper, wood, cotton, mica, pressboards, Bakelite, Perspex, Ebonite, Teflon, etc.
- Introduction of nano materials are in offing.

(2) In this lecture you will learn the following:

Importance of Electric Field Intensity in the Dielectrics, Types of Electric Fields,

Degree of Uniformity of Fields (Schwaiger Factor),

ELECTRIC FIELDS:

Faraday described the space around a magnet to be filled with 'lines of magnetic force'. Similarly, the region around an electrified object may be considered to be filled with 'lines of electric force'. To Faraday, these lines existed as mechanical structures in the surrounding medium (the dielectric) and could exert force on an object placed therein. Two typical electrostatic field structures are shown in Fig. 2.1. In figure (a), the field between a sphere or a cylinder and plane is sketched, and in figure (b), the field pattern on a bundle of four conductors used for transmission lines is shown, neglecting the effect of ground.

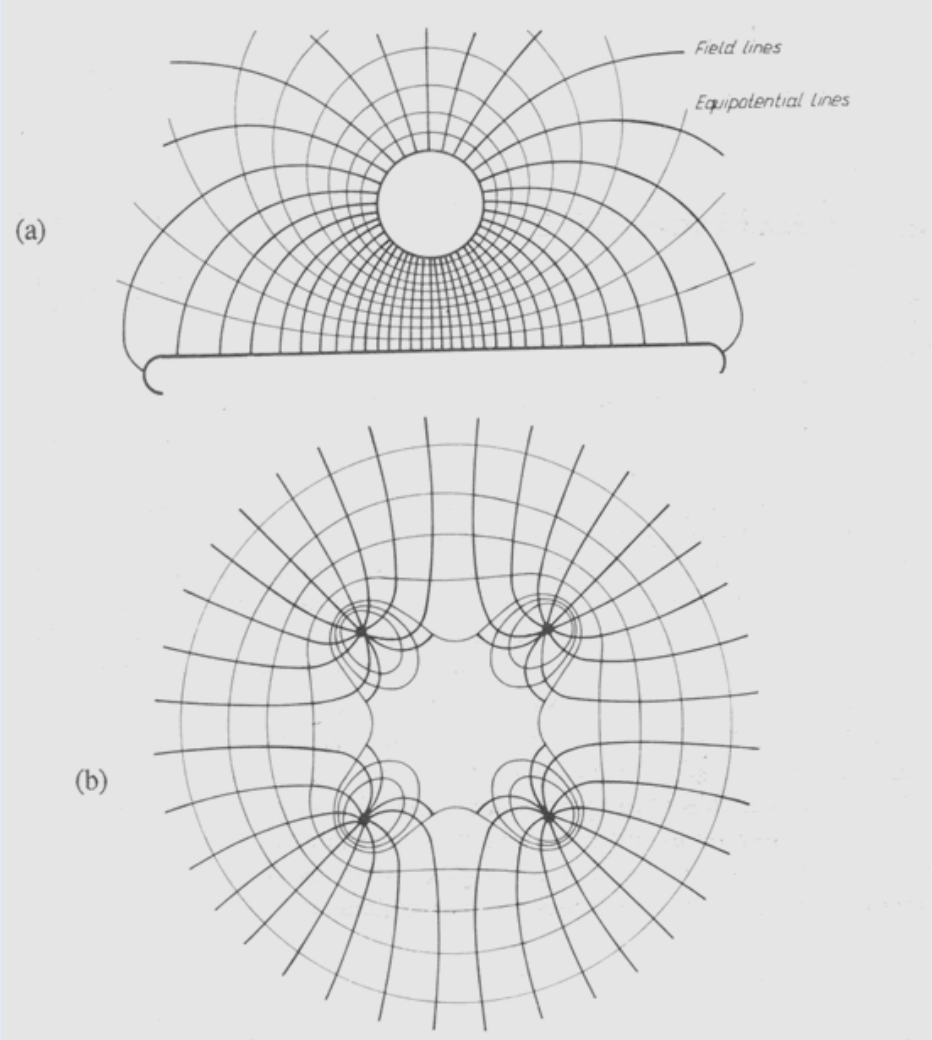


Fig 2.1 Typical electrostatic field configurations.
(a) Field between sphere or cylinder and plane,
(b) Field on a bundle of four conductors.

- The 'electric field intensity', also known as the' electric field strength', is defined as the electrostatic force F exerted by the field on a unit positive test charge q, placed at a particular point P in a dielectric. It is denoted by E, expressed in unit 'Newton's per Coulomb', the force per unit charge.
- The electric field intensity is measured in its practical units of 'Volts per meter' (V/m or kV/mm).

- The electric field intensity is often more specifically mentioned as 'electric stress' experienced by a dielectric or an electrical insulating material.
- The potential difference between two points a and b, having scalar potential ϕ_a, ϕ_b in a space charge free electric field $\vec{E}$, is defined as the work done by an external source in moving a unit positive charge from b to a,

$$U_{ab} = -\int_b^a |\vec{E}|\,dx = (\phi_a - \phi_b) \tag{2.1}$$

- U_{ab} Is positive if the work is done in carrying the positive charge from b to a.
- The maximum magnitude of electric field intensity is therefore, given by the maximum value of the rate of change of potential with distance. It is obtained when the direction of the increment of distance is opposite to the direction of $\vec{E}$, in other words, the maximum value of the rate of change of potential is obtained when the direction of $\vec{E}$ is opposite to the direction in which the potential is increasing most rapidly,

$$\frac{dU_{ab}}{dx}\Big|_{max} = -|\vec{E}|_{max} \tag{2.2}$$

The operator on ϕ by which $\vec{E}$ is obtained, is thus known as the 'gradient'. The relationship between ϕ and $\vec{E}$ may be written as,

$$\vec{E} = -\text{grad}\,\phi \tag{2.3}$$

- The electric field intensity is, therefore, numerically equal to the 'potential gradient'.

Electric Strength of Dielectrics

- The qualitative definition of 'electric strength' of a dielectric is 'the maximum electric stress a dielectric can withstand'.
- A large number of factors affect the electric breakdown of a dielectric; these include pressure, humidity, temperature, electric field configuration (electrode shape and size) electrode material, applied voltage waveform, its duration and magnitude, presence of impurities and imperfections in the dielectric, the composition of dielectric material. Hence a quantitative definition is complicated.
- In a time varying ac power frequency field (quasi stationary field), the maximum electric stress occur at the peak value of the applied voltage.
- Intrinsic strength of a dielectric: It is defined for gaseous and other than gaseous dielectric differently.
    - Gaseous dielectric: It is the magnitude of breakdown voltage measured across a gap distance of one cm in uniform field ($\eta = 1$) at normal temperature and pressure.
    - Liquid and Solid dielectrics: It is the highest value of breakdown strength obtained after eliminating all known secondary effects which may influence the breakdown adversely. It is measured for the ideal conditions of the dielectric in uniform field. Since it is very high for solid and liquid dielectrics compared to gaseous dielectrics, it is measured for mm and μm thin films of the liquid and solid dielectrics respectively instead of 1 cm gap distance.

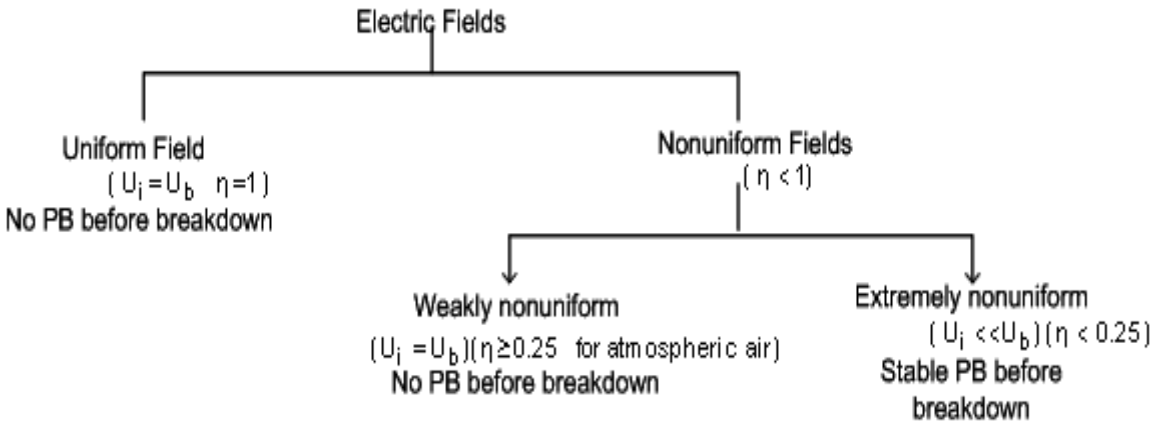
Classification of Electric Fields

Electric field configurations can be classified into two forms of fields;

1. Uniform field.
2. Non-Uniform field.

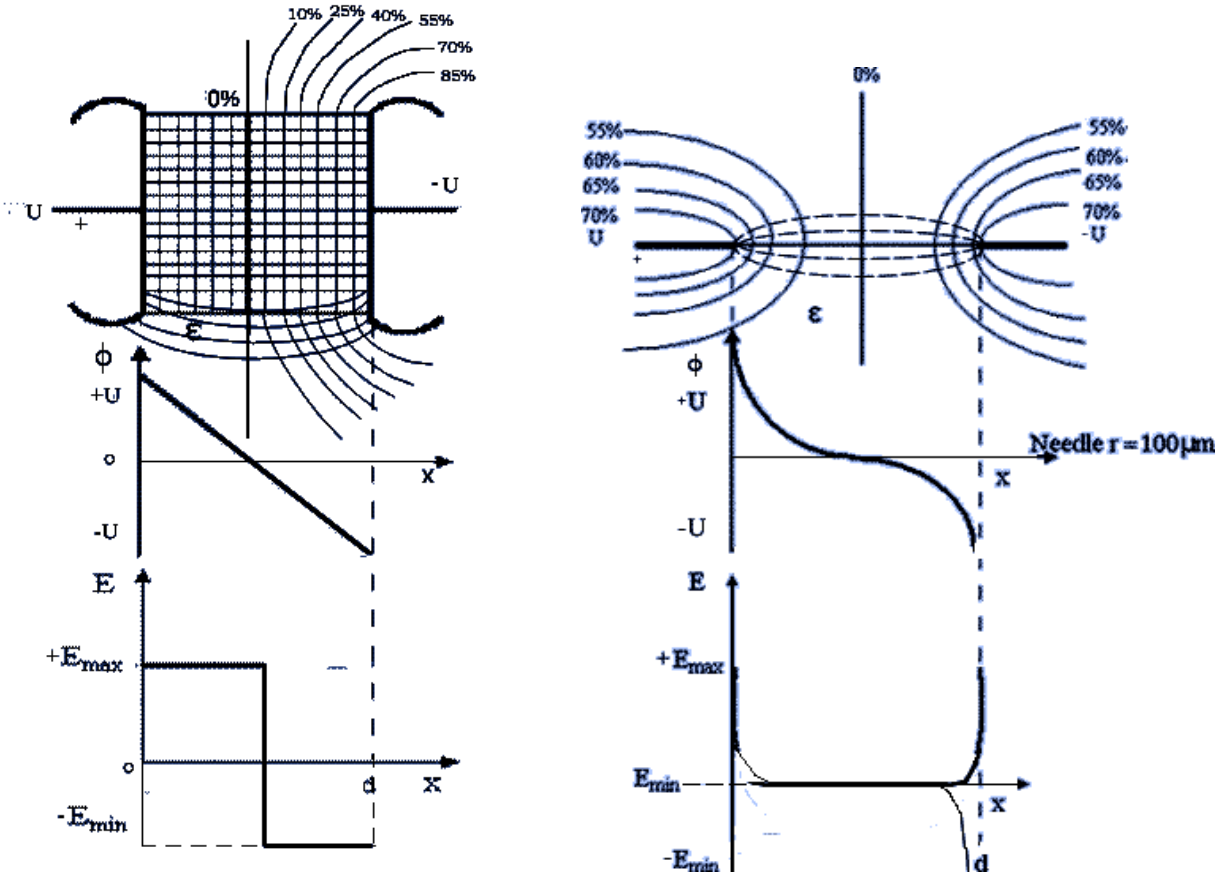
Non-uniform fields can be further distinguished between two types;

1. Weakly nonuniform fields.
2. Extremely nonuniform fields.



PB – Partial Breakdown
U_i – PB inception voltage
U_b – complete breakdown voltage
η – Schwaiger Factor

- The two extreme forms of fields, the 'uniform' and the 'extremely nonuniform' fields, are shown in Fig.3.1.
  The electric field between two electrodes is plotted beginning with the equipotential lines. An electrode is always at equi-potential. Hence, the electrode surface is the first equipotential line to be plotted. The field lines intersect the equipotential lines at right angle. Smaller are the squares formed, higher the field intensity.



(a)

(b)

Fig 3.1 the extreme field configurations (a) Uniform field between two parallel plates.
(b) Extremely nonuniform field between needle-needle electrodes.
(Effect of grounding is neglected in these plots)

- In a 'uniform field', the potential is linearly distributed and the electric field intensity is constant throughout the space in the main field region between the two electrodes, as shown in Fig. 3.1 (a). An important characteristic of this type of field is that the insulation breakdown takes place without any partial discharge preceding the breakdown ($U_i=U_b$)

- There is an extreme nonlinear distribution of potential in the space between two needle electrodes, leading to strong nonuniformity in electric field intensity as in Fig. 3.1 (b). This is a typical case of an 'extremely nonuniform field'. Unlike in uniform fields, the insulation breakdown in extremely nonuniform fields takes place after stable partial breakdown are set ($U_i<<U_b$). The partial breakdown is rendered to be unstable only just before the complete breakdown. This field configuration is of great technical importance, as it is the most unfavorable condition of electric field faced by a dielectric. At the tip of the electrodes the dielectric is subjected to a very high electric stress, but elsewhere between the electrodes it is stressed moderately.

- For a given electrode gap distance in uniform field a dielectric has the highest breakdown strength. However, it is very difficult to realize a uniform field in practice. It is accomplished only for experimental purposes in research laboratories with tremendous effort and utmost care. The size of the electrodes may have to be increased extraordinarily large, whereas the slightest irregularity on the electrode surface may change the field characteristics in case of small gap distance.

- Between the two extreme field configurations explained above, another important type of field is classified as 'weakly nonuniform field'. Like in uniform field, in weakly nonuniform fields also no

stable partial breakdown occur before the breakdown ($U_i=U_b$). Electrodes like concentric spheres and coaxial cylinders having a 'radial field' are typical examples of weakly nonuniform fields, if the concentric electrode dimensions are suitably designed. The exact value of η, defining weakly nonuniform field, depends upon the particular dielectric and its physical conditions. Nevertheless, the main criterion must be fulfilled that no stable partial breakdown occurs before the breakdown.

Degree of Uniformity of Electric Fields

- The degree of uniformity η introduced by Schwaiger in 1922 as a measure of the uniformity of a field ,is defined as following

$$\eta = \frac{\hat{E}_{mean}}{\hat{E}_{max}} = \frac{\hat{U}}{d} \cdot \frac{1}{\hat{E}_{max}}$$

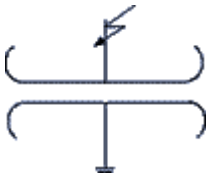
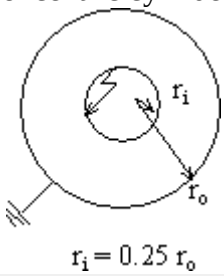
Or

$$\hat{U} = \hat{E}_{max} \cdot \eta \cdot d$$

$\hat{E}_{mean}$ and $\hat{E}_{max}$ are the peak values of the Mean and the Maximum field Intensities in a dielectric respectively. $\hat{U}$ is the peak value of potential difference applied between the two electrodes at a distance 'd ' apart.

- The value of η also represents the degree of utilization of the dielectric in between two electrodes. A higher value of η represents better utilization of the insulating properties of a dielectric. Thus η, a dimensionless quantity enables a comparison of the uniformity of field configuration formed between different electrodes. Table 3.1 gives the values of η for typical fields. The value of η lies between, $0 \leq \eta \leq 1$

Table 3.1

Field Classification	**Uniform**	**Weekly non-uniform**	**Extremely non-uniform**
Electrode Configuration	Parallel plates 	Concentric cylinders 	Needle-plane 
H	1	≤ 0.25	<< 0.01

- Knowledge of the value for η serves as a ready reference, important information for insulation design in equipment. For determining the exact magnitude of maximum electric stress, numerical estimation techniques have to be applied for the shapes of electrodes used in the equipment.
- Schwaiger also introduced 'p', a geometrical characteristics for an electrode configuration and established that it is possible to represent η as a function of 'p',

$$p = \frac{r+d}{r} \qquad (1.5)$$

$$(1 \leq p < \infty)$$

and $$\eta = f(p) \qquad (1.6)$$

Where r is the radius of curvature of the sharpest electrode and d the shortest gap distance between the two electrodes under consideration.

For some common and practical electrode configurations, the equation (1.6) is represented graphically in Figure 2.2 in double logarithmic scale. These are known as 'Schwaiger curves'.

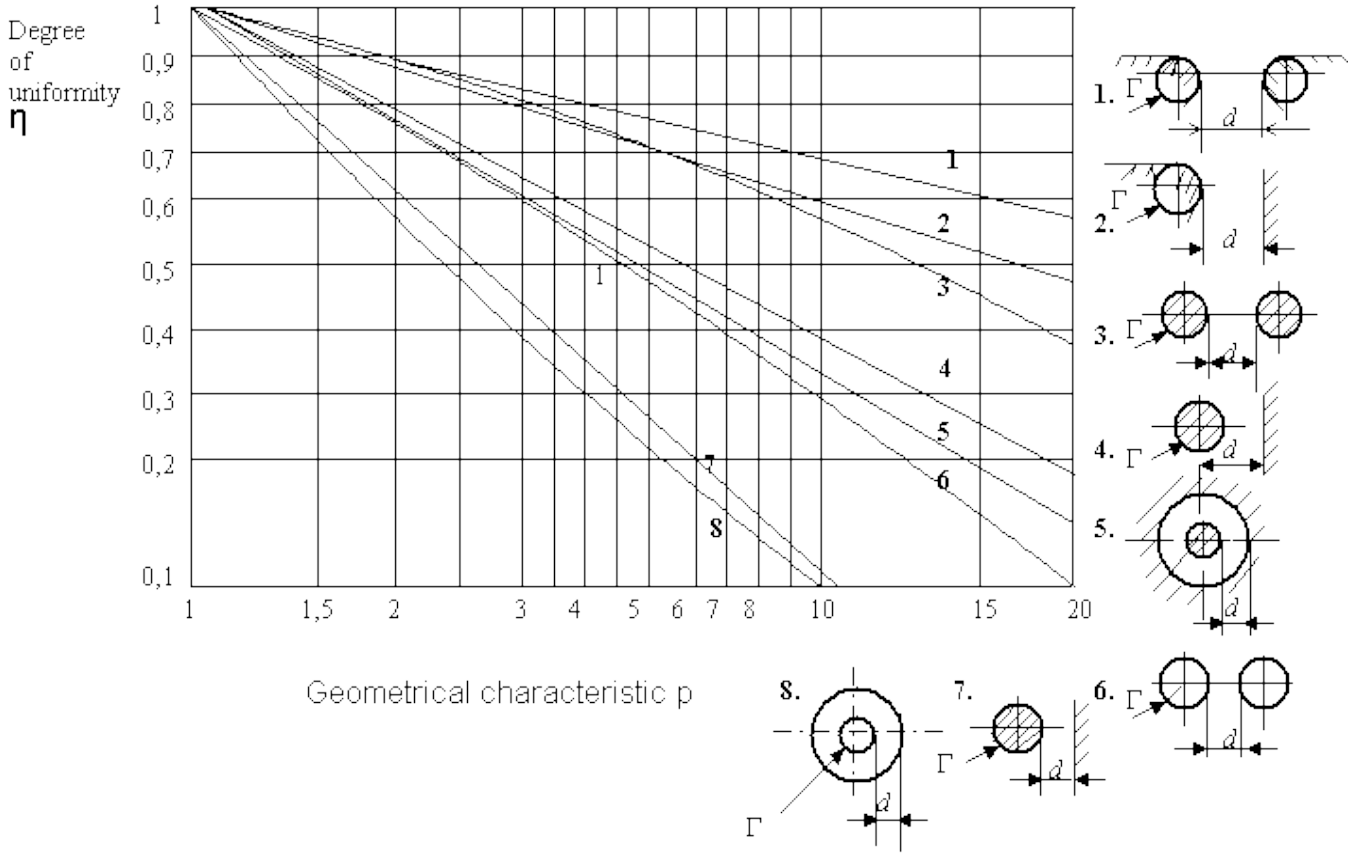


Fig 2.2 Schwaiger curves for spherical, cylindrical and curved electrode field configurations.

For a fixed value of 'p', the following important basic relations of dependency of η are observed from these curves,

- fields between cylindrical electrode systems; cylinder-cylinder (3) , cylinder - plane (4) , concentric cylinders (5) etc., have a higher value of η, that is , they are more uniform than the fields in spherical electrode systems; sphere - sphere (6) , sphere - plane (7) , concentric spheres (8) , etc.,
- A symmetrical electrode system, for example, sphere - sphere or cylinder - cylinder, has a higher value of η than the corresponding unsymmetrical system that is sphere - plane or cylinder - plane systems.
- The field between two similar electrodes, cylinders or spheres, placed adjacent to each other is more uniform or has a higher value of η than when the electrodes are placed coaxial or concentric.

(3) In this lecture you will learn the following:

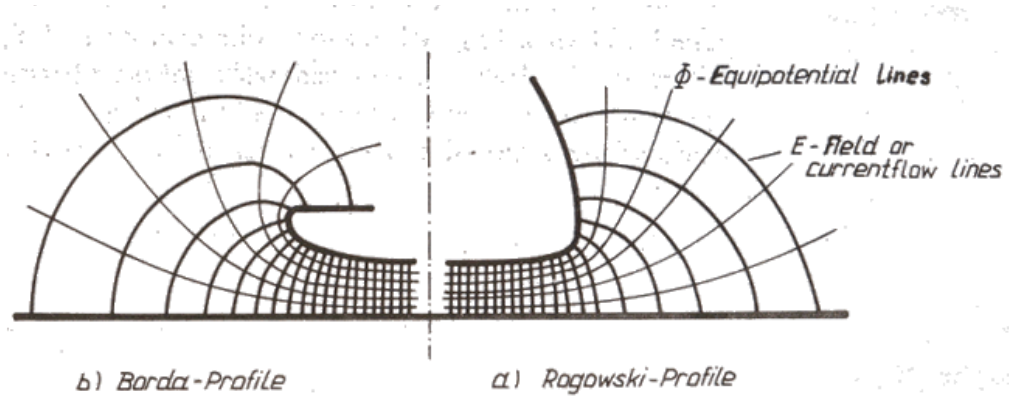
Utilization of Dielectric Properties, Stress Control

Utilization of Dielectric Properties The value of η also represents the degree of utilization of the dielectric in between two electrodes. A higher value of η represents better utilization of the insulating properties of a dielectric. It compares the ideal condition of electric field intensity (uniform field between electrodes at the same distance *d* apart) with the existing actual maximum field intensity. Thus η, a dimensionless quantity enables a comparison of the degree of uniformity of field configurations formed between different electrodes. Table 2.1 gives the values of η for typical fields. The value of η lies between, $0 \leq \eta \leq 1$ with the knowledge of the value of η for a particular field configuration, the maximum electric field intensity or the maximum electric stress on a dielectric can easily be estimated. η serves as a ready reference which is important information for insulation design in equipment. However, for determining the exact magnitude of maximum electric stress, at different shapes of electrodes used in the equipment, numerical estimation techniques have to be applied.

