1. CONDUCTION AND BREAKDOWN IN GASES

The high-voltage power system, in general consists of a complex configuration of generators, long-distance transmission lines and localized distribution networks with above- and below-ground conductors for delivering energy to users. Associated with this are a wide range of high-voltage components whose successful operation depends on the correct choice of the electrical insulation for the particular application and voltage level. The condition of the insulating materials when new, and especially as they age, is a critical factor in determining the life of much equipment. The need for effective maintenance, including continuous insulation monitoring in many cases, is becoming an important requirement in the asset management of existing and planned power systems.
As the voltages and powers to be transmitted increased over the past hundred years the basic dielectrics greatly improved following extensive research by industry and in specialized high voltage laboratories, where much of this work continues.

BACK GROUND MATERIAL

Recollect kinetic theory of gases (Developed by Maxwell)

$PV=nRT$ where numerically R is equal to 8.314 joules/□Kmol.

The fundamental equation for the kinetic theory of gas is derived with the following assumed conditions:

- Gas consists of molecules of the same mass which are assumed spheres.
- Molecules are in continuous random motion.
- Collisions are elastic – simple mechanical.
- Mean distance between molecules is much greater than their diameter.
- Forces between molecules and the walls of the container are negligible.

1.1 Gases as Insulating Media

The most common dielectrics are gases. Many electrical apparatus use air as the insulating medium, while in a few cases other gases such as N_2, CO_2, CCl_2F_2 (freon) and SF_6 (hexafluoride) are used.

Gases consist of neutral molecules, and are, therefore, good insulators. Yet under certain conditions, a breakdown of the insulating property occurs, and current can pass through the gas. Several phenomena are associated with the electric discharge in gases; among them are spark, dark (Townsend) discharge, glow, corona, and arc.

In order to conduct electricity, two conditions are required. First, the normally neutral gas must create charges or accept them from external sources, or both. Second, an electric field should exist to produce the directional motion of the charges.

Various phenomena occur in gaseous dielectrics when a voltage is applied.
-When low voltage is applied, small current flow between the electrodes and the insulation retains its electrical properties.
-If the applied voltage is large, the current flowing through the insulation increases very sharply and an electrical breakdown occur. A strongly conducting spark formed during breakdown, practically produces a short circuit between the electrodes. The maximum voltage applied to the insulation at the moment of breakdown is called the breakdown voltage.

In order to understand the breakdown phenomenon in gases, the electrical properties of gases should be studied. The processes by which high currents are produced in gases is essential. The electrical discharges in gases are of two types;

i) non-sustaining discharges
ii) self-sustaining types.

The breakdown in a gas (spark breakdown) is the transition of a non-sustaining discharges into a self-sustaining discharge. The build up of high currents in a breakdown is due to the ionization in which electrons and ions are created from neutral atoms or molecules, and their migration to the anode and cathode respectively leads to high currents. Townsend theory and Streamer theory are the present two types of theories which explain the mechanism of breakdown under different conditions as pressure, temperature, electrode field configuration, nature of electrode surfaces and availability of initial conducting particles.

1.2 Ionization Process

The Townsend discharge is named after John Sealy Edward Townsend, (7 June 1868 – 16 February 1957) a mathematical physicist of Oxford University. He has discovered the fundamental ionization mechanism by his work between 1897 and 1901.
Consider a simple electrode arrangement as shown in the Fig 1.1, having two parallel plate electrodes(representing uniform field geometry) separated by a distance d and immersed in a gas at pressure *p*. A uniform electric field E is applied between two electrodes. Due to any external radiation (ultra violet illumination) free electrons are liberated at the cathode. When an electron, *e* is placed in an *E*, it will be accelerated with a force *eE* (coulomb force) towards the anode, and it gains an energy

$$u = eEx = \frac{1}{2}mv^2 \qquad \text{(eqn. 1.1)}$$

where *x* is the distance traveled by the electron from the cathode, *m* is the mass and *v* is the velocity of the electron.
This electron collides with the other gas molecules while it is traveling towards the anode. If the energy of the electron is sufficiently large (about 12.2 eV for N_2 or 15.5 eV for O_2), on collision it will cause a break-up of the atom or molecule into positive ion and

electron, so the new electrons and positive ions are created. Thus created electrons form a group or an avalanche and reach the anode. This is the electric current and if it is sufficiently large it results in the formation of a conducting path between the electrodes resulting in the breakdown of the gap.
Townsend conducted experiments on the growth of these currents which led to breakdown under d.c. voltage conditions, and he proposed a theory to explain the phenomenon.

