A Course Material

On

High Voltage Engineering

UNIT 1

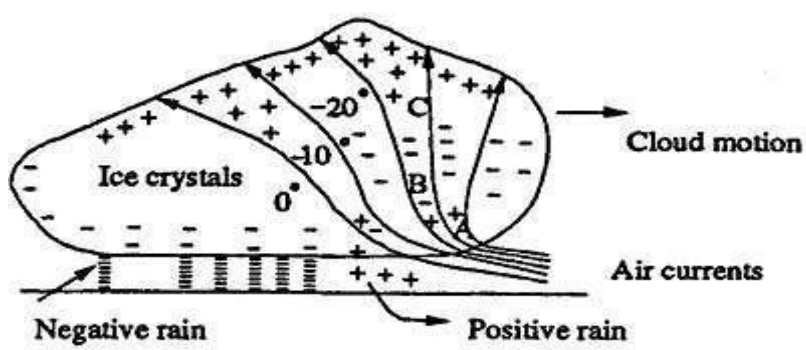
OVER VOLTAGES IN ELECTRICAL POWER SYSTEM

Show the charge distribution pattern in the cloud following Wilson and Simpson theory.

Simpson's Theory:

According to the Simpson's theory there are three essential regions in the cloud to be considered for charge formation.

- ✓ Below region A, air currents travel Ground Cloud motion Field gradient at ground above 800 cm/s, and no raindrops fall through.
- ✓ In region A, air velocity is high enough to break the falling rain drops causing a positive charge spray in the cloud and negative charge in the air
- ✓ As the spray is blown upwards, but as the velocity of air decreases, the positively charged water drops recombine with the larger drops and fall again Thus region A, becomes positively charged,
- ✓ In region B above it, becomes negatively charged by air currents.
- ✓ In the region C the temperature is low (below freezing point) and only ice crystals exist so the impact of air on these crystals makes them negatively charged, thus the distribution of the charge within the cloud becomes as shown in Fig.



Cloud Model According To Simpson's Theory

Reynolds and Mason Theory:

- ✓ Reynolds and Mason proposed modification, according to which the thunder clouds are developed at heights 1 to 2 km above the ground level and may extend up to 12 to 14 km above the ground.
- ✓ For thunder clouds and charge formation air currents, moisture and specific temperature range are required and the air currents controlled by the temperature gradient move upwards carrying moisture and water droplets.

- ✓ The temperature is 0^0C and water droplets do not freeze at about 4 km from the ground and may reach - 50^0C and they freeze below - 40^0 C only as solid particles on which crystalline ice patterns develop and grow at about 12 km height.
- ✓ Thus in clouds, the effective freezing temperature range is around – 30 C to - $4O^0$C.
- ✓ When such freezing occurs, the crystals grow into large masses and due to their weight and gravitational force start moving downwards. Thus, a thunder cloud consists of super cooled water droplets moving upwards and large hail stones moving downwards.
- ✓ When the process of cooling extends to inside warmer water in the core ,it expands, thereby splintering and spraying the frozen ice shell. The splinters being fine in size are moved up by the air currents and carry a net positive charge to the upper region of the cloud.
- ✓ The hail stones that travel onwards carry an equivalent Negative rain Positive rain Air currents Cloud motion Ice crystals negative charge to the lower regions of the cloud and thus negative charge builds up in the bottom side of the cloud.
- ✓ According to Mason, the ice splinters should carry only positive charge upwards. Therefore, the lower portion which is warmer will have a net negative charge density, and hence the upper portion, i.e. cooler region will have a net positive charge density.
- ✓ According to the Reynold's theory, which is based on experimental results, the hail packets get negatively charged when impinged upon by warmer ice crystals.
- ✓ When the temperature conditions are reversed, the charging polarity reverses. However, the extent of the charging and consequently the rate of charge generation were found to disagree with the practical observations relating to thunder clouds. This type of phenomenon also occurs in thunder clouds.

Explain the mechanism of Lightning with neat diagrams.

Mechanism of Lightning Stroke

- ✓ Lightning phenomenon is the discharge of the cloud to the ground. The cloud and the ground form two plates of a gigantic capacitor and the dielectric medium is air. Since the lower part of the cloud is negatively charged, the earth is positively charged by induction.
- ✓ Lightning discharge will require the puncture of the air between the cloud and the earth. For breakdown of air at steady condition the electric field required is 30 kV/cm peak. But in a cloud where the moisture content in the air is large and also because of the high altitude (lower pressure) it is seen that for breakdown of air the electric field required is

only 10 kV/cm. After a gradient of approximately 10 kV/cm is set up in the cloud, the air surrounding gets ionized.

- ✓ At this a streamer starts from the cloud towards the earth which cannot be detected with the naked eye; only a spot travelling is detected. The current in the streamer is of the order of 100 amperes and the speed of the streamer is 0.16 m/μ sec. This streamer is known as pilot streamer because this leads to the lightning phenomenon.
- ✓ Depending upon the state of ionization of the air surrounding the streamer, it is branched to several paths and this is known as stepped leader . The leader steps are of the order of 50 m in length and are accomplished in about a microsecond.
- ✓ The charge is brought from the cloud through the already ionized path to these pauses. The air surrounding these pauses is again ionized and the leader in this way reaches the earth .Once the stepped leader has made contact with the earth it is believed that a power return stroke moves very fast up towards the cloud through the already ionized path by the leader.
- ✓ This streamer is very intense where the current varies between 1000 amps and 200,000 amps and the speed is about 10% that of light and the –ve charge of the cloud is being neutralized by the positive induced charge on the earth. It is this instant which gives rise to lightning flash which we observe with our naked eye.
- ✓ There may be another cell of charges in the cloud near the neutralized charged cell. This charged cell will try to neutralize through this ionised path. This streamer is known as dart leader . The velocity of the dart leader is about 3% of the velocity of light.
- ✓ The effect of the dart leader is much more severe than that of the return stroke. The discharge current in the return streamer is relatively very large but as it lasts only for a few microseconds the energy contained in the streamer is small and hence this streamer is known as cold lightning stroke.
- ✓ Dart leader is known as hot lightning stroke because even though the current in this leader is relatively smaller but it lasts for some milliseconds and therefore the energy contained in this leader is relatively larger.
- ✓ It is found that each thunder cloud may contain as many as 40 charged cells and a heavy lightning stroke may occur. This is known as multiple stroke.

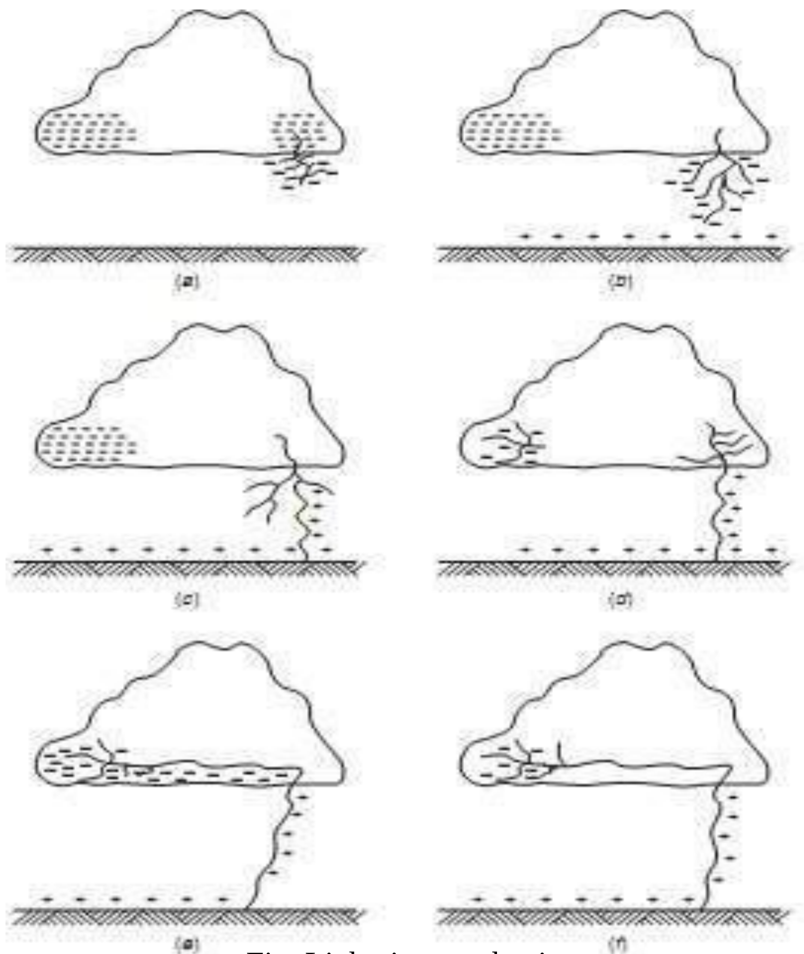


Fig. Lightning mechanism

Explain the mathematical model for lightning.

- ✓ During the charge formation process, the cloud may be considered to be a non-conductor. Hence, various potentials may be assumed at different parts of the cloud.
- ✓ If the charging process is continued, it is probable that the gradient at certain parts of the charged region exceeds the breakdown strength of the air or moist air in the cloud. Hence, local breakdown takes place within the cloud.
- ✓ This local discharge may finally lead to a situation where in a large reservoir of charges involving a considerable mass of cloud hangs over the ground, with the air between the cloud and the ground as a dielectric.

- ✓ When a streamer discharge occurs to ground by first a leader stroke, followed by main strokes with considerable currents flowing, the lightning stroke maybe thought to be a current source of value Z/Q with source impedance Z_0 discharging to earth. If the stroke strikes an object of impedance Z, the voltage built across it may be taken as

$$V = IZ$$
$$= I_0 \frac{ZZ_0}{Z + Z_0}$$
$$= I_0 \frac{Z}{1 + \frac{Z}{Z_0}}$$

- ✓ The source impedance of the lightning channels are not known exactly, but it is estimated to be about 1000 to 3000 Ω. Therefore, the value Z/Z_0 will usually be less than 0.1 and hence can be neglected. Hence, the voltage rise of lines, etc. may be taken to be approximately V $/I_0Z$, where I_0 is the lightning stroke current and Z the line surge impedance
- ✓ If a lightning stroke current as low as 10,000 A strikes a line of 400Ω surge impedance, it may cause an overvoltage of 4000 kV. This is a heavy overvoltage and causes immediate flashover of the line conductor through its insulator strings.
- ✓ In case a direct stroke occurs over the top of an unshielded transmission line, the current wave tries to divide into two branches and travel on either side of the line.