Stress Control

- More the uniformity in field better is the utilization of the dielectric.
- An ideal utilization is accomplished only where η is equal to one, which is not possible in practice.
- More nonuniform field represents higher electric stress in the dielectric. It could be at only a particular location. Insulation design in an equipment is made with due consideration to the value of estimated maximum electric field intensity.
- It is possible to achieve a higher degree of uniformity of fields by giving suitable shapes and sizes to various electrodes in an equipment.
  For example, abrupt interruption of electrodes, both anode and cathode, in high voltage equipment leads to concentration of electric field at the brim, resulting in a tremendous enhancement of electric stress on the dielectric. The dielectric in the vicinity thus becomes highly vulnerable to breakdown.

- The electrodes must be given a suitable shape at the brim to control the stress.
- For stress control, in principle the electrodes are extended and formed in such a way that higher field intensity than in the main field region does not appear anywhere in the dielectric.
- Rogowski suggested in 1923, a shape by which the electrodes could be extended, known as 'Rogowski Profile', Fig. 4.1(a).
- One can see in this figure that the field intensity continuously reduces beyond the main field region.
- Another shape of the electrode credited to Borda known as 'Borda Profile', Fig 4.1(b), was actually worked out by him in as early as 1766 in France, more than 200 years ago.



- Fig 4.1 Equipotential and Field (current flow) lines between plane and brim field Electrodes at high potentials in the laboratory are given large, smooth shaped dome like bodies or shapes like triodes to bring down electric stress on the atmospheric air (dielectric). The modern trend in such electrode design includes 'segmented electrodes', constituting a number of small, identical, smooth discs given

a large desired continuous shape as per requirement. The curvatures of the individual segment discs are worked out by optimization of the suggested profiles. Fig 4.2 shows both, single metallic body and segmented electrodes used in HV test apparatus for stress control.

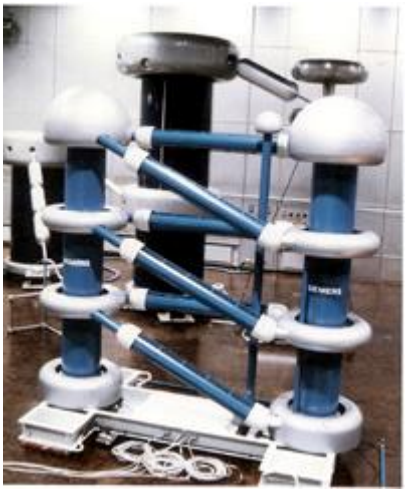
- Extended shapes of electrodes, also known as 'shields', are suitably provided on high voltage apparatus for electric stress control as shown in Fig 4.3. Sharp contacts are often enveloped by a large diameter hemispherical electrode having an aperture, or provided with concentric toroidal rings (doughnut shaped ring). Spheres with smooth holes are provided at bends for the connections of circular and tubular electrodes. Instead of wires, tubular electrodes of large diameters are used for connections in high voltage laboratories which bring down the field intensity at higher voltages considerably. These measures are necessary not only to prevent any partial breakdown (corona) occurring in the laboratory but also to check radio interference.

- It is a common practice to use bundles of two or more number of conductors at the same potential instead of a single conductor, to bring down the electric stress, i.e., for stress control, (Fig. 2.1 b). As the transmission voltages are increasing, bundles with eight or even more number of conductors are being used at higher voltages.

- Capacitive grading is provided in high voltage bushings, potential transformers and cable terminations in order to achieve a better potential distribution leading to a more uniform field distribution in the dielectric. It is achieved by inserting concentric conductive layers at appropriate positions, known as 'floating screens', to control the electric stress as shown in Fig. 4.4. This enables an economic utilization of the insulating material by evenly distributing the equipotential surfaces in the complete dielectric.

- Use of screen (also known as concentric conductor at ground potential) over the insulation in coaxial high voltage cables is made to control the electric stress. The field achieved in these screened cables is radial and generally a weakly nonuniform field. For making cable joints and terminations, the, screen is extended in the form of a cone, known as 'stress cone'. This helps in achieving a more uniform distribution of electric stress in the dielectric at cable end termination as shown in Fig. 4.3 (d).

- A modest thumb rule to control electric stress in high voltage apparatus is to avoid sharp points and edges. Symmetrical, smooth shaped and large electrodes are preferable. It must be borne in mind that even the roughness on metallic surfaces can lead to distortions in the field at higher voltages. Furthermore, micro protrusions may grow and penetrate deeper in the dielectric leading to excessive field enhancement. These must be prevented from developing, firstly during manufacturing stage and subsequently during service and maintenance.



Segmented electrodes (Complete HV lab (600 kV AC))

Single metallic body (DC Generator 900 kV)
Fig 4.2 (Click on images to have an enlarged view)

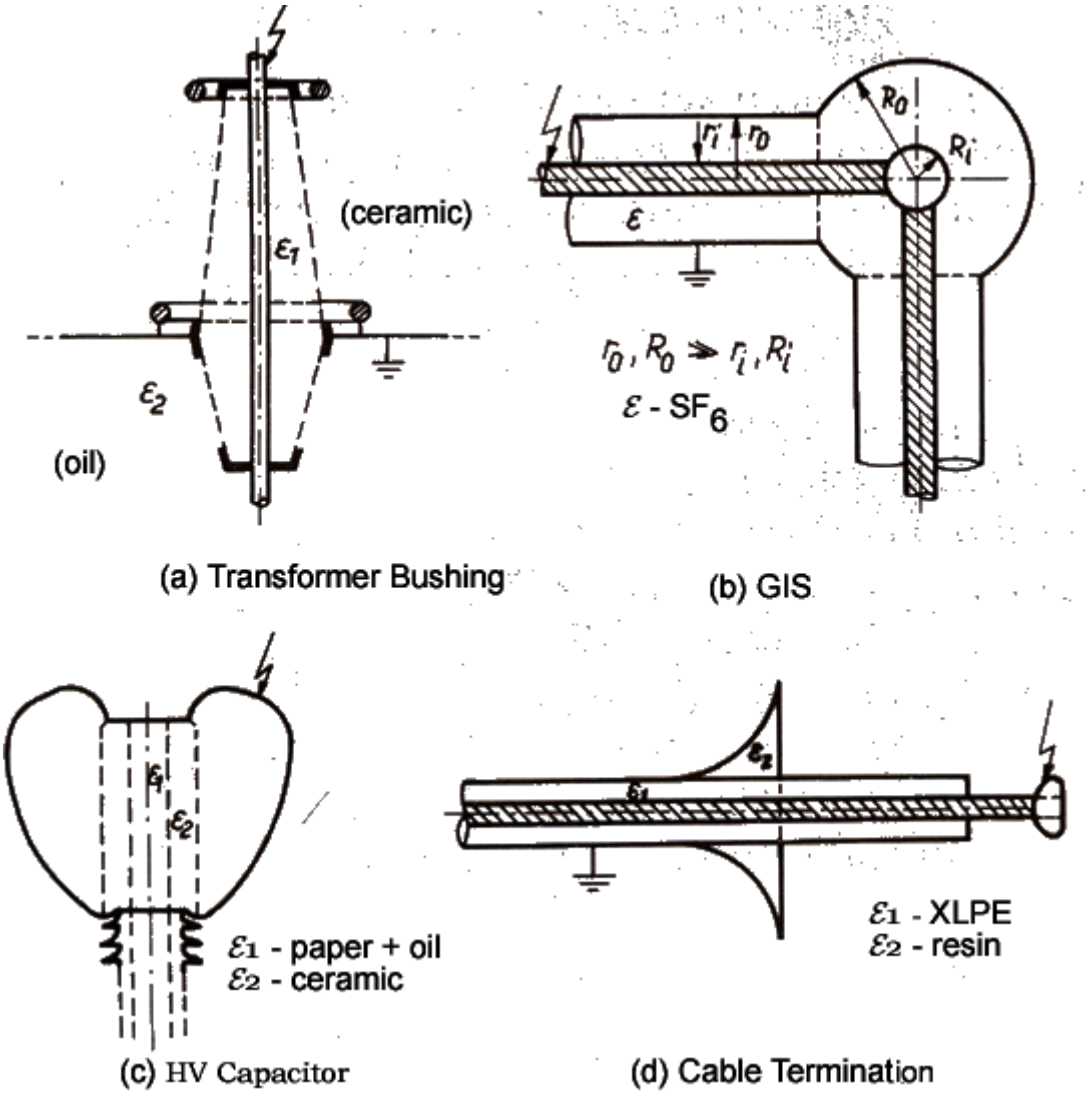


Fig 4.3 Extended shapes of electrodes for stress control (a) A bushing with toroids (b) Right angle bend of a bus bar in gas insulated switchgear (GIS), (c) HV electrode on a condenser, (d) stress cone at a screened cable end.

(4) In this lecture you will learn the following:

Properties of atmospheric air (N_2), Properties of Sulphurhexafluoride SF_6 Gas, Electrical Properties of Vacuum as High Voltage Insulation

Properties of atmospheric air (N_2) the most important, freely available and the cheapest gaseous dielectric is air. The atmospheric air is in fact a mixture of a number of gases. The detailed composition of earth's atmosphere is given in Table 5.1 as given by Goody and Walker in their book Atmospheres.

Table 5.1 Composition of the earth's atmosphere

Constituent	**Percent by volume or by number of molecules of dry air**
Nitrogen (N_2)	78.084
Oxygen (O_2)	20.946
Argon (A)	0.934
Carbon dioxide (CO_2)	0.031
Neon (Ne)	1.82×10^{-3}
Helium (He)	5.24×10^{-4}
Methane (CH_4)	1.5×10^{-4}
Krypton (Kr)	1.14×10^{-4}
Hydrogen (H_2)	5×10^{-5}
Nitrous oxide (N_2O)	3×10^{-5}
Xenon (Xe)	8.7×10^{-6}
Carbon monoxide (CO)	1×10^{-5}
Ozone (0_3)	up to 10^{-5}
Water (average)	up to 1

The largest percentage content of atmospheric air is nitrogen (about 78%), which is an electropositive gas. The second largest constituent is oxygen (about 20%), which is a very weak electronegative gas. The content of hydrogen, an electronegative gas too, is so low (5×10^{-5}%) that for all practical purposes the air can be considered as an electropositive gas. Majority of the theoretical as well as experimental research work available in literature to study the complicated discharge processes in gaseous dielectrics have been performed on air.

Properties of Sulphurhexafluoride, SF_6 Gas

Sulphurhexafluoride was first produced in 1900 by French scientists Moissan and Lebeau by direct fluoronisation of sulphur. In the beginning it was mainly used as a dielectric in atomic physics. During late 1950s, it found application in high voltage circuit breakers. Its application in power systems has been continuously increasing.

Physical Properties

In SF_6 molecule, six fluorine atoms arrange themselves uniformly like an octahedron on a central sulphur atom. An excited sulphur atom can therefore form six stable covalence bonds with the strongly electronegative fluorine atoms by sharing the pair of electrons.

- Amongst halogens, the fluorine element and the sulphur atom both have very high coefficients of electro-negativity, of the order of 4 and 2.5, respectively. This coefficient is a measure of the tendency to attract electrons of other atoms to form dipole bondage.

- The rigid symmetrical structure, small binding distance and high binding energy between atoms of a SF_6 molecule provide it high stability.
- Thermal dissociation in highly purified SF_6 gas begins at extremely high temperatures (above 1000 K). Such high temperatures in power systems occur only in electrical arcs. Even at continuous temperatures up to about 500 K, neither thermal decomposition of SF_6 nor its chemical reaction with other materials has been reported.
- Further, SF_6 is a nontoxic, colourless and odourless gas.

- The molecular mass of SF_6 is quite high (146), it has a high density. Because of high density the charge carriers have short mean free path. This property, along with the properties of electron attachment, that is, electronegativity and high ionization energy result in high dielectric strength of SF_6.

Electrical Properties of Vacuum as High Voltage Insulation

The idea of vacuum as insulation is quite old. Tracing the historical development, it goes back to 1897 when R.W. Wood first gave description of discharges in vacuum while investigating the production of X-ray tubes. The desire to produce X-ray tubes operating at high voltages impelled the investigators to study the dielectric properties of vacuum. Ever since, the vacuum as insulation has gradually found its application in electronic valves, microwave tubes, Klystrons, photocells, particle accelerators and separators, controlled nuclear fusion devices, etc. On the other hand vacuum insulation is applied in high voltage apparatuses such as electrostatic generators, low-loss capacitors, circuit breakers and also for outer space applications.

- At extremely low gas pressures, electron ionization process becomes inadequate to cause a breakdown because the 'mean free path' of an electron (defined as the distance an electron can travel without colliding with another particle) is very long.
- In a vacuum better than 10^{-4} Torr (1.333×10^{-2} Pa), less than 3×10^{12} molecules per cm^3 are estimated to be present and the length of the mean free path is of the order of meters. In such vacuum, an electron may cross a gap of a few cm between two electrodes without any collision.
- Therefore, unlike in gases, in vacuum the initial stage of breakdown cannot be due to the formation of electron avalanche.
- The process of multiplication of charged particles by collision in the space between the electrodes is far too insufficient to create avalanches. However, if a gas cloud forms in the vacuum, the usual kind of breakdown process can take place. Thus investigations of the breakdown mechanism in vacuum have been oriented to establish the way gas clouds could be created in a vacuum. Mechanism, suggests that the prebreakdown currents that flow between vacuum insulated high voltage electrodes, frequently originate from nonmetallic emission mechanisms. These are associated with some kind of insulating/semiconducting surface oxides or impurity concentrations. From the technological point of view, the microscopic conditions of electrode surfaces continue to play an important role.

Breakdown in vacuum is rather a complicated phenomenon involving a large number of processes with high electric field intensities. The' field emission' process, that is, the electron emission from metallic surfaces in presence of strong electric fields, established itself through a considerable amount of work performed in the 20^{th} century. After this a new process, a form of complex nonmetallic emission mechanism has made its break through to explain the prebreakdown conduction.

(5) In this lecture you will learn the following:

Prebreakdown of electron emission in vacuum, Generation of Charge Carriers, Impact Ionization, Photoionization and Interaction of Metastables with Molecules

PREBREAKDOWN ELECTRON EMISSION IN VACUUM

- When the voltage across a very small gap (a few mm) is sufficiently increased, a relatively steady current begins to flow.
- A general observation made for small gaps is, that the prebreakdown current flow has been found to consist mainly of electrons.
- For longer gap spacing (> 1 cm), small pulse currents of millisecond durations and charges of the order of micro-Coulombs (micro-discharges) are measured.
- On raising the voltage further, the micro-discharge eventually gives rise to a steady current.

Mechanisms of Electron Emission from Metallic Surfaces

There are a large number of mechanisms described in the literature that can produce electron emission from metallic surfaces under different conditions, for example, thermionic emission, field assisted thermionic, also known as Schottky or T-F emission, field or cold emission, photoelectric emission, secondary emission caused by electron bombardment of an electrode and emissions caused by positive ion bombardment and metastable atoms [2.2]. Out of these, the most important mechanisms of electron emission in vacuum are due to field, field assisted thermionic and thermionic emission. Non-Metallic Electron Emission Mechanisms Prebreakdown conduction currents between vacuum insulated high voltage electrodes frequently originate from nonmetallic mechanisms. These are associated with some form of insulating/semiconducting oxide layer on the surfaces or impurity concentrations. The microinclusions present on electrode surfaces can stimulate strong electron emission and significantly reduce the breakdown strength of the gap.

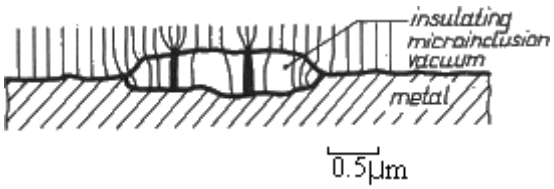


Fig 6.1 A schematic representation of insulating microinclusion emission regime with conducting channels and the associated microscopic field enhancement, Latham, [2.3, 2.4]

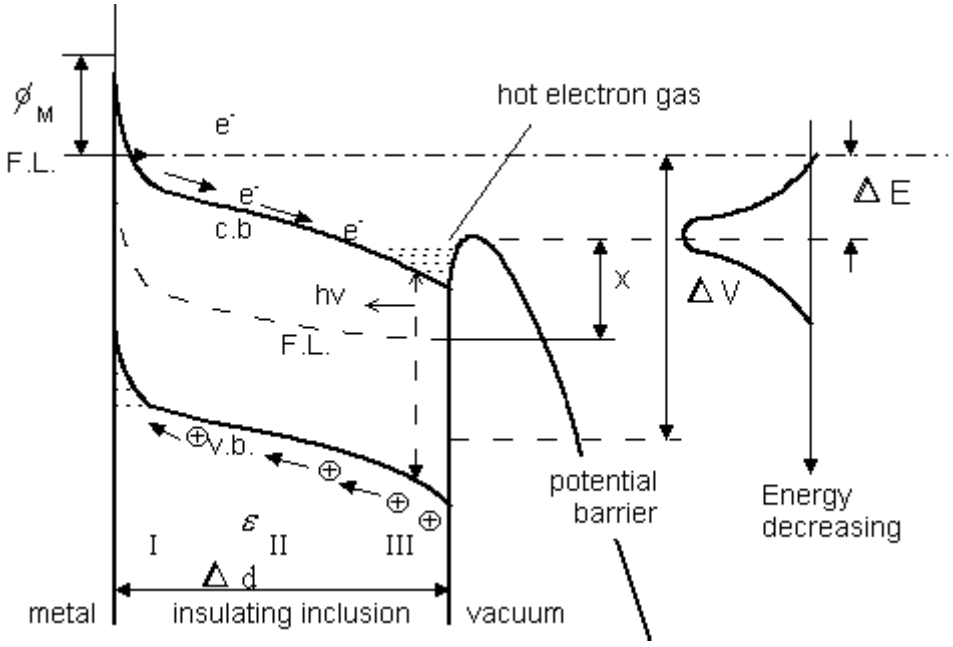


Fig 6.2 A band structure representation of an insulating microparticle in 'switched on state' of a conducting channel yielding electron emission. F.L.-Fermi level, c.b.-conduction band, v.b.-valence band, Latham

Generation of Charge Carriers

In a gas, the electrons and ions are the electric charge carriers. Ions are produced from neutral molecules or atoms by ejection or attachment of an electron. Ejection of an electron from a neutral molecule leaves behind a positive ion, whereas absorption of an electron by a molecule produces negative ion. The mass of an electron compared to that of a molecule is very less (approximately 1/1840), therefore the mass of an ion can be considered to be equal to the corresponding molecule. Because of the lower mass, the drift velocity of an electron in atmospheric air is ~10^7 cm/sec, whereas a heavy ion moves with a drift velocity of ~10^5 cm/sec only. For a small gap distance between electrodes, ions can therefore be assumed not to have moved from the place where they are generated.

During an electrical breakdown, the insulating gas between the electrodes is bridged by a conducting discharge canal (channel). In small gap distance the charge carriers required in order to build this discharge canal are not only produced within the gaseous dielectric across the gap (primary or α- process), but are also released from the electrode surfaces (secondary or γ - process).

The production of charge carriers from the neutral gas molecules is known as ionization process. The ionization process in a gas in long gap distances is the deciding factor leading to breakdown. One of the most significant features of ionization process is the electron energy in different shells of a molecule. The total energy of an electron while still attached to the molecule can be divided into two types of energies. First the kinetic energy W_{KE}, which depends upon its mass and velocity, and second the potential energy W_{pot} depending upon its charge in the Coulomb field of the nucleus of a molecule. These energies are given as,

$$W_{KE} = \frac{1}{2} m_e v_e^2 = \frac{1}{8\pi\varepsilon} \cdot \frac{e^2 z}{r_e} \qquad (6.1)$$

$$W_{pot} = -\frac{1}{4\pi\varepsilon} \cdot \frac{e^2 z}{r_e} = -2W_{KE} \qquad (6.2)$$

Where m_e is the electron mass, v_e its velocity and ε the permittivity of the dielectric. z is the atomic number representing z electrons with negative elementary charge e = -1.6 x 10^{-19} As, lying in the discrete circular orbits r_e of an atom.

When an electron gets ejected out of an atom shell, that is, $r_e \longrightarrow \infty$, the potential energy of the electron tends to be zero. Then the only energy it has, is the kinetic energy acquired externally. The total energy with which an electron is attached to the nucleus of the molecule is given from Equations 6.1 and 6.2 as follows:

$$W_{total} = W_{KE} + W_{pot} = \frac{1}{2} W_{pot}$$
$$= -\frac{1}{8\pi\varepsilon_0} \cdot \frac{e^2 z}{r_e} \qquad (6.3)$$

The binding energy of an electron in the n^{th} shell to its nucleus is given as,

$$W_{total} = -13.61\,eV \cdot \frac{z^2}{n^2} = -W_1 \qquad (6.4)$$

This is the amount of energy required for releasing an electron from its molecule and, therefore, it is known as ionization energy 'W_1' of an electron. If a free electron is absorbed by a molecule forming a negative ion, the energy of ionization is released, known as 'energy of recombination'. The ionization energy W_1 in eV for different gases are given in Table 6.1

Table 6.1 Ionization energies for the first electron in gas

Gas	First Ionization energy W_1 (eV)
N_2	15.6
SF_6	15.6
H_2	15.9
O_2	12.1
H_2O (vapour)	12.7
CO_2	14.4
He	24.0

Impact Ionization

- Impact or collision of particles amongst each other, accelerated under electrical field, leads to the formation of charge carriers from neutral gas molecules.
- The multiplication of charge carriers in gas takes place mainly by impact of electrons with neutral molecules known as α - process (also primary process).
- The positive ions make a moderate contribution to ionization only at solid insulation surfaces, which known as β - process (also secondary process) is shown in Fig. 6.3.