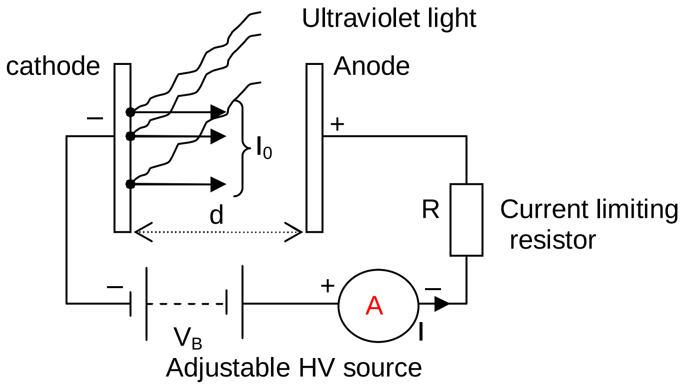

Fig. 1.1 Arrangement for study of a Townsend discharge

1.3 Townsend's Current Growth Equation

Assuming n_0 electrons are emitted from the cathode and when one electron collides with a neutral particle, a positive atom and electron formed. This is called an ionization collision.
Let α be the average number of ionizing collisions made by an electron per centimeter travel in the direction of the field where it depends on gas pressure *p* and *E/p*, and is called the **Townsend's first ionization coefficient or primary ionization coefficient**. At any distance *x* from the cathode(cathode is at x=0) when the number of electrons, n_x , travel a distance of *dx* they give rise to ($\alpha n_x dx$) electrons. Then, the number of electrons reaching the anode at *x=d*, n_d will be $n_0 = n_x\big|_{x=0}$ (eqn. 1.2)

$$\frac{dn_x}{dx} = \alpha n_x \text{ or } n_x = n_0 e^{\alpha x} \qquad \text{(eqn. 1.3)}$$

and

$$n_d = n_0 e^{\alpha d} \text{ at } x=d. \qquad \text{(eqn. 1.4)}$$

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

$$e^{\alpha d} - 1 = \frac{n_d - n_0}{n_0} \qquad \text{(eqn. 1.5).}$$

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

$I = I_0 e^{\alpha d}$ where I_0 is the initial current at the cathode. (eqn. 1.6)

This current being dependent on I_0 does not represent self sustaining discharge.

1.4 Current Growth Equation in the Presence of Secondary Processes

When the initial set of electrons reaches the anode, the single avalanche process is completed. Since the amplification of electrons $e^{\alpha d}$ is occurring in the field, the probability of additional new electrons being liberated by other mechanisms increases, and created further avalanches and are called as secondary electrons. The other mechanisms resulting in secondary processes are

i) The positive ions created in the gap due to ionization shall drift towards cathode and may have sufficient energy to cause liberation of electrons from the cathode(emission) when they impinge on it.(less efficient)

ii) The exited atoms or molecules in avalanches may emit photons, and this will lead to the emission of electrons due to photo-emission.

iii) the metastable particles (like mercury, and rare gases) may diffuse back causing electron emission.

Defining the Townsend's secondary ionization coefficient γ in the same way as α, then the net number of secondary electrons produced per incident positive ion, photon, excited particle or metastable particle and the total value of γ due to the three different processes is $\gamma = \gamma_1 + \gamma_2 + \gamma_3$ and is function of gas pressure *p* and *E/p*.

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

$n_0^{'} =$ number of secondary electrons produced due to secondary γ processes.

Let $n_0^{''} =$ total number of electrons leaving the cathode.

Then $n_0^{''} = n_0 + n_0^{'}$ (eqn. 1.7)

the total number of electrons *n* reaching to the anode becomes,

$n = n_0^{''} e^{\alpha d} = (n_0 + n_0^{'}) e^{\alpha d}$ and $n_0^{'} = \gamma [n - (n_0 + n_0^{'})]$

Eliminating $n_0^{'}$, $n = \dfrac{n_0 e^{\alpha d}}{1 - \gamma (e^{\alpha d} - 1)}$ or $I = \dfrac{I_0 e^{\alpha d}}{1 - \gamma (e^{\alpha d} - 1)}$ (eqn. 1.8)

1.5 Townsend's Criterion for Breakdown

Eqn. 1.8 give the total average current in a gap before the occurrence of breakdown. The denominator in this Eqn.1.8 (2nd Term) is less than unity. So as α increases due to more gradient or d is increased, the denominator becomes smaller and current larger.

As the distance between the electrodes *d* is increased, the denominator of equation tend to zero and at some critical distance $d = d_s$

$1 - \gamma (e^{\alpha d} - 1) = 0$ (eqn. 1.9)

For values of $d < d_s$, I is approximately equal to I_0 and if the external source for the supply of I_0 is removed, I becomes zero. If $d = d_s$, $I \Rightarrow \infty$ and the current will be limited only by the resistance of power supply and the external circuit.

This condition is called **Townsend's Breakdown Criterion** and can be written as $\gamma (e^{\alpha d} - 1) = 1$.

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

$$\gamma e^{\alpha d} = 1 \qquad \text{(eqn. 1.10)}$$

For a given gap spacing and at a given pressure the value of voltage V which gives the values of α and γ satisfying the breakdown criterion is called the spark breakdown voltage V, and the corresponding distance d is called the sparking distance.

Townsend Mechanism explains the phenomena of breakdown only at low pressures, corresponding to $p \times d$ values of 1000 torr-cm and below.