Explain the sources and characteristics of switching surges

OVERVOLTAGE DUE TO SWITCHING SURGES,

Origin of Switching Surges

- ✓ The making and breaking of electric circuits with switchgear may result in abnormal over voltages in power systems having large inductances and capacitances. The over voltages may go as high as six times the normal power frequency voltage.
- ✓ In circuit breaking operation, switching surges with a high rate of rise of voltage may cause repeated restriking of the arc between the contacts of a circuit breaker, there by using destruction of the circuit breaker contacts.

- ✓ The switching surges may include high natural frequencies of the system, a damped normal frequency voltage component, or the restriking and recovery voltage of the system with successive reflected waves from terminations.

Characteristics of Switching Surges

The wave shapes of switching surges are quite different and may have origin from any of the following sources.

(i) De-energizing of transmission lines, cables, shunt capacitor, banks, etc.

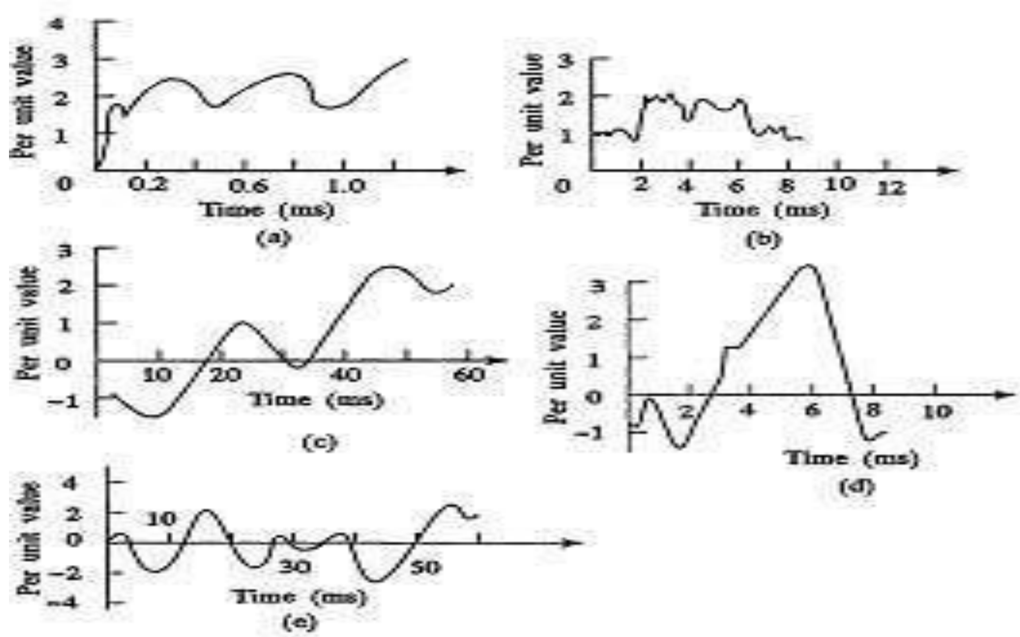
(ii) Disconnection of unloaded transformers, reactors, etc.

(iii) Energization or reclosing of lines and reactive loads,

(iv) Sudden switching off of loads.

(v) Short circuits and fault clearances.

(vi) Resonance phenomenon like ferro-resonance, arcing grounds, etc. From the figures of the switching surges it is clear that the over voltages are irregular (oscillatory or unipolar) and can be of high frequency or power frequency with its harmonics. The relative magnitudes of the over voltages may be about 2.4 p.u.in the case of transformer energizing and 1.4 to 2.0 p.u. in switching transmission lines.



(a) Recovery voltage after fault clearing
(b) Fault initiation
(c) Overvoltage at the line end after fault clearing
(d) Energization of long transmission line
(e) Overvoltage at line end during (d)

Switching over voltages in EHV and UHV Systems

- ✓ The insulation has the lowest strength for switching surges with regard to long airgaps. Further, switching over voltages is relatively higher magnitudes as compared to the lightning over voltages for UHV systems.
- ✓ Over voltages are generated in EHV systems when there is a sudden release of internal energy stored either in the electrostatic form (in the capacitance) or in the electromagnetic form (in the inductance). The different situations under which this happens are summarized as

(i) Interruption of low inductive currents (current chopping) by high speed circuit breakers. This occurs when the transformers or reactors are switched off

(ii) Interruption of small capacitive currents, such as switching off of unloaded lines etc.

(iii) ferro-resonance condition This may occur when poles of a circuit breaker do not close simultaneously

(iv) energization of long EHV or UHV lines.

Transient over voltages in the above cases can be of the order of 2.0 to 3.3 p.u. and will have magnitudes of the order of 1200 kV to 2000 kV on 750 kV systems. The duration of these over voltages varies from 1 to 10 ms depending on the circuit parameters. It is seen that these are of comparable magnitude or are even higher than those that occur due to lightning. Sometimes the over voltages may last for several cycles.

The other situations of switching that give rise to switching over voltages of shorter duration (0.5 to 5 ms) and lower magnitudes (2.0 to 2.5 p.u.) are:

(a) single pole closing 6f circuit breaker
(b) interruption of fault current when the L-G or L-L fault is cleared
(c) resistance switching used in circuit breakers
(d) switching lines terminated by transformers
(e) series capacitor compensated lines
(f) Sparking of the surge diverter located at the receiving end of the line to limit the lightning Over voltages

The over voltages due to the above conditions are studied or calculated from:

(a) mathematical modeling of a system using digital computers
(b) scale modeling using transient network analyzers
(c) By conducting field tests to determine the expected maximum amplitude of the over voltages and their duration at different points on the line.

The main factors that are investigated in the above studies are:

(i) the effect of line parameters, series capacitors and shunt reactors on the magnitude and duration of the transients
(ii) the damping factors needed to reduce the magnitude of over voltages
(iii) the effect of single pole closing, restriking and switching with series resistors or circuit breakers on the over voltages, and
(iv) The lightning arrester spark over characteristics.

It is necessary in EHV and UHV systems to control the switching surges to a safe value of less than 2.5 p.u. or preferably to 2.0 p.u. or even less. The measures taken to control or reduce the over voltages are

(i) one step or multi-step energisation of lines by pre insertion of resistors,
(ii) phase controlled closing of circuit breakers with proper sensors,
(iii) drainage of trapped charges on long lines before the reclosing of the lines, and
(iii) limiting the over voltages by using surge diverters.

What are causes of power frequency over voltages in power system? Explain them in detail.

The power frequency over voltages occur in large power systems and they are of much concern in EHV systems, i.e. systems of 400 kV and above. The main causes for power frequency and its harmonic over voltages are

(a) sudden loss of loads,
(b) disconnection of inductive loads or connection of capacitive loads,
(c) Ferranti effect, unsymmetrical faults, and
(d) saturation in transformers, etc.

- ✓ Over voltages of power frequency harmonics and voltages with frequencies nearer to the operating frequency are caused during tap changing operations, by magnetic or ferro-resonance phenomenon in large power transformers and by resonating over voltages due to series capacitors with shunts reactors or transformers.
- ✓ The duration of these over voltages may be from one to two cycles to a few seconds depending on the overvoltage protection employed in the system.

$$I_C = j\omega C V_1 = \frac{V_1}{X_C}$$

and the voltage $V_2 = V_1\left[1 - \frac{X_L}{2X_C}\right]$

where, X_L = line inductive reactance, and
X_C = line capacitive reactance.

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a) Sudden Load Rejection

Sudden load rejection on large power systems causes the speeding up of generator prime movers. The speed governors and automatic voltage regulators will intervene to restore normal conditions. But initially both the frequency and voltage increase. The approximate voltage rise, neglecting losses, etc. may be taken as

$$v = \frac{f}{f_0} E' \left[\left(1 - \frac{f}{f_0}\right)\frac{x_s}{x_c}\right]$$

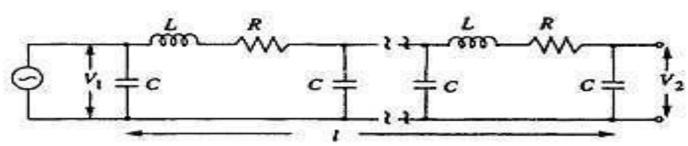
where Xs is the reactance of the generator (« the sum of the transient reactance of the generator and the transformer), Xc is the capacitive reactance of the line at open end at increased frequency, if the voltage generated before the over-speeding and load rejection, is the instantaneous increased frequency, and/o is the normal frequency.

(b) Ferranti Effect

Long uncompensated transmission lines exhibit voltage rise at the receiving end. The voltage rise at the receiving end V2 is approximately given by considering that the line capacitance is concentrated at the middle of the line, under open circuit conditions at the receiving end, the line charging current

$$V_2 = \frac{V_1}{\cos \beta l}$$

where, V_1 = sending end voltage,
l = length of the line,
β = phase constant of the line
$\approx \left[\frac{(R + j\,\omega L)(G + j\,\omega C)}{LC}\right]^{1/2}$
$\approx$ about 6° per 100 km line at 50 Hz frequency.
R, L, G, and C are as defined in Sec. 8.1.5, and
ω = angular frequency for a line shown in Fig. 8.17.



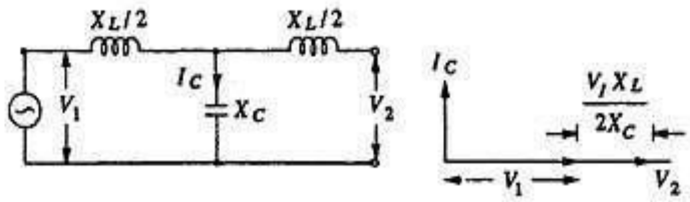
L, R and C — Inductance, resistance and capacitance per unit length of the line
l — Length of the line

(c) Ground Faults and Their Effects

Single line to ground faults cause rise in voltages in other healthy phases. Usually, with solidly grounded systems, the increases in voltage (phase to ground value) will be less than the line-to-line voltage.

$$\frac{X_0}{X_1} \leq 3.0 \text{ and } \frac{R_0}{X_1} \leq 1.0$$

With effectively grounded systems, i.e. with (where, RQ and XQ are zero sequence resistance and reactance and X] is the positive sequence reactance of the system), the rise in voltage of the healthy phases does not usually exceed 1.4 per unit.