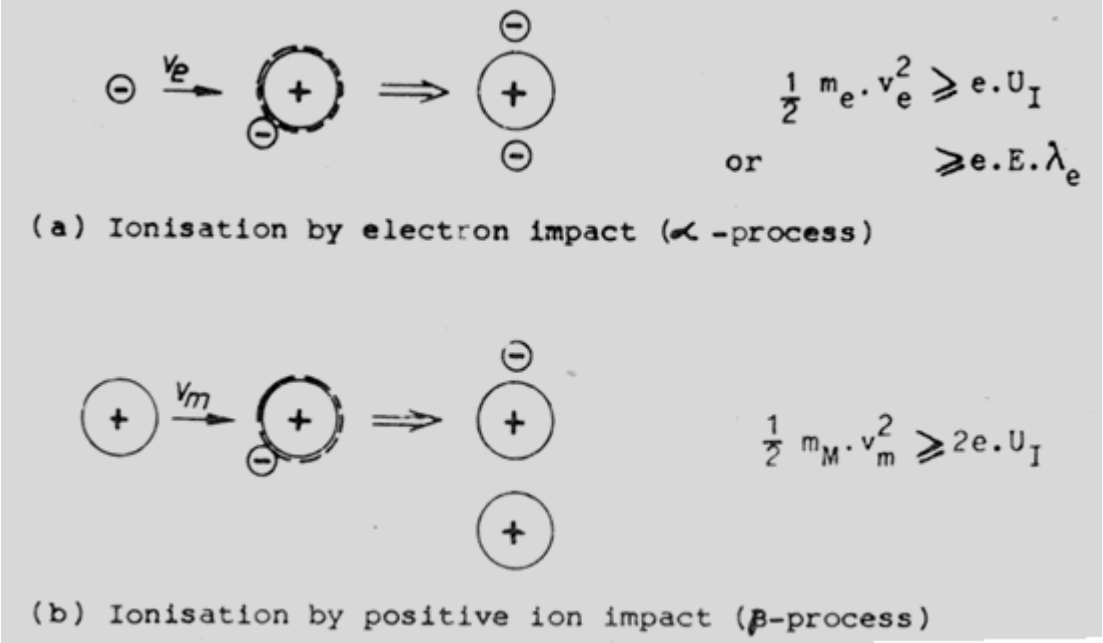


Fig 6.3 Impact ionization by electron and ion

Where λ_e - The mean free path;
e - electron charge;
U_I - The ionization potential

- The β - process does not play any significant role in gaseous dielectrics during the discharge leading to breakdown.
- It is the α -process alone which plays the major role.
- When an electron gains more kinetic energy than the required ionization energy $W_1$of the gas molecule, it is capable of ionizing by impact that is, ejecting an electron from a neutral molecule and thus leaving behind a positive ion.
- To cause ionization, the incoming electron must have a kinetic energy greater than or equal to the ionization energy of the molecule (eU_I).
- However, not all electrons having gained energy $\geq (eU_I)$ cause ionization on collision with neutral molecules. Ionization by impact is actually a probability process.
- The mean number of ionizing collisions made by a single electron per centimeter drift across the gap in a uniform field is given by α. It is known as the Townsend's first or primary 'ionization coefficient', which represents basically a probability process. For gas discharge, it is a very important coefficient strongly dependent upon the electric field intensity,

$$\alpha = f(E)$$

Thermal Ionization

- If a gas is heated to sufficiently high temperature, to the order of 10,000 K and above, many of the gas atoms or molecules acquire high velocity to cause ionization on collision with other atoms or molecules.
- The molecules excited by photon radiation also affect the ionization process.
- Thermal ionization is the principal source of ionization in flames and arcs.
- Saha derived an expression for the degree of ionization θ in terms of gas pressure *p* and absolute temperature *T*, with the assumption that under thermodynamic equilibrium conditions,

the rate of new ion formation must be equal to the rate of recombination. This expression is given as follows:

$$\frac{\theta^2}{1-\theta^2} = \frac{2.4\times10^{-4}}{p} T^{5/2} \; e^{-W_i/kT} \qquad (6.5)$$

Where *p* is the pressure in Torr, W_1 the ionization energy of the gas, *k* Boltzmann's constant (k = 1.38 x 10^{-23} *J/K)*, θ the ratio n_1/n that is, the number of ionized to total particles, and *T* the absolute temperature in K.

- Thermal ionization becomes significant only at temperatures above 10,000 K , as shown in Fig. 6.4

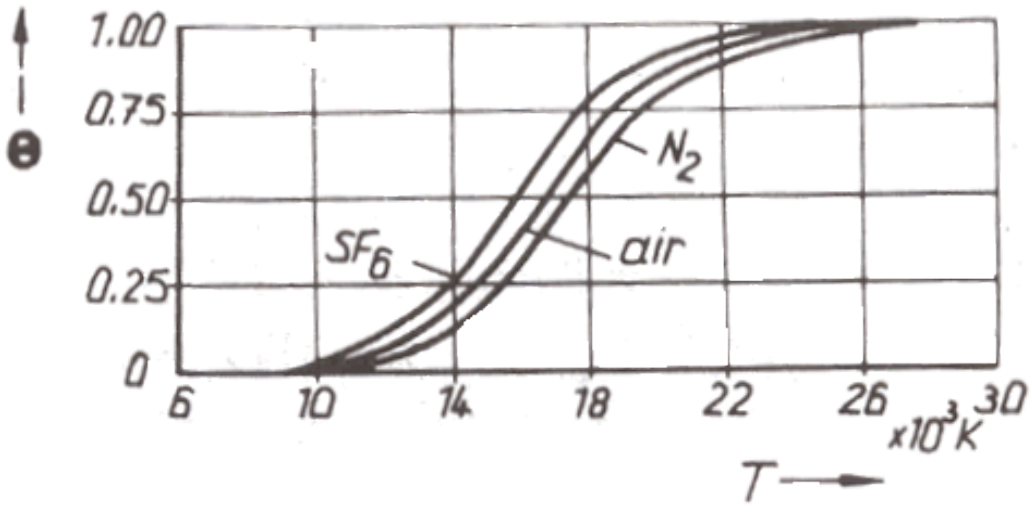


Fig 6.4 Degree of ionization of thermally ionized gases at 1 bar

- During electrical breakdown in gases, thermal ionization has its significance only towards the final stage of breakdown. Because of the transformation of large amount of energy in the electrically conductive channel (known as 'leader') towards the final stage of breakdown, an exceptionally high temperature rise in this channel core is possible.

Photoionization and Interaction of Metastables with Molecules

- The impact ionization process is possible only when the energy exchanged in collision is more than the energy required for ionization (eU_I). The electrons having energy lower than the ionization energy may excite the gas molecules to higher energy states on collision. Under this condition, an electron is raised from a lower energy level to a higher one.
- On recovering from the excited state of electron in 10^{-7} *to* 10^{-10} sec, a molecule radiates a quantum of energy of photon ($h\nu$).
- This energy in turn may ionize another molecule whose ionization potential energy is equal to or less than the photon energy.
- This process is known as photoionization and may be represented as $A+h\nu \longrightarrow A^+ + e$, where A represents a neutral atom or molecule in the gas and $h\nu$ the photon energy.
- For the photoionization *to* occur,

$$h\nu \geq e.U_I$$

Or the photon wavelength λ is,

$$\lambda \leq \frac{c_o h}{e.U_I}$$

Where c_0 is the velocity of light (C_o= 2.998 X 10^8 m/s), h is Planck's constant (h = 6.63 x 10^{-34} J.s) and v is the frequency of light.

- Only a very strong radiation of light quantum (photon) having a short wave-length of less than 65 to 100 nm, can cause photoionization of a gas.
- The basic requirement for photoionization to occur is that the quantum energy of electromagnetic radiation must be greater than the ionization energy of the gas.
- If the photon energy is less than (eU_I), it may still be absorbed by the molecule and raise it to a higher energy level. This process is known as photoexcitation.
- For certain gas molecules, the lifetime in the excited state may extend to a few tens of milliseconds. This is known as 'Metastable state' and the molecules under this state are referred as 'Metastables'.
- Metastables have a relatively higher potential energy and, therefore, ionize neutral particles on collision.
- However, the photons released by this reaction have too low energy to cause ionization in pure gases, but they may release electrons on striking the cathode. This process is known as the cathode emission or secondary ionization also ϒ- process as described by Townsend. Since the ionization caused by metastable interaction is accompanied with a time delay, it has been observed that these reactions are responsible for longer time-lags than usual in some gases.

(6) In this lecture you will learn the following:

Development of Electron Avalanche in uniform field,

Townsends primary ionization coefficient

Development of Electron Avalanche

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

- When an electron gains more energy than required for ionization of the gas molecules (Table 6.1), then it is capable of ionizing, that is, ejecting an electron from the neutral molecule, and leaving behind a positive ion.
- The new electron thus ejected along with the primary one repeat the process of ionization.
- Since a molecule is much heavier compared to an electron, it can be considered relatively stationary, making no contribution to the ionization process.

- On the contrary, the electrons move very fast under the influence of applied electric field and continue to release further electrons from the gas molecules.
- An 'avalanche' of electrons finally reaches the anode as shown in Fig. 7.1

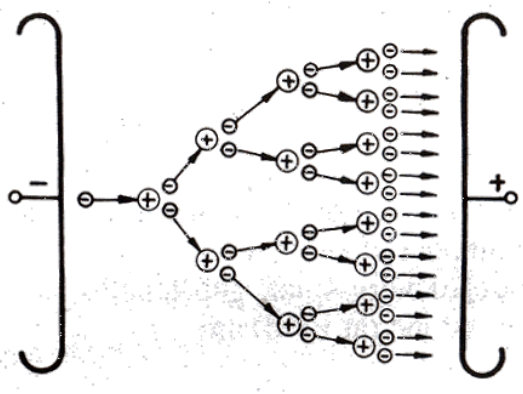


Fig 7.1 Development of an electron avalanche in uniform field

- At the field intensities at which impact ionization occurs, the value of drift velocity of electrons in air is usually ~10^7 cm/s, while of positive ions it is about 150 times lower ~10^5 cm/s. Accordingly, the transit time required by electrons and ions to cross a gap differ about 150 times.
- The process of avalanche form of charge carrier multiplication was first described by Townsend(1901). Later he also gave its mathematical formulation.
- If only the process of electron multiplication by electron collision is considered in uniform field between

two plates, Fig. 7.2, then neglecting other processes (recombination and diffusion), the number of electrons produced by collision at an element dx, at distance x from the cathode is,

$$dn_x = n_x \alpha \, dx \tag{7.1}$$

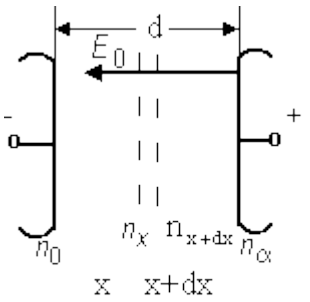


Fig. 7.2 Electrons in a uniform field

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

- In a uniform field where the field intensity E is constant, the ionization coefficient α can be considered constant. By integrating Equation 7.1 and applying the initial condition $n_x = n_0$ at x = 0, the following equation is derived for a uniform field,

$$n_x = n_0 e^{\alpha x} \tag{7.2}$$

- For weakly nonuniform fields, where α is not constant, the above equation is written as,

$$n_x = n_0 \exp\left[\int_0^x \alpha \, dx\right] \tag{7.3}$$

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

- Therefore, in case of very small gap distances, the number of electrons striking the anode per second (at x = d) are,

$$n_d = n_0 e^{\alpha d} \tag{7.4}$$

- This means that on an average each electron leaving the cathode produces ($e^{\alpha d} - 1$) new electrons and the same number of positive ions in traversing the distance d.
- The expressions 7.2 - 7.4 show distinctly the exponential or avalanche form of growth of the number of

charge carriers by primary or α process.

- The Townsend's first ionization coefficient α is a function of the electric field intensity E, and at constant temperature it is dependent upon the gas pressure p. It can be proved that,

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

- The coefficient α can be calculated with the help of molecular parameters. However, α is usually obtained experimentally by measuring the multiplication of electrons in high electric fields. For air, the following equation is approximated [2.5].

$$\frac{\alpha}{p} \approx 1.11 \times 10^{-4} \left(\frac{E}{p} - 25.1\right)^2 \qquad (7.5)$$

where E is in V/cm, p in Torr and α in cm^{-1}.

- Equation 7.5 is plotted for α/p and *Elp* in Fig. 7.3 at constant temperature.
- Raether was able to take first photographs of the trace of an electron avalanche in 1939 [2.6]. He used the so called 'Wilson Cloud Chamber', which caused condensation of water vapour droplets on the charge carriers of an avalanche at appropriate gas pressure.

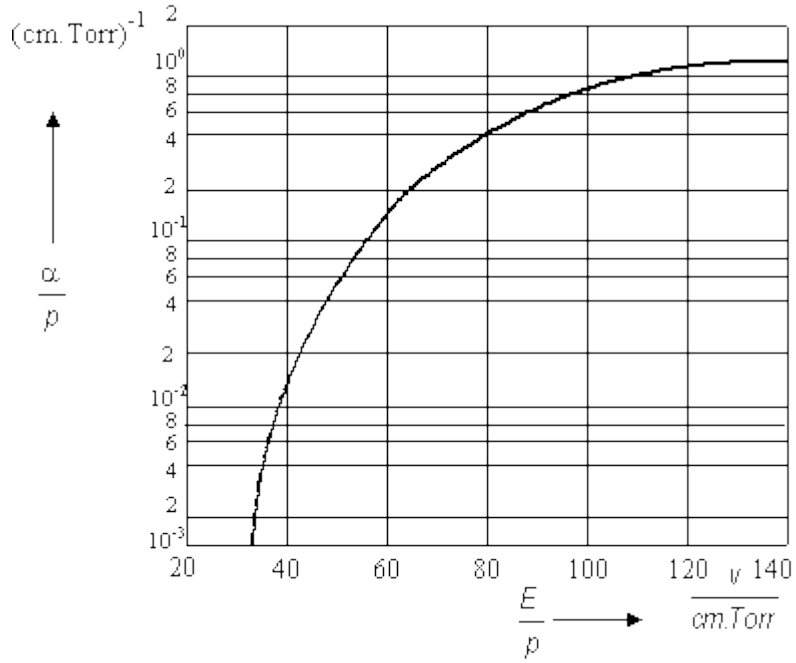


Fig 7.3 Apparent ionization coefficient α / p as function of E/p for air.

- In his experiment, a short duration voltage pulse was applied on the electrode system shown in Fig 7.4 (a,c).
- When the voltage applied reached its desired peak value, just sufficient to develop an avalanche, it was maintained at this magnitude, but was not allowed to lead to a breakdown.
- Just at this stage, primary electrons were produced in the electrode system with the help of an external spark discharge source as shown in Fig. 7.4 (b).
- This gave rise to the development of an electron avalanche.
- In order to avoid a breakdown, the process was controlled by a steep reduction in the applied voltage to

zero after the duration of a few tens of nanoseconds.

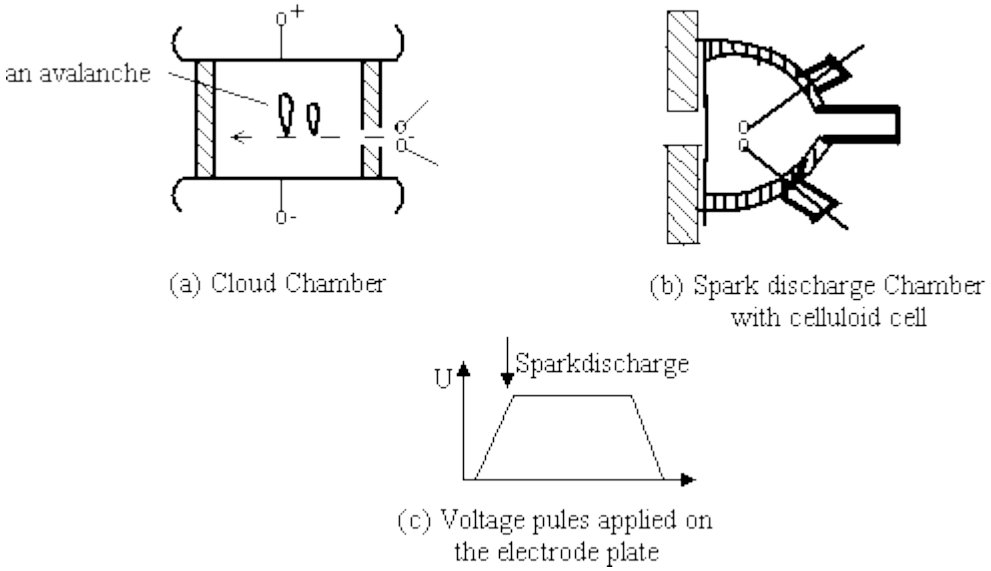


Fig 7.4 Experimental arrangement to produce an avalanche.

- Since the drift velocity of electrons is about 150 times more than that of the ions, hence as soon as an avalanche is formed, the positive ions remain practically stationary where they are produced, i.e., at the tail of the avalanche.
- The head of the avalanche is consequently built-up by electrons.

- The form of the track is wedge shaped, apparently due to the thermal diffusion of the drifting electron swarm having acceleration in the direction of electric field.
- The head of the avalanche is rounded since the diffusion of electrons takes place in all directions.
- Fig 7.5 shows the distribution of charge carriers and actual photographs of avalanche [2.7, 2.8].

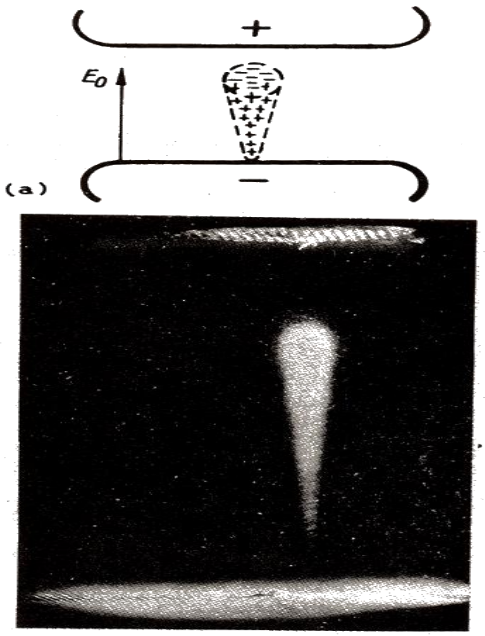


Fig 7.5 An electron avalanche in uniform field.
(a) Distribution of charge carrier and the shape,
(b) Actual photograph by Raether[2.7]

- The experiments conducted by Wagner [2.8] in 1966 were on slightly longer gap distances in uniform field. He also photographed the electron avalanche in a cloud chamber.
- It was revealed that when the light was first detected in the chamber, the number of charge carriers in the avalanche, that is the space charge was insufficient to cause any distortion in the applied electric field E_0.
- The center of the electron cloud moved at the electron drift velocity corresponding to the field E_0.
- This light first detected is known as 'primary avalanche' shown in Fig. 7.5 (b).
- Through these experiments it was concluded that only after further development, when the total number of electrons reach ~10^7 to $l0^8$, the space charges of ions and electrons in the avalanche become strong enough to distort the applied field E_0.

(7) In this lecture you will learn the following:

Breakdown with Avalanche Discharge (Townsend Mechanism),

Growth of conduction current in gaseous dielectrics

Breakdown by Avalanche Discharge (Townsend Mechanism)

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

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

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

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

- 'γ ' is known as Townsend's secondary ionization coefficient. It is defined as the number of secondary electrons on an average produced at the cathode per electron generated by the primary process, that is, per ionizing collision in the gap. ' γ' strongly depends upon the cathode material and is a function of field intensity and pressure of the gas."

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

- Like α, γ also represents a probability process. If the mean number of secondary electrons per avalanche produced are μ, then considering Equation 7.4,

$$\mu = \gamma(e^{\alpha d} - 1) \tag{8.1}$$

If the primary electron generation process begins with n_0 number of electrons, the second generation begins with μn_0 number of electrons.

- Average current growth with respect to the applied voltage and time are shown in Figs. 8.1 - 8.3

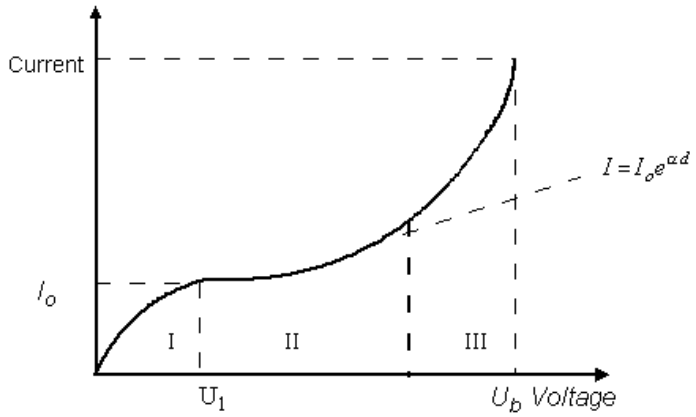


Fig 8.1 General conduction current-voltage characteristics before breakdown.

- In order to measure the U-I characteristic, Townsend's original experimental arrangement had uniform field electrodes enclosed in a glass vessel. This vessel was provided with a quartz window for irradiating the cathode with ultra violet light to emit photo electrons [2.9].
- As the voltage applied is raised, the initial current through the gap increases slowly to a value I_o
- The magnitude of this current depends upon the ultra violet illumination level of the cathode, region I, shown in Fig. 8.1.
- The electrons emitted from the cathode move through the gas with an average velocity determined by their mobility at the field intensity in the gap.
- The initial increase in current is followed by an approach to saturation because some of the electrons emitted from the cathode return to it by diffusion.
- The proportion of electrons which diffuse back decreases as the voltage is increased, but not all the electrons emitted reach the anode, even at the voltages at which ionization in the gas begins to occur.
- Thus, in general, there is no well defined plateau in the U-I characteristic, and the current eventually increases rapidly through the regions II and III with increasing voltage until a breakdown occurs at some well defined voltage $U = U_b$[2.10].
- Whatever may be the level of initial illumination of cathode, the voltage U_b at which the breakdown occurs remains unaltered.
- The increase in current in region II is derived from the process of field intensified ionization by primary or α -process.
- The secondary or γ -process accounts for the sharper increase in current in region III and for an eventual spark breakdown of the gap. Figure. 8.2 show the U-I characteristic in helium at a pressure of 488 Torr, measured by Rees [2.11]. It is evident from the Fig. 8.1 and 8.2 that the characteristics measured by Townsend and Rees are very similar.

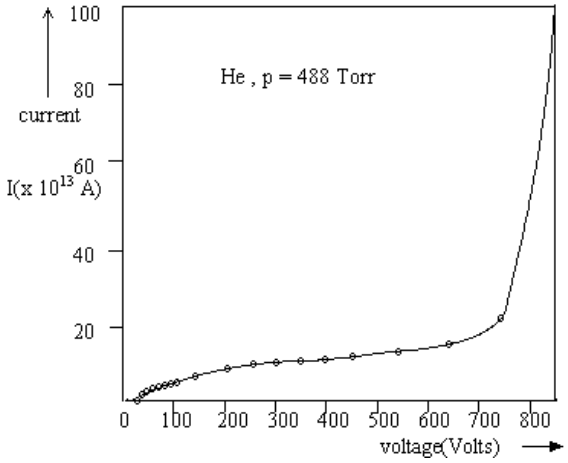


Fig 8.2 Voltage-current (U-I) characteristics in helium measured by Rees [2.11] in 1963.

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

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

For this case, μ(t) can be written as,

$$\mu(t) = \gamma\left\{\exp\left[\int_0^d \alpha(x,t)dx\right] - 1\right\}$$

which grows continuously above 1, till breakdown occurs.

- Experiments have been performed to study the current growth in uniform fields in air and other gases initiated by a single electron (n_0 =1) with the help of a light flash. The process with higher number of electrons (n_0 » 1) is achieved by illuminating the cathode with constant intense light [2.12-2.14].
- Hoger [2.13] developed one such method of measurement in nitrogen.
- With the help of theoretical considerations confirmed with experimental results, he computed the current growth started by a single and more number of electrons as in Fig. 8.3. The measured values are indicated by the vertical lines.
- At lower values of current, the statistical distribution scatters more compared to the distribution at higher current values.