1.5.1 Determination of Townsend's Coefficients α and γ

Townsend's coefficients are determined in an ionisation chamber which is first evacuated to a very high vacuum of the order of 10^{-4} and 10^{-6} torr before filling with the desired gas at a pressure of a few torr. The applied direct voltage is about 2 to 10 kV, and the electrode system consists of a plane high voltage electrode and a low voltage electrode surrounded by a guard electrode to maintain a uniform field. The low voltage electrode is earthed through an electrometer amplifier capable of measuring currents in the range 0.01 pA to 10nA. The cathode is irradiated using an ultra-violet lamp from the outside to produce the initiation electron. The voltage current characteristics are then obtained for different gap settings. At low voltage the current growth is not steady. Afterwards the steady Townsend process develops as shown in Fig. 1.2.

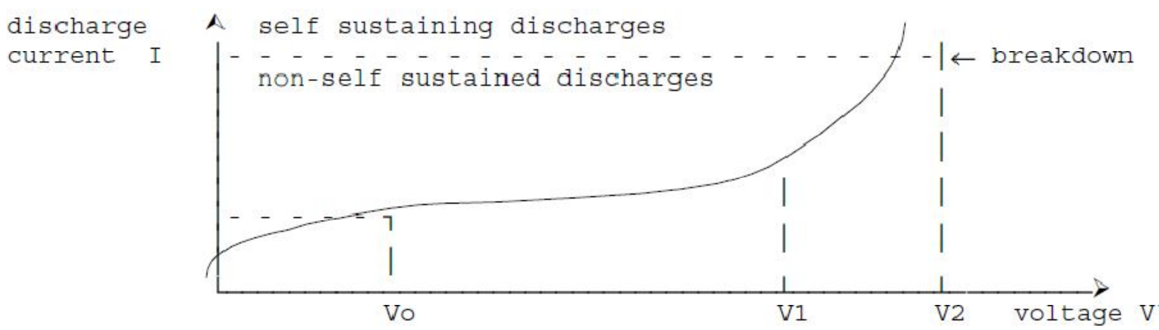

Fig.1.2 Growth of Current in gaseous dielectrics

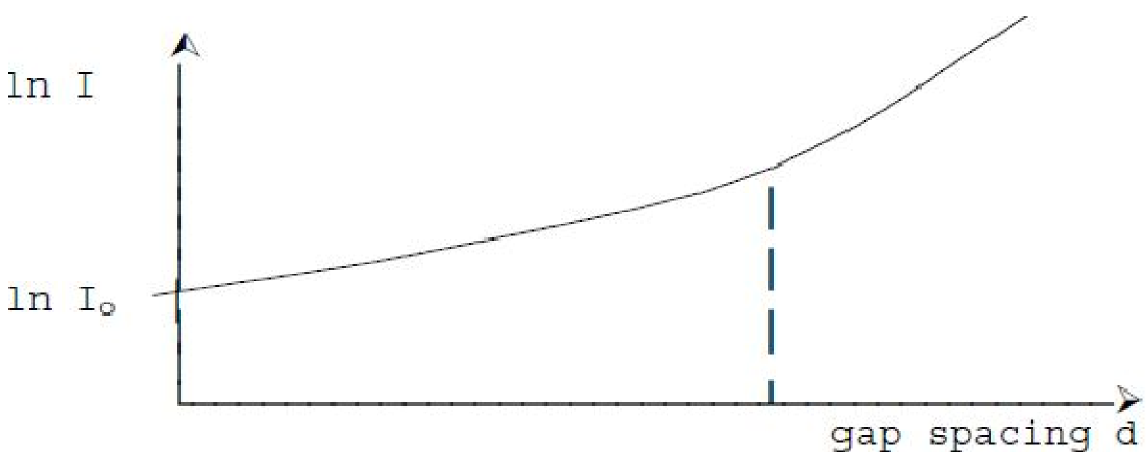

Fig.1.3 Plot of ln I vs. gap spacing d to determine the coeeficients α and γ

1.6 Breakdown in Electronegative Gases

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

a) Associative or Direct attachment: An electron directly attaches to form a negative ion.

$$AB + e \cdots \rightarrow AB^-$$

b) Dissociative attachment: The gas molecules split into their constituent atoms and the electronegative atom forms a negative ion.

$$AB + e \cdots \rightarrow A + B^-$$

A simple gas for this type is the oxygen and others are sulphur hexafluoride(SF_6), Freon, carbon dioxide and fluorocarbons. In these gases, 'A' is usually sulphur or carbon atom and 'B' is oxygen atom or one of the halogen atoms or molecules.

