1

Breakdown of Gaseous Insulation

1.1 Ionisation of Gases

Electrical Insulating Materials (or Dielectrics) are materials in which electrostatic fields can remain almost indefinitely. These materials thus offer a very high resistance to the passage of direct currents. However, they cannot withstand an infinitely high voltage. When the applied voltage across the dielectric exceeds a critical value the insulation will be damaged. The dielectrics may be gaseous, liquid or solid in form.

Gaseous dielectrics in practice are not free of electrically charged particles, including free electrons. The electrons, which may be caused by irradiation or field emission, can lead to a breakdown process to be initiated. These free electrons, however produced, on the application of an electric field are accelerated from the cathode to the anode by the electric stress applying a force on them. They acquire a kinetic energy ($\frac{1}{2} mu^2$) as they move through the field. The energy is usually expressed as a voltage (in electron-volt, eV, where e is the charge on an electron) as the energies involved are extremely small. [The energy $E_i = e\,V_i$ is expressed in electron volt. $1\ e\ V = 1.6 \times 10^{-19}$ J]. These free electrons, moving towards the anode collide with the gas molecules present between the electrodes. In these collisions, part of the kinetic energy of the electrons is lost and part is transmitted to the neutral molecule. If this molecule gains sufficient energy (more than the energy E_i necessary for ionisation to occur), it may ionise by collision. The (mean) number of ionising collisions by one electron per unit drift across the gap is not a constant but subject to statistical fluctuations. The newly liberated electron and the impinging electron are then accelerated in the field and an electron avalanche is set up. Further increase in voltage results in additional ionising processes. Ionisation increases rapidly with voltage once these secondary processes take place, until ultimately breakdown occurs.

It is worth noting that in uniform fields, the ionisation present at voltages below breakdown is normally too small to affect engineering applications. In non-uniform fields, however, considerable ionisation may be present in the region of high stress, at voltages well below breakdown, constituting the well known corona discharge.

1.1.1 Ionisation processes in gas discharges

The electrical breakdown of a gas is brought about by various processes of ionisation. These are gas processes involving the collision of electrons, ions and photons with gas molecules, and electrode processes which take place at or near the electrode surface [Electrons can be emitted from the cathode if the stress is around 100 - 1000 kV/cm due to field emission].

Ionisation is the process by which an electron is removed from an atom, leaving the atom with a nett positive charge (positive ion). Since an electron in the outermost orbit is subject to the least attractive force from the nucleus, it is the easiest removed by any of the collision processes. The energy required to remove an outer electron completely from its normal state in the atom to a distance well beyond the nucleus is called the first ionisation potential.

The reciprocal process of an electron falling from a great distance to the lowest unoccupied orbit is also possible. In this case, a photon will be emitted having the same energy as previously absorbed.

1.1.2 Relevant gas ionisation processes

(i) Ionisation by simple collision

When the kinetic energy of an electron ($\frac{1}{2}\,mu^2$), in collision with a neutral gas molecule exceeds the ionisation energy ($E_i = e\,V_i$) of the molecule, then ionisation can occur.
(i.e. when $\frac{1}{2}\,mu^2 > E_i$)

$$M + e^- (\tfrac{1}{2}\,mu^2) \rightarrow M^+ + 2\,e^-$$

In general, a positive ion and 2 slow moving electrons will result. The probability of this process is zero for electron energies equal to the ionisation energy E_i, but increases almost linearly at first, and then gradually with electron energy up to a maximum.

When the gas molecules are bombarded with electrons, other electrons bound to atoms may be freed by the collision with the high energy electron. The ratio of the electrons given by collision to the primary electrons depend, mainly on the energy of the primaries. This is maximum at primary electron energies of about 200 - 500 eV. For lower energy values, the energy transferred may not be sufficient to cause electrons to escape from the surface of the molecules, and thus the probability of ionisation is small. For much higher values of primary energies, the energy of the impinging electron would be sufficient for this electron to penetrate the surface deeper into the molecule, so that again the chance of escape of other electrons decreases.

Thus the variation of the ionisation probability in air with increase of electron energy is as shown in figure 1.1.

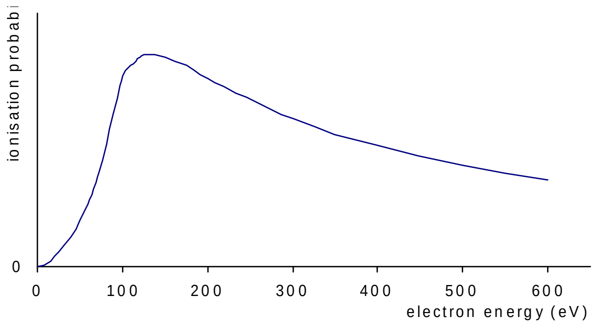

Figure 1.1 - Ionisation probability curve in air

(ii) Excitation

In the case of simple collision, the neutral gas molecule does not always gets ionised on electron impact. In such cases, the molecule will be left in an excited state M^*, with energy E_e.

$$M + e^- (\tfrac{1}{2}\,mu^2) \rightarrow M^* + e^-$$

This excited molecule can subsequently give out a photon of frequency v with energy emitted h v. The energy is given out when the electron jumps from one orbit to the next.

$$M^* \rightarrow M + h\,v$$

where h = Planck's constant = 6.624×10^{-34} J s

(iii) Ionisation by Double electron impact

If a gas molecule is already raised to an excited state (with energy E_e) by a previous collision, then ionisation of this excited molecule can occur by a collision with a relatively slow electron. This electron would need less energy than the ionisation energy, but the energy must exceed the additional energy required to attain the ionisation energy.

(i.e. $\frac{1}{2} mu^2 > E_i - E_e$)

$$M^* + e^- (\tfrac{1}{2} mu^2) \rightarrow M^+ + 2\,e^-$$

(iv) Photo-ionisation

A molecule in the ground state can be ionised by a photon of frequency v provided that the quantum of energy emitted h v (by an electron jumping from one orbit to another), is greater than the ionisation energy of the molecule.

(i.e. $h\,v > E_i$, where h = Plank's constant = 6.624×10^{-34} joule)

$$M + h\,v \rightarrow M^+ + e^-$$

(v) Electron Attachment

If a gas molecule has unoccupied energy levels in its outermost group, then a colliding electron may take up one of these levels, converting the molecule into a negative ion M^-.

$$M + e^- \rightarrow M^-$$

The negative ion thus formed would be in an excited state, caused by the excess energy.

Note: Electron attachment decreases the number of free electrons, unlike ionisation which increases the free electrons.