(e) Saturation Effects

- ✓ When voltages above the rated value are applied to transformers, their magnetizing currents (no load currents also) increase rapidly and may be about the full rated current for 50% overvoltage. These magnetizing currents are not sinusoidal in nature but are of a peaky waveform.
- ✓ The third, fifth, and seventh harmonic contents may be 65%, 35%, and 25% of the exciting current of the fundamental frequency corresponding to an overvoltage of 1.2 p.u. For third and its multiple harmonics, zero sequence impedance values are effective, and delta connected windings suppress them.
- ✓ But the shunt connected capacitors and line capacitances can form resonant circuits and cause high third harmonic over voltages. When such over voltages are added, the voltage rise in the lines may be significant.
- ✓ For higher harmonics a series resonance between the transformer inductance and the line capacitance can occur which may produce even higher voltages.

Explain the control methods of over voltages due to switching.

Control of over voltages Due to Switching

The over voltages due to switching and power frequency may be controlled by

(a).Energization of transmission lines in one or more steps by inserting resistances and withdrawing them afterwards,

(b).Phase controlled closing of circuit breakers,

(c).Drainage of trapped charges before reclosing,

(d).Use of shunt reactors, and

(e) .Limiting switching surges by suitable surge diverters.

(a) Insertion of Resistors

- ✓ It is normal and a common practice to insert resistances in series with circuit breaker contacts when switching on but short circuiting them after a few cycles. This will reduce the transients occurring due to switching. The voltage step applied is first reduced to $Z_0/(R + Z_0)$ per unit where ZQ is the surge impedance of the line. It is reflected from the far end unchanged and again reflected back from the near end with reflection factor $(R – Z_0)/(R + Z_0)$ per unit
- ✓ If $R = Z_0$, there is no reflection from the far end. The applied step at the first instance is only 0.5 per unit.When the resistor is short circuited, a voltage step equal to the instantaneous voltage drop enters the line. If the resistor is kept for a duration larger than 5ms (for50 Hz sine wave = 1/4 cycle duration), it can be shown from successive reflections and transmissions, that the overvoltage may reach as high as 1.2 p.u. for a line length of 500 km.
- ✓ But for conventional opening of the breaker, the resistors have too high an ohmic value to be effective for resistance closing. Therefore, pre-insertion of suitable value resistors in practice is done to limit the overvoltage to less than 2.0 to 2.5 p.u. Normal time of insertion is 6 to 10 m s.

(b) Phase Controlled Switching

Over voltages can be avoided by controlling the exact instances of the closing of the three phases separately. But this necessitates the use of complicated controlling equipment and therefore is not adopted.

(c) Drainage of Trapped Charge

- ✓ When lines are suddenly switching off, "electric charge" may be left on capacitors and line conductors. This charge will normally leak through the leakage path of the insulators, etc. Conventional potential transformers (magnetic) may also help the drainage of the charge.
- ✓ An effective way to reduce the trapped charges during the lead time before reclosing is by temporary insertion of resistors to ground or in series with shunt reactors and removing before the closure of the switches.

(d) Shunt Reactors:

Normally all EHV lines will have shunt reactors to limit the voltage rise due to the Ferranti effect. They also help in reducing surges caused due to sudden energizing. However, shunt reactors cannot drain the trapped charge but will give rise to oscillations with the capacitance of the system. Since the compensation given by the reactors will be less than 100%, the frequency of oscillation will be less than the power frequency and over voltages produced may be as high as 1.2 p.u. Resistors in series with these reactors will suppress the oscillations and limit the over voltages.

2. What are the different methods employed for lightning protection of overhead lines?

Over voltages due to lightning strokes can be avoided or minimized in practice by

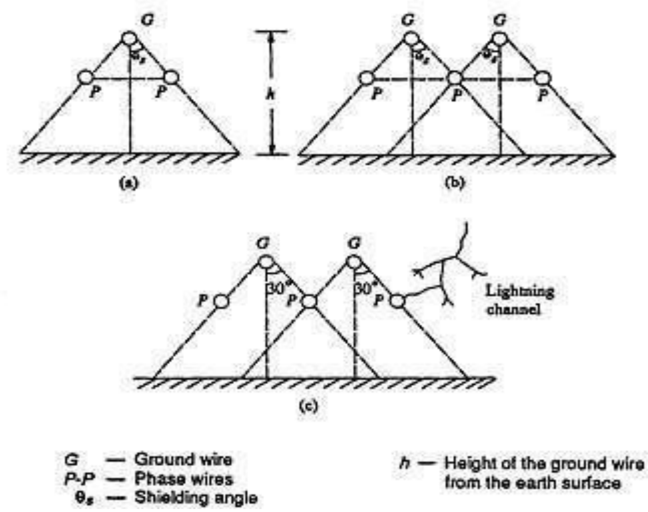
(a) shielding the overhead lines by using ground wires above the phase wires,
(b) using ground rods and counter-poise wires, and
(c) including protective devices like expulsion gaps, protector tubes on the lines, and surge diverters at the line terminations and substations.

(a) Lightning Protection Using Shielded Wires or Ground Wires

- ✓ Ground wire is a conductor run parallel to the main conductor of the transmission line supported on the same tower and earthed at every equally and regularly spaced towers. It is run above the main conductor of the line. The ground wire shields the transmission line conductor from induced charges, from clouds as well as from a lightning discharge.
- ✓ The mechanism by which the line is protected may be explained as follows. If a positively charged cloud is assumed to be above the line, it induces a negative charge on the portion below it, of the transmission line. With the ground wire present, both the ground wire and the line conductor get the induced charge.
- ✓ But the ground wire is earthed at regular intervals, and as such the induced charge is drained to the earth potential only; the potential difference between the ground wire and the cloud and that between the ground wire and the transmission line wire will be in the inverse ratio of their respective capacitances [assuming the cloud to be a perfect conductor and the atmospheric medium (air) a dielectric].

The shielding angle :

- ✓ As the ground wire is nearer to the line wire, the induced charge on it will be much less and hence the potential rise will be quite mall. The effective protection or shielding given by the ground wire depends on the height of the ground wire above the ground and the protection or shielding angle Ɵs (usually 30°)
- ✓ The shielding angle 65 « 30° was considered adequate for tower heights of 30 more or less. The shielding wires may be one or more depending on the type of the towers used. But for EHV lines, the tower heights may be up to 50 m, and the lightning strokes sometimes occur directly to the line wires as shown. The present trend in fixing the tower heights and shielding angles is by considering the "flash overrates" and failure probabilities.



(b) Protection Using Ground Rods and Counter-Poise Wires

When a line is shielded, the lightning strikes either the tower or the ground wire. The path for drainage of the charge and lightning current is (a) through the tower frame to ground, through the ground line in opposite directions from the point of striking. Thus the ground wire reduces the instantaneous potential to which the tower top rises considerably, as the current path is in three directions. The instantaneous potential to which tower top can rise is

$$V_T = \frac{I_0 Z_T}{\left(1 + \frac{Z_T}{Z_S}\right)}$$

where,

Z_T = surge impedance of the tower, and

Z_S = surge impedance of the ground wire.

If the surge impedance of the tower, which is the effective tower footing resistance, is reduced, the surge voltage developed is also reduced considerably. This is accomplished by providing driven ground rods and counter-poise wires connected to tower legs at the tower foundation. Lightning channel Ground rods are a number of rods about IS mm diameter and 2.5 to 3 m long driven into the ground. In hard soils the rods may be much longer and can be driven to a depthof, say, 50 m.

They are usually made of galvanized iron or copper bearing steel. The spacings of the rods, the number of rods, and the depth to which they are driven depend on the desired tower footing resistance. With 10 rods of 4 m long and spaced5 m apart, connected to the legs of the tower, the dynamic or effective resistance maybe reduced to 10 ft.

The above effect is alternatively achieved by using counter-poise wires. Counter-poise wires are wires buried in the ground at a depth of 0.5 to 1.0 m, running parallel to the transmission line conductors and connected to the tower legs these wires maybe 50 to 100 m long.

'These are found to be more effective than driven rods and the surge impedance of the tower may be reduced to as low as 25 £1. The depth does not materially affect the resistance of the counter-poise, and it is only necessary to bury it to a depth enough to prevent theft. It is desirable to use a larger number of parallel wires than a single wire. But it is difficult to lay counter-poise wires compared to ground or driven rods.

(c) Protective Devices

In regions where lightning strokes are intensive or heavy, the overhead lines within these zones are fitted with shunt protected devices. On the line itself two devices known as expulsion gaps and protector tubes are used. Line terminations, junctions of lines, and sub-stations are usually fitted with surge diverters.

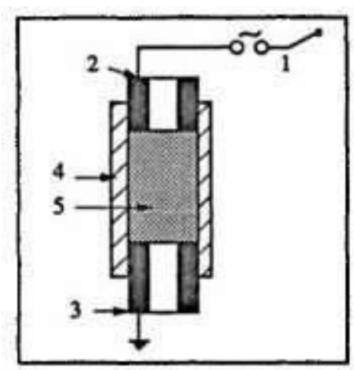
(i) Expulsion gaps

Expulsion gap is a device which consists of a spark gap together with an arc quenching device which extinguishes the current arc when the gaps break over due to over-voltages. A typical such arrangement is shown in Fig. 8.2Oa. This essentially consists of a rod gap in air in series with a second gap enclosed within a fiber tube. In the event of an overvoltage, both the spark gaps breakdown simultaneously. The current due to the overvoltage is limited only by the tower footing resistance and the surge impedance of the ground wires. The internal arc in the fibre tube due to lightning current vaporizes a small portion of the fibre material.

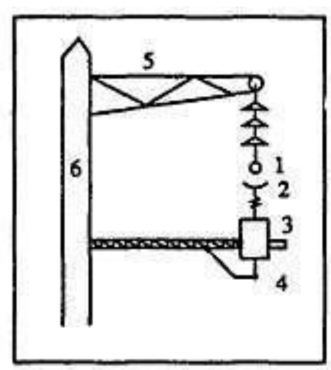
The gas thus produced, being a mixture of water vapour and the decomposed fibre product, drive away the arc products and ionized air. When the follow-on power frequency current passes through zero value, the arc is extinguished and the path becomes open circuited. Meanwhile the insulation recovers its dielectric strength, and the normal conditions are established. The lightning and follow-up power frequency currents together can last for 2to 3 half cycles only. Therefore, generally no disturbance in the network is produced. For 132 or 220 kV lines, the maximum current rating may be about 7,500 A.