The Townsend current growth equation is modified to include ionization and attachment with such gases. The current reaching the anode, can be written as,

$$I = I_0 \frac{\left[\frac{\alpha}{\alpha-\eta} e^{(\alpha-\eta)d}\right] - \left[\frac{\eta}{\alpha-\eta}\right]}{1 - \left[\gamma \frac{\alpha}{\alpha-\eta} e^{(\alpha-\eta)d} - 1\right]} \quad \text{(eqn. 1.11)}$$

where η is the number of attaching collisions made by one electron drifting one centimeter in the direction of the field

The Townsend breakdown criterion for attaching gases can also be deduced from the denominator as,

$1 - \left[\gamma \frac{\alpha}{\alpha-\eta} e^{(\alpha-\eta)d} - 1\right] = 0$. When $\alpha > \eta$, breakdown is always possible irrespective of the values of $\alpha, \eta\, and\, \gamma$. If $\alpha < \eta$ then an asymptotic form is approached with increasing value of d, $\gamma \frac{\alpha}{\alpha-\eta} = 1$ or $\alpha = \frac{\eta}{1-\gamma}$

Normally γ is very small $\left(\leq 10^{-4}\right)$ and the above equation can be written $\alpha = \eta$. This condition puts a limit for E/p below which no breakdown is possible irrespective of the value of d, and the limit value is called the critical E/p. For SF_6 it is 117 $Vcm^{-1}torr^{-1}$, for CCl_2F_2 121 $Vcm^{-1}torr^{-1}$ both at 20˚C. η values can also experimentally determined.

1.7 Paschen's Law

The breakdown criterion $1 - \gamma(e^{\alpha d} - 1) = 0$ (1.9) where α and γ are functions of E/p, i.e.

$\alpha / p = f_1\left(E / p \right)$ and $\gamma = f_2\left(E / p \right)$.

Also for uniform field gap $E = V / d$.

Substituting for E in the expressions α and γ and rewriting equation (1.9) we have

$$f_2\left(V / pd \right)\left[e^{pd\, f_1\left(V / pd \right)} - 1 \right] = 1 .$$

This equation shows a relationship between *V and pd*, and implies that the breakdown voltage varies as the product pd varies. Knowing the nature of functions f_1 *and* f_2 we can write the equation $V = f\left(pd\right)$ known as Paschen's law and has been experimentally established for many gases. Paschen's law is a very important law in high voltage engineering.

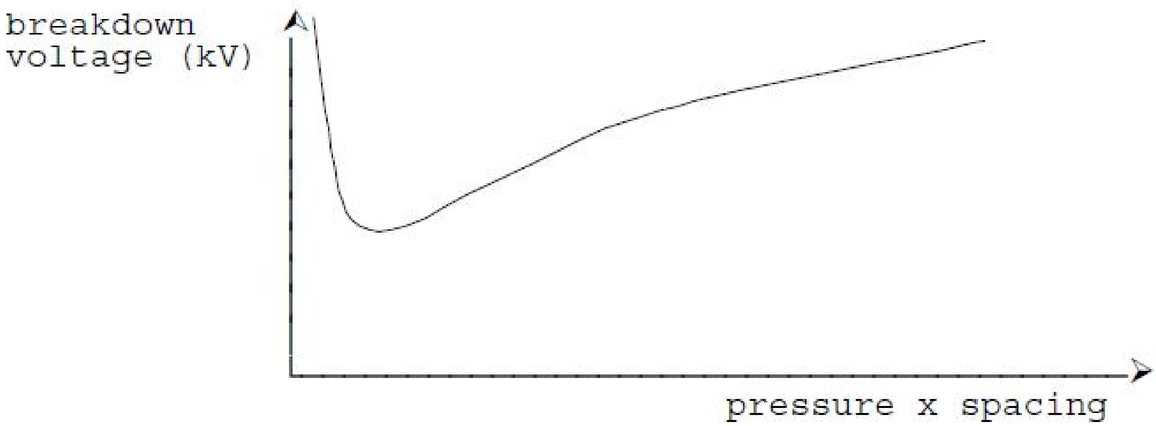

Fig.1.4 Variation of Breakdown voltage vs. pd

The relationship between *V and pd* is not linear and has has a minimum value for any gas. The minimum breakdown voltages for various gases are as follow;

Gas	$V_s$min(V)	pd at $V_s$min(torr-cm)
Air	*327*	*0.567*
H_2	*273*	*1.15*
CO_2	*420*	*0.51*
O_2	*450*	*0.7*
SO_2	*457*	*0..33*
Helium	*156*	*4.0*

The existence of a minimum sparking potential in Paschen's curve may be explained as follows:

For values $pd > \left(pd\right)_{\min}$ electrons crossing the gap make more frequent collisions with gas molecules than $\left(pd\right)_{\min}$, but the energy gained between collisions is lower. Hence to maintain the desired ionization more voltage has to be applied.

For $pd < \left(pd\right)_{\min}$ electron may cross the gap without even making a collision or making only less number of collisions. Hence more voltage has to be applied for breakdown to occur.