(vi) Electron detachment

This occurs when a negative ion gives up its extra electron, and becomes a neutral molecule.

$$M^- \rightarrow M + e^-$$

(vii) Other Processes

The above processes are the most important in relation to the gas discharge phenomena. Other possible gas processes include ion-atom collisions, excited atom-molecule collisions, and atom-atom collisions. It should be noted that collisions between ions and atoms rarely result in ionisation, due to the relatively slow interaction time, which allows the internal motion of the atomic system to adjust itself gradually to the changing condition without any energy transition occurring.

In order to cause ionisation of a neutral unexcited atom of its own kind, a positive ion must possess energy of at least 2 eV. Normally ions and atoms having such energies are encountered only in high current arcs and thermonuclear discharges.

1.2 Breakdown Characteristic in gases

Two mechanisms of breakdown in gasses is known. These are the **avalanche** and **streamer** mechanisms.

1.2.1 Electron Avalanche Mechanism (Townsend Breakdown Process)

One of the processes which are considered in breakdown is the Townsend breakdown mechanism. It is based on the generation of successive secondary avalanches to produce breakdown.

Suppose a free electron exists (caused by some external effect such as radio-activity or cosmic radiation) in a gas where an electric field exists. If the field strength is sufficiently high, then it is likely to ionize a gas molecule by simple collision resulting in 2 free electrons and a positive ion. These 2 electrons will be able to cause further ionization by collision leading in general to 4 electrons and 3 positive ions. The process is cumulative, and the number of free electrons will go on increasing as they continue to move under the action of the electric field. The swarm of electrons and positive ions produced in this way is called an electron avalanche. In the space of a few millimetres, it may grow until it contains many millions of electrons. This is shown in Figure 1.2.

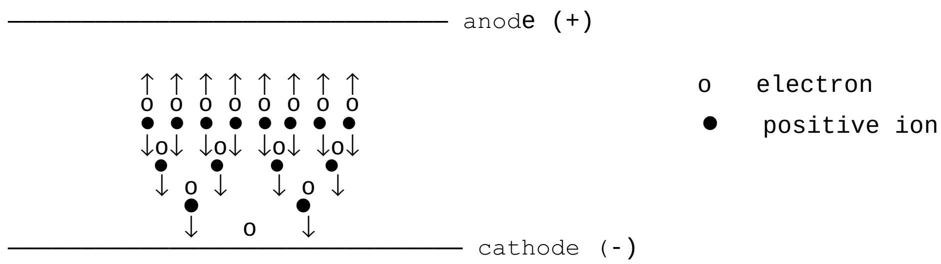

Figure 1.2 - Electron Avalanche

1.2.1.1 Mathematical Analysis

When the voltage applied across a pair of electrodes is increased, the current throughout the gap increases slowly, as the electrons emitted from the cathode move through the gas with an average velocity determined by their mobility for the field strength existing for the particular value of voltage. Impact ionization by electrons is probably the most important process in the breakdown of gasses, but this process alone is not sufficient to produce breakdown.

Let n_0 = number of electrons/second emitted from the cathode,

n_x = number of electrons/second moving at a distance x from the cathode
[$n_x > n_0$ due to ionising collisions in gap]

α = number of ionising collisions, on average, made by one electron per unit drift in the direction of the field. [Townsend's first ionisation coefficient]

then $1/\alpha$ = average distance traversed in the field direction between ionising collisions.

Consider a laminar of thickness dx at a distance x from the cathode. The n_x electrons entering the laminar will traverse it in the presence of the applied field E. The ionising collisions generated in the gas gap will be proportional to both dx and to n_x.

Thus

$$dn_x \propto n_x$$

$$\propto dx$$

Therefore $dn_x = \alpha \cdot n_x \cdot dx$ (from definition of α)

Rearranging and integrating gives

$$\int_{n_0}^{n_x} \frac{d\,n_x}{n_x} = \alpha \int_0^x dx$$

$$\log_e (n_x / n_0) = \alpha \, . \, x$$

$$n_x = n_0 \cdot e^{\alpha x}$$

If the anode is at a distance x = d from the cathode, then the number of electrons n_d striking the anode per second is given by

$$n_d = n_0 \, . \, e^{\alpha d}$$

Therefore, on the average, each electron leaving the cathode produces $(n_d - n_0)/n_0$ new electrons (and corresponding positive ions) in the gap.

In the **steady state**, the number of positive ions arriving at the cathode/second must be exactly equal to the number of newly formed electrons arriving at the anode. Thus the circuit current will be given by

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

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

In the actual breakdown process, the electron impact ionization is attended by secondary processes on the cathode, which replenish the gas gap with free electrons, with every newly formed avalanche surpassing the preceding one in the number of electrons.

Consider now the current growth equations with the secondary mechanism also present.

Let γ = number of secondary electrons (on average) produced at the cathode per ionising collision in the gap. [Townsend's second ionisation coefficient]

n_0 = number of primary photo-electrons/second emitted from the cathode

n_0' = number of secondary electrons/second produced at the cathode

n_0'' = total number of electrons/second leaving the cathode

Then $n_0' = n_0 + n_0''$

On the average, each electron leaving the cathode produces $[e^{\alpha d} - 1]$ collisions in the gap, giving the number of ionising collisions/second in the gap as $n_0'' (e^{\alpha d} - 1)$. Thus by definition

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

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

but $n_0'' = n_0 + n_0'$

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

This gives the result

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

Similar to the case of the primary process (with α only), we have

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

Thus, in steady state, the circuit current I will be given by

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

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

As the applied voltage increases, $e^{\alpha d}$ and $\gamma\, e^{\alpha d}$ increase until $\gamma\, e^{\alpha d} \rightarrow 1$, when the denominator of the circuit current expression becomes zero and the current $\mathbf{I} \rightarrow \infty$. In this case, the current will, in practice, be limited only by the resistance of the power supply and the conducting gas.

This condition may thus be defined as the breakdown and can be written as

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

This condition is known as the **Townsend criteria for spark breakdown**.

The avalanche breakdown develops over relatively long periods of time, typically over 1 μs and does not generally occur with impulse voltages.

1.2.1.2 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 10 nA. 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 figure 1.3.