(ii) Protector tubes

A protector tube is similar to the expulsion gap in, construction and principle. It also consists of a rod or spark gap in air formed by the line conductor and its high voltage terminal. It is mounted underneath the line conductor on a tower. The arrangement is shown in Fig. . The hollow gap in the expulsion tube is replaced by a nonlinear element which offers a very high impedance at low currents but has low impedance for high or lightning currents. When an overvoltage occurs and the spark gap breaks



1. External series gap
2. Upper electrode
3. Ground electrode
4. Fibre tube
5. Hollow space



1. Line conductor on string insulator
2. Series gap
3. Protector tube
4. Ground connection
5. Cross arm
6. Tower body

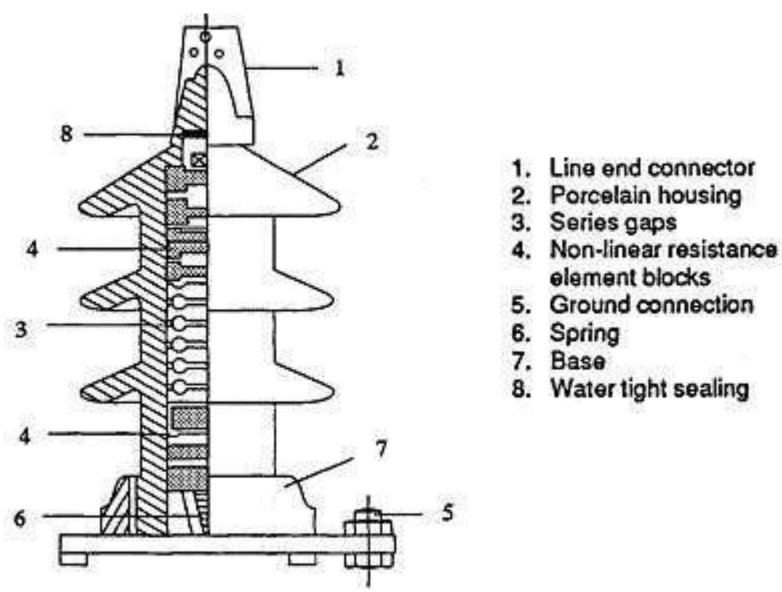
down, the current is limited both by its own resistance and the tower footing resistance. The overvoltage on the line is reduced to the voltage drop across the protector tube. After the surge current is diverted and discharged to the ground, the follow-on normal power frequency current will be limited by its high resistance. After the current zero of power frequency, the spark gap recovers the insulation strength quickly. Usually, the flashover voltage of the protector tube is less than that of the line insulation, and hence it can discharge the lightning overvoltage effectively.

(iv) Rod gaps

- ✓ A much simpler and effective protective device is a rod-gap However, it does not meet the complete requirement. The spark over voltage of a rod gap depends on the atmospheric conditions. There is no current limiting device provided so as to limit the current after spark over, and hence a series resistance is often used.
- ✓ Without a series resistance, the sparking current may be very high and the applied impulse voltage suddenly collapses to zero thus creating a steep step voltage, which sometimes proves to be very dangerous to the apparatus to be protected, such as transformer or the machine windings. Nevertheless, rod gaps do provide efficient protection where thunderstorm activity is less and the lines are protected by ground wires.

(v) Surge diverters or lightning arresters

- ✓ Surge diverters or lightning arresters are devices used at sub-stations and at line terminations to discharge the lightning over voltages and short duration switching surges. Theseare usually mounted at the line end at the nearest point to the sub-station.
- ✓ They have a flashover voltage power than that of any other insulation or apparatus at the sub-station. These are capable of discharging 10 to 20 kA of long duration surges (8/20 p. s) and 100 to 250 kA of the short duration surge currents (1/5\JL s)

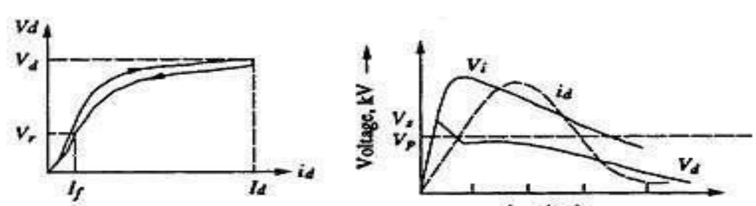


- ✓ These are non-linear resistors in series with spark gaps which act as fast switches. A typical surge diverter or lightning arrester is shown in Fig. and its characteristics are given in Fig. A number of non-linear resistor elements made of silicon carbide are stacked one over the other into two or three sections.

- ✓ They are usually separated by spark gaps .The entire assembly is housed in a porcelain water-tight housing. When a surge voltage is applied to the surge diverter, it breaks down giving the discharge current I and maintains a voltage V across it The lighter designs operate for smaller duration of currents, while the heavy duty surge diverters with assisted or active gaps are designed for high currents and long duration surges.

- ✓ The lighter design arresters can interrupt 100 to 300 A of power frequency follow-on current and about 5000 A of surge currents. If the current is to be more and has to be exceeded, the number of series elements has to be increased or some other method to limit the current has to be used.
- ✓ In heavy duty arresters, the gaps are so arranged that the arc burns in the magnetic field of the coils excited by power frequency follow-on currents. During lightning discharges, a high voltage is induced in the coil by the steep front of the surge, and sparking occurs in an auxiliary gap. For power frequency follow-on currents, the auxiliary gap is extinguished, as sufficient voltage will not be present across the auxiliary gap to maintain an arc.

- ✓ The main gap arcs occur in the magnetic field of the coils. The magnetic field, aided by the born shaped main gap electrodes, elongates the arc and quenches it rapidly. The follow-on current is limited by the voltage drop across the arc and the resistance element.
- ✓ During surge discharge the lightning protective level becomes low. Sometimes, it is possible to limit the power frequency and other over voltages after a certain number of cycles using surge diverters. The permissible voltage and duration depend on the thermal capacity of the diverter. The rated diverter voltage is normally chosen so that it is not less than the power frequency overvoltage expected (line to ground) at the point of installation, under any faulty or abnormal operating condition.



(a) Volt-ampere characteristic of a non-linear resistor block
(b) Surge diverter operation

I_f — Power frequency follow-on current at system voltage V_r
V_d — Max. voltage across the diverter during discharge of surge current with peak value I_d

V_s — Sparkover voltage
V_p — Protective level
V_i — Surge voltage
i_d — Discharge current
V_d — Voltage across the diverter when discharging the current i_d

Explain corona and its effect on power system.

Corona, also known as partial discharge, is a type of localized emission resulting from transient gaseous ionization in an insulation system when the voltage stress, i.e., voltage gradient, exceeds a critical value. The ionization is usually localized over only a portion of the distance between the electrodes of the system. Corona can occur within voids in insulators as well as at the conductor/insulator interface.

Corona Inception

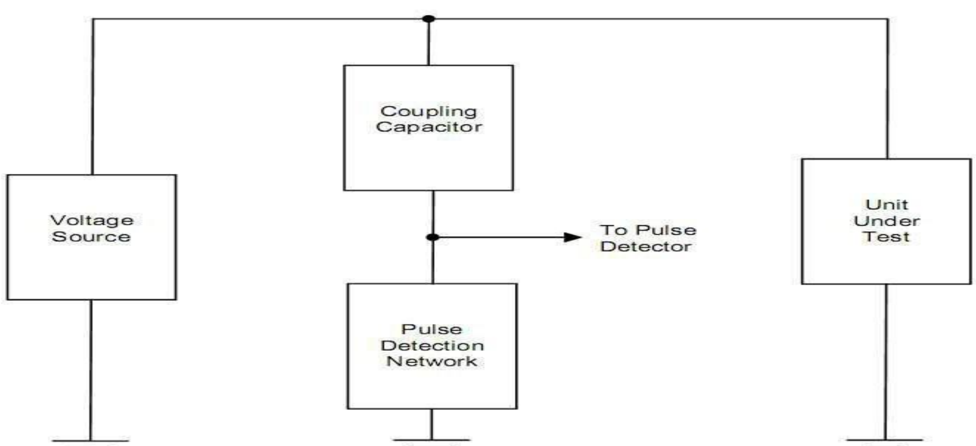
Corona inception voltage is the lowest voltage at which continuous corona of specified pulse amplitude occurs as the applied voltage is gradually increased. Corona inception voltage decreases as the frequency of the applied voltage increases. Corona can occur in applications as low as 300V.

Corona Extinction

Corona extinction voltage is the highest voltage at which continuous corona of specified pulse amplitude no longer occurs as the applied voltage is gradually decreased from above the corona inception value. Thus, once corona starts, the voltage must be decreased to get it to stop.

Corona Detection

Corona can be visible in the form of light, typically a purple glow, as corona generally consists of micro arcs. Darkening the environment can help to visualize the corona. Corona discharges in insulation systems result in voltage transients. These pulses are superimposed on the applied voltage and may be detected, which is precisely what corona detection equipment looks for. In its most basic form, the following diagram is a corona (or partial discharge) measuring system:



Corona Effects

The presence of corona can reduce the reliability of a system by degrading insulation While corona is a low energy process, over long periods of time, it can substantially degrade insulators, causing a system to fail due to dielectric breakdown. The effects of corona are cumulative and permanent, and failure can occur without warning.

Corona causes:

- Light
- Ultraviolet radiation
- Sound (hissing, or cracking as caused by explosive gas expansions)
- Ozone
- Nitric and various other acids
- Salts, sometimes seen as white powder deposits
- Other chemicals, depending on the insulator material
- Mechanical erosion of surfaces by ion bombardment
- Heat (although generally very little, and primarily in the insulator)
- Carbon deposits, thereby creating a path for severe arcing

Corona Prevention

Corona can be avoided by minimizing the voltage stress and electric field gradient. This is accomplished by using utilizing good high voltage design practices, i.e., maximizing the distance between conductors that have large voltage differentials, using conductors with large radii, and avoiding parts that have sharp points or sharp edges.

Corona inception voltage can sometimes be increased by using a surface treatment, such as a semiconductor layer, high voltage putty or corona dope. Also, use a good, homogeneous insulator. Void free solids, such as properly prepared silicone and epoxy potting materials work well. If you are limited to using air as your insulator, then you are left with geometry as the critical parameter. Finally, ensure that steps are taken to reduce or eliminate unwanted voltage transients, which can cause corona to start.