For the effect of temperature, the Paschen's law is generally stated as $V = f(Nd)$ where N is the density of the gas molecules. This is necessary since the pressure of the gas changes with temperature according to the gas law $pv = NRT$ .The breakdown potential of air is expressed due to the experimental results as;

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

At 760 torr and 293˚K

$E = V/d = 24.22 + \left[\frac{6.08}{\sqrt{d}}\right] kV/cm$. This equation yields a limiting value for E of 24 kV/cm for long gaps and a value of 30 kV/cm for $\left[\frac{293pd}{760T}\right] = 1$, which means a pressure of 760 torr at 20˚C with 1 cm gap. This is the breakdown strength of air at room temperature and at atmospheric pressure.

1.8 Time Lags for Breakdown

Theoretically the mechanism of spark breakdown is considered as a function of ionization processes under uniform field conditions. In practical engineering designs, the breakdown due to rapidly changing voltages or impulse voltages is of great importance. Actually there is a time difference between the application of a voltage sufficient to cause breakdown and the occurrence of breakdown itself. This time difference is called as the time lag.

In considering the time lag observed between the application of a voltage sufficient to cause breakdown and the actual breakdown the two basic processes of concern are the appearance of avalanche initiating electrons and the temporal growth of current after the criterion for static breakdown is satisfied.

In the case of slowly varying fields, there is usually no difficulty in finding an initiatory electron from natural sources (ex. cosmic rays, detachment of gaseous ions etc). However, for impulses of short duration (around 1 microsecond), depending on the gap volume, natural sources may not be sufficient to provide an initiating electron while the voltage is applied, and in the absence of any other source, breakdown will not occur.

The time ts which elapses between the application of a voltage greater than or equal to the static breakdown voltage (V_s) to the spark gap and the appearance of a suitably placed initiatory electron is called the statistical time lag of the gap, the appearance being usually statistically distributed.

After such an electron appears, the time tf required by the ionisation processes to generate a current of a magnitude which may be used to specify breakdown of the gap is known as the formative time lag. The sum $t_f + t_s = t$ is the total time lag, and is shown in the diagram. The ratio V/V_s, which is greater than unity, is called the impulse ratio, and clearly depends on $t_s + t_f$ and the rate of growth of the applied voltage.

(i) Statistical Time lag t_s

The statistical time lag is the average time required for an electron to appear in the gap in order that breakdown may be initiated.

If ß = rate at which electrons are produced in the gap by external irradiation

P_1 = probability of an electron appearing in a region of the gap where it can lead to a spark

P_2 = probability that such an electron appearing in the gap will lead to a spark

then, the average time lag

$t_s = 1/(ß P_1 P_2)$

If the level of irradiation is increased, ß increases and therefore t_s decreases. Also, with clean cathodes of higher work function ß will be smaller for a given level of illumination producing longer time lags.

The type of irradiation used will be an important factor controlling P_1, the probability of an electron appearing in a favourable position to produce breakdown. The most favourable position is, of course near the cathode.

(ii) Formative time lag(t_f)

After the statistical time lag, it can be assumed that the initiatory electron is available which will

eventually lead to breakdown. The additional time lag required for the breakdown process to form is the formative time lag. An uninterrupted series of avalanches is necessary to produce the requisite gap current (μA) which leads to breakdown, and the time rate of development of ionisation will depend on the particular secondary process operative. The value of the formative time lag will depend on the various secondary ionisation processes. Here again, an increase of the voltage above the static breakdown voltage will cause a decrease of the formative time lag t_f.

The Townsend criterion for breakdown is satisfied only if at least one electron is present in the gap between the electrodes as in the case of applied d.c. or slowly varying (50 Hz a.c.) voltages. With rapidly varying voltages of short duration ($\approx 10^{-6}$s), the initiatory electron may not be present in the gap that the breakdown can not occur.

(iii) Time lag characteristics

The time lag characteristic is the variation of the breakdown voltage with time of breakdown, and can be defined for a particular waveshape. The time lag characteristic based on the impulse waveform is shown in Fig.1.5.