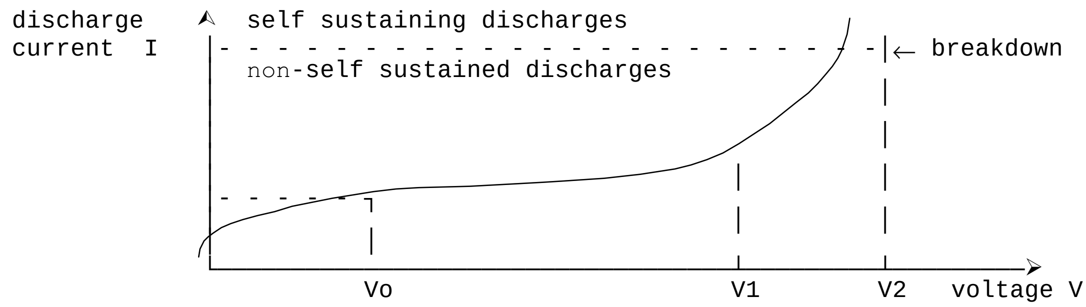

Figure 1.3 - Typical Current growth

From the Townsend mechanism, the discharge current is given by

$$I = \frac{I_0 e^{\alpha d}}{1 - \gamma (e^{\alpha d} - 1)} \approx I_0 e^{\alpha d} \quad \text{when } \alpha \text{ d} \gg 1$$

This can be written in logarithmic form as

$$\ln I = \alpha d + \ln I_0$$

$$y = m x + c$$

From a graph of ln I vs d, the constants α and I_0 can be determined from the gradient and the intercept respectively, as in figure 1.4.

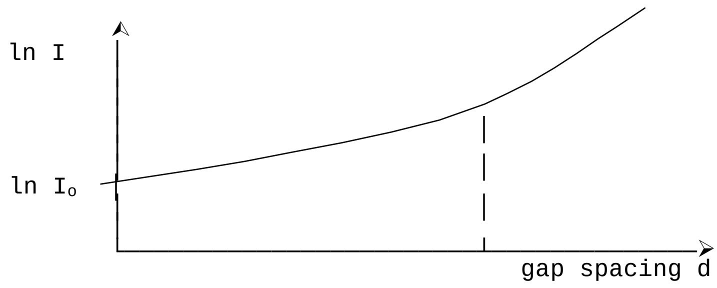

Figure 1.4 - Variation of ln I vs d

Once I_0 and α are known, γ can be determined from points on the upward region of the curve. The experiment can be repeated at different pressures if required.

1.2.1.3 Breakdown in electronegative gases

In the above analysis, electron attachment to neutral molecules was not considered. Electron attachment removes free electrons and thus gives gases very high dielectric strengths. The gases in which electron attachment occurs are electro-negative gases.

An attachment coefficient η can be defined, analogous with α, as the number of attachments per electron per unit drift in the direction of the field. Under these conditions, the equation for the average current growth in a uniform field can be shown to be as follows.

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

The corresponding criteria for spark breakdown is

$$\gamma \frac{\alpha}{\alpha - \eta}\left[e^{(\alpha - \eta) d} - 1\right] = 1$$

1.2.2 Paschen's Law

When electrons and ions move through a gas in a uniform field E and gas pressure p, their mean energies attain equilibrium values dependant on the ratio E/p; or more precisely

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

For a uniform field gap, the electric field E = V/d. Thus applying Townsend's criterion for spark breakdown of gases gives

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

which may be written in terms of the functions as

$$f_2\left(\frac{V}{p\,d}\right)\left[e^{p\,d\,f_1\left(\frac{V}{p\,d}\right)} - 1\right] = 1$$

This equation shows that the breakdown voltage V is an implicit function of the product of gas pressure p and the electrode separation d.

That is V = f (p.d)

In the above derivation the effect of temperature on the breakdown voltage is not taken into account. Using the gas equation **pressure . volume = mass . R . absolute Temperature**, we see that **pressure = density . R . absolute Temperature**. Thus the correct statement of the above expression is **V = f(ρ.d)**, where ρ is the gas density. This is the statement of **Paschen's Law**.

Under constant atmospheric conditions, it is experimentally found that the breakdown voltage of a uniform field gap may be expressed in the form

$$V = A\,.\,d + B\,.\,\sqrt{d} \qquad \text{where } \mathbf{d} \text{ is the gap spacing}$$

For air, under normal conditions, A = 24.4 kV/cm and B = 6.29 $kV/cm^{1/2}$.

[The breakdown voltage gradient is about 30 kV/cm in uniform fields for small gaps of the order of 1 cm, but reduces to about 6 kV/cm for large gaps of several meters]

Figure 1.5 shows a typical breakdown vs spacing characteristic.

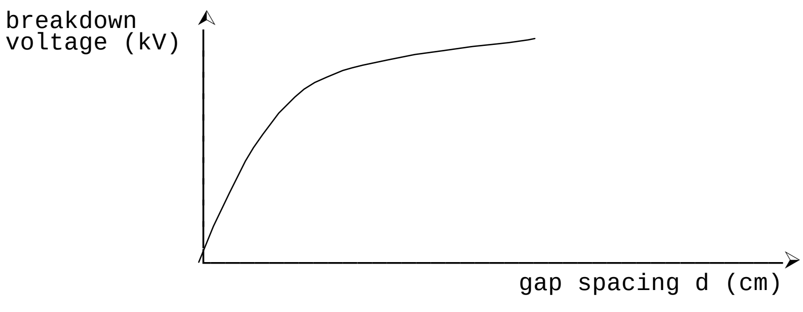

Figure 1.5 - Breakdown characteristic

This variation with spacing can be modified using Paschen's Law to include the variation with gas density as follows.

$$V = \frac{A}{\rho_0}\,.\,\rho\,d + \frac{B}{\rho_0^{1/2}}\,.\,(\rho\,d)^{1/2}$$

$$= A(\delta\,d) + B(\delta\,d)^{1/2}$$

where δ = relative density (or gas density correction factor).

This equation is true for gap spacings of more than 0.1 mm at N.T.P. However, with very low products of **pressure x spacing**, a minimum breakdown voltage occurs, known as the **Paschen's minimum**. This can be explained in the following manner.

Consider a gap of fixed spacing, and let the pressure decrease from a point to the right of the minimum (Figure 1.6).

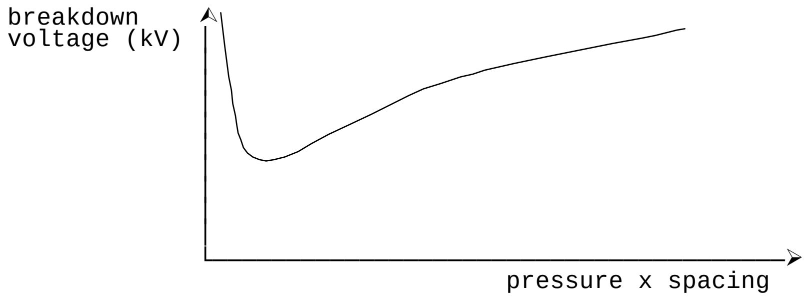

Figure 1.6 - Breakdown characteristic

The density therefore, decreases and an electron moving in the field consequently makes fewer collisions with gas molecules as it travels towards the anode. Since each collision results in a loss of energy, it follows that a lower electric stress suffices to impart to electrons the kinetic energy (½ m u^2) required to ionize by collision.