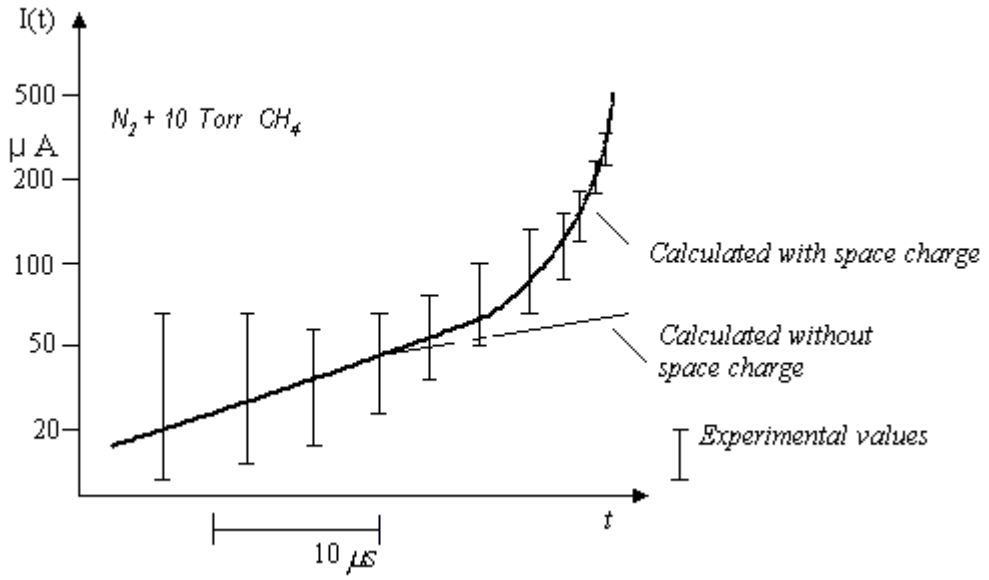


Fig 8.3 Current growth initiated by a single electron, (E/p_{20} = 44.8 V/cm. Torr, d = 2 cm, α d = 12.3, μ = 1) on semilogarithmic plot by Hoger [2.13] 1963.

- The movement of charge carriers (electrons and positive ions) in the gap is responsible for the growth of circuit current.
- The saturation level of the curve in Fig 8.1 (region II) is also called the steady state region.
- If it is assumed that the number of positive ions diffusing per second at the cathode are just equal to the number of newly formed electrons arriving at the anode, the growth of current in this region can be given by,

$$I = I_0 e^{\alpha d} \qquad (8.2)$$

where I_0 is the initial photo-electric current at the cathode.

- Although this expression represents the averaged effect of a number of avalanches, it fails to signify the breakdown.
- The current in region III has a much steeper rise till a breakdown occurs which is rendered to the γ, or secondary ionization process.
- The Townsend's current growth equation in this region is derived as follows: Let
- n_0 = the number of primary electrons (photo electrons) emitted from the cathode (at *x = 0)* per second. In other words, an avalanche in uniform field develops at the cathode with $n_0$initial electrons. n_0' = the number of secondary electrons produced at the cathode per second, and n_0'' = the total number of electrons leaving the cathode per second.

Thus $$n_0'' = n_0 + n_0' \qquad (8.3)$$

- Since each electron leaving the cathode makes on an average $(e^{\alpha d} - 1)$ collisions in the gap *d,* therefore, the total number of ionizing collisions per second in the gap will be n_0'' $(e^{\alpha d} - 1)$.
- By definition, γ is the number of secondary electrons produced on an average at the cathode per ionizing collision in the gap, then,

$$n_0' = \gamma \; n_0'' \; (e^{\alpha d} - 1) \qquad (8.4)$$

Substituting Equation 5.9 in 5.8, we have

$n_0'' = n_0 + \gamma \; n_0'' \; (e^{\alpha d} - 1)$

$$n_0'' = \frac{n_0}{1 - \gamma(e^{\alpha d} - 1)} \qquad (8.5)$$

From Equation 7.4, the number of electrons arriving at the anode is given by,

$n_d = n_0'' \; e^{\alpha d}$

By putting the value of n_0'' in the above equation, we have

$$n_d = \frac{n_0 e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)} \qquad (8.6)$$

- Under the steady state conditions, the current in the gap can therefore be given by,

$$I = \frac{I_0 e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)} \qquad (8.7)$$

This equation describes the growth of average current in the gap before the breakdown.

- According to Equation 8.1, $\gamma(e^{\alpha d} - 1)$ in the denominator of Equation 8.7 represents μ, the mean number of secondary electrons produced per avalanche. For μ << 1, the secondary ionization, or γ - process is insignificant. Then equation 8.7 reduces to $I \approx I_0 e^{\alpha d}$, which represents the region II in Fig. 8.1. The applied voltage and hence the field intensity is low in this region. This condition is also described as 'non-self-sustaining discharge', or ionization process, under which a breakdown would not be able to develop by itself.
- As the applied voltage, and thus the field intensity *E* is increased, the value of μ approaches 1. Then the denominator of this equation approaches zero and, therefore, the current I tends to rise unlimitedly. At this stage, the current is however limited by the impedance offered by the power supply and by the gas itself. Under these conditions, the discharge or ionization process becomes self-sustained to maintain the level of required charge carriers, described as a 'self-sustaining discharge'. The quantitative condition for breakdown can be expressed as,

$$\mu = \gamma(e^{\alpha d} - 1) = 1 \qquad (8.8)$$

This equation is known as the 'Townsend Criterion' for spark breakdown in uniform field. At the final stage of breakdown, the electron amplification is normally much greater than one ($e^{\alpha d} >> 1$), so the criterion reduces to

$$\gamma e^{\alpha d} = 1 \qquad (8.9)$$

- Under the condition when μ > 1, a strong concentration of charge carriers grow in the subsequent 'generations' of electron production.
- These equations and conclusions are also valid for weakly nonuniform fields where the μ is defined in slightly different way as follows:

$$\mu = \gamma\left[\exp\left(\int_0^d \alpha dx\right) - 1\right] \qquad (8.10)$$

- The Townsend's mechanism of spark breakdown can, therefore, be explained on the basis of the observation that the ionization process begins with a number of 'series of avalanches'.
- It extends over the whole gap and ultimately constricts into a spark or breakdown channel. A conceptual schematic of the breakdown mechanism is shown in Fig. 8.4.

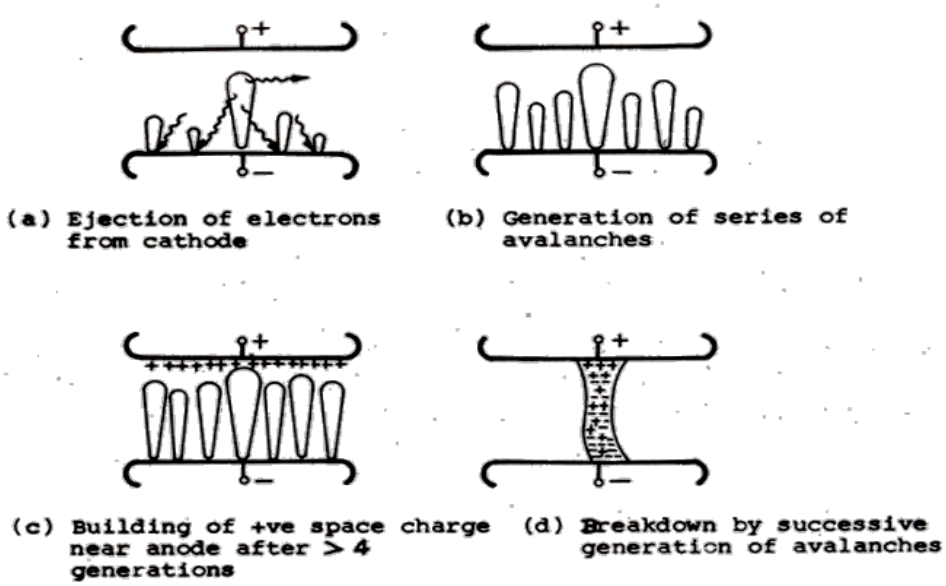


Fig 8.4 Townsend breakdown mechanism schematic.

(8) In this lecture you will learn the following:

Breakdown with Streamer Discharge (Streamer or Kanal Mechanism),

Critical amplification of avalanche

According to Townsend's generation mechanism, the time required for breakdown by normal avalanche propagation is determined by the drift velocity of electrons in a few generations. The estimated time required for breakdown in comparatively longer gap distances by this theory was too long, contrary to the actual time measured experimentally. With the development of electrical and optical measurement methods, this was confirmed by Raether as early as 1939 [2.6]. This necessitated a novel approach for breakdown mechanism suitable for longer gap distances than as explained by Townsend in uniform fields.

- The streamer breakdown mechanism describes the development of spark breakdown directly from a single avalanche.
- The space charge developed by the avalanche itself due to rapid growth of charge carriers, transforms it into a conducting channel. As described by Raether, it is the 'eigen space charge' which produces the instability of the avalanche.

- The word streamer literally means a ribbon attached at one end and floating or waving at the other, which appears to be a set of waves or ripples moving forward. Streamer also means a column of light shooting up in aurora.
- This kind of visual display results during a discharge due to the movement of pockets of ionized particles.
- The term 'Kanal' is taken from German language which means a canal or a channel.

- The approximate calculations of the conditions required for the space charge field of avalanche E_a to be able to acquire the magnitude of the order of the externally applied field E_0, confirmed that the transformation from avalanche to streamer began to develop from the head of an electron avalanche, when the number of charge carriers increased to a critical value,

$$n_0 \, e^{\alpha x_c} \approx 10^8$$

- For an avalanche initiated by a single electron ($n_0 = 1$) in a uniform field, this corresponds to a value,

$$\alpha x_c = \alpha d_c = \ln 10^8 \approx 20$$

Where x_c is the length of avalanche in the field direction when it amplifies to its critical size.

In other words, x_c is the critical length of the electrode gap d_c. This means that the streamer mechanism is possible only when $d \geq x_c$. If x_c is longer than the gap length d ($x_c > d$) then the initiation of streamer is unlikely as shown in Fig.9.1

- On the basis of experimental results and some simple assumptions, Raether developed the following empirical formula for the 'streamer breakdown criterion'.

$$\alpha x_c = 17.7 + \ln x_c + \ln \frac{E_a}{E_o}$$

- The interaction between the space charges and the polarities of the electrodes results in distortion of the uniform field.

- Field intensities towards the head and the tail of avalanche acquire a magnitude ($E_a + E_o$), while above the positive ion region, just behind the head, the field is reduced to a value ($E_0 - E_a$), (see Fig. 9.1).

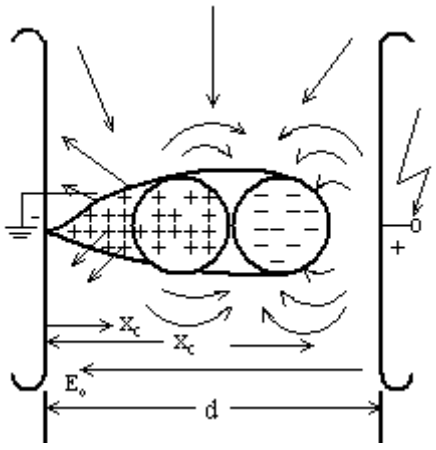


Fig 9.1 Effect of space charge field E_a of an avalanche of critical amplification on the applied uniform field.

- If the charge lies nearly in a spherical shape of radius r_a then the field at the surface of this space charge in the form of a sphere is,

$$E_a = \frac{e \exp(\alpha x)}{4\pi\varepsilon_0 \, r_a^2}$$

Where *e* is the elementary charge of an electron and ε_0 the absolute permittivity constant.

- The condition for transition from avalanche to streamer breakdown assumes that this eigen space charge field approaches near the externally applied field ($E_a \approx E_0$). Hence the above breakdown criterion becomes,

$$\alpha x_c = 17.7 + \ln x_c$$

- The minimum value of αx_c required for breakdown in a uniform field gap by streamer mechanism is obtained on the assumption that the transition from avalanche to streamer occurs when an avalanche of critical size just extends across the gap d. By incorporating this condition, the breakdown criterion takes the form,

$$\alpha d_c = 17.7 + \ln x_c$$
$$\approx 20$$

- Thus the condition $x_c = d_c$ gives the smallest value of α to produce streamer breakdown, where d_c is given in cm. For $\alpha x_c = \ln 10^8$, x_c works out to be equal to 2cm which can be considered to be critical gap distance, d_c, for streamer phenomenon to take place in atmospheric air in uniform field.
- The 'streamer breakdown criterion' can be therefore interpreted as a condition for the development of significant field distortion caused by stark space charge within a single avalanche so that its field intensity is comparable to the externally applied field.

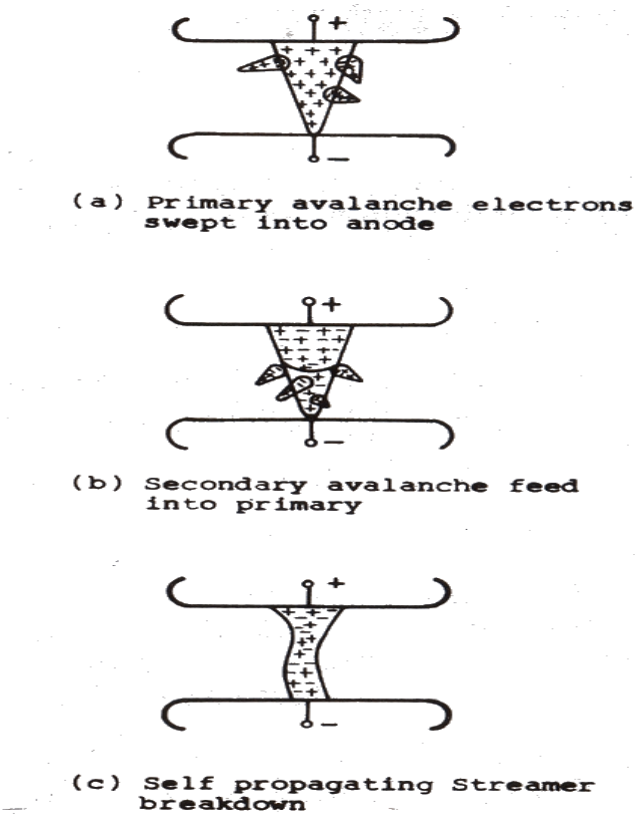


Fig 9.2 Schematic of a cathode directed streamer breakdown showing development stages.

- In sufficiently long air gap in uniform field when the avalanche extends across the gap, the electrons are swept into the anode, and the positive ions in the tail of the avalanche stretch out across the gap as shown in Fig. 9.2.
- A highly localized space charge field due to positive ions is produced near the anode but since the ion density elsewhere is low, it does not constitute a breakdown in the gap.
- In the gas surrounding the avalanche, secondary electrons are produced by photons and photo-electric effect from the cathode.

- The secondary electrons initiate the secondary avalanches, which are directed towards the stem of the main avalanche, if the space charge field developed by the main avalanche is of the order of the applied field. Thus the secondary avalanches feed into the primary avalanche as shown in Fig. 9.2 (a), (b).
- The positive ions left behind by the secondary avalanches effectively lengthen and intensify the space charge of the main avalanche in the direction of the cathode and the process develops a self propagating streamer breakdown shown in Fig. 9.2 (c).

- Significant development in high-speed photographic techniques, strengthened by the incorporation of image converters and image intensifiers have made it possible to record the progress of the discharge light output at earlier stages than hitherto.

- Figure 9.3 shows the photograph of an avalanche where secondary avalanches are feeding into the primary avalanche, taken in a gap of 3.6 cm in air at 270 Torr and a field intensity of about 12,200 V/cm by Raether .

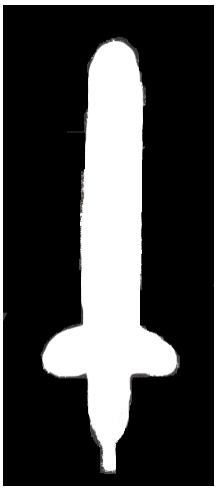


Fig. 9.3 Photograph of a cathode directed streamer developed from an avalanche, Raether [2.7]

(9) In this lecture you will learn the following:

Paschen's Law, Breakdown in gaseous dielectrics in Uniform Fields, Breakdown Voltage Characteristics in Uniform Fields (Paschen's Law)

- In uniform fields, the Townsend's criterion for breakdown in electropositive gases is given by the following equation,

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

Or $$\alpha d = \ln (1/\gamma + 1)$$

Where the coefficients α and γ are functions of *E/p* and are given as follows:

$$\alpha = p f_1\left(\frac{E_0}{p}\right)$$

and

$$\gamma = f_2\left(\frac{E_0}{p}\right)$$

Where E_0 is the applied electric field, and p the gas pressure. In a uniform field electrode system of gap distance d,

$$E_b = \frac{U_b}{d}$$

Where U_b is the breakdown voltage and E_b the corresponding field intensity. E_b is equal to the electric

strength of the dielectric under given conditions. When the applied field intensity $E_0 = E_b$, the Townsend's criterion for breakdown in electropositive gases in uniform field can be represented in terms of the product of the gas pressure and the electrode gap distance *'pd' as,*

$$f_2\left(\frac{U_b}{pd}\right)\left\{\exp\left[pd f_1\left(\frac{U_b}{pd}\right)\right] - 1\right\} = 1 \qquad (10.1)$$

or $$U_b = f(pd) \qquad (10.2)$$

This is known as Paschen's law. The scientist, Paschen, established it experimentally in 1889 from the measurement of breakdown voltage in air, carbon dioxide and hydrogen. It can be shown that this law is also applicable to electronegative gases. The values of α depend upon the particular gas and of γ upon the electrode material. The breakdown voltage of a gas in uniform field is, therefore, a unique function of the product of gas pressure, *'p'* and the gap distance between electrodes '*d'* for a given electrode material and its condition.

- At low value of *Elp*, that is at high pressures, where a steady state can be achieved, experiments have been performed on the spatial growth of ionization in a large number of both, electropositive and

electronegative gases. In these experiments the conduction gap currents were maintained below 0.1μA, so that the field distortions due to space charge remained at a minimum. The results have shown that this generalized Townsend's theory of breakdown is applicable over a wide range of physical conditions. The values of the breakdown voltages U_b estimated theoretically have been found in good agreement with those observed experimentally.

- A schematic of the variation of U_b with respect to *'pd'* is shown in Fig. 10.1. Equation 10.1 does not imply that the breakdown voltage varies linearly with *'pd'*, although in practice it is found to be nearly linear over certain regions. The breakdown voltage attains a minimum value $U_{b\ min}$ around a particular value of the product $(Pd)_{min}$.

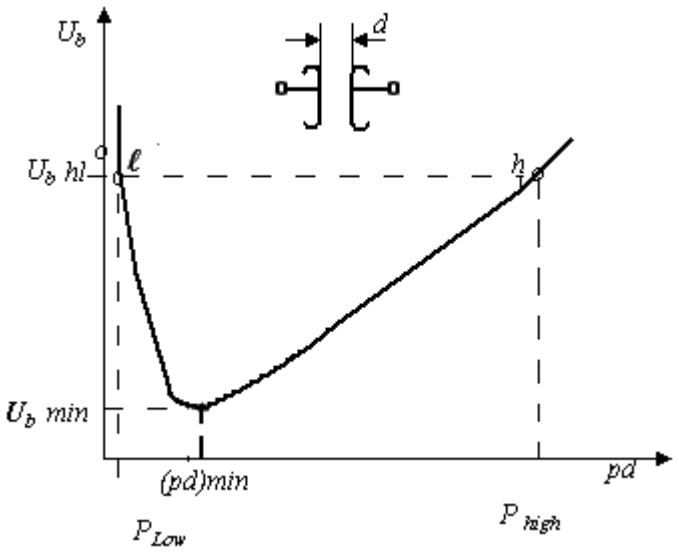


Fig 10.1 Breakdown voltage vs pd characteristics in uniform field (Paschen's curve)

Breakdown Voltage Characteristics in Uniform Fields (Paschen's Law)

- To explain the shape of the curve in last slide, it is convenient to consider a gap with fixed spacing *(d* = constant), and let the pressure decrease from a point P_{high} on the curve at the right of the minimum. As the pressure is decreased, the density of the gas decreases, consequently the probability of an electron making collisions with the molecules goes down as it travels towards the anode. Since each collision results in loss of energy, lower electric field intensity, hence a lower voltage suffices to provide electrons the kinetic energy required for ionization by collision to achieve breakdown.
- When the minimum of the breakdown voltage is reached and the pressure still continues to be decreased, the density of the gas becomes so low that relatively fewer collisions occur. Under such conditions, an electron may not necessarily ionize a molecule on colliding with it, even if the kinetic energy of the electron is more than the energy required for ionization. In other words, an electron has a finite chance of ionizing which depends upon its energy. The breakdown can occur only if the probability of ionization becomes greater by increasing the field intensity. This explains the increase in breakdown voltage to the left of the minimum. At low pressures, P_{low} , partial vacuum conditions exist, hence this phenomenon is applicable in high voltage vacuum tubes and switchgears. Under these conditions, the effect of electrode material surface roughness plays an important role on the breakdown voltage especially at small gap distances and the Paschen's law is no more valid to the left of the minimum of this curve.

With the help of many scientists, Schumann, Sohst and Schröeder, the following equation for breakdown voltage of air in uniform field was derived.

$$\hat{U}_b = 6.72\sqrt{pd} + 24.36(pd)\ kV \qquad (10.3)$$

Where p is given in bar and d in cm, therefore pd in bar.cm

- Calculated values of breakdown voltages using Equation 10.3 for uniform field in air have been compared with the available experimental results from different authors by Dakin et al. [2.15] as shown in Fig. 10.2. The peak values of the breakdown voltages in kV and pd in bar. mm are plotted on a double logarithmic scale paper. As seen in this figure, the calculated and the measured results agree with each other well, except for the very low values of *pd.* In this region where the *Elp* values are quite high due to low pressures, the equation 10.3 no longer holds good and the Paschen's law is no more valid. In this region or in the pressure range of ≤ 25Torr till up to 10^{-3} Torr, the phenomenon of Faraday Glow occurs. The air acquires a plasma state on applying quite low voltages depending upon the actual pressure.

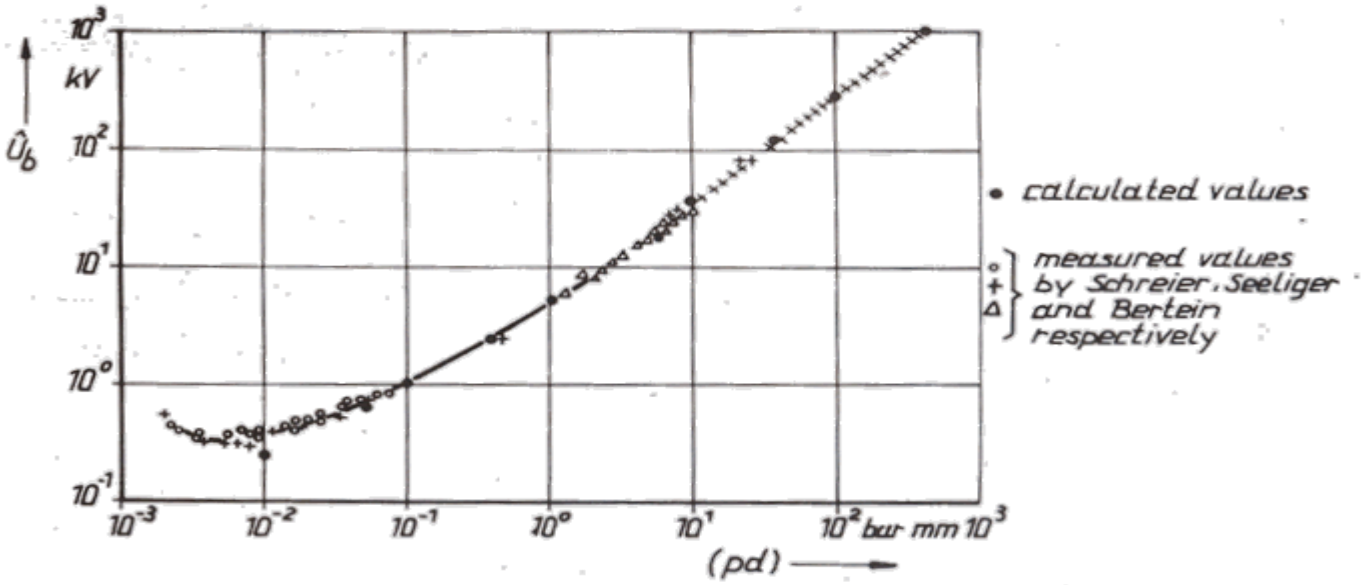


Fig 10.2 Paschen's curve for air at temperature 20^0C

- It is more convenient to introduce the 'relative gas density', δ - a dimensionless quantity; in place of gas pressure *p*. ' δ' takes care of the effect of temperature on the mean free path of electrons in the gas at constant pressure. The number of collisions made by an electron in crossing a gap is, therefore, proportional to the product *δd* and ϒ. Correction for the variation in ambient conditions of air is made by introducing the 'relative air density', δ, defined as,

$$\delta = \frac{p}{760} \cdot \frac{293}{273+t} = 0.386\frac{p}{273+t} \qquad (10.4)$$

Where *p* is in Torr and *t* in °C.