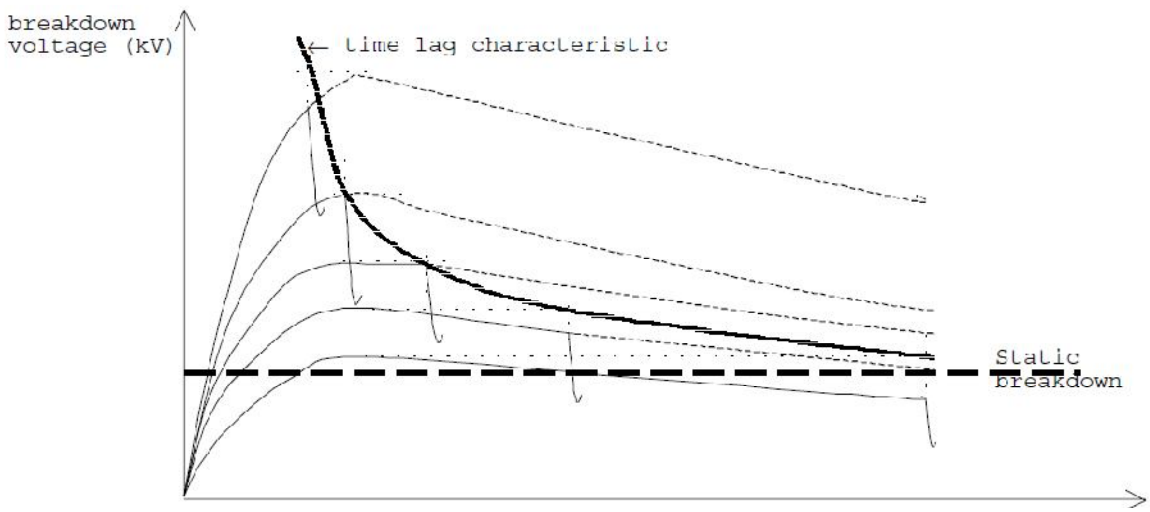

Fig.1.5 Time lag characteristic based on impulse waveform

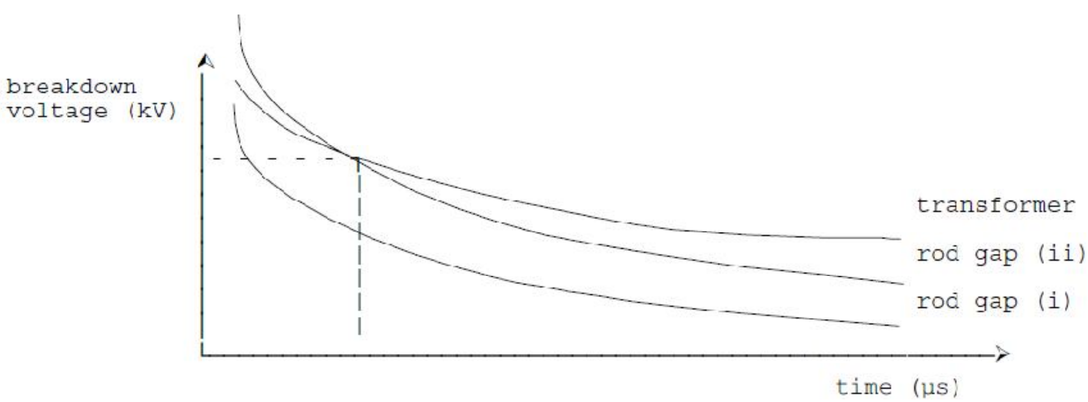

Fig.1.6 Voltage Time characeteristics

The time lag characteristic is important in designing insulation. If a rod gap is to provide secondary protection to a transformer, then the breakdown voltage characteristic of the rod gap must be less than that of the transformer at all times (gap i) to protect it from dangerous surge voltages. This will ensure that the gap will always flashover before the protected apparatus. This is shown in figure 1.6.

However, with such a rod gap, the gap setting will be low, as the sharpness of the two characteristics are different. Thus it is likely that there would be frequent interruptions, even due to the smallest overvoltages which would in fact cause no harm to the system. Thus it is usual to have the rod gap characteristic slightly higher (gap ii) resulting in the intersection of the characteristics as shown. In such a case, protection will be offered only in the region where the rod gap characteristic is lower than that of the transformer. This crossing point is found from experience for a value of voltage which is highly unlikely to occur. The other alternative is of course to increase the transformer characteristic which would increase the cost of the transformer a great deal. [This decision is something like saying, it is better and cheaper to replace 1 transformer a year due to this decision than have to double the cost of each of 100 such transformers in the system.]

1.9. Limitations of Townsend Theory

(i) Fails to explain the formative time lag of breakdown
(ii) Fails to explain the effect of space charge
(iii) Fails to explain the discharge under high PD

1.10 Streamer Theory of Breakdown in Gases

According to the Townsend theory;

- firstly, current growth occurs as a result of ionization process only. But in practice, breakdown voltages were found to depend on the gas pressure and the geometry of the gap;
- secondly, the mechanism predicts time lags of order of 10^{-5} s, but practically it was observed to occur at a very short time of 10^{-8} s.
- Also the Townsend mechanism predicts a very diffused form of discharge, that actually discharges were found to be filamentary and irregular.

Townsend mechanism failed to explain all these observed phenomena and as a result The Streamer theory was proposed.