Gas	V_{min} (V)	p.d at V_{min} (torr-cm)
Air	327	0.567
Argon	137	0.9
Hydrogen	273	1.15
Helium	156	4.0
Carbon dioxide	420	0.51
Nitrogen	251	0.67
Nitrous oxide	418	0.5
Oxygen	450	0.7
Sulphur dioxide	457	0.33
Hydrogen Sulphide	414	0.6

Table 1.1 - Minimum sparking voltages

Near the minimum of the characteristic, the density is low and there are relatively few collisions. It is necessary now to take into account the fact that an electron does not necessarily ionize a molecule on collision with it, even if the energy of the electron exceeds the ionisation energy. The electrons have a finite chance of ionizing, which depends upon its energy. If the density and hence the number of collisions is decreased, breakdown can occur only if the chance of ionising is increased, and this accounts for the increase in voltage to the left of the minimum.

It is worth noting that if the density is fixed, breakdown to the left of the minimum occurs more readily (i.e. at lower voltage) at longer distances. Typically the voltage minimum is 300 V and occurs at a product or **p.d** of **5 torr mm**, or at a gap of about 0.06 mm at N.T.P.

At very low pressures, and at very high pressures (compared with atmospheric), Paschen's Law fails. Also, Paschen's Law is valid for temperatures below about 1100^0C. A further increase in temperature ultimately results in the failure of Paschen's Law because of thermal ionisation.

It can be seen from the breakdown characteristic, that for a constant gap spacing, the breakdown voltage, and hence the breakdown stress required, is very much higher than at atmospheric conditions, under very high pressure and under very low pressures (high vacuum) conditions. Thus both high vacuum as well as high gas pressure can be used as insulating media. [The vacuum breakdown region is that in which the breakdown voltage becomes independent of the gas pressure] Under normal conditions, operation is well to the right of Paschen's minimum.

The table 1.1 gives the minimum sparking potential for various gases.

1.2.3 Streamer Mechanism

This type of breakdown mainly arises due to the added effect of the space-charge field of an avalanche and photo-electric ionization in the gas volume. While the Townsend mechanism predicts a very diffused form of discharge, in actual practice many discharges are found to be filamentary and irregular. The Streamer theory predicts the development of a spark discharge directly from a single avalanche. The space charge produced in the avalanche causes sufficient distortion of the electric field that those free electrons move towards the avalanche head, and in so doing generate further avalanches in a process that rapidly becomes cumulative. As the electrons advance rapidly, the positive ions are left behind in a relatively slow-moving tail.The field will be enhanced in front of the head. Just behind the head the field between the electrons and the positive ions is in the opposite direction to the applied field and hence the resultant field strength is less. Again between the tail and the cathode the field is enhanced. (Figure 1.7)

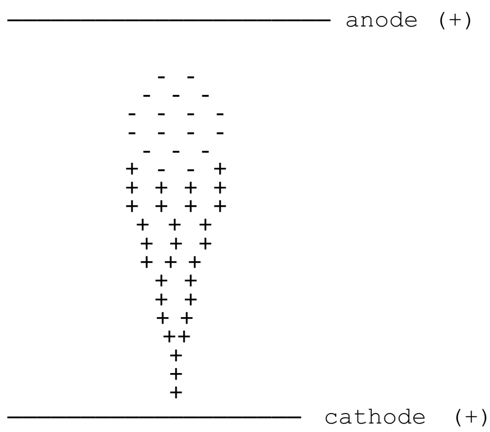

Figure 1.7 - Streamer Mechanism

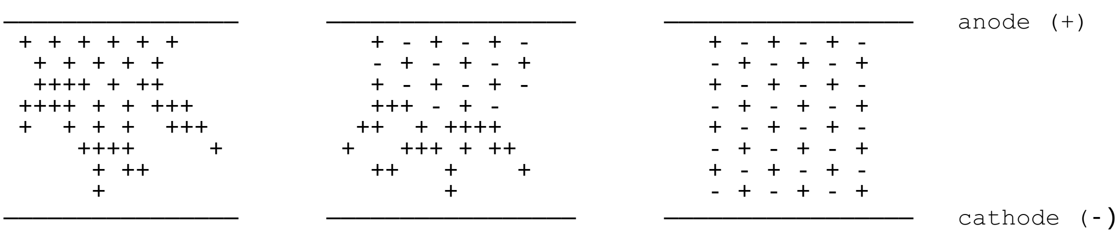

Figure 1.8 - Streamer breakdown

Due to the enhanced field between the head and the anode, the space charge increases, causing a further enhancement of the field around the anode. The process is very fast and the positive space charge extends to the cathode very rapidly resulting in the formation of a streamer. Figure 1.8 shows the breakdown process.

1.2.4 Factors affecting the breakdown voltage a Vacuum gap

Vacuum is ideally the best insulator, with breakdown strengths of the order of 10^4 kV/c. The breakdown voltage of a high vacuum is the voltage which when increased by a small amount will cause the breakdown of the gap that was held at that voltage for an infinite time. However, this definition is not always practicable as the breakdown is affected by many factors.

(i) Electrode Separation

For vacuum gaps less than about 1 mm, the breakdown voltage is approximately proportional to the length, all other parameters remaining constant. This gives a constant breakdown strength. For these small gaps, the breakdown stress is relatively high, being of the order of 1 MV/cm. Field emission of electrons probably plays an important part in the breakdown process.

$$V = k \cdot d \qquad \text{for } d < 1 \text{ mm}$$

For gaps greater than about 1 mm, the breakdown voltage does not increase at an equal rate and the apparent breakdown stress for longer gaps is much reduced, being about 10 kV/cm at a spacing of 10 cm. [Apparent stress is defined as the voltage required to cause breakdown divided by the distance between the electrodes]. Figure 1.9.