At normal temperature (*t* = 20°C) and pressure (*p* = 760 Torr), δ is equal to one. Equation for normal temperature and pressure will be,

$$\hat{U}_b = 6.72\sqrt{d} + 24.36\, d$$

or

$$\hat{E}_b = 24.36 + \frac{6.72}{\sqrt{d}} \qquad \text{kV/cm}$$

(10.5)

It is interesting to note that even in uniform field at constant pressure and temperature, the electric strength of air is not constant. It tends to 24 kV /cm for very long gaps. The value 31 kV/cm is applicable only for *d = 1,* that is for one cm gap at 760 Torr and 20°C. For gaps of a few mm, the electric strength is much higher than 31 kV/cm. It has been measured to rise to about 92 kV/cm for a gap of 0.1 mm. A plot of Equation 10.5 is shown in Fig. 6.3. This is representing the breakdown characteristic of atmospheric air at normal temperature and pressure in uniform fields. The electric strength value 31 kV/cm, measured across one cm gap in uniform field at normal temperature and pressure, is known as the 'inherent' or 'intrinsic strength' of air *Ebi.* For longer gap lengths in uniform fields, the electric strength of air reduces to about 25 kV/cm, where a breakdown with streamer mechanism is more likely to develop.

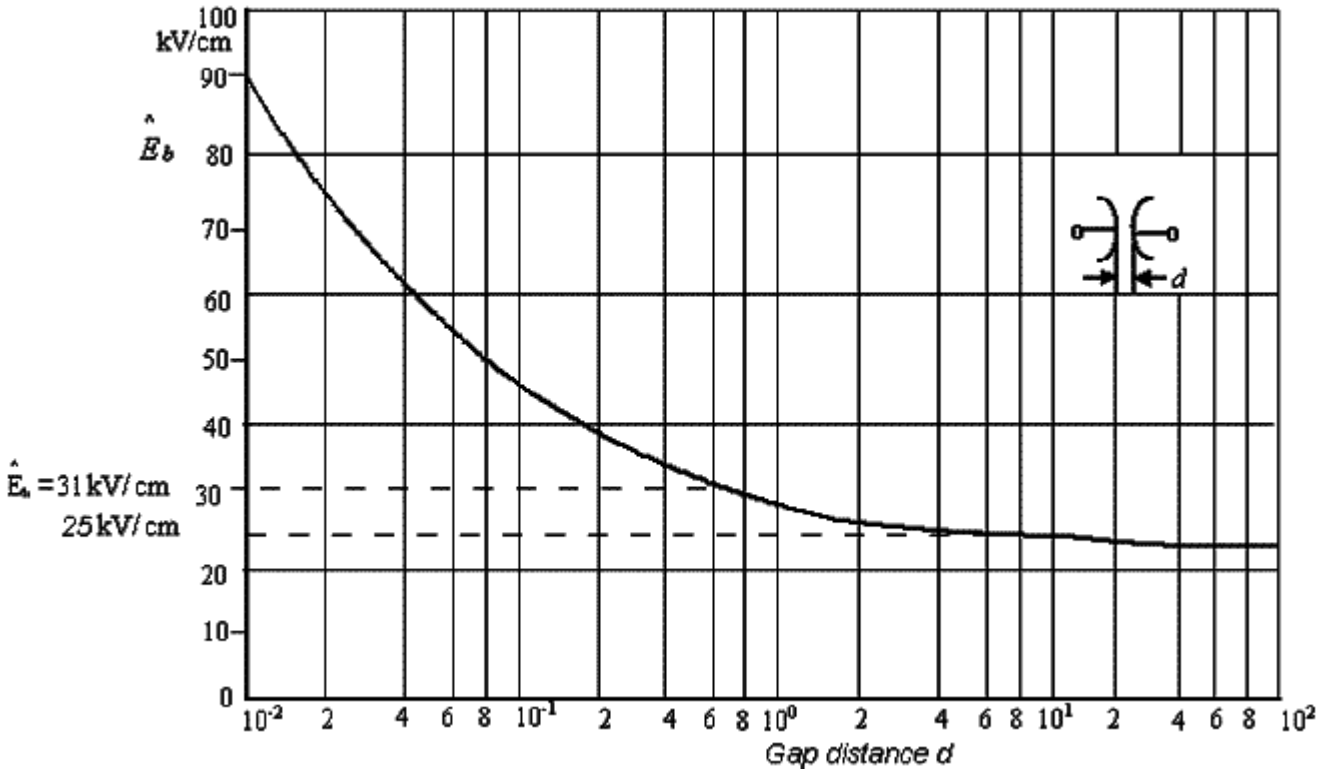


Fig 10.3 Breakdown voltage characteristics of atmospheric air in uniform fields.

(10) In this lecture you will learn the following:

Breakdown Voltage Characteristics in Weakly Nonuniform Fields,

Limiting value of Schwaiger factor

Breakdown Voltage Characteristics in Weakly Non-Uniform Fields

- The breakdown mechanism in weakly nonuniform fields is similar to uniform fields. Like in uniform fields the PB inception, U_i , and the breakdown voltages in weakly nonuniform fields are equal, the breakdown voltage can be estimated from the following relationship given by Schwaiger,

$$U_i = U_b \approx E_{bmax}\, d\eta \qquad (11.1)$$

- At breakdown the 'maximum breakdown field intensity', E_{bmax} in an electrode system or equipment having gaseous dielectric is always higher than the intrinsic 'electric strength', E_b, of the gas in uniform fields. The breakdown characteristics in weakly nonuniform fields mainly depend upon the geometrical factor of uniformity η of the electrode configuration. Breakdown characteristic for different gap lengths between two spheres in air having diameters of 10 cm each is shown in Fig. 11.1 for ac power frequency voltage. Knowing the dimensions, the factor η can be found out. It can be seen that as the gap distance d between the spheres is increased, the Schwaiger factor decreases, i.e. the field becomes more nonuniform. If the measured values of U_b- d characteristic are known, E_{bmax} - d characteristic can be plotted. From these curves it is evident that E_{bmax} does not change much within a certain range of gap distance d, as also shown by the straight-line part of the U_b- d curve. For this particular electrode configuration, it is limited up to a gap distance nearly equal to the radius of the sphere. For a rough estimation of breakdown voltage, one may take, therefore, a mean value of E_{bmax} from the curve in Fig. 11.1. It works out to be equal to 34.5 kV/cm.

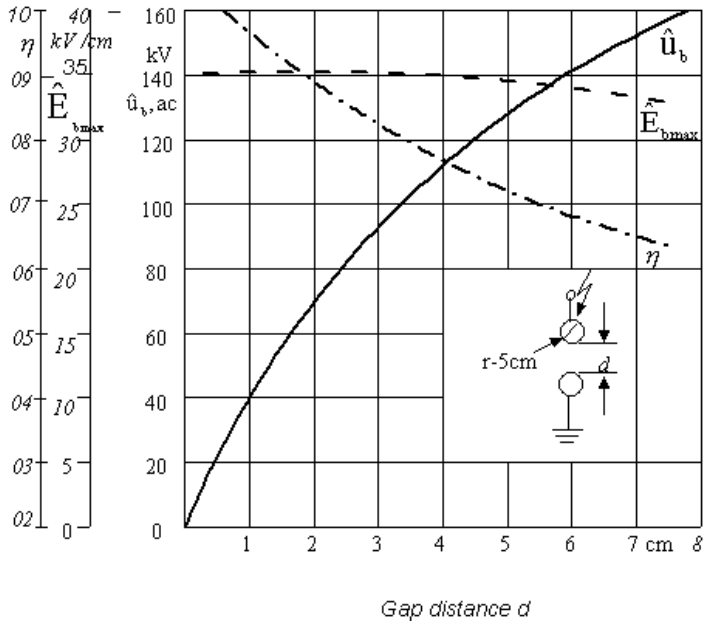


Fig 11.1 ac Breakdown voltage in air, maximum breakdown field intensity at the electrode and factor of uniformity for different gap distances in weakly nonuniform field

Limiting value of η, the η_{lim}, The value of η at which the transition from a weakly nonuniform to extremely nonuniform filed configuration takes place is termed as η_{lim} . The exact value of η_{lim} in gaseous dielectrics depends not only upon the field nonuniformity but also upon the gas pressure and the type and polarity of the voltage since it is related with the inception of PB (Lecture 2). The distinction between breakdown with and without stable PB can be made in terms of the value of degree of uniformity, η of the field. Consider a positive sphere-plane electrode configuration. As the gap distance'd' between these two electrodes is increased, the filed becomes more nonuniform, resulting in decrease in the value of η. For small gap distances, a weakly nonuniform field exists in the gap. On applying a sufficient magnitude of the voltage to the sphere, the required maximum field intensity for breakdown E_{bmax} is achieved. An abrupt breakdown without any stable PB takes place, region A in Fig. 11.2.

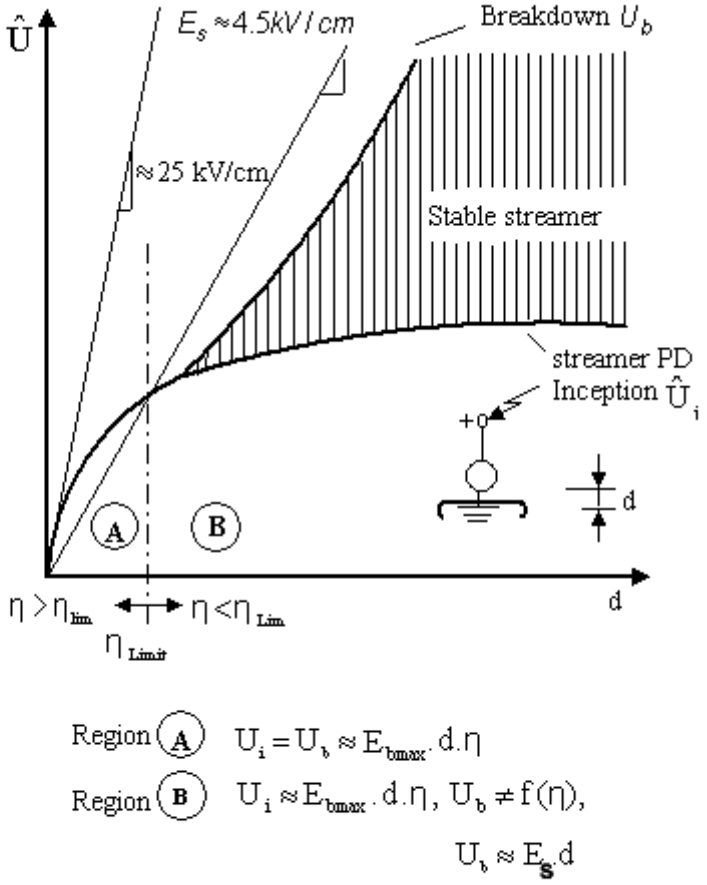


Fig 11.2 Threshold curves showing breakdown with stable streamer for positive sphere-plane electrode configuration.

On increasing the gap distance d, the field becomes more nonuniform. In the region B, in contrast to region A, stable PB takes place below the breakdown voltage. The borderline between these two regions is described in terms of η limit or η_{lim} , the threshold degree of uniformity. As illustrated in this figure, stable PB take place only in the shaded area in region B. As explained, the breakdown voltage in the region A and the PB inception voltage in the region B can be estimated with the knowledge of E_{bmax} and the electrode geometry determining the value of η. The borderline between the two regions A and B, represented by η_{lim} , represents the transition from the weakly to the extremely non uniform fields.

(11) In this lecture you will learn the following:

Development of corona in extremely nonuniform fields, Development of Star Corona, Development of Streamer or Kanal Discharge (Corona), Development of Leader corona

BREAKDOWN IN EXTREMELY NONUNIFORM FIELDS AND CORONA

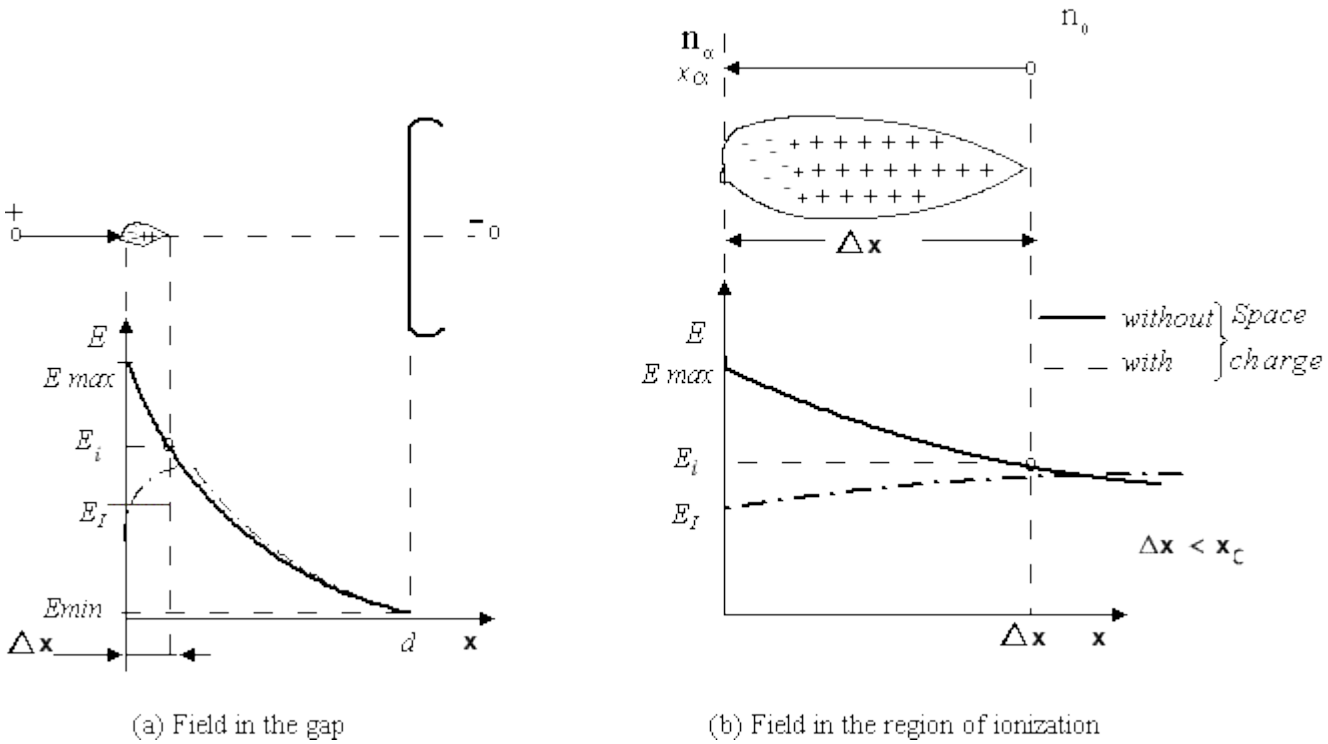
As the difference between the maximum and the mean field intensities increases leading to smaller η factor, the field becomes more nonuniform. Consequently, a poorer utilization of the insulating properties of the dielectric takes place. In extremely nonuniform fields at voltages much below the breakdown, a stable partial breakdown in the gas, confined locally to the region of extreme field intensity, can be maintained. This phenomenon is known as 'Partial Breakdown' (PB) and when it occurs at free electrodes in a gas, it is called 'corona'. At higher working voltages (above 100 kV), it is often very difficult, and economically not viable, to produce apparatus free of PB at normal working voltages. Three types of coronas can be distinguished as they appear at different electrode shapes and gap distances in the power system. These are given names Star, Streamer and Leader coronas described in the following lectures.

Development of Star Corona

Consider a point or needle and plane electrode configuration in air, Fig 12.1, with a positive dc voltage greater than required for producing electric field to cause impact ionization at the tip of the needle electrode. The plane electrode being grounded. The impact ionization grows in the form of development of avalanche process in the direction shown in the figure. The avalanche process becomes vigorous on increasing the applied voltage. It then leads to Partial or Local Breakdown of the air in the region where the field intensity in the dielectric is higher than the required for PB inception. The local breakdown process leads to the development of production of very large amount of charge particles. Due to the considerable difference in the movement of electrons and positive ions, it leads to space charge formation. Since the resultant electric field in the gap depends upon the interaction between the fields produced by space charge and the applied electric field, it is very much dependent upon the polarity of the electrode. Both, the positive and the negative polarities are therefore, considered separately.

Positive Point - Plane Electrode Configuration (Positive or Anode Star Corona)

The process through which an avalanche is formed at a positive point electrode is analogous to the one in uniform field. However, the applied field intensity E in this case of electrode system falls sharply close to the point electrode. Beyond a short-distance Δx, the field intensity falls below the minimum filed required for partial breakdown, E_i (Fig 12.1a). Thus the strong space charge formation process is able to extend itself to a maximum length of Δx in the gap, which is shorter than the critical amplification of length required by the avalanche. This is given again in Fig. 12.1(b) on a lower scale ratio diagram for x. At an advance stage of space charge formation the basic ionization process must be considered once again. When a positive dc voltage is applied to the point (the anode) the direction of the avalanche is as shown in Fig 12.1(a).



(a) Field in the gap (b) Field in the region of ionization

Fig 12.1 An Electron avalanche in front of positive point electrode. (a) Field in the gap, (b) Field in the region of ionization.

The electrons are absorbed fast by the positive electrode. A positive space charge due to the heavy and slow ions remains at the back. It has a very slow movement, especially because of rapidly decreasing applied field at the tip of the anode. This results in weakening of the resultant electric field in the region in front of the tip due to like polarity space charge at the positive electrode, as shown by the dotted lines in Fig 12.1(b) . Inception of further partial breakdown is possible only when there is a drift of space charge away from the anode due to radial diffusion which re-establishes the applied electric field, Fig 12.2(a). This type of a discontinuous process gives rise to an impulse form of discharge current at voltages just above the inception of PB, in spite of applying a dc voltage. The rise time of this PB current is of the order of a few tens of ns, whereas the time required to reach the instant on the tail when it decreases to half of its peak value is about 100ns. The peak value of this current is of the order of 50 μA and the impulse charge is about 1pC. The frequency of the impulse discharge current may go beyond 400 MHz. Knowledge of this information may be of particular interest to communication engineers who would like to site their radio instruments away from such source of electromagnetic interference (EMI).

On increasing the applied voltage considerably above the PB inception voltage, the PB process becomes intensive. It leads ultimately to a continuous time variant overlapping process, establishing a balance among the ionization, diffusion and recombination processes. The impulse character of PB current is gradually lost and a direct current is observed which however, is accompanied with irregular fluctuations. The PB process becomes more intensive and concentrated in the region near the point. The magnitude of mean potential gradient, required for complete breakdown between the electrodes with stable positive PB (star corona) process lies between 15-10 kV/cm.

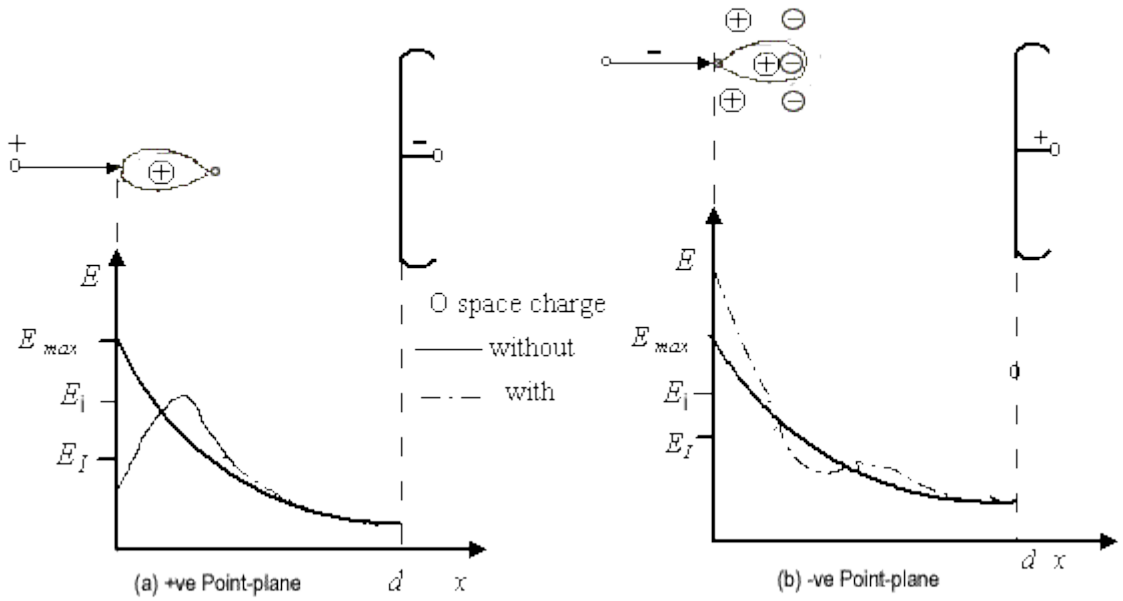


Fig 12.2 Field intensity distribution between point-plane electrodes for when PB occur.

The optical impression of this quasi stationary partial breakdown process is a weak, bluish 'glow' adjacent to the point electrode. This light phenomenon is explained owing to the excited state of gas molecules due to ionization. The electrons at higher energy levels emit a quantum of light and fall back to the original state of lower energy level. This PB process is known as positive (anode) (in German Glimmentladung) or popularly 'corona discharge', also mentioned sometimes as 'continuous discharge'. It appears like a 'star' in the sky when seen in dark. Hence it is proposed to be called 'star corona'. The word 'corona' is taken from Greek where it means the halo of light seen around a heavenly body. In Latin it means a crown. The corona discharge usually takes place at extremely sharp and pointed electrodes, for example, at needles, thin wires and sharp edges etc., on applying a relatively slower changing either dc or power frequency ac voltages. The situation demands on one hand a steep fall in potential gradient so that the avalanches do not achieve their critical length of amplification, and on the other, the charge carriers must get enough time to build the space charge. The audible noise produced by star corona is a continuous 'hissing' sound.