UNIT-II

DIELECTRIC BREAKDOWN

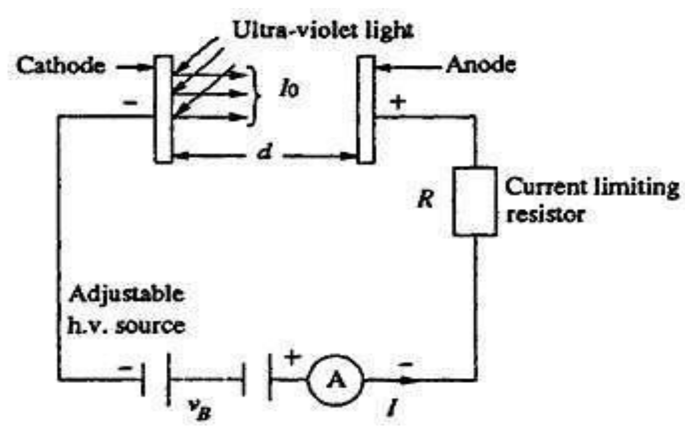
Deduce an expression for Townsend's criteria for breakdown of gaseous medium.

GASES AS INSULATING MEDIA

- ✓ The simplest and the most commonly found dielectrics are gases. Most of the electrical apparatus use air as the insulating medium,
- ✓ If the applied voltages are large, the current flowing through the insulation increases very sharply, and an electrical breakdown occurs.
- ✓ 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, a study of the electrical properties of gases and the processes by which high currents are produced in gases is essential.
- ✓ The build-up of high currents in a breakdown is due to the process known as ionization
- ✓ At present two types of theories (i) Townsend theory, and (ii) Streamer theory

TOWNSENDS FIRST IONIZATION PROCESSES

- ✓ A gas in its normal state is almost a perfect insulator. However, when a high voltage is applied between the two electrodes immersed in a gaseous medium, the gas becomes a conductor and an electrical breakdown occurs. A gas in its normal state is almost a perfect insulator. However, when a high voltage is applied between the two electrodes immersed in a gaseous medium, the gas becomes a conductor and an electrical breakdown occurs.
- ✓ The processes that are primarily responsible for the breakdown of a gas are ionization by collision, photo-ionization, and the secondary ionization processes. In insulating gases (also called electron-attaching gases) the process of attachment also plays an important role.



Ionization by Collision

- ✓ The process of liberating an electron from a gas molecule with the simultaneous production of a positive ion is called ionization.
- ✓ In the process of ionization by collision, a free electron collides with a neutral gas molecule and gives rise to a new electron and a positive ion. In a low pressure gas column in which an electric field E is applied across two plane parallel electrodes, then, any electron starting at the cathode will be accelerated more and more between collisions with other gas molecules during its travel towards the anode.
- ✓ If the energy (E) gained during this travel between collisions exceeds the ionisation potential, Viy which is the energy required to dislodge an electron from its atomic shell, then ionisation takes place. This process can be represented as

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

- ✓ Where, A is the atom, A+ IS the positive ion and e~ is the electron. A few of the electrons produced at the cathode by some external means, say by ultra-violet light falling on the cathode,
- ✓ ionise neutral gas particles producing positive ions and additional electrons.
- ✓ The additional electrons, then, themselves make 'ionising collisions' and thus the process repeats itself. This represents an increase in the electron current, since the number of electrons reaching the anode per unit time is greater than those liberated at the cathode.
- ✓ In addition, the positive ions also reach the cathode and on bombardment on the cathode give rise to secondary electrons.

TOWNSEND'S FIRST IONIZATION COEFFICIENT

- ✓ Consider a parallel plate capacitor having gas as an insulating medium and separated by a distance d as shown in Fig.1.1. When no electric field is set up between the plates, a state of equilibrium exists between the state of electron and positive ion generation due to the decay processes. This state of equilibrium will be disturbed moment a high electric field is applied.
- ✓ Let n_0 be the number of electrons leaving the cathode and when these have moved through a distance x from the cathode, these become n. Now then these n electrons move through a distance dx produce additional d_n electrons due to collision.

$$dn = \alpha\, n\, dx$$

or $$\frac{dn}{n} = \alpha\, dx$$

or $$\ln n = \alpha x + A$$

Now at $x = 0$, $n = n_0$. Therefore,

$$\ln n_0 = A$$

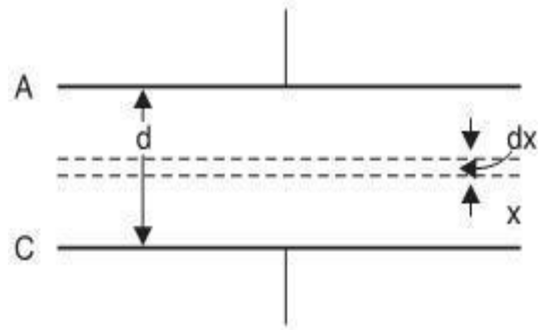
or $$\ln n = \alpha x + \ln n_0$$

or $$\ln \frac{n}{n_0} = \alpha x$$

At $x = d$, $n = n_0\, e^{\alpha d}$. Therefore, in terms of current

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

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



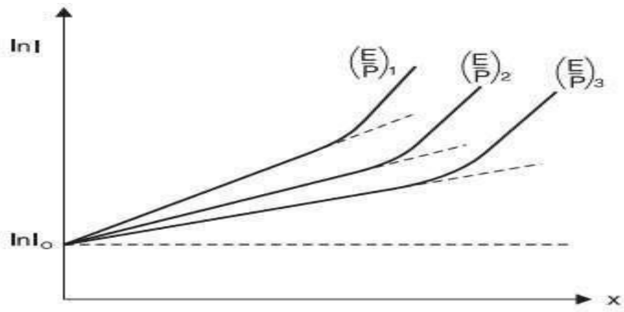
TOWNSEND SECOND IONISATION COEFFICIENT

From the equation

$$I = I_0\, e^{\alpha x}$$

We have, taking log on both the sides.

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



- ✓ This is a straight line equation with slope α and intercept ln I_0 as shown in Fig. if for a given pressure p, E is kept constant. Townsend in his earlier investigations had observed that the current in parallel plate gap increased more rapidly with increase in voltage as compared to the one given by the above equation.
- ✓ Townsend suggested that a second mechanism must be affecting the current. He postulated that the additional current must be due to the presence of positive ions and the photons. The positive ions will liberate electrons by collision with gas molecules and by bombardment against the cathode. Similarly, the photons will also release electrons after collision with gas molecules and from the cathode after photon impact.The phenomenon of self-sustained discharge where the electrons are released from the cathode by positive ion bombardment.
- ✓ Let n_0 be the number of electrons released from the cathode by ultraviolet radiation, n+ the number of electrons released from the cathode due to positive ion bombardment and n the number of electrons reaching the anode.
- ✓ Let ν, known as Townsend second ionization co-efficient be defined as the number of electrons released from cathode per incident positive ion, Then

$$n = (n_0 + n_+)e^{\alpha d}$$

Now total number of electrons released from the cathode is $(n^0 + n^+)$ and those reaching the anode are n, therefore, the number of electrons released from the gas = $n^- (n^0 + n^+)$, and corresponding to each electron released from the gas there will be one positive ion and assuming each positive ion releases ν effective electrons from the cathode then

$$n_+ = \nu[n - (n_0 + n_+)]$$

or $$n_+ = \nu n - \nu n_0 - \nu n_+$$

or $$(1 + \nu)\, n_+ = \nu(n - n_0)$$

or $$n_+ = \frac{\nu(n - n_0)}{1 + \nu}$$

Substituting n_+ in the previous expression for n, we have

$$n = \left[n_0 + \frac{\nu(n - n_0)}{1 + \nu}\right] e^{\alpha d} = \frac{(1 + \nu)\, n_0 + \nu n - \nu n_0}{1 + \nu} e^{\alpha d}$$

$$= \frac{n_0 + \nu n}{1 + \nu} e^{\alpha d}$$

or $$(n + \nu n) = n_0\, e^{\alpha d} + \nu n e^{\alpha d}$$

or $$n + \nu n - \nu n e^{\alpha d} = n_0 e^{\alpha d}$$

or $$n[1 + \nu - \nu e^{\alpha d}] = n_0 e^{\alpha d}$$

or $$n = \frac{n_0 e^{\alpha d}}{1 + \nu n(1 - e^{\alpha d})} = \frac{n_0 e^{\alpha d}}{1 - \nu(e^{\alpha d} - 1)}$$

In terms of current

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

Earlier Townsend derived an expression for current as

$$I = I_0 \frac{(\alpha - \beta)\, e^{(\alpha - \beta)d}}{\alpha - \beta\, e^{(\alpha - \beta)d}}$$

where β represents the number of ion pairs produced by positive ion travelling 1 cm path in the direction of field.

It is to be noted that the value of ν depends upon the work function of the material. If the work function of the cathode surface is low, under the same experimental conditions will produce more emission. Also, the value of ν is relatively small at low value of E/p and will increase with increase in E/p.

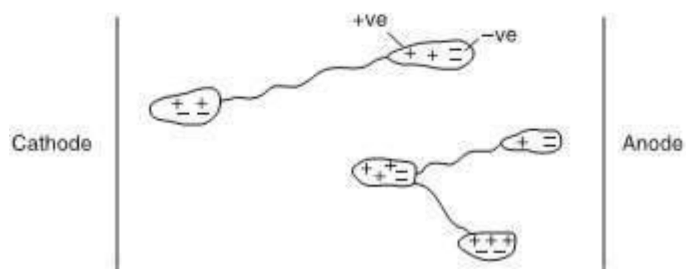
This is because at higher values of E/p, there will be more number of positive ions and photons of sufficiently large energy to cause ionization upon impact on the cathode surface. It is to be noted that the influence of ν on breakdown mechanism is restricted to Townsend breakdown mechanism i.e., to low-pressure breakdown only.

Explain streamer breakdown.