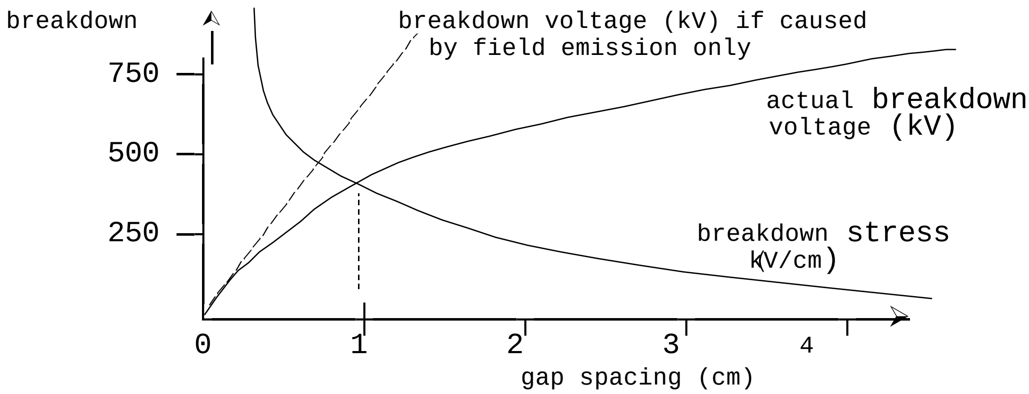

Figure 1.9 - Breakdown characteristic

Cranberg has shown theoretically that for longer gaps, it is the product of breakdown voltage and breakdown stress that remains constant.

$$V \cdot E = k_1 \qquad \text{for } d > 1 \text{ mm.}$$

where the constant k_1 depends on the material and surface conditions of the electrodes.

For an **Uniform field gap**, $E = V/d$, so that

$$V = k_2\, d^{1/2}$$

Or in a more general form, both regions can be expressed by the equation

$$V = k\, d^x \qquad \text{where } x = 0.5 \text{ for long gaps} > 1 \text{ mm}$$
$$= 1 \quad \text{for gaps} < 1\text{mm}$$

(ii) Electrode Effects

Conditioning

The breakdown voltage of a gap increases on successive flashovers, until a constant value is reached. The electrodes are then said to be conditioned. This increase in voltage is ascribed to the burning off by sparking of microscopic irregularities or impurities which may exist on the electrodes. When investigating the effect of various factors on breakdown, the electrodes must first be conditioned in such a way that reproducible results are obtained.

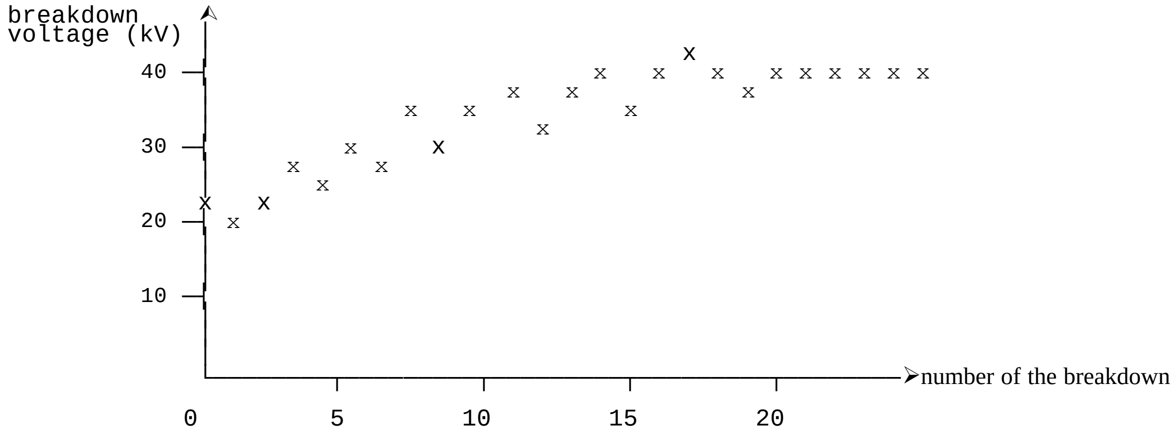

Figure 1.10 - Breakdown characteristics

The effect of conditioning is shown in figure 1.10. The breakdown voltage of conditioned electrodes or gaps is very much reproducible than otherwise, and hence breakdown values that are normally obtained experimentally are those of conditioned electrodes. Unconditioned electrodes may have breakdown values a low as 50% of the breakdown voltage with conditioned electrodes.

(iii) Material and Surface Finish

Electrode Material	Voltage across 1 mm gap (kV)
Steel	122
Stainless Steel	120
Nickel	96
Monel metal	60
Aluminium	41
Copper	37

Table 1.2 - Effect of electrode material on breakdown

The electrode surfaces form the physical boundaries between which the breakdown finally takes place. Thus it is not surprising to find that the breakdown strength of a given size of gap is strongly dependant on the material of the electrodes. In general, the smoother the surface finish, the greater the breakdown voltage.

(iv) Surface contamination

Presence of contamination in the test cell reduces the breakdown voltage sometimes by as much as 50% of the clean electrode value.

(v) Area and configuration of electrodes

Increasing the area of the electrodes makes it more difficult to maintain a given breakdown voltage. Thus breakdown voltage decreases slightly with increase in surface area. For example, electrodes of 20 cm^2 area gives the breakdown voltage across a 1 mm gap of 40 kV, whereas electrodes of the same material of area 1000 cm^2 gives a breakdown voltage across the same 1 mm gap as 25 kV.

Up to 1 mm gap, the more convex electrodes have higher breakdown voltage than the more nearly plane electrodes even though at the same voltage they carried a higher electric field at the surface.

(vi) Temperature

The variation of the breakdown voltage with temperature is very small, and for nickel and iron electrodes, the strength remains unchanged for temperatures as high as 500^0C. Cooling the electrodes to liquid Nitrogen temperature increases the breakdown voltage.

(vii) Frequency of applied voltage

It is known that a given gap stands a higher impulse voltage than an alternating voltage, and a higher alternating voltage than a direct voltage. However, it has been shown that for a small gap (2 mm) there is no dependence of the breakdown voltage on the frequency in the range 50 Hz to 50 kHz.

(viii) Vacuum Pressure

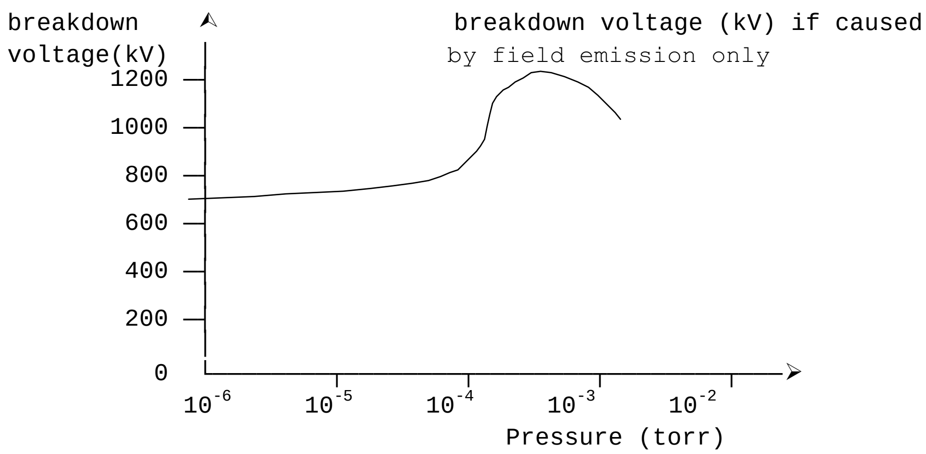

Figure 1.11 - Breakdown characteristic

For small gaps, increasing the degree of vacuum increases the breakdown voltage until below a certain pressure there is no change. The vacuum breakdown region is the region in which the breakdown voltage becomes independent of the nature of the pressure of the gap between the electrodes.