Negative Point-Plane Electrode Configuration (Negative or Cathode Glow Corona)

When a negative dc voltage, just sufficient for the inception of PB, is applied to a point (the cathode), the condition is similar to the one discussed in the previous section. In this case also, the possibility of PB is limited to a short distance Δx because of a steep potential gradient fall from the point towards the plane. The ionization process adjacent to the point is able to extend the avalanche to a maximum length of Δx only, analogous to the conditions shown in Fig. 12.1. However, in this case the avalanche develops in the opposite direction, that is, the avalanche head is towards the plane (anode), as shown in Fig. 12.2(b). The avalanche does not acquire its critical length of amplification. Hence the PB process limits itself within a short region and it is not able to expand farther. Due to the high field, the electrons first drift very fast nearer to the point electrode but then slow down because of the steep fall in field intensity. Since oxygen in the air is an electronegative gas, the slow electrons in front of the avalanche are absorbed by oxygen molecules forming negative ions. Again, because of these heavy and slow ions, a negative space charge is developed leading to weakening of the field at a short distance away from the negative point electrode, preventing the avalanche hence the PB process from developing further. In the mean time, the positive space charge left behind, shifts towards the negative point electrode, increasing the field intensity there considerably, as shown in Fig. 12.2 (b). After a certain time, even the negative space charge shifts away from the vicinity of point,

diminishing the field weakening effect. New avalanche and PB processes are then possible. Under the influence of the +ve and -ve space charges, a less nonuniform field is resulted away from the gap, leading to a higher breakdown voltage.

In short, it can be concluded that like in case of positive polarity point, in case of negative polarity point also a discontinuous process of charge carrier production and their migration takes place. Under static conditions above the inception level, an impulse form of partial breakdown current is conducted in a very regular and repetitive pulse form, as shown in Fig. 12.3. The frequency of these current pulses varies from a few kHz to MHz. This pulse current was first measured and studied in detail by Trichel [2.16] in 1939, and hence are named after him as "TRICHEL pulses". These have been measured by many researchers later on. An oscillogram of measured Trichel pulses by Woboditsch [2.17] is shown in Fig. 12.3.

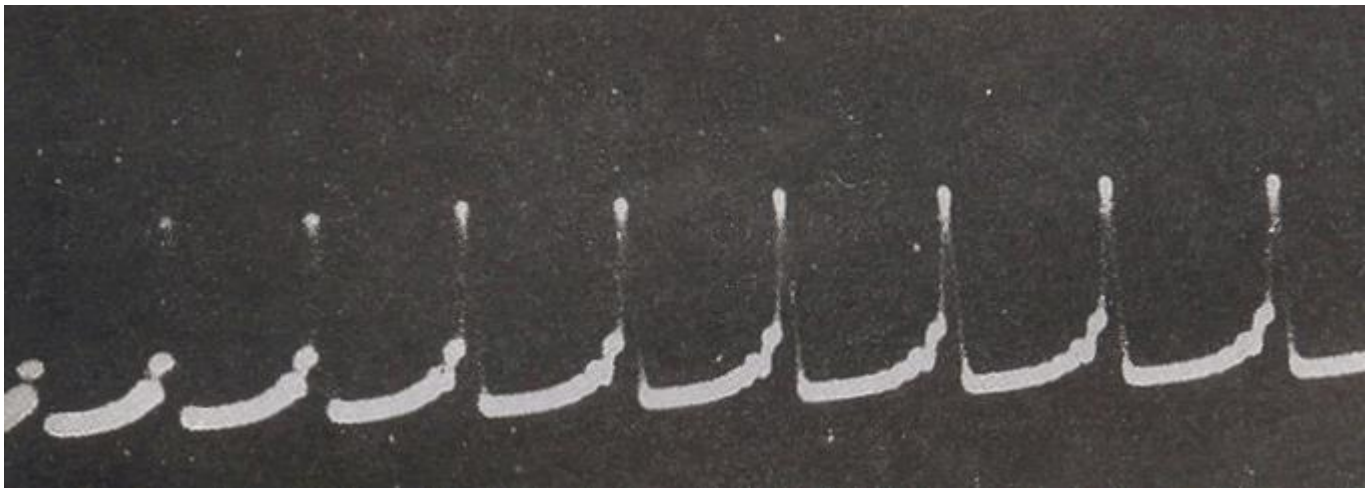


Fig 12.3 Impulse form of PD current measured at negative point electrode. 'Trichel pulses' by Woboditsch [2.17].

The inception voltage of Trichel pulses is practically independent of the gap length. The pulse frequency increases with the voltage and depends upon the geometrical radius of the cathode, the gap length and the gas pressure. On raising the voltage, the mode of these pulses does not change over a wide range. Eventually, at much higher voltages, the impulse character of the PB current is lost due to overlapping of individual pulses. A direct current is then measured, which is accompanied with certain fluctuations. A steady 'star like' discharge' or 'corona discharge', similar to anode corona is also observed in this case but it is located slightly away from the tip. The cathode corona appears as a reddish glow unlike the bluish glow in case of anode corona. The average breakdown strength of the gap for this case is measured slightly higher, between 20-15 kV/cm.

Development of Streamer or Kanal Discharge (Corona)

Let the field distribution between the point-plane electrode system be modified in such a way that the fall in field intensity (the potential gradient) at the tip of the electrode is no more as steep as in the case of star corona. It can be achieved, for example, by increasing the radius of curvature of the point, taking most suitably a rod in place of a needle electrode. This will increase the depth region of Δx, where the impact ionization and PB is possible at a given voltage application.

With the result, the avalanche developed in this region can acquire their critical length of amplification x_c, leading to a transformation from avalanche to streamer discharge.

As a consequence of the interaction between field produced by the space charge and the applied basic field, a strong effect of polarity is observed here too as in case of the development of star corona. Both the polarities are, therefore, discussed separately. Practical experience has shown that pure stable streamer discharge may be produced on applying dc, ac as well as switching (si) impulse type of voltages to a hemispherical rod-plane electrode system for gap lengths beginning with a few cm. The magnitude of voltage required is comparatively higher than needed to produce star corona with below critical amplification of avalanche because of a lower intensity of field at a given voltage in this case.

Positive Rod-Plane Electrode (Positive Steamer Corona)

Consider a situation after the inception of an avalanche discharge in the region next to a positive rod. When the avalanche has grown to its critical amplification, the following equation must hold true:

$$\int_0^{x_c} \alpha \, dx = \ln \frac{n_{xc}}{n_0} \approx 20 \qquad (12.1)$$

Where x_c is the length of an avalanche when it acquires its critical amplification. The avalanche developed under this condition must, however, remain in the field region above E_I the minimum field intensity required for impact ionization, as shown in Fig. 12.1.

Electrons at the head of the avalanche are absorbed immediately by the positive rod electrode (anode). The positive space charge left behind can lead to a weakening of the field next to the anode to such an extent that further discharges may not be possible in this region. Since the avalanche has acquired its critical stage, there is a strong concentration of positive space charge till up to the tail end of the avalanche, shown in a circular form for the sake of explanation in Fig. 12.4. An increase in field intensity towards the tail of this avalanche results due to the presence of a weak negative space charge, produced at the front of the next avalanche which is formed by photon emission from the avalanche head. The resultant enhanced field intensity magnitude may, therefore, be much higher than the minimum intensity required for impact ionization E_I or even for partial breakdown inception E_i at higher voltages (curve 1 in Fig.12.4). In this process, the second avalanche grows to some extent into the first avalanche. Because of similar reasons explained above, an increase in field intensity is caused again due to the positive space charge of the second and the negative of the third avalanche at its head, which has grown to some extent into the second (curve 2 in Fig. 12.4). This process continues so long as a subsequent avalanche started by photoionization falls in the field region above E_i, in spite of the basic field decreasing below this level.

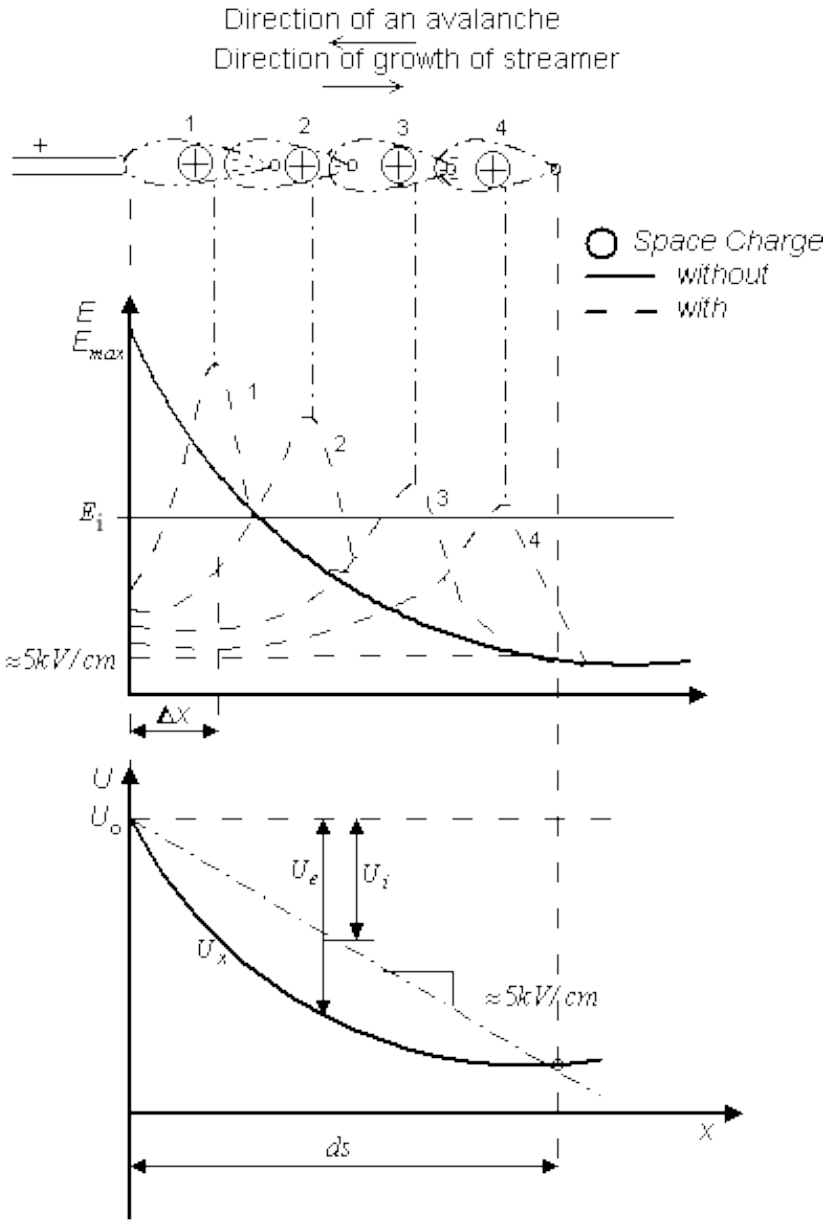


Fig 12.4 Schematic of streamer discharge in front of a positive rod electrode with variation in field and potential as a consequence of space charge

The mechanism of development of streamer described above can be compared to the one explained for uniform fields. The positive and the negative space charges involved in the growth of the streamer string compensate for each other. The conductivity of this nearly neutral charge carrier channel is, therefore, quite low. However, the basic condition for the development of streamer discharge ($\int_0^{x_a} \alpha\, x_a \approx 20$) must be accomplished at each point. Since the positive charge carriers, being heavier particles, do not move themselves much, the process is comparable to the movement of a wave. **In** fact, numerous avalanches begin together and the whole process is a continuous development of a large number of streamer trajectories of partial breakdown in the region where the resultant (enhanced) field intensity is greater than E_i . These spread in space around the rod electrode in the main field direction as shown in the photograph in Fig. 12.5.

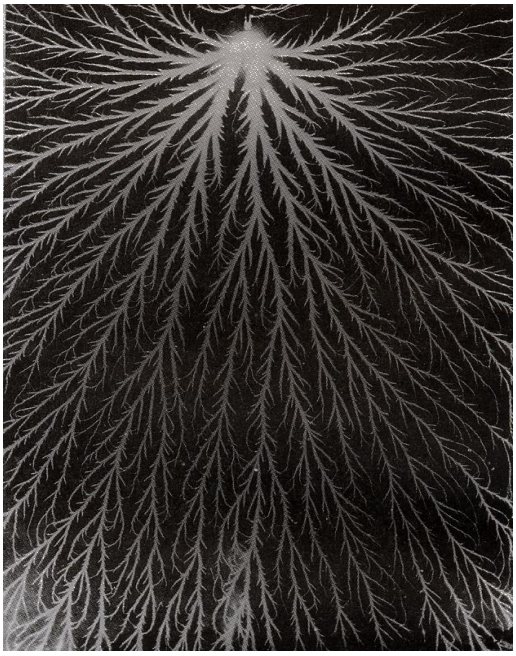


Fig 12.5 Photograph of a positive streamer discharge Lemke [2.18, 2.19].

This photograph was taken by Lemke [2.18] on applying a long duration 1/5000 μs 100 kV positive peak impulse voltage on a point-plane electrode system having a gap distance of 20 cm. Similar photographs were also taken by Nasser [2.20]. The experiments conducted by Nasser revealed that, on applying a single impulse voltage, even 200 partial discharge branches may develop in a gap length of only 2.5 cm. The number of these branches grows exponentially with increasing gap length, but it is an interesting characteristic to note that these large number of branches never cross each other.

The streamer corona is also accompanied with an impulse form of current. Depending upon the range of streamer, this current may acquire its maximum magnitude of a few milliampere to an ampere within nano seconds. The streamer current decays to its 50% value within about 100 ns. The impulse discharge is generally in the range of 100 pC to 100 nC but may be even higher in some cases. The next process of displacement and formation of space charge introduces a time lag. The streamer discharges are, therefore, repetitive having irregular frequency. This is the reason that the audible noise produced by streamer corona is a flutter sound, unlike a hiss in case of star corona.

The integrated optical light appearance of streamer corona is like a weakly illuminated 'bunch' or more appropriately a 'shower' of discharge. Hence, it is also known as 'bunch discharge', mentioned sometimes as 'illuminated string discharge', (in German *'Büschel'* and *'Leuchtfaden'* discharge respectively). However, it is popularly known as 'streamer corona'.

Referring to Fig. 12.4, it can be seen that, for a known potential distribution U_x in the gap, the range of growth of streamer discharge can be determined, if the potential gradient requirement for the streamer to grow is known. Let the process be analyzed through the involvement of energy in the space between electrodes. The gain in potential due *to* space charge U_e is represented by its corresponding energy gain (where $U_e = U_0 - U_x$). Because of continuous production of new charge carriers, some energy is consumed simultaneously. Hence a loss of energy in the gap is caused. Let this loss be represented by a potential U_l . The discharge process ceases to continue when this loss of energy is no more compensated by the gain, that is, when $U_l \approx U_e$. This occurs at $x = d_s$, the extent of streamer as shown in Fig. 12.4. Measurements by Lemke [2.18] in 1967 revealed that the mean potential drop per centimeter length in a positive streamer is 4.5 kV. In other words, it can be said that, for a positive streamer discharge to grow, a potential gradient above 4.5 kV/cm is required.

Negative Rod-Plane Electrode (Negative Streamer Corona)

Like positive rod-plane electrode, in case of negative rod also, the development of a streamer discharge begins with an avalanche which acquires its critical amplification. The mechanism in principle is comparable to the positive streamer discharge except for the location of space charge formation. The direction of the avalanches is however opposite, that is, their heads are away from the rod. A strong positive space charge is, therefore, built in front of the rod in the dielectric, increasing the field intensity right at the tip of the electrode. The electrons form a negative space charge at the head of the avalanche slightly away from the electrode tip, thereby weakening the field in the vicinity.

When the discharge process develops farther, a sort of 'scattering' of negative space charge takes place by radial diffusion, because of the high mobility of electrons. Consequently, a weakening of the negative space charge results. The field intensity, which is affected by the concentration of the space charge, increases to some extent again. Because of this space charge effect on the field, the negative discharge process does not grow towards the opposite electrode to that extent compared to positive discharge at the same applied potential magnitude, as shown in Fig. 12.6. The radial diffusion of electrons is also responsible for a comparatively lesser number of distinct trajectories of negative streamer corona able to develop at the rod. This phenomenon is very clearly seen in Fig. 12.6. These photographs, commonly known as 'Lichtenberg figures', were originally taken by Toepler in Technische Hochschule, Dresden. Lichtenberg, a German scientist, lived in the eighteenth century and studied this phenomenon in 1777.

While the average potential gradient requirement for the propagation of positive streamer is estimated to be about 5 kV /cm, it is of the order of 10 to 15 k V/cm for negative streamer. This has also been confirmed by Les Renardieres [2.21].

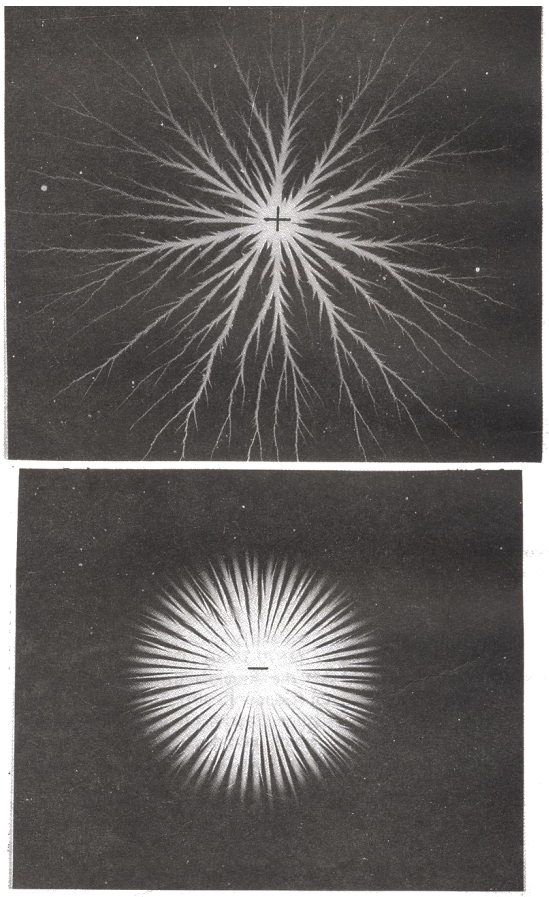
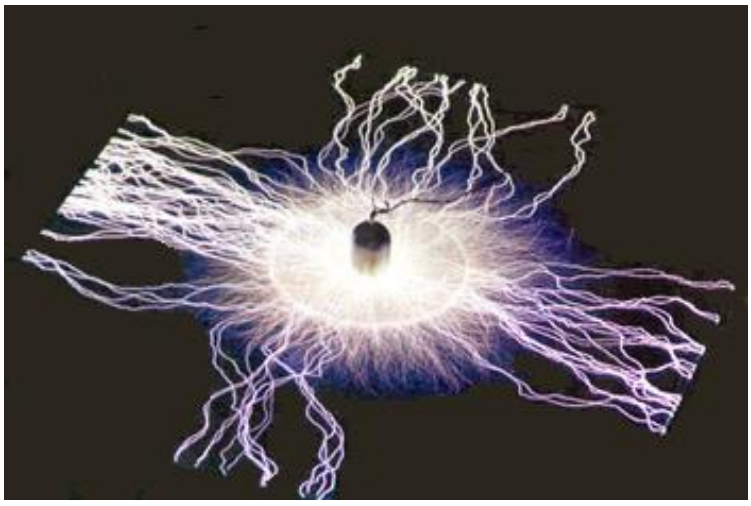


Fig 12.6 Photographs of positive and negative streamer discharge,'Lichtenberg figures' taken by Toepler, TU Dresden.

Development of Leader Corona:

If the gap distance between the rod and plane electrodes is increased above one meter and sufficient potential applied to the rod, after vigorous activity of streamer corona at the tip a 'constriction' of streamer trajectories takes place and a stem is formed. On increasing the applied voltage further, the stem of this discharge grows in to a few bright, stepped trajectories in the gap towards the plane. This is described as 'Leader corona'. Much higher magnitude of the voltage is required to be applied on log gap distance as compared to star and streamer coronas. However, Leader corona can easily be produced as 'Surface Discharge' on a glass plate on applying quite low magnitude of voltage. Fig 12.7 shows (a) Leader corona as surface discharge on a glass plate and (b) Leader corona in free air. The mean axial potential gradient across stable leader corona channels is quite low due to high charge density or current. For stable positive leader it was estimated by Lemke to be about 1 kV/cm and for negative leader it is estimated to be 2-3 kV/cm. The audible noise produced by Leader corona is a loud cracking sound. The EMI produced by this corona extends to a band width up to 2 GHz. The leader corona can be seen to happen in nature. The cloud to cloud as well as cloud to ground lightning discharge phenomenon is accomplished with leader channels.



(a) AC Discharges over surfaces of a $1m^2$ glass plate

(b) Leader corona in free air

Fig. 12.7 Stable Leader corona in free air gap and as Surface discharge on a glass plate

Summary of the Development of discharges in Extremely Nonuniform Fields

The quasi continuous partial breakdown process in air is basically characterized by three distinguished stages of its development. These essential stages are star, streamer and leader corona. It took a very long time (over two centuries, beginning with Lichtenberg) for the researchers to be able to distinctly separate and understand these partial breakdown phenomena. Thanks to advance electrical measurement and photographic techniques for achieving these results. Beginning with very small gaps, of the order of a few mm and cm, the production of very high voltages aspired the scientists to study the discharge phenomena in very long gaps, of a few tens of meters.

A fairly large variety of terminology, evolved in different countries with time, is available in the literature. Even the same stage of development of discharge is sometimes described with different technical terms by different authors. Besides, some stages of discharge are so closely intermingled that to find the appropriate term becomes difficult. Hence, it might lead to confusion for some, while going through the part of this chapter describing development of discharge process in extremely nonuniform fields.

(12) In this lecture you will learn the following:
Breakdown with Stable Star corona, Breakdown with Stable Streamer & Leader Coronas

Breakdown with Stable Star corona

- Unlike uniform and weakly nonuniform fields, in case of extremely nonuniform fields, the process of avalanche formation at the tip of a sharp electrode is not able to grow deeper in the gap towards the opposite electrode because of steep fall in potential gradient at the tip.

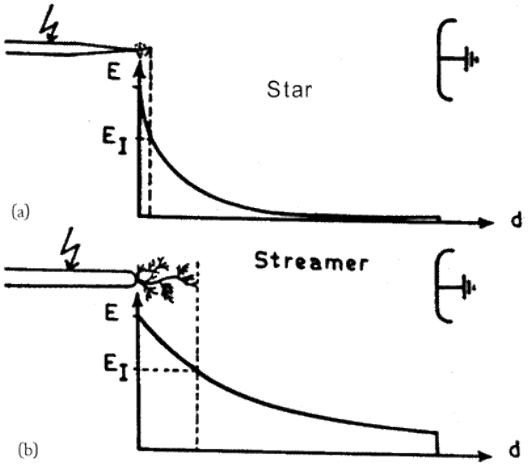


Fig 13.1 Variation of field intensity at needle and rod-plane electrode configurations

- Hence, the partial breakdown process, in this case, begins at the tip of the sharp electrode. Breakdown with stable avalanche discharge is therefore possible in this case only in very small gap length of a few mm to a few cm ranges, having a high potential gradient at the electrode. Stable avalanche discharges are possible to be produced only with static dc or slow changing ac power frequency voltages. These provide sufficient time to build a steady space charge field. Under these conditions, the avalanches formed are not able to achieve their critical stage of amplification before the breakdown. With the result, the mean breakdown voltage in the electrode gap acquires comparatively higher value, of the order of 10 to 20 kV/cm (peak) depending upon the polarity of the applied voltage. Uhlmann measured breakdown voltage characteristics between a 30° point and plane electrode configuration for increasing gap distance with positive as well as negative polarity dc voltages, shown in Fig. 13.2. A strong effect of polarity on the breakdown voltage magnitudes is observed in this case of extremely nonuniform field. The ratio is almost 1:2. The ac (peak) breakdown voltage characteristic would fall nearly in between the positive and negative polarity dc.