The theory predicts the development of a spark discharge directly from a single avalanche in which the space charge develop by the avalanche itself is said to transform the avalanche into a plasma steamer. In the Fig 1.7, a single electron starting at the cathode by ionization builds up an avalanche that crosses the gap. The electrons in the avalanche move very fast compared with the positive ions. By the time the electrons reach the anode the positive ions are in their original positions and form a positive space charge at the anode. This enhances the field, and the secondary avalanches are formed from a few electrons produced due to the photo-ionization in the space charge region. This occurs first near the anode where the space charge is maximum and a further increase in the space charge. This process is very fast and the positive space charge extends to the cathode very rapidly resulting in the formation of a streamer. Comparatively narrow luminous tracks occurring at breakdown at pressures are called streamers. As soon as the streamer tip approaches to the cathode, a cathode spot is formed and a stream of electrons rush from the cathode to neutralize the

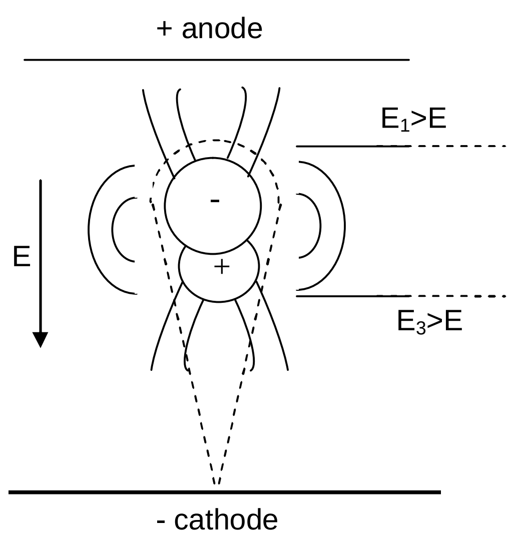

Fig.1.7 Effect of space charge produced by an avalanche on the applied electric field

positive space charge in the streamer; the result is a spark and the spark breakdown has occurred.

A simple quantitative criterion to estimate the electric field E_r which is produced by the space charge, at the radius *r and* that transforms an avalanche into streamer is given by

$E_r = 5.27\times10^{-7}\dfrac{\alpha e^{\alpha x}}{\sqrt{x/p}}\dfrac{V}{cm}$ where α is the Townsend's first ionization coefficient, p is the gas pressure in torr and x is the distance to which the streamer has extended in the gap. When $E_r = E$ and $x = d$ the equation above simplifies into;

$\alpha d + \ln \alpha/p = 14.5 + \ln E/p + 0.5 \ln d/p$. This equation is solved between α/p *and* E/p at which a given p and d satisfy the equation. The breakdown voltage is given by the corresponding product Ed.

It is generally assumed that for *pd* values below 1000 torr-cm and gas pressures varying from 0.01 to 300 torr, The Townsend mechanism operates, while at higher pressures and pd values the streamer mechanism plays the dominant role in explaining the breakdown phenomena. However controversies still exist in these statements.

1.11 Breakdown in non-uniform field and Corona Discharges

In a uniform electric field, a gradual increase in voltage across a gap produces a breakdown of the gap in the form of a spark without any preliminary discharges. On the other hand, if the field is non-uniform, an increase in voltage will first cause a localised discharge in the gas to appear at points with the highest electric field intensity, namely at sharp points or where the electrodes are curved or on transmission line conductors. This form of discharge is called a corona discharge and can be observed as a bluish luminance. This phenomena is always accompanied by a hissing noise, and the air surrounding the corona region becomes converted to ozone. Corona is responsible for considerable power loss in transmission lines and also gives rise to radio interference. This also leads to deterioration of insulation by the combined action of the discharge ion bombarding the surface and the action of chemical compounds that are formed by the corona discharge.

In non-uniform fields, e.g. in point-plane, sphere-plane gaps or coaxial cylinders, the field strength and hence the effective ionization coefficient α vary across the gap. The electron multiplication is governed by the integral of α over the path $\int \alpha dx$.

The electrode configuration has great influence on the characteristics of the corona discharge. The typical configurations include point-to-plane or point-to-point, wire-to-wire, wire-to-plane or wire-to-cylinder, etc. Among them, the point-to-plane (or needle-to-plate) is the most typical and popular configuration. The corona discharge with the point-to-plane configuration has been investigated widely in air under various conditions

Investigation with point-plane gaps in air have shown that when point is positive, the corona current increases steadily with voltage. At sufficiently high voltage, current amplification increases rapidly with voltage upto a current of about 10^{-7} *A*, after which the current becomes pulsed with repetition frequency of about 1 kHz composed of small bursts. This form of corona is known as *burst corona*.

The average current then increases steadily with applied voltage, leading to breakdown. With point-plane gap in air when negative polarity voltage is applied to the point and the voltage exceeds the onset value, the current flows in vary regular pulses known as *Trichel pulses*. The onset voltage is independent of the gap length and is numerically equal to the onset of streamers under positive voltage for the same arrangement. The pulse frequency increases with voltage and is a function of the radius of the cathode, the gap length and the pressure. A decrease in pressure decreases the frequency of the pulses. It should be noted that the breakdown voltage with negative polarity is higher than with positive polarity except at low pressure. Therefore, under alternating power frequency voltage the breakdown of non-uniform field gap invariably takes place during the positive half cycle of the voltage wave. Table 1 gives out the measured onset voltage V_C, the inception voltage of spark V_{spark} and the corresponding transition current I_{spark}

Table 1. The breakdown voltage and current in different gases and voltage polarity.