However, for large gaps (about 200 mm spacing) it is found that below a certain pressure the breakdown voltage starts decreasing again, so that the breakdown stress at this stage could in fact be improved by actually worsening the vacuum.

For example, using a 1.6 mm diameter sphere opposite a plane cathode and a gap of 200 mm, the characteristics shown in figure 1.11 was obtained. The breakdown voltage was constant for pressure less than 5×10^{-4} torr, but rose with increasing pressure to a maximum at 5×10^{-4} torr, with further increase in pressure the voltage fell sharply.

1.2.5 Time lags of Spark breakdown

In practice, particularly in high voltage engineering, breakdown under impulse fields is of great importance. On the application of a voltage, a certain time elapses before actual breakdown occurs even though the applied voltage may be much more than sufficient to cause breakdown.

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.

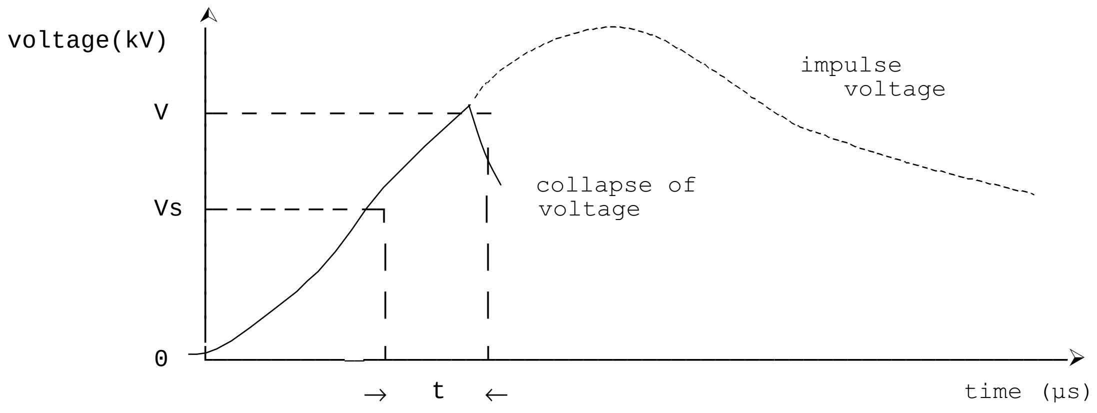

Figure 1.12 - Time lag of impulse breakdown

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 μs), 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. Figure 1.12 shows the time lag for an impulse voltage waveform.

The time t_s 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 t_f 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.

The breakdown can also occur after the peak of the voltage pulse, (i.e. on the wavetail). Depending on the time lag, the breakdown may occur in the wavefront or the wavetail of the impulse waveform.

(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 β = 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
$$t_s = \frac{1}{\beta P_1 P_2}$$

If the level of irradiation is increased, β increases and therefore t_s decreases. Also, with clean cathodes of higher work function β 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.

If the gap is overvolted, then the probability of producing a current sufficient to cause breakdown rapidly increases. P_2 therefore increases with overvoltage and may tend to unity when the overvoltage is about 10%. As $P_2 \rightarrow 1$ with increasing overvoltage, $t_s \rightarrow 1/\beta P_1$.

(ii) Formative time lag

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 tf.

(iii) Time lag characteristic

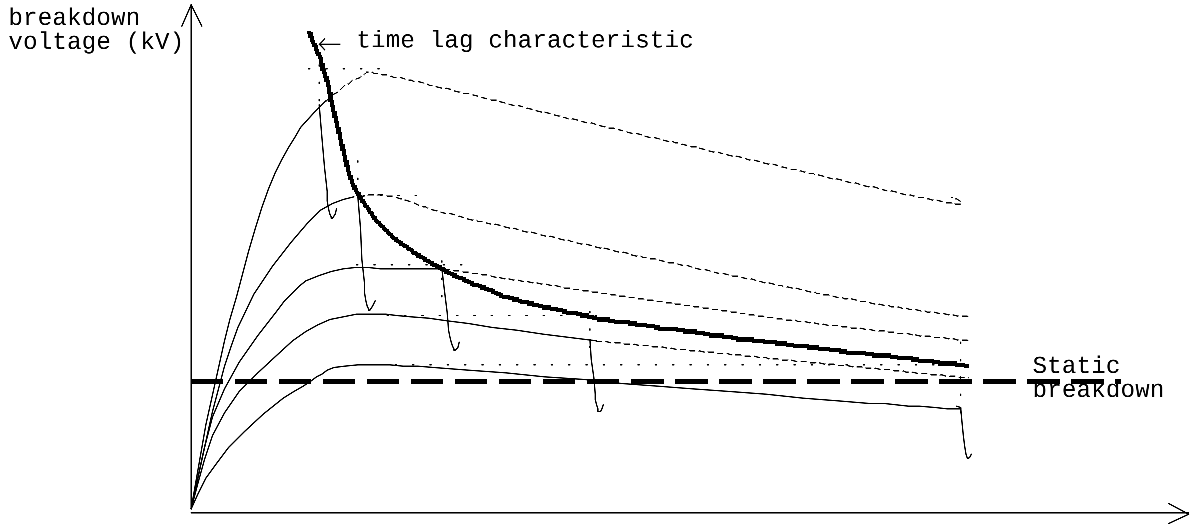

Figure 1.13 - Time-lag characteristics

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 figure 1.13.

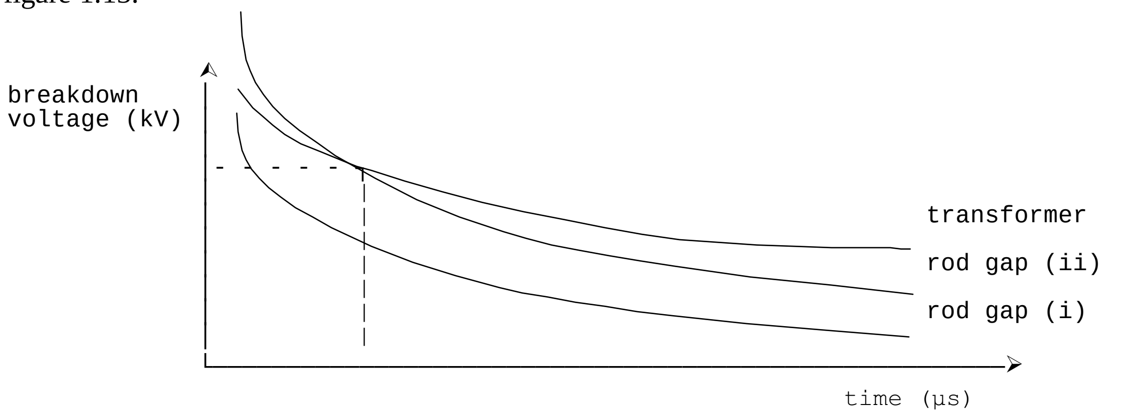

Figure 1.14 - Typical Time lag characteristics

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 1.14.