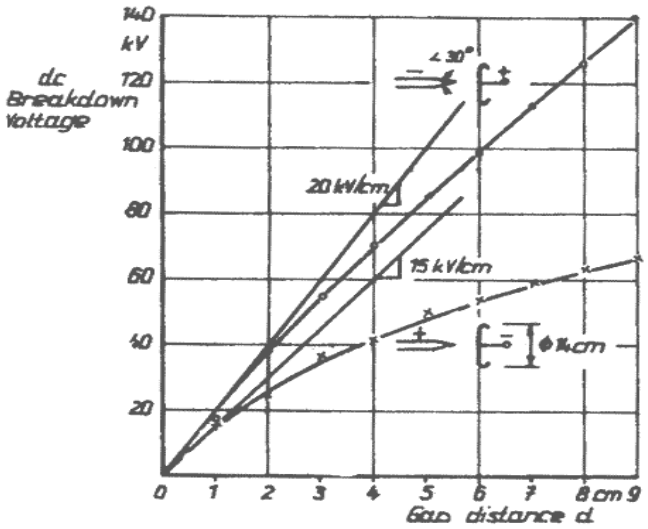


Fig 13.2 dc breakdown voltage characteristics of a 30° point and a plane of 14 cm dia in air, with respect to increasing gap distance, Uhlmann.

- As seen in Fig. 13.2, the average potential gradient required for breakdown decreases as the electrode gap distance is increased. This is because at larger gap distances breakdown with stable pure avalanche discharge is no more possible. One may conclude that for this electrode configuration, breakdown with stable pure avalanche discharge is possible only up to a gap length of about 2 cm. Under these conditions, the average potential gradient for breakdown in the gap is about 10 kV/cm for positive polarity, and 20 kV/cm for negative polarity voltages, as described earlier. At longer gap lengths, where a lower average breakdown potential gradient is required, streamer discharge may commence.
- Similar characteristics were measured for negative polarity point-plane electrode with dc for different gap lengths by Kuffel. The point electrode (cathode) is reported to have a radius of 0.06 mm (Fig. 13.3). Below the lowest curve, no conduction current is measurable. The PB and the Trichel pulse inception voltages, U_i, for increasing gap length are given by this curve. As it can be observed, the gap length does not appreciably change the PB inception voltage. On increasing the voltage applied between the two electrodes, the mode of Trichel pulse does not change over a wide range of voltage. The avalanche process is limited within its critical stage, as explained earlier. A steady and stable partial breakdown phenomenon is observed like a 'star' in the dark. On raising the voltage the PB process at the tip of the sharp electrode intensifies, increasing the current density so much that thermal ionization begins. This gives rise to an unstable leader discharge extending instantaneously towards the opposite electrode, accomplishing a spark breakdown with an arc.

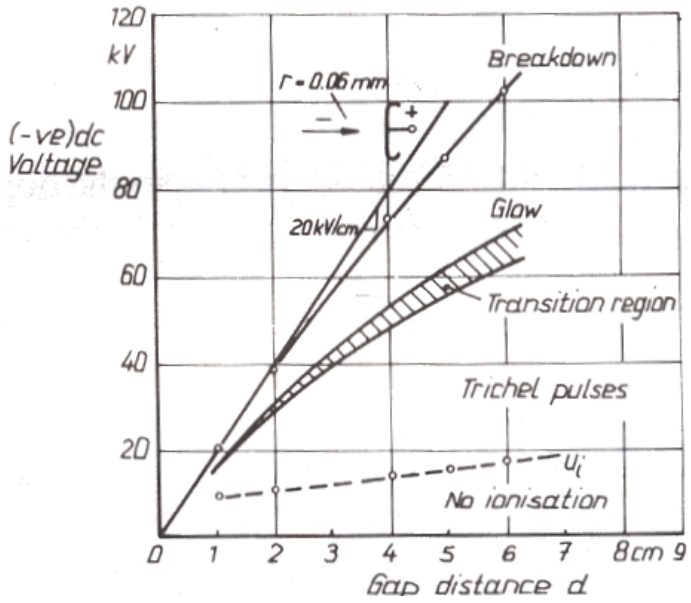


Fig 13.3 dc negative point-plane breakdown and corona discharge characteristics in atmospheric air, Kuffel.

Breakdown with Stable Streamer Corona

- As described in earlier lecture, when the basic requirement for the field intensity distribution in the gap is met, streamer or Kanal discharge, that is, avalanche with above critical amplification incept. On raising the applied voltage, these streamers propagate in the main field direction towards the opposite electrode, besides spreading in radial direction also as shown in Fig. 13.1(b). If the conditions required for the growth of streamer are met throughout the gap length, the discharge can extend up to the opposite electrode. It is at this stage that a stable streamer discharge is rendered instable. A schematic illustration of the development of breakdown mechanism with stable positive streamer discharge throughout the gap length is shown in Fig. 13.4.

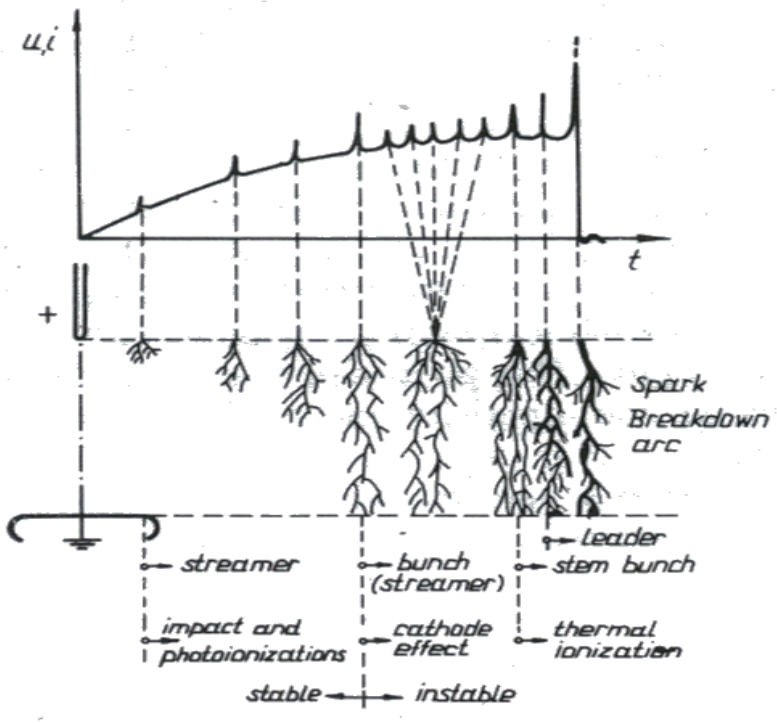


Fig 13.4 Breakdown mechanism development with stable streamer discharge.

- As soon as the streamer is able to extend itself up to the opposite electrode, say the cathode, more dense streamer discharge erupts from the anode because of 'cathode effect', also known as ' γ-effect' or secondary process. The current density at the tip of the rod electrode increases considerably due to the conduction of charge carriers, leading to an excessive temperature rise. This causes thermal ionization in front of the tip of the electrode due to the constriction of streamer channels. Subsequently, first a short bright 'stem' and then a 'stem bunch' discharge breaks out, turning into a thriving instable leader as shown in Fig. 13.4. Breakdown is accomplished with a 'final jump' of the leader bridging the two electrodes. Ultimately an arc is produced which conducts the short circuit current. This type of breakdown mechanism is primarily observed in medium gap lengths; say up to about 1 m, depending upon the electrode configuration and the type of applied voltage. All the three types of voltages, that is, ac, dc and si may produce breakdown with stable streamer. Since the total duration of li is very short, it is unable to produce a stable corona.

- An analytical explanation of the mechanism described above is difficult. However, a distinction between breakdown with stable and instable streamers can be made in terms of the degree of uniformity of the field.

Consider in fig 11.2, a breakdown when η is greater or equal to η_{lim} . The breakdown voltage for the region A can be estimated by Equation 13.1;

$$U_b = E_{bmax} \cdot d \cdot \eta_{lim} \qquad (13.1)$$

The breakdown voltage for the region B is given by the equation;

$$U_b = E_s \cdot d \qquad (13.2)$$

Where E_s is the average potential gradient required for breakdown with stable streamer discharge or across the streamer channels which is about 4.5 kV/cm for positive polarity voltage. A round figure of 5 kV/cm is accepted in this case. Equating the two equations given above and considering a value of 25 kV/cm for E_{bmax} (the maximum breakdown field intensity for air in weakly nonuniform fields), the value *of* η_{lim} for atmospheric air can be determined as follows:

$$E_{bmax} \cdot d \cdot \eta_{lim} = E_s \cdot d$$

or

$$\eta_{lim} = \frac{E_s}{E_{bmax}}$$

$$= \frac{4.5}{25} \approx 0.2$$

- Characteristics of breakdown with dc voltage for air gaps up to 2.5 m are shown in Fig. 13.5 with both positive and negative polarities for sphere-sphere and rod-plane electrode gaps. The curve number 1 for gaps between large size sphere-sphere configuration represents the weakly nonuniform field even up to 50 cm of gap distance. Since no partial breakdown takes place before the breakdown in this field, no effect of polarity is measured on the breakdown voltage. The curve number 2, measured with negative polarity voltage on a rod-plane gap, a case of extremely nonuniform field, is accompanied with stable negative streamer corona. The mean potential gradient requirement of about 10 kV/cm for negative streamer is observed to have met for this curve. The last curve, number 3, accompanied with stable positive streamer, represents an average potential gradient requirement of about 5 kV/cm in the gap.

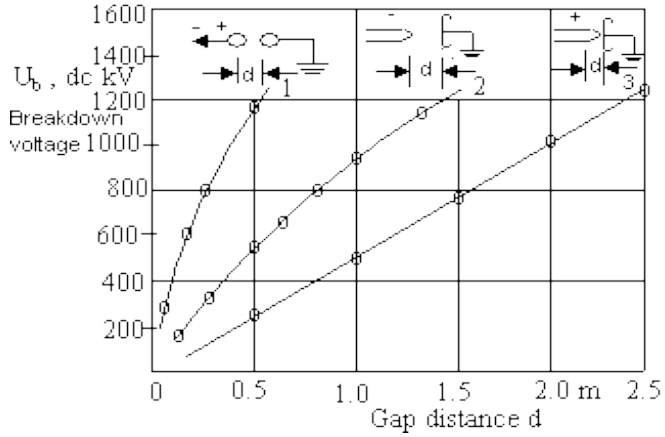


Fig 13.5 dc breakdown voltage characteristic, with both polarities, for 'sphere-sphere' and rod-plane long air gap.

- The development of different breakdown characteristics strongly suggests that the breakdown voltage magnitudes depend upon the type of stable partial breakdown that occur in the gap before the final jump. The breakdown voltage characteristic for a rod-plane gap (Fig. 13.6), on applying positive 60/2500 μs shape of impulse voltages, represented breakdown with stable streamer corona up to a relatively small gap distance of 1 m.

  The average potential gradient required for breakdown in this region was 4.5 kV/cm. On increasing the gap distance, a lower average potential gradient requirement for breakdown was measured continuously. Finally, an average potential gradient of 1 kV/cm was required for breakdown of the gaps above 4 m in this case. Stable leader corona could be observed for gap lengths above 2 m for the given electrode system.

As illustrated in Fig. 13.6, the breakdown voltage characteristic falls between the two tangents to the curve, representing the potential gradients of circa 4.5 and 1 kV/cm. The region of breakdown with stable streamer corona preceding the breakdown extends to a maximum of 2 m. The breakdown characteristic in the region beyond this length is determined by stable leader corona before the complete breakdown.

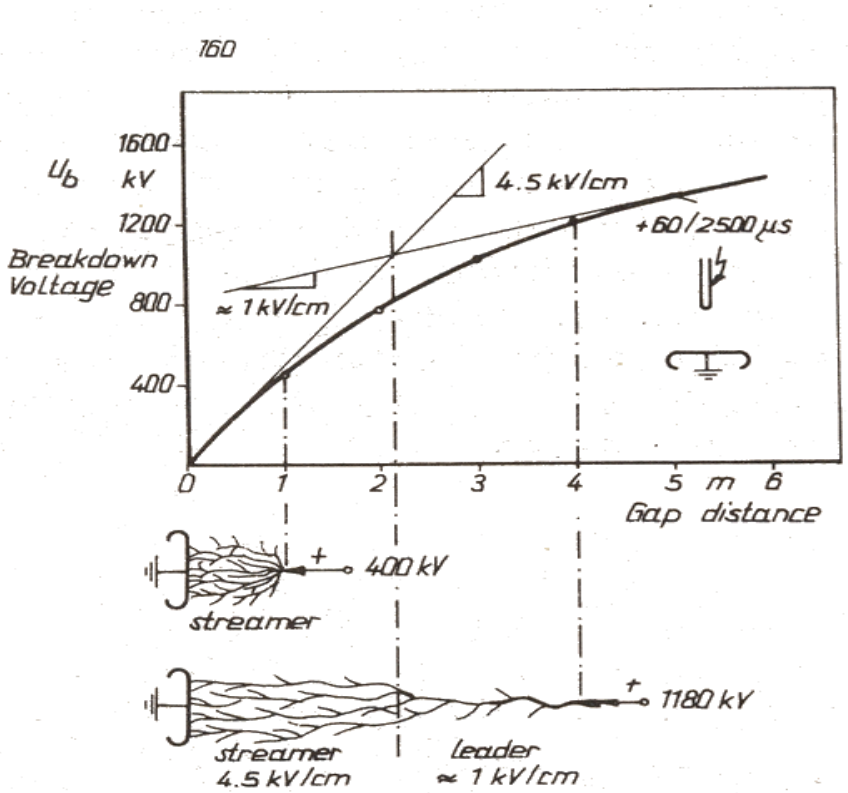


Fig 13.6 Relationship between breakdown voltage characteristics and mean potential gradient requirement for the propagation of stable streamer and leader coronas.

Breakdown with Stable Streamer and Leader Coronas

- Consider a very long gap distance, above 2 m, between positive rod or sphere and plane electrode configuration. On applying preferably a slow changing voltage, that is, ac or si of sufficient large magnitude, at first a very strong and dense filamentary streamer corona appears at the high voltage electrode. This is known as 'first corona' shown in the schematic of breakdown (Fig. 13.7). Unlike in case of shorter gap lengths, in this case the minimum collective current density in discharge channel required to produce a 'leader' (about 200 mA) may be achieved even without the cathode effect.The first corona goes through constriction phenomenon and is then followed by stable stem and leader discharges in the gap. The stepped form of leader is accompanied with streamer coronas at their tips. The leader discharge propagates, traversing the path laid down by streamer corona, as it provides the leader the required current density.

- The stable leader corona prevails in the gap until it extends to the opposite electrode, as illustrated in Fig. 13.7. Breakdown of air between electrodes is accomplished with the 'final jump' of a leader channel bridging the gap, followed by an arc. Photographs of stable leader and breakdown with its final jump on a 7m gap length between rod-plane, applying positive polarity si voltage were taken by Lemke [2.18], shown in Fig. 13.7.

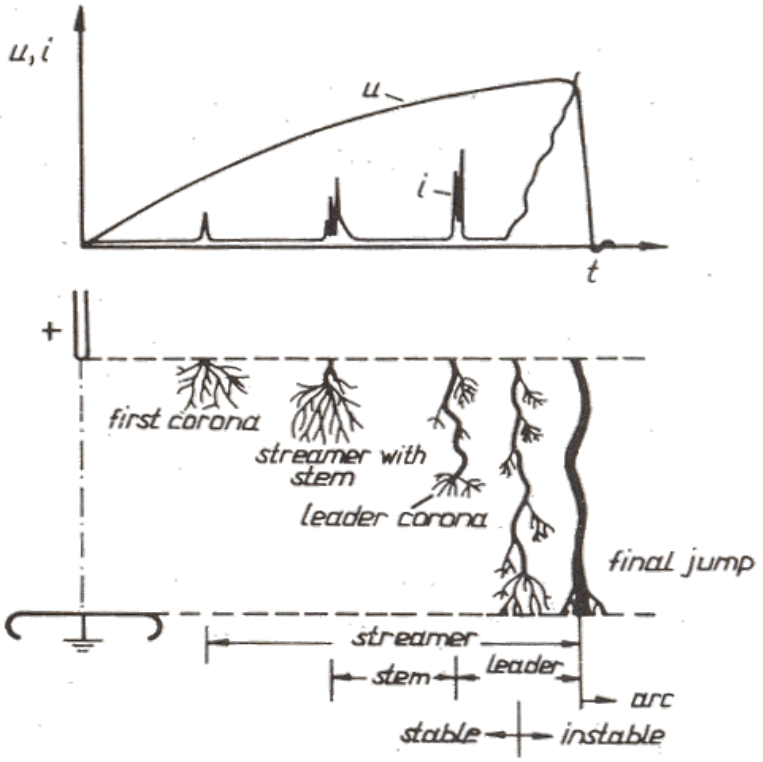


Fig. 13.7 Breakdown mechanism schematic with stable leader and streamer coronas

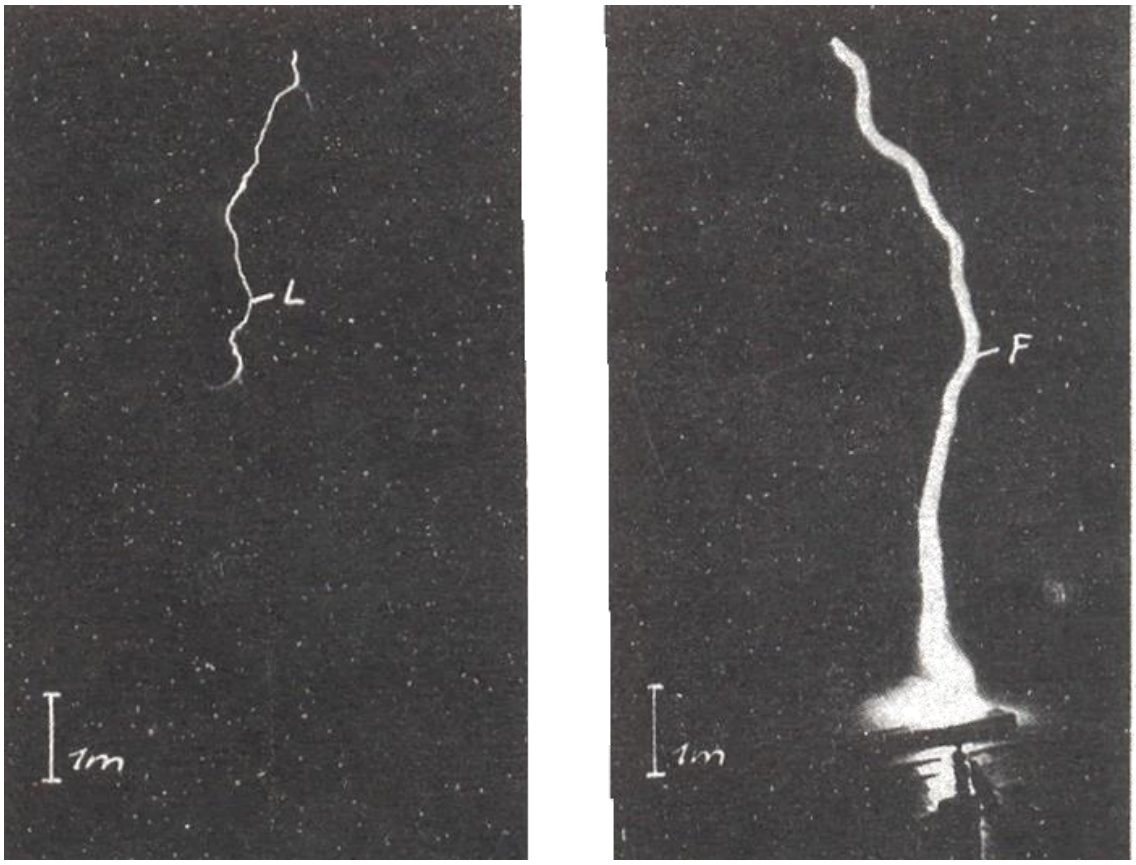


Fig 13.8 Stable leader corona and breakdown with final jump for a 7 m gap with positive polarity si voltage, Lemke [2.18].

(13) In this lecture you will learn the following:
Classification of Liquid Dielectrics, Electric Conduction in Insulating Liquids

Liquid Dielectrics and their Classification

From the point of view of molecular arrangements, liquids can be described as 'highly compressed gases ' in which the molecules are very closely arranged. This is known as kinetic model of the liquid structure. However, the movement of charged particles, their microscopic streams and interface conditions with other materials cause a distortion in the otherwise undisturbed molecular structure of the liquids. The well known terminology describing the breakdown mechanisms in gaseous dielectrics, such as, impact ionization, mean free path, electron drift etc. is, therefore, also applicable for liquid dielectrics.

Liquid dielectrics are accordingly classified in between the two *states* of matter that is gaseous and solid insulating materials. This intermediate position of liquid dielectrics is also characterized by its wide range of *application* in power apparatus. Insulating oils are used in power and instrument *transformers,* power cables, circuit breakers, power capacitors etc. Here they perform a number of functions simultaneously, namely:

- Insulation between the parts carrying voltage and the grounded container, as in transformers.
- Impregnation of insulation provided in thin layers of paper or other materials, as in Transformers, cables and capacitors, where oils or impregnating compounds are used.
- Cooling action by convection in transformers and oil filled cables through circulation.
- Filling up of the voids to form an electrically stronger integral part of a composite dielectric.
- Arc extinction in oil circuit breakers.
- High capacitance provided by liquid dielectrics with high permittivity to power capacitors.

A large number of natural and synthetic liquids are available which can be used as dielectrics. These possess a very high electric strength and their viscosity and permittivity vary in a wide range. The appropriate application of a liquid dielectric in an apparatus is determined by its physical, chemical and electrical properties on one hand, and on the other, it depends upon the requirements of the functions to be performed.