STREAMER OR KANAL MECHANISM OF SPARK

Townsend mechanism when applied to breakdown at atmospheric pressure was found to have certain drawbacks. Firstly, according to the Townsend theory, current growth occurs as a result of ionization processes only. But in practice, breakdown voltages were found to depend on the gas pressure and the geometry of the gap. Secondly, the mechanism predicts time lags of the order of 10^{-5} s, while in actual practice breakdown was observed to occur at very short times of the order of 10^{-8} s. Also, while the Townsend mechanism predicts a very diffused form of discharge, in actual practice, discharges were found to be filamentary and irregular. The Townsend mechanism failed to explain all these observed phenomena and as a result, around 1940, Raether and, Meek and Loeb independently proposed the Streamer Theory of Breakdown in Gases.

These electrons under the influence of the electric field develop into secondary avalanches as shown in Fig. Since photons travel with velocity of light, the process leads to a rapid development of conduction channel across the gap.



- ✓ Raether after thorough experimental investigation developed an empirical relation for the streamer spark criterion of the form

$$\alpha x_c = 17.7 + \ln x_c + \ln \frac{E_r}{E_0}$$

- ✓ whereEr is the radial field due to space charge and E0 is the externally applied field. Now for transformation of avalanche into a streame r Er ≈ E

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

- ✓ For a uniform field gap, breakdown voltage through streamer mechanism is obtained on theassumption that the transition from avalanche to streamer occurs when the avalanche has just crossed the gap. The equation above, therefore, becomes

$$\alpha d = 17.7 + \ln d$$

- ✓ When the critical length xc ≥ d minimum breakdown by streamer mechanism is brought about.The condition Xc = d gives the smallest value of α to produce streamer breakdown. Meek suggested that the transition from avalanche to streamer takes place when the radial field about the positive space charge in an electron avalanche attains a value of the order of the externally applied field. He showed that the value of the radial field can be otained by using the expression.

$$E_r = 5.3 \times 10^{-7} \frac{\alpha e^{\alpha x}}{(x/P)^{1/2}} \text{ volts/cm.}$$

- ✓ where x is the distance in cm which the avalanche has progressed, p the gas pressure in Torr and Townsend coefficient of ionization by electrons corresponding to the applied field E.

- ✓ The minimum breakdown voltage is assumed to correspond to the condition when the avalanche has crossed the apof length d and the space charge field Er approaches the externally applied field i.e., at x = d, Er = E. Substituting these values in the above equation, we have

$$E = 5.3 \times 10^{-7} \frac{\alpha e^{\alpha d}}{(d/p)^{1/2}}$$

Taking ln on both the sides, we have

$$\ln E = -14.5 + \ln \alpha - \frac{1}{2} \ln \frac{d}{p} + \alpha d$$

$$\ln E - \ln p = -14.5 + \ln \alpha - \ln p - \frac{1}{2} \ln \frac{d}{p} + \alpha d$$

$$\ln \frac{E}{p} = -14.5 + \ln \frac{\alpha}{p} - \frac{1}{2} \ln \frac{d}{p} + \alpha d$$

The experimentally determined values of α/p and the corresponding E/p are used to solve the above equation using trial and error method. Values of α/p corresponding to E/p at a given pressure are chosen until the equation is satisfied.

State and explain paschen's law.

THE SPARKING POTENTIAL—PASCHEN'S LAW

The Townsend's Criterion

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

enables the evaluation of breakdown voltage of the gap by the use of appropriate values of α/p and ν corresponding to the values E/p when the current is too low to damage the cathode and also the space charge distortions are minimum.

A close agreement between the calculated and experimentally determined values is obtained when the gaps are short or long and the pressure is relatively low. An expression for the breakdown voltage for uniform field gaps as a function of gap length and gas pressure can be derived from the threshold equation by expressing the ionization coefficient α/p as a function of field strength E and gas pressure p i.e.,

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

Substituting this, we have

$$e^{f(E/p)\,pd} = \frac{1}{\nu} + 1$$

Taking ln both the sides, we have

$$f\left(\frac{E}{p}\right)pd = \ln\left[\frac{1}{\nu} + 1\right] = K \text{ say}$$

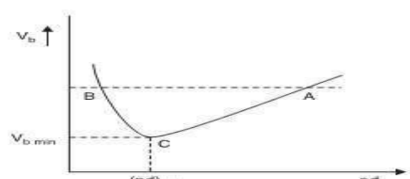
For uniform field $E = \dfrac{V_b}{d}$.

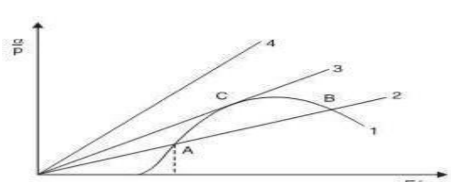
Therefore, $$f\left(\frac{V_b}{pd}\right).\, pd = K$$

or $$f\left(\frac{V_b}{pd}\right) = \frac{K}{pd}$$

or $$V_b = F\,(p.d)$$

This shows that the breakdown voltage of a uniform field gap is a unique function of the product of gas pressure and the gap length for a particular gas and electrode material. This relation is known as Paschen's law. This relation does not mean that the breakdown voltage is directly proportional to product pd even though it is found that for some region of the product pd the relation is linear i.e., the breakdown voltage varies linearly with the product pd. The variation over a large range is shown in Fig





Explain the phenomenon of corona discharges and breakdown mechanism in non uniform field.

CORONA DISCHARGES

If the electric field is uniform and if the field is increased gradually, just when measurable ionization begins, the ionization leads to complete breakdown of the gap. However, in non-uniform fields, before the spark or breakdown of the medium takes place, there are many manifestations in the form of visual and audible discharges. These discharges are known as Corona discharges.

In fact Corona is defined as a self-sustained electric discharge in which the field intensified ionization is localized only over a portion of the distance (non-uniform fields) between the electrodes. The phenomenon is of particular importance in high voltage engineering where most of the fields encountered are non-uniform fields unless of course some design features are involved to make the filed almost uniform.

Corona is responsible for power loss and interference of power lines with the communication lines as corona frequency lies between 20 Hz and 20 kHz. 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.

When a voltage higher than the critical voltage is applied between two parallel polished wires, the glow is quite even. After operation for a short time, reddish beads or tufts form along the wire, while around the surface of the wire there is a bluish white glow.

If the conductors are examined through a stroboscope, so that one wire is always seen when at a given half of the wave, it is noticed that the reddish tufts or beads are formed when the conductor is negative and a smoother bluish white glow when the conductor is positive.

The a.c. corona viewed through a stroboscope has the same appearance as direct current corona. As corona phenomenon is initiated a hissing noise is heard and ozone gas is formed which can be detected by its characteristic colour.

When the voltage applied corresponds to the critical disruptive voltage, corona phenomenon starts but it is not visible because the charged ions in the air must receive some finite energy to cause further ionization by collisions.

For a radial field, it must reach a gradient (visual corona gradient) g_u at the surface of the conductor to cause a gradient g0, finite distance away from the surface of the conductor.

The distance between g0 and g_V is called the energy distance. From this it is clear that g_V is not constant as g_0 is, and is a function of the size of the conductor. The electric field intensity for two parallel wires is given as

$$E = 30\left(1+\frac{0.301}{\sqrt{r}\,\delta}\right)\delta \text{ kV/cm}$$

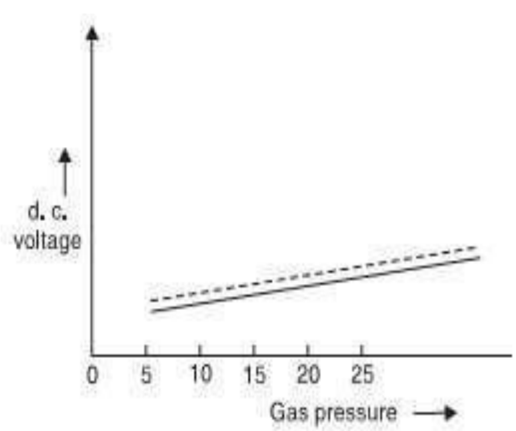
$$E = 30\left(1+\frac{0.308}{\sqrt{r}\delta}\right)\delta$$

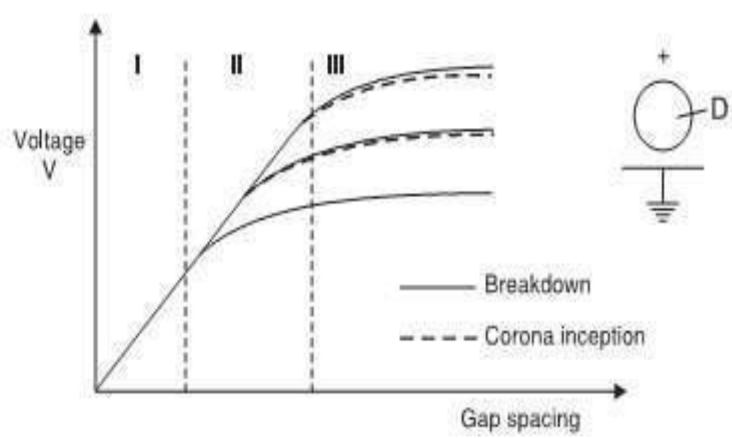
Investigation with point-plane gaps in air have shown that when point is positive, the corona current increases steadily with voltage. At sufficiently high voltage, current amplification increases rapidly with voltage up to a current of about 10–7 A, after which the current becomes pulsed with repetition 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.Fig.gives comparison between the positive and negative point-plane gap breakdown characteristics measured in air as a function of gas pressure

When the spacing is small the breakdown characteristics for the two polarities nearly coincide and no corona stabilized region is observed. As the spacing is increased, the positive characteristics display the distinct high corona breakdown up to a pressure of about 7 bars, followed by a sudden drop in breakdown strengths.

Under the negative polarity, the corona stabilized region extends to much higher pressures. Fig. shows the corona inception and breakdown voltages of the sphere-plane arrangement. From the figure, it is clear that

(i) For small spacing (Zone–I), the field is uniform and the breakdown voltage depends mainly on the gap spacing.

(ii) In zone–II, where the spacing is relatively larger, the electric field is non-uniform and the breakdown voltage depends on both the sphere diameter and the spacing.

(iii) For still larger spacings (Zone-III) the field is non-uniform and the breakdown is preceded by corona and is controlled only by the spacing. The corona inception voltage mainly depends on the sphere diameter.

TIME-LAG

In order to breakdown a gap, certain amount of energy is required. Also it depends upon the availability of an electron between the gap for initiation of the avalanche. Normally the peak value of A.C. and D.C. are smaller as compared to impulse wave as the duration of the former are pretty large as compared to the letter and the energy content is large.