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.]

1.2.6 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.

1.2.6.1 Mechanism of Corona formation on a 2 conductor line

When a gradually increasing voltage is applied across two conductors, initially nothing will be seen or heard. As the voltage is increased, the air surrounding the conductors get ionised, and at a certain voltage a hissing noise is heard caused by the formation of corona. This voltage is known as the disruptive critical voltage (**dcv**). A further increase in the voltage would cause a visible violet glow around the conductors. This voltage is the visual corona inception voltage.

If the applied voltage is direct, the glow observed will be uniform on the positive conductor, while the negative conductor will be more patchy and often accompanied by streamers at rough points. In the case of alternating voltages, both conductors appear to have a uniform glow, but when observed stroboscopically the effect is seen to be similar to the direct voltage case.

If the voltage is further increased, the corona increases and finally spark over would occur between the two conductors. If the conductors are placed quite close together, corona formation may not occur before the spark over occurs. The condition for this will be considered later.

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 ionisation.

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 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.

1.2.6.2 Waveform of Corona Current

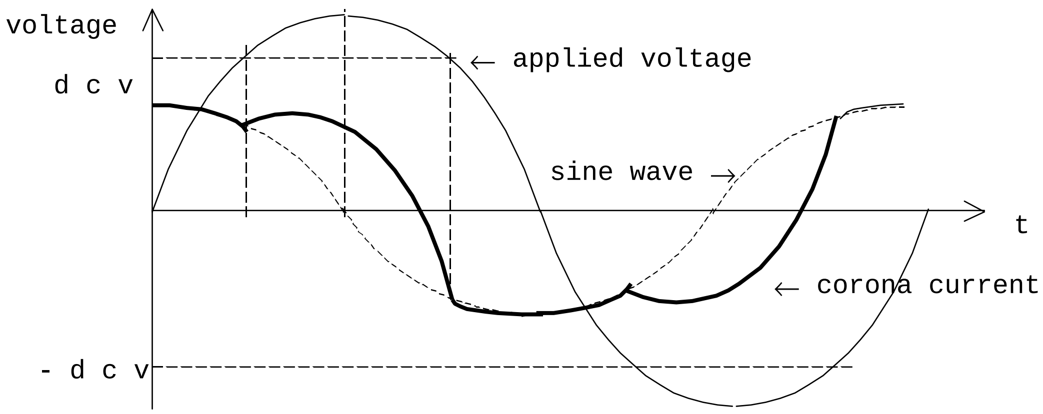

Figure 1.15 Waveform of corona current

The shunt current in a line is almost purely capacitive under normal conditions, and leads the applied voltage by 90^0, and there is no power loss in the line under no-load conditions. When the applied voltage is increased and corona is formed, the air is rendered conducting, and power loss occurs. The shunt current would no longer be leading the voltage by 90^0. Thus the current waveform would consist of two components. The lossy component would be non-sinusoidal and would occur only when the disruptive critical voltage is exceeded in either polarity. This resultant waveform is shown in figure 1.15. The corona current can be analysed and shown to possess a strong third harmonic component.

1.2.6.3 Mechanism of corona formation

The stress surrounding the conductor is a maximum at the conductor surface itself, and decreases rapidly as the distance from the conductor increases. Thus when the stress has been raised to critical value immediately surrounding the conductor, ionisation would commence only in this region and the air in this region would become conducting. The effect is to increase the effective conductor diameter while the voltage remains constant. This results in two effects. Firstly, an increase in the effective sharpness of the conductor would reduce the stress outside this region, and secondly, this would cause a reduction of the effective spacing between the conductors leading to an increase in stress. Depending on which effect is stronger, the stress at increasing distance can either increase or decrease. If the stress is made to increase, further ionisation would occur and flashover is inevitable.

Under ordinary conditions, the breakdown strength of air can be taken as 30 kV/cm. Corona will of course be affected by the physical state of the atmosphere. In stormy weather, the number of ions present is generally much more than normal, and corona will then be formed at a much lower voltage than in fair weather. This reduced voltage is generally about 80% of the fair weather voltage.

The condition for stable corona can be analysed as follows.

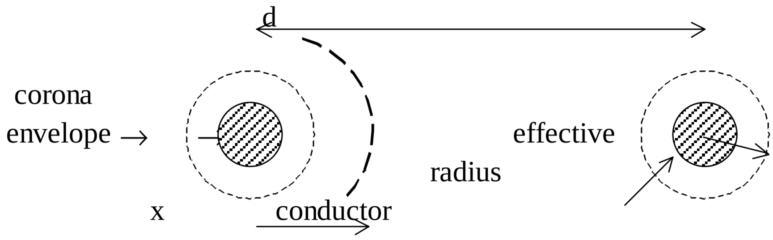

Figure 1.16 - Electric Stress in two conductor system

The electric stress ξ at a distance x from a conductor of radius x, and separated from the return conductor by a distance d is given by

$$\xi = \frac{1}{\varepsilon_0} \cdot \frac{q}{2\pi\, x\, l}$$

where q is the charge on each conductor in length *l*.

Thus the potential V can be determined from $V = \int \xi \, dx$

$$V = \int_{r}^{d-r} \frac{q}{2\pi\, x\, \varepsilon_0} . dx$$

Since both charges (+q and -q) produce equal potential differences, the total potential difference between the two conductors is double this value. Thus the conductor to neutral voltage, which is half the difference would be equal to this value. Thus the conductor to neutral voltage is

$$V = \frac{q}{2\pi\, \varepsilon_0} . \log_e \left(\frac{d-r}{r} \right)$$

Therefore the electric stress at distance x is given by

$$\xi_x = \frac{V}{x \log_e \frac{d-r}{r}}$$

$$\xi_x = \frac{V}{x \log_e \frac{d}{r}} \quad \text{if } d \ll r$$

[Note; ξ_x and V can both be peak values or both rms values]

For three phase lines, with equilateral spacing, it can be shown that the stress is still given by the same expression when V is the voltage to neutral and d is the equilateral spacing.