Classification of Liquid Dielectrics

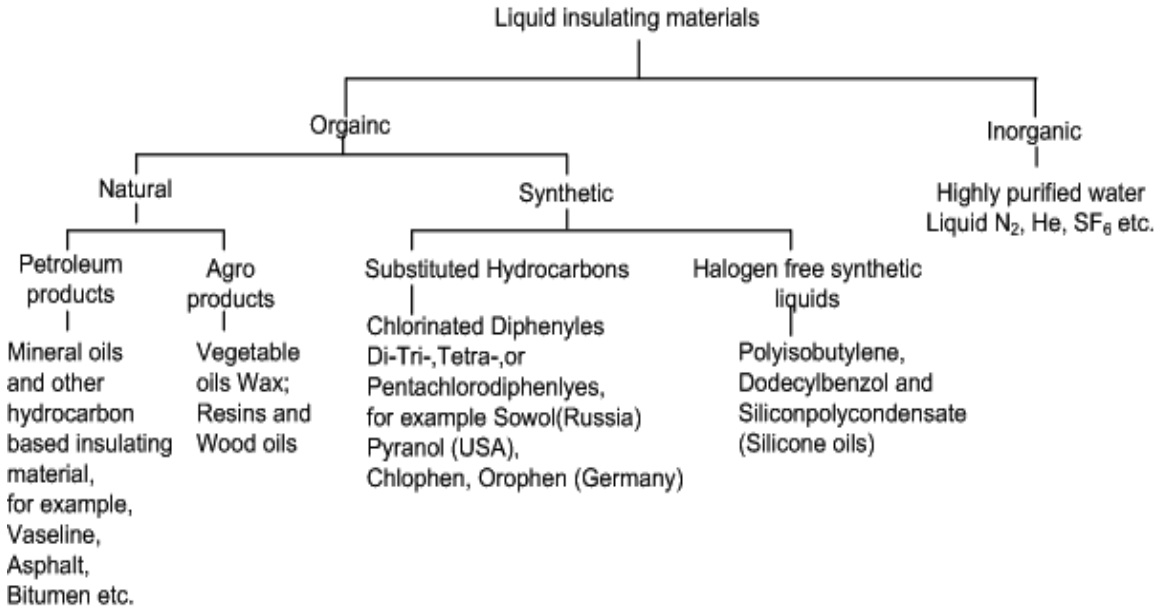
Dielectric materials can be divided into two broad classifications: organic and inorganic. Organic dielectrics are basically chemical compounds containing carbon. Earlier, under organic chemistry only those compounds which were derived from either plant or animal organism were considered. This concept underwent changes with concurrent developments in chemical technology. Carbon compounds, in general, are now called organics. Among the main natural insulating materials of this type are: petroleum products and mineral oils. The most important and widely used organic liquid dielectrics for electrical power equipment are mineral oils. The other natural organic insulating materials are asphalt, vegetable oils, wax, natural resins, wood and fiber plants (fibrins).

A large number of synthetic organic insulating materials are also produced. These are nothing but substituents of hydrocarbons in gaseous or liquid forms. In gaseous forms are fluorinated and chlorinated carbon compounds. Their liquid forms are chlorinated diphenyles, besides some nonchlorinated synthetic hydrocarbons. The chlorodiphenyles, although possessing some special properties, are not widely used because of being unfriendly to human beings and very costly.

Among halogenfree synthetic oils are polymerization products, the polyisobutylenes and the siliconpolycondensates. Polyisobutylene offers, better dielectric and thermal properties than mineral oils for its application in power cables and capacitors, but it is many times more expensive. Silicon oils are top grade, halogenfree synthetic insulating liquids. They have excellent stable properties, but because of being costly, have so far found limited application in power apparatus for special purpose.

Among inorganic liquid insulating materials, highly purified water, liquid nitrogen, oxygen, argon, sulphurhexafluoride, and helium etc. have been investigated for possible use as dielectrics. Liquefied gases, having high electric strength, are more frequently used in cryogenic applications, whereas, because of its high relative permittivity, low cost, easy handling and disposal, Water and water mixtures are being actively investigated for use as dielectrics (for example, in pulse power capacitors and pulsed power modulators etc.).

To summarize the classification of liquid dielectrics explained above, a schematic is drawn in the following diagram. The insulating liquids, commonly applied in high voltage apparatus, are classified as illustrated in the following diagram.



Electric Conduction in Insulating Liquids

The conduction mechanism in a dielectric liquid is strongly affected by the degree of its purity. In liquids, which have not been highly purified, when subjected to fields up to about a few kV/cm the conduction is primarily ionic. Ionic conduction is affected by the dissociation process of impurities as well as the injection of charge by the electrodes through electrochemical reactions. The electrons do not take part in the passage of current through such liquids. A typical characteristic of conduction current density J versus the applied dc voltage U in a pure liquid is shown in Fig.14.1. At low voltages, the current varies proportionally to the voltage, region 1, representing the ohmic behavior. On raising the applied voltage, hence the field intensity, the ionic current gets saturated, region 2. At still higher applied voltage the current density increases rapidly until the breakdown occurs, region 3.

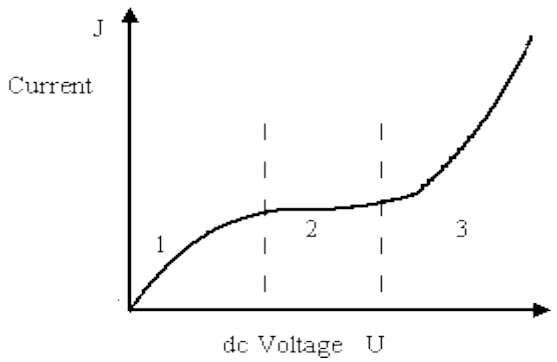


Fig. 14.1 Typical voltage-current (U-J) characteristic in dielectric liquids.

Similar behavior is observed generally in, both, polar and nonpolar liquids. In some cases the saturation region may be completely missing. This characteristic has an analogy to what has also been observed commonly in gases.

In Fig. 14.2 the conduction current characteristics are shown for negative direct voltage applied to a needle-plane electrode configuration in transformer oil and liquid nitrogen, measured by Takashima et al. [3.1] for different radii of curvature 'r_t' of the needle tip. For these experiments, the needle constituted of a polished platinum wire of radius 0.25 mm and the plane of 50 mm diameter Rogowsky profile curved plate of stainless steel. The current was measured through the plane electrode for a constant gap distance of 4 mm. The sharp bend measured on the curve is supposed to represent the development of a strong space charge around the needle.

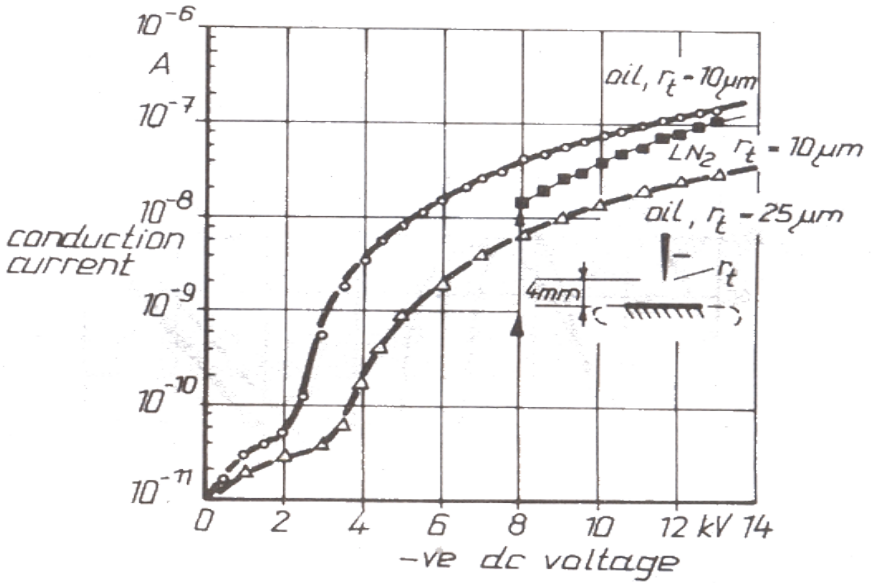


Fig 14.2 Conduction current in oil and liquid nitrogen for negative needle-plane electrode gap of 4mm with increasing voltage. Oil at 20°C and LN_2 at 77.3 K .

The concentration of charge carriers and the viscosity of insulating liquids are both strongly affected by the temperature which in turn influences the conductivity of the liquid. According to Van't Hoffsch law, the conductivity 'κ' within a certain range of temperature follows the relation:

$$\kappa = \kappa_0 \exp(-F/kT)$$

where k is Boltzmann constant, T absolute temperature, κ_0 and F are material constants. F is known as 'activation energy' and is expressed as kcal/mole.

However, Van't Hoffsch law is valid only in the region where the conduction current follows the ohmic behavior that is region 1 in Fig. 14.1. It thus depends upon the particular liquid and its impurity contents (for example, humidity content etc.).

Transformer oil conductivity variation for a wide range of temperature for different moisture contents measured by Holle [3.2] are illustrated in Fig. 14.3. It is evident from this figure that the conductivity of oil increases as the water ppm content raises.

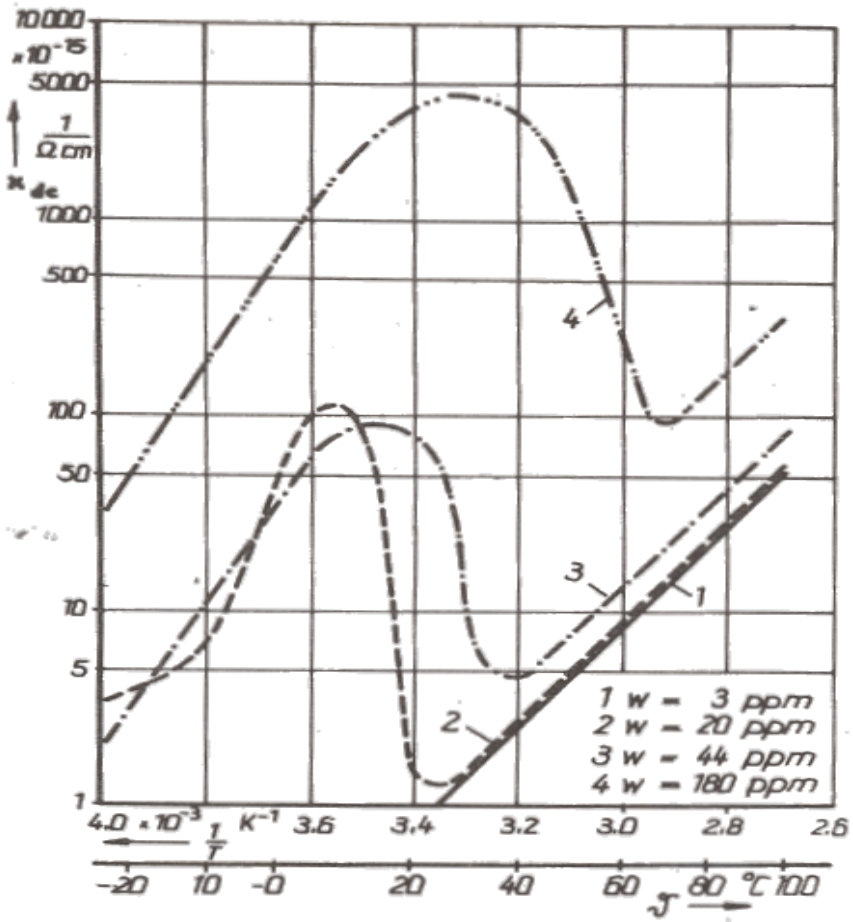


Fig 14.3 Direct current conductivity of transformer oil for different water contents w (ppm) with respect to the reciprocal of absolute temperature, Holle [3.2].

In case of highly purified liquids which are able to withstand high field intensity, the conduction phenomenon is different. By increasing the field intensity to the order of a few hundred kV/cm, the conduction current in both polar and nonpolar liquids is augmented predominantly by charge carriers injected into the liquid from the electrode surfaces. Besides, the field aided dissociation process of molecules is intensified. Under certain given conditions, the presence of an injected space charge, say of density q, gives rise to a Coulomb's force of density qE. Due to the action of this force, hydrodynamic instability is caused, developing convection motion in the liquid. Investigations made by many authors, on both polar and nonpolar liquids, have concluded that whenever conduction in an insulating fluid is accompanied with a significant charge injection, the convection motions occur, which are also known as 'electrohydrodynamic' (EHD) motions. The EHD motions augment the passage of current depending upon the charge injection intensity, which in turn is determined by the applied voltage, the nature of liquid and the electrode material.

Atten [3.4] explained the effect of the phenomenon of EHD motion on the conduction in liquid dielectrics under two extreme conditions: with and without unipolar injection of charge. For his experimentation, an extremely nonuniform field configuration between a knife and a plane was taken, as shown in Fig. 14.4.

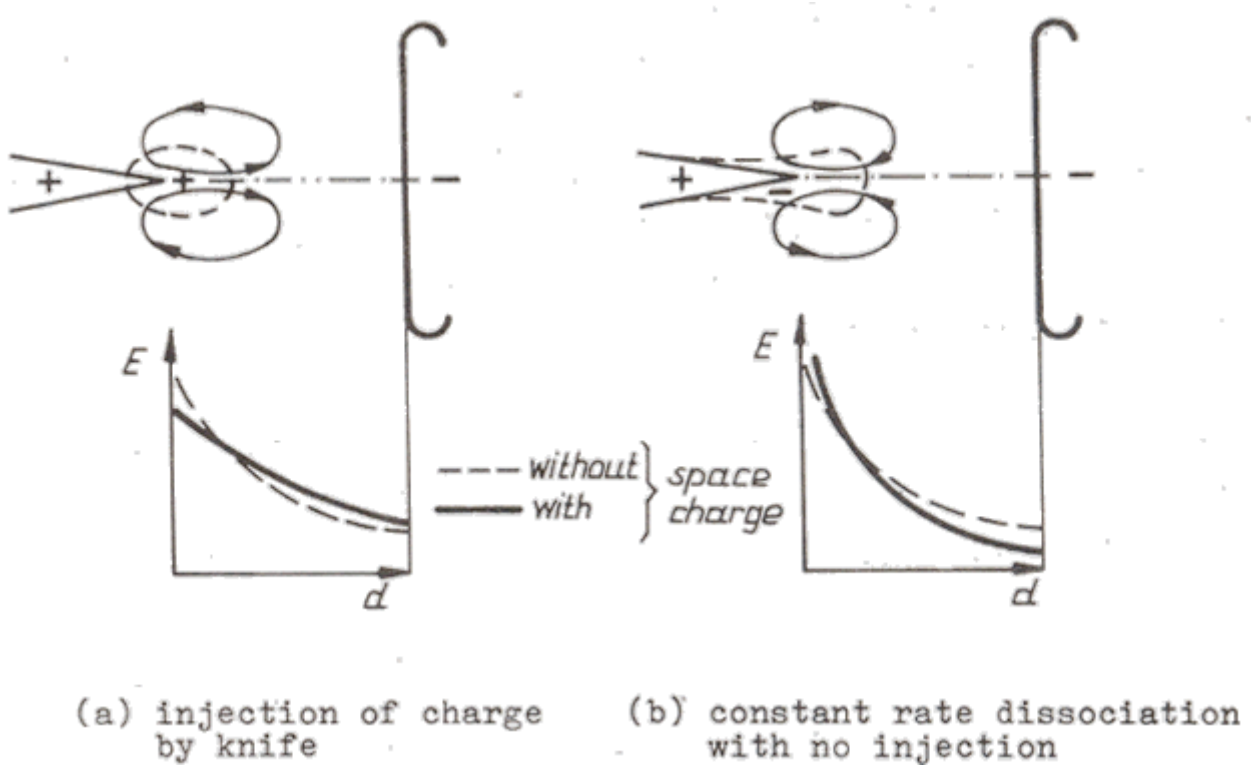


Fig 14.4 Schematic representation of space charge zone and liquid motion streams between knife-plane electrodes and the field distribution along the axis.

Consider first the case of injection of unipolar charge (ions) by the knife (Fig. 14.4 a). The field at the tip of the knife electrode is reduced because of the same polarity space charge being injected, whereas an increase in the field intensity is caused over the basic field towards the plane electrode. The space charge zone is of finite extent when a moderate voltage is applied. Under this condition, the liquid relaxation time is lower than the transit time of the ions from the knife to the plane. The total current is, therefore, higher than the ohmic current because of the enhancement of field intensity near the plane. Moreover, due to the action of the electric field on the same polarity charge close to the knife, a 'stream' or 'jet' of liquid towards the plane is induced in this region.

In case of pure conduction with no injection of charge, Fig. 14.4(b), an opposite polarity space charge near the knife extends further. Consequently, the space charge field at the tip increases, and is reduced with respect to the basic field towards the plane. This results in lower total current than the ohmic current (sub-ohmic behavior). The opposite polarity space charge in the vicinity of the knife gives rise to a liquid motion directed towards the knife.

At extremely high field intensities (1000 kV/cm and above) approaching the 'intrinsic strength' of liquid dielectrics, the field emission at the electrode surfaces affects the conduction phenomenon. Under these conditions, the conduction current is dominated by electrons.

(14) In this lecture you will learn the following:

Classification of solid insulating Materials, Thermoplastic and Thermoset Polymers, Composite Insulating Systems:

CLASSIFICATION OF SOLID INSULATING MATERIALS

A vast number of solid insulating materials are used in electrical power engineering. With the invention of modem insulating materials, many earlier conventional materials have been discarded, especially in case of electrical machines, capacitors and power cables. From the usage point of view, the solid insulating materials can be divided into the following three broad categories:

Moulding materials: These are used for providing mechanically rigid forms of insulation, for example,

insulators and bushings etc. Such materials are required to have good electrical insulating properties besides having high mechanical strength. These are usually made out of ceramics, glass (toughened glass), fibre glass reinforced plastics and epoxyresins.

Jacketing materials: Polymers have been found suitable for providing insulating jackets to the conductors. For

example, polyethylene (PE), polyvinylchloride (PVC), natural and synthetic rubber and paper used in power cables, capacitors and transformers. Mica and fibre glass based plastic tapes are used in electrical machines.

Filling materials: Beside oils, wax based draining land non draining impregnating compounds of different types are used to impregnate paper in power cables, transformers, capacitors, and instrument transformers. Insulating mechanical support: In the form of plates, pipes and ledges insulating supports are required in transformers, GIS,

circuit breakers and isolators. The products, such as press boards, hard paper (thin paper laminates), wood (yellow

teak) are used in transformers. Ebonite, also known as vulcanite, is a form of cross linked rubber containing large proportion of sulphur, bakelite, a hard synthetic material, and acrylic resin plates are used for insulating supports in other equipment.

However, the most common method of classifying the solid insulating materials is based upon their chemical compositions, distinguished mainly between inorganic and organic materials.

Among the inorganic materials; ceramics, glass, fibre glass, enamel, mica and asbestos are important and have found their wide application as dielectrics in the order of the mentioned sequence. They distinguish themselves in their unique ability to withstand high temperatures in addition to their being highly chemical resistant. There is practically negligible sign of ageing in these materials. However, it is difficult to machine or process them. These materials are basically inhomogeneous both microscopically as well as macroscopically. Solid organic materials used in electrical engineering are: paper, wood, wax, leather, cotton besides a number of natural and synthetic resins, rubbers and plastics, also known as polymers. Wood being so hygroscopic is rarely used as such, but wooden poles supporting overhead cables and distribution lines are being widely used in North America.

The polymeric organic insulating materials used in electrical engineering have a very high molecular weight and consist of two or more polymeric compounds of several structural units normally bound together by covalent bonds. The individual structural units may consist of single atoms or may be molecular in nature, which repeat in a regular order.

A polymer can be obtained by the reaction of compounds having at least two reactive functional groups which can react under suitable conditions. These chemical compounds are known as 'monomers'. There can be one or a mixture of reacting monomers and in the latter case, the resulting material is called 'copolymer'.

There are several ways of classifying polymers and one of them is by their response to heat. Accordingly, the polymers are divided into two groups of materials as follows.

Thermoplastic Polymers

Thermoplastic polymers soften and supple on heating and 'solidify' on cooling. The heating and cooling cycle within a certain temperature limit can be applied to these materials several times without affecting their properties. Polymers which generally have a linear structure fall in this category. The synthetic thermoplastic materials used in electrical engineering for insulation purpose is; polyethylene (PE), polyvinylchloride (PVC), polypropylene (PP) and polyamide (PA). The extent of their application in the industry is in the order of their above mentioned sequences. Such materials have relatively poor thermal resistance and their properties deteriorate rapidly at higher temperature.

Thermoset Polymers

The polymers which soften when heated for the first time resulting into cross-linking reaction (network formation), are known as thermoset polymers. This reaction, leading to the formation of network structure, is also known as curing or setting of the polymer. All monomers having functionality equal to two would give rise to linear polymers and, therefore, thermoplastic materials. However, when they have functionality more than two, the resulting polymer has a network structure. The polymers used for electrical insulation purpose are desired to retain their rubbery (flexible) properties. Hence, these are defined as 'lightly cross-linked polymers'.

The chemical reaction leading to cross-linking is achieved with the help of an additive, known as 'agent'. The term 'cross-linking agent' is very general. It refers to (a) molecules which bridge two polymer molecules, for example, vulcanizing agents; such as sulphur, selenium and sulphur monochloride for rubbers; and polyamines in expoxide resins, (b) molecules which initiate a cross-linking reaction, for example, peroxides which initiate a double bond polymerisation in polyesters and dicumyl peroxide in low density polyethylene (LDPE); (c) those which are purely catalytic in their action such as, acids for phenolic resins, amines in epoxides; and (d) active site generators, for example, peroxides which abstract protons from the polymer chains.

The thermal, mechanical and electrical properties of different cross-linked materials vary considerably from each other. However, in general, after crosslinking a material does not soften on reheating, instead it becomes thermally more stable compared to thermoplastic materials. Cross-linked polymer resins are, for example; polyester-resin, phenolresin, siliconresin and the most widely used in electrical engineering are the expoxyresins. Among rubbers, typical examples used for electrical insulation are; natural rubber also known as 'India rubber', and a large number of synthetic rubbers like silicon rubber (SiR), ethylene-propylene rubber (EPR), etc.

The bulk properties of a polymer can be altered suitably by incorporation of a number of additives. Variations in the choice of additives can produce widely differing products. This is true in particular with PVC. In terms of functions, there are a large number of groups of additives, of which the following most important are commonly used in preparing polymer compounds for electrical insulation purpose:

1. Fillers-usually applied to modify physical properties, mainly mechanical, of a polymer.

2. Plasticisers and Softeners-to lower the melt viscosity and also to change physical properties (softness, flexibility).
3. Colorants-normally soluble colorants (dyestuffs) are used.
4. Anti-ageing additives to prevent structural degradation due to chemical reactions like oxidation, ozone attack, dehydroclorination (especially with PVC) and ultra-violet attack, e.g. sunlight.
5. Flame retarders - to improve the degree of fire resistance of polymers.
6. Cross-linking agents-to achieve intermolecular combination at the chain ends.

Composite Insulating Systems

Some very high quality solid insulating systems have been produced by combining different dielectric materials. Common composites of organic and inorganic materials are; fiber glass reinforced plastics, mica based plastic tapes, quartz, fiber and mica mixed with synthetic resins, such as epoxyresin used in electrical machines, etc. Oil and wax based compound impregnated insulation systems with paper and polymer tapes are commonly applied in power cables, capacitors and transformers. 'Uniaxially oriented polyethylene' (UOPE) tape, developed recently has been found to have very good compatibility with oils besides having good mechanical properties. In such composite insulating systems, the advantages of inherent properties of their constituent materials are made use of. Thus, it is possible to create insulating systems having better thermal, mechanical and electrical properties.

Nano-composite Dieleictics

Research worldwide has been able to document significant improvement in the electrical and other properties of polymer composites through incorporation of nanoparticulates. Research in polymer processing is necessary to study the functionalization of the particulate surfaces to provide preferential coupling to the host polymer in the utilization of the emerging breed of new dielectric material. The nano-composites are intrinsically different in that they appear to be dominated by the characterstics of the internal interfaces. These properties appear to arise when the infilled material has a similar length scale to that of the polymer chain. Attempts to engineer nanodielectrics by changing the conditions at the interface do suggest that indeed some degree of tailoring of dielectric properties and self assembly may be possible. In table 15., examples of nano-composite insulating materials currently under investigation are given [3.5]

Table 15.1 Examples of nano-composite systems under investigations

Base polymers	Nano-materials
Polyolephins	Clays
Epoxies/phenolics	Inorganic oxides
Elastomers	Carbon nanotubes
Ethylene-vinyl copolymers	Graphite