Also with D.C. and A.C. as the duration is large there are usually sufficient initiatory electrons created by cosmic ray and naturally occurring radioactive sources. Suppose V_d is the maximum value of D.C. volt-age applied for a long time to cause breakdown of a given gap. Fig. 1.10.Let the same gap be subjected to a step volt-age of peak value $V_{d1}>V_d$ and of a duration such that the gap breaks down in time t.

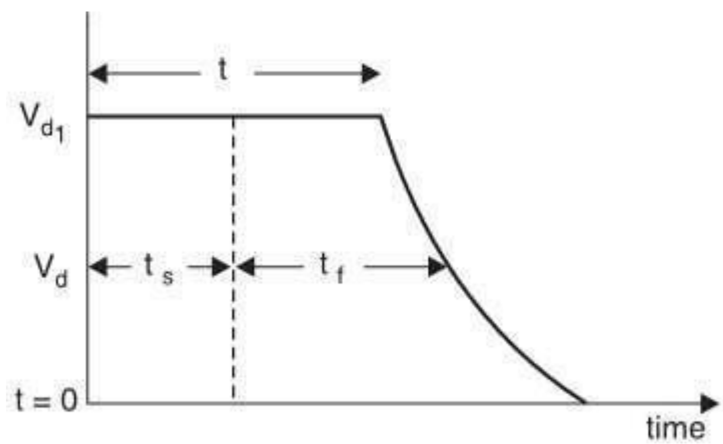
If the breakdown were purely a function of voltage magnitude, the breakdown should have taken place the moment the step voltage had just crossed the voltage V_d. The time that elapses between the application of the voltage to a gap sufficient to cause breakdown, and the breakdown, is called the time lag. In the given case shown in Fig. 1.10, t is the time lag.

It consists of two components.

One is the that elapses during the voltage applications until a primary electron appears to initiate the discharge and is known as the statistical time lag t_s and the other is the time required for the breakdown to develop once initiated and is known as the formative time lag t_f.

The statistical time lag depends upon (i) The amount of pre-ionization present in between the gap (ii) Size of the gap (iii) The amount of over voltage ($V_{d1} – V_d$) applied to the gap. The larger the gap the higher is going to be the statistical time lag. Similarly, a smaller over voltage results in higher statistical time lag. However, the formative time lag depends mainly on the mechanism of breakdown.

In cases when the secondary electrons arise entirely from electron emission at the cathode by positive ions, the transit time from anode to cathode will be the dominant factor determining the formative time. The formative time lag increases with increase in gap length and field non-uniformity, decreases with increase in over voltage applied.



Breakdown in Electronegative Gases

SF6, has excellent insulating strength because of its affinity for electrons (electronegativity) i.e., whenever a free electron collides with the neutral gas molecule to form negative ion, the electron is absorbed by the neutral gas molecule. The attachment of the electron with the neutral gas molecule may occur in two ways:

$$SF_6 + e \longrightarrow SF_6^-$$
$$SF_6 + e \longrightarrow SF_5^- + F$$

The negative ions formed are relatively heavier as compared to free electrons and, therefore, under a given electric field the ions do not attain sufficient energy to lead cumulative ionization in the gas. Thus, these processes represent an effective way of removing electrons from the space which otherwise would have contributed to form electron avalanche. This property, therefore, gives rise to very high dielectric strength for SF_6.

The gas not only possesses a good dielectric strength but it has the unique property of fast recombination after the source energizing the spark is removed. The dielectric strength of SF_6 at normal pressure and temperature is 2–3 times that of air and at 2 atm its strength is comparable with the transformer oil.

Although SF_6 is a vapour, it can be liquefied at moderate pressure and stored in steel cylinders. Even though SF_6 has better insulating and arc-quenching properties than air at an equal pressure, it has the important disadvantage that it cannot be used much above 14 kg/cm^2 unless the gas is heated to avoid liquefaction.

Application of Gases in Power System

The gases find wide application in power system to provide insulation to various equipment and substations. The gases are also used in circuit breakers for arc interruption besides providing insulation between breaker contacts and from contact to the enclosure used for contacts. The various gases used are (i) air (ii) oxygen (iii) hydrogen (iv) nitrogen (v) CO_2 and **(vi)** electronegative gases like sulphur hexafluoride, arcton etc.

The various properties required for providing insulation and arc interruptions are:

(i) High dielectric strength.

(ii) Thermal and chemical stability

(iii) Non-inflammability.

(iv) High thermal conductivity. This assists cooling of current carrying conductors immersed in the gas and also assists the arc-extinction process.

(v) Arc extinguishing ability. It should have a low dissociation temperature, a short thermal time constant (ratio of energy contained in an arc column at any instant to the rate of energy dissipation at the same instant) and should not produce conducting products such as carbon during arcing.

(vi) Commercial availability at moderate cost. Of the simple gases air is the cheapest and most widely used for circuit breaking. Hydrogen has better arc extinguishing property but it has lower dielectric strength as compared with air. Also if hydrogen is contaminated with air, it forms an explosive mixture.

(vii) Nitrogen has similar properties as air, CO_2 has almost the same dielectric strength as air but is a better arc extinguishing medium at moderate currents. Oxygen is a good extinguishing medium but is chemically active. SF_6 has outstanding arc-quenching properties and good dielectric strength. Of all these gases, SF_6 and air are used in commercial gas blast circuit breakers.

Air at atmospheric pressure is 'free' but dry air costs a lot when stored at say 75 atmosphere. The compressed air supply system is a vital part of an air blast C.B. Moisture from the air is removed by refrigeration, by drying agents or by storing at several times the working pressure and then expanding it to the working pressure for use in the C.B. The relative cost of storing the air reduces with increase in pressure. If the air to be used by the breaker is at 35 kg/cm2 it is common to store it at 210 kg/cm2.

Air has an advantage over the electronegative gases in that air can be compressed to extremely high pressures at room temperature and then its dielectric strength even exceeds that of these gases. The SF_6 gas is toxic and its release in the form of leakage causes environmental problems. Therefore, the electrical industry has been looking for an alternative gas or a mixture of SF_6 with some other gas as an insulating and arc interrupting medium.

It has been observed that a suitable mixture of SF_6 with N_2 is a good replacement for SF_6. This mixture is not only finding acceptability for providing insulation e.g., gas insulated substation and other equipment, it is able to quench high current magnitude arcs. The mixture is not only cost effective, it is less sensitive to find non-uniformities present within the equipment.

Electric power industry is trying to find optimum SF_6 to N_2 mixture ratio for various components of the system viz., GIS, C.B., capacitors, CT, PT and cables. A ratio 70% of SF_6 and 30% of N_2 is found to be optimum for circuit breaking. With this ratio, the C.B. has higher recovery rate than pure SF_6 at the same partial pressure. The future of using SF_6 with N_2 or He for providing insulation and arc interruption is quite bright.

Explain clearly various process which explain electric breakdown in vacuum

Vacuum Breakdown

In the Townsend type of discharge in a gas described earlier, electrons get multiplied due to various ionization processes and an electron avalanche is formed. In a high vacuum, even if the electrodes are separated by, say, a few centimeters, an electron crosses the gap without encountering any collisions. Therefore, the current growth prior to breakdown cannot be due to the formation of electron avalanches.

However, if a gas is liberated in the vacuum gap, then, breakdown can occur in the manner described by the Townsend process. Thus, the various breakdown mechanisms in high vacuum aim at establishing the way in which the liberation of gas can be brought about in a vacuum gap. During the last 70 years or so, many different mechanisms for breakdown in vacuum have been proposed. These can be broadly divided into three categories

(a) Particle exchange mechanism

(b) Field emission mechanism

(c) lump theory

(a) Particle Exchange Mechanism

In this mechanism it is assumed that a charged particle would be emitted from one electrode under the action of the high electric field, and when it impinges on the other electrode, it liberates oppositely charged particles. These particles are accelerated by the applied voltage back to the first electrode where they release more of the original type of particles. When this process becomes cumulative, a chain reaction occurs which leads to the breakdown of the gap. The particle-exchange mechanism involves electrons, positive ions, photons and the absorbed gases at the electrode surfaces.

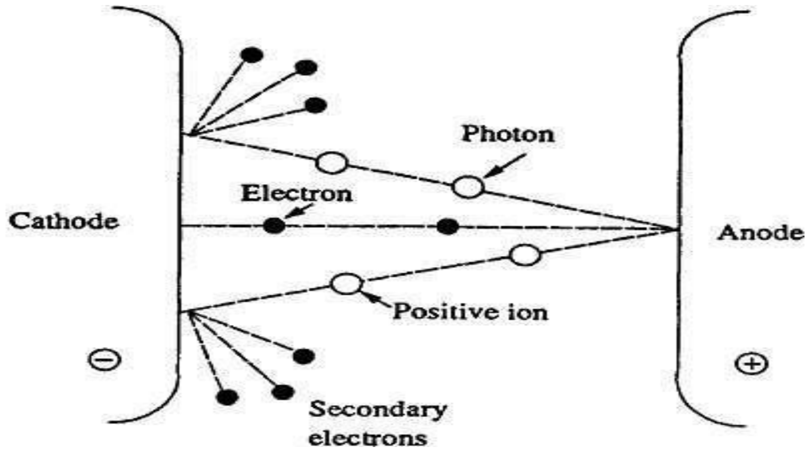
Qualitatively, an electron present in the vacuum gap is accelerated towards the anode, and on impact releases A positive ions and C photons. These positive ions are accelerated towards the cathode, and on impact each positive ion liberates B electrons and each photon liberates D electrons. This is shown schematically in Fig. 2.24. The breakdown will occur if the coefficient of production of secondary electrons exceeds unity. Mathematically, the condition for breakdown can be written as

$$(AB + CD) > 1$$

Later, Trump and Van de Graaff measured these coefficients and showed that they were too small for this process to take place. Accordingly, this theory was modifie4 to allow for the presence of negative ions and the criterion for breakdown then becomes Where A and B are the same as before and E and F represent the coefficients for negative and positive ion liberation by positive and negative ions.

$$(AB + EF) > 1$$

It was experimentally found that the values of the product EF were close enough to unity for copper, aluminum and stainless steel electrodes to make this mechanism applicable at voltages above 250 kV.

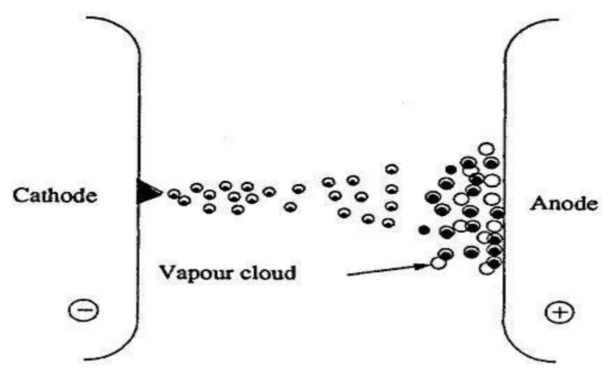


Field Emission Theory

(i) Anode Heating Mechanism

This theory postulates that electrons produced at small micro-projections on the cathode due to field emission bombard the anode causing a local rise in temperature and release gases and vapours into the vacuum gap. These electrons ionise the atoms of the gas and produce positive ions.

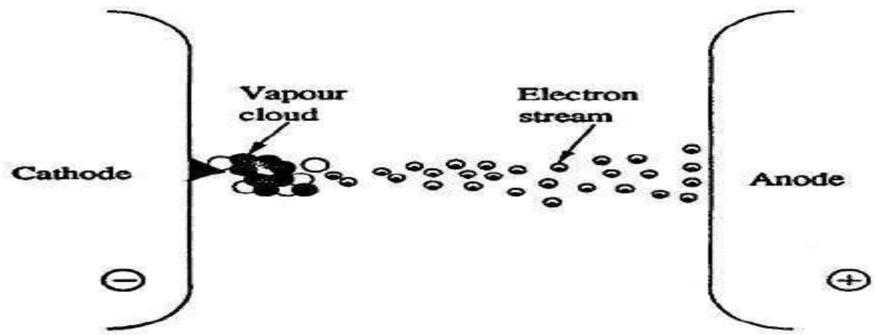
These positive ions arrive at the cathode, increase the primary electron emission due to space charge formation and produce secondary electrons by bombarding the surface. The process continues until a sufficient number of electrons are produced to give rise to breakdown, as in the case of a low pressure Townsend type gas discharge. This is shown schematically in Fig.



(ii) Cathode Heating Mechanism

This mechanism postulates that near the breakdown voltages of the gap, sharp points on the cathode surface are responsible for the existence of the pre-breakdown current, which is generated according to the field emission process described below. These current causes resistive heating at the tip of a point and when a critical current density is reached, the tip melts and explodes, thus initiating vacuum discharge.

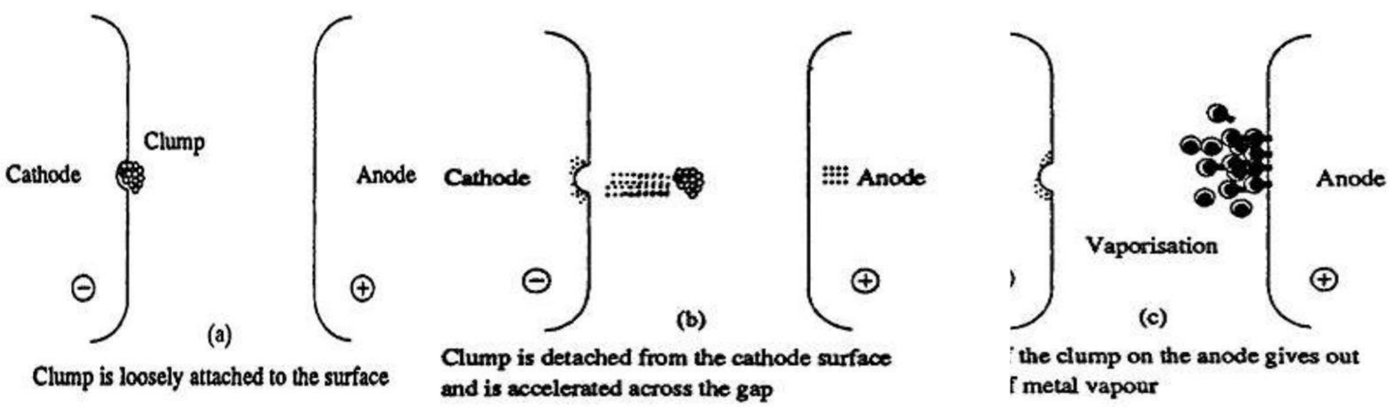
This mechanism is called field emission as shown schematically in Fig. 2.26. Thus, the initiation of breakdown depends on the conditions and the properties of the cathode surface. Experimental evidence shows that breakdown takes place by this process when the effective catliode electric field is of the order of 106 to 107 V/cm.



Clump Mechanism

Basically this theory has been developed on the following assumptions .A loosely bound particle (clump) exists on one of the electrode surfaces On the application of a high voltage, this particle gets charged, subsequently gets detached from the mother electrode, and is accelerated across the gap.(///)

The breakdown occurs due to a discharge in the vapour or gas released by the impact of the particle at the target electrode.Cranberg was the first to propose this theory. He initially assumed that breakdown will occur when the energy per unit area, W9 delivered to the target electrode by a clump exceeds a value C, a constant, characteristic of a given pair of electrodes. The quantity W is the product of gap voltage (V) and the charge density on the clump. The latter is proportional to the electric field E at the electrode of origin. The criterion for breakdown, therefore, is



In case of parallel plane electrodes the field E = V/d, where d is the distance between the electrodes. So the generalized criterion for breakdown becomes

$$V = (C\,d)^{1/2}$$

Where C is another constant involving C and the electrode surface conditions. Cranberg presented a summary of the experimental results which satisfied this breakdown criterion with reasonable accuracy. However the equation was later modified as V = C d_{01}, where a varies between 0.2 and 1.2 depending on the gap length and the electrode material, with a maximum at 0.6. The dependence of V on the electrode material comes from the observations of markings on the electrode surfaces. Craters were observed on the anode and melted regions on the cathode or vice-versa after a single breakdown.

Explain the various theories involved in commercial liquid dielectric.

CONDUCTION AND BREAKDOWN IN COMMERCIAL LIQUIDS

Commercial insulating liquids are not chemically pure and have impurities like gas bubbles, suspended particles, etc. These impurities reduce the breakdown strength of these liquids considerably.

The breakdown mechanisms are also considerably influenced by the presence of these impurities. In addition, when breakdown occurs in these liquids, additional gases and gas bubbles are evolved and solid decomposition products are formed.

The electrode surfaces become rough, and at times explosive sounds are heard due to the generation of impulsive pressure through the liquid.

The breakdown mechanism in commercial liquids is dependent, as seen above, on several factors, such as, the nature and condition of the electrodes, the physical properties of the liquid, and the impurities and gases present in the liquid. Several theories have been proposed to explain the breakdown in liquids, and they are classified as follows:

(a) Suspended Particle Mechanism

(b) Cavitation and Bubble Mechanism

(c) Stressed Oil Volume Mechanism

Suspended Particle Theory

In commercial liquids, the presence of solid impurities cannot be avoided. These impurities will be present as fibres or as dispersed solid particles. The permittivity of these particles (t^) will be different from the permittivity of the liquid . If we consider these impunities to be spherical particles of radius r, and if the applied field is E9 then the particles experience a force F, where

$$F = \frac{1}{2r^3}\frac{(\varepsilon_2 - \varepsilon_1)}{2\varepsilon_1 + \varepsilon_2}\,\text{grad}\,E^2$$

this force is directed towards areas of maximum stress, if 62 > EI for example, in thecase of the presence of solid particles like paper in the liquid. On the other hand, if only gas bubbles are present in the liquid, i.e. 62 < EI, the force will be in the direction of areas of lower stress. If the voltage is continuously applied (D.C.) or the duration of the voltage is long (a.c.), then this force drives the particles towards the areas of maximum stress.

If the numbers of particles present are large, they become aligned due to these forces, and thus form a stable chain bridging the electrode gap causing a breakdown between the electrodes. If there is only a single conducting particle between the electrodes, it will give rise to local field enhancement depending on its shape.

If this field exceeds the breakdown strength of the liquid, local breakdown will occur near the particle, and this will result in the formation of gas bubbles which may lead to the breakdown of the liquid.

The vales of the breakdown strength of liquids containing solid impurities were found to be much less than the values for pure liquids. The impurity particles reduce the breakdown strength, and it was also observed that the larger the size of the particles the lower were the breakdown strengths.

Cavitation and the Bubble Theory

It was experimentally observed that in many liquids, the breakdown strength depends strongly on the applied hydrostatic pressure, suggesting that a change of phase of the medium is involved in the breakdown process, which in other words means that a kind of vapour bubble formed is responsible for breakdown. The following processes have been suggested to be responsible for the formation of the vapour bubbles:

(a) Gas pockets at the surfaces of the electrodes;

(b) Electrostatic repulsive forces between space charges which may be sufficient to overcome the surface tension;

(c) Gaseous products due to the dissociation of liquid molecules by electron collisions;

(d) Vaporization of the liquid by corona type discharge from sharp points and irregularities on the electrode surfaces.

Once a bubble is formed it will elongate in the direction of the electric field under the influence of electrostatic forces. The volume of the bubble remains constant during elongation.

Breakdown occurs when the voltage drop along the length of the bubble becomes equal to the minimum value on the Paschen's curve for the gas in the bubble. The breakdown field is given as

$$E_0 = \frac{1}{(\varepsilon_1 - \varepsilon_2)}\left[\frac{2\pi\sigma(2\varepsilon_1 + \varepsilon_2)}{r}\left\{\frac{\pi}{4}\sqrt{\left(\frac{V_b}{2rE_0}\right)} - 1\right\}\right]^{\frac{1}{2}}$$

where σ = surface tension,

R = initial radius of the bubble,

ε_1 = permittivity of the liquid dielectric,

This theory does not take into account the production of the initial bubble and hence the results given by this theory do not agree well with the experimental results. This is shown in Fig. 3.6.Later this theory was modified, and it was suggested that only incompressible bubbles like water globules can elongate at constant volume, according to the simple gas law pv = RT. Under the influence of the applied electric field the shape of the globule is assumed to be approximately a prolate spheroid. The incompressible bubbles reach the condition of instability when B, the ratio of the longer to the shorter diameter of the spheriod, is about 1.85, and the critical field producing the instability will be:

$$E_c = 600\sqrt{\frac{\pi\sigma}{\varepsilon_1 R}}\left[\frac{\varepsilon_1}{\varepsilon