For air, ξ_{max} = 30 kV/cm, so that ξ_{rms} = 30/√2 = 21.2 kV/cm.

Since there is no electric stress within the conductor, the maximum stress will occur when x is a minimum, that is at x = r.

Thus if $E_{0,rms}$ is the rms value of the disruptive critical voltage to neutral,

$$\xi_{rms} = 21.2 = \frac{E_{0,rms}}{r \log_e \frac{d}{r}}$$

When the surface of the conductor is irregular, it is more liable to corona. Thus an irregularity factor m_0 is introduced to account for this reduction. Typical values of this factor are

m_0 = 1.0 for smooth polished conductors,
= 0.98 to 0.93 for roughened conductors,
≈ 0.90 for cables of more than 7 strands, and
= 0.87 to 0.83 for 7 strand cables.

Since the corona formation is affected by the mean free path, and hence by the air density, a correction factor δ is introduced. This air density correction factor is given by the usual expression, with **p** being the pressure expressed in **torr** and **t** being the temperature expressed in ^{0}C.

$$\delta = \frac{p}{760} \cdot \frac{273 + 20}{273 + t} = \frac{0.386\ p}{273 + t}$$

The disruptive critical voltage can then be written as in the following equation.

$$E_{0,rms} = 21.2\ \delta\ m_0\ r \log_e (d/r) \qquad \text{kV to neutral}$$

1.2.6.4 Visual Corona

Visual corona occurs at a higher voltage than the disruptive critical voltage. For the formation of visual corona, a certain amount of ionization, and the raising of an electron to an excited state are necessary. The production of light by discharge is not due to ionisation, but due to excitation, and subsequent giving out of excess energy in the form of light and other electromagnetic waves. To obtain the critical voltage for visual corona formation, the disruptive critical voltage has to be multiplied by a factor dependant on the air density and the conductor radius. Further the value of the irregularity factor is found to be different.

The empirical formula for the formation of visual corona is

$$E_{v,rms} = 21.2\ m_v\ \delta\ r \left[1 + \frac{0.3}{\sqrt{\delta\ r}}\right] . \log_e \frac{d}{r}$$

The values of the irregularity factor m_v for visual corona is given by

m_v = 1.0 for smooth conductors,
= 0.72 for local corona on stranded wires (patches)
= 0.82 for decided corona on stranded wires (all over the wire)

1.2.6.5 Stable Corona formation

Consider two conductors, just on the limit of corona formation. Assume that there is a thin layer Δr of ionised air around each conductor, so that the effective radius becomes $(r + \Delta r)$. The change in electric stress $\Delta\xi$ due to this layer can be determined using differentiation.
Thus

$$\Delta\xi = \Delta\left(\frac{E}{r\log_e\frac{d}{r}}\right)$$

$$\Delta\xi = \left[\frac{-E}{(r\log_e\frac{d}{r})^2}.\left(\log_e\frac{d}{r} + r.\frac{r}{d}.\frac{-d}{r^2}\right)\right].\Delta r$$

$$\Delta\xi = \frac{E(1-\log_e\frac{d}{r}).\Delta r}{(r\log_e\frac{d}{r})^2}$$

When $\log_e > 1$, the above expression is negative. i.e. $d/r > e$ (=2.718)

Under this condition, the effective increase in diameter lowers the electric stress and no further stress increase is formed, and corona is stable. If on the other hand, $d/r < e$, then the effective increase in the diameter raises the electric stress, and this causes a further ionisation and a further increase in radius, and finally leads to flash-over.

In practice, the effective limiting value of d/r is about 15 and not **e** (=2.718). For normal transmission lines, the ratio d/r is very much greater than 15 and hence stable corona always occurs before flashover.

For example, in a 132 kV line with a spacing of 4 m and a radius of conductor of 16 mm, the ratio has a value $d/r = 4/16\text{x}10^{-3} = 250 >> 15$.

1.2.6.6 Power Loss due to Corona

The formation of corona is associated with a loss of power. This loss will have a small effect on the efficiency of the line, but will not be of sufficient importance to have any appreciable effect on the voltage regulation. The more important effect is the radio interference.

The power loss due to corona is proportional to the square of the difference between the line-to-neutral voltage of the line and the disruptive critical voltage of the line. It is given by the empirical formula

$$P_c = \frac{243}{\delta}.(f+25).\sqrt{\frac{r}{d}}.(E - E_{0,rms})^2.10^{-5} \text{ kW/km/phase}$$

where $E_{0,rms}$ = disruptive critical voltage (kV)
f = frequency of supply (Hz)
E = Phase Voltage (line to neutral) (kV)

For storm weather conditions, the disruptive critical voltage is to be taken as 80% of disruptive critical voltage under fair weather conditions.

Example

Determine the Disruptive Critical Voltage,the Visual Corona inception voltage, and the power loss in the line due to corona, both under fair weather conditions as well as stormy weather conditions for a 100 km long 3 phase, 132 kV line consisting of conductors of diameter 1.04 cm, arranged in an equilateral triangle configuration with 3 m spacing. The temperature of the surroundings is 40^0 C and the pressure is 750 torr. The operating frequency is 50 Hz. [The irregularity factors may be taken as m_o = 0.85, m_v = 0.72]

The Air density correction factor δ is given by

$$\delta = \frac{p}{760} \cdot \frac{273+20}{273+t} = \frac{0.386\ p}{273+t}$$

$$\delta = \frac{750}{760} \cdot \frac{293}{313} = 0.925$$

∴ Disruptive critical voltage = 21.2 δ m_0 r $\log_e$ (d/r) kV to neutral
= 21.2 x 0.925 x 0.85 x 0.52 x $\log_e$ (3/0.0052)
= 55.1 kV

Similarly,
Visual corona voltage = 21.2 x 0.925 x 0.72 x 0.52 x $\log_e$ (3/0.0052) x [1 + 0.3/(0.895 x 0.52)^{½}]
= 67.2 kV

Power loss under fair weather condition is given by

$$P_c = \frac{243}{0.925} . (50+25) . \sqrt{\frac{0.0052}{3}} . \left(\frac{132}{\sqrt{3}} - 55.1\right)^2 . 10^{-5} . 100 \quad \text{kW/phase}$$

$$= 365 \text{ kW/phase}$$

Similarly, power loss under stormy weather condition is given by

$$P_c = \frac{243}{0.925} . (50+25) . \sqrt{\frac{0.0052}{3}} . \left(\frac{132}{\sqrt{3}} - 55.1 * 0.8\right)^2 . 10^{-5} . 100 \quad \text{kW/phase}$$

$$= 847 \text{ kW/phase}$$