	Ar		He		Air		N_2		O_2	
	+	-	+	-	+	-	+	-	+	-
V_C (kV)	1.91	1.23	2.37	1.02	3.10	2.05	2.94	1.68	3.08	2.50
V_{spark} (kV)	3.24	2.15	5.07	2.24	5.42	5.08	5.10	4.32	5.82	6.69
I_{spark} (μA)	6.00	32.0	50.0	101.0	20.0	145.0	15.0	365.0	33.0	94.0

The results show a significant polarity-effect. In all gases the onset voltage of positive corona is much higher than the negative corona. The breakdown Voltage of positive corona to spark is also higher than the negative except in O_2 that the result is inversed. The current of the negative corona is much larger than the positive in all gases. The current-voltage dependence of negative or positive corona shows the Townsend's relation. The negative corona has a large luminous area than the positive in all gases and shows a stable bell-shaped glow before spark, except in case of O_2 in which the negative corona exists near the tip of the cathode. The positive corona in all gases occurs only in a small region around the anode needle. The electronegative oxygen is suggested to play an important role in the characteristics of negative corona discharge.

The formation of corona causes the current waveform in the line, and hence the voltage drop to be non-sinusoidal. It also causes a loss of power. There is always some electrons present in the atmosphere due to cosmic radiation etc. When the line voltage is increased, the velocity of the electrons in the vicinity of the line increases, and the electrons acquire sufficient velocity to cause ionization.

To prevent the formation of corona, the working voltage under fair weather conditions should be kept at least 10% less than the disruptive critical voltage. Corona formation may be reduced by increasing the effective radius. Thus steel cored aluminium has the advantage over hard drawn copper conductors on account of the larger diameter, other conditions remaining the same. The effective conductor diameter can also be increased by the use of bundle conductors. Corona acts as a safety valve for lightning surges, by causing a short circuit. The advantage of corona in this instance is that it reduces transients by reducing the effective magnitude of the surge by partially dissipating its energy due to corona.

The effect of corona on radio reception is a matter of some importance. The Corona frequency lies between 20 Hz and 20 kHz. The current flowing into a corona discharge contains high-frequency components. These cause interference in the immediate vicinity of the line. As the voltage is gradually increased, the disturbing field makes its appearance long before corona loss becomes appreciable. The field has its maximum value under the line and attenuates rapidly with distance. The interference fails to about a tenth at 50 m from the axis of the line

1.12 Post-Breakdown Phenomena and Applications

Post-Breakdown phenomenon (after actual breakdown) is of technical importance which occurs after the actual breakdown has taken place. Glow and arc discharges are the post-breakdown phenomena and there are many devices that operate over these regions. In a Townsend discharge (see Fig 1.8) the current increases gradually as a function of the applied voltage from point A. Further to this point B only the current increases and the discharge

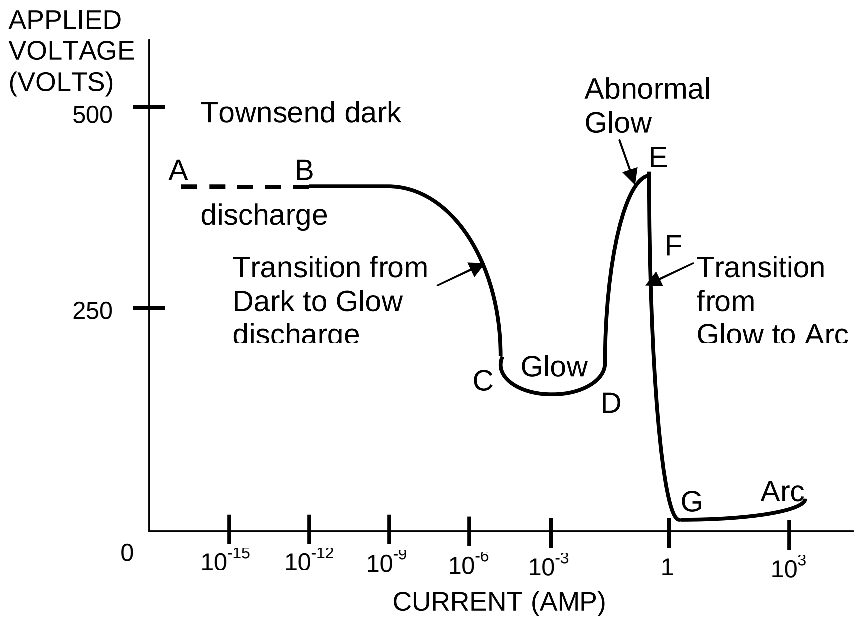

Fig.1.8 DC. voltage current characteristic at an electrical discharge with electrodes having no sharp points or edges

changes from the Townsend type to Glow type (BC). Further increase in current results in a very small reduction I voltage across the gap (CD) corresponding to the normal glow region. The gap voltage again increases (DE), when the current increase more, but eventually leads a considerable drop to the applied voltage. This is the region of the Arc discharge (EG). The phenomena occur in the region CG are the post-breakdown phenomena consisting of glow discharge CE and the arc discharge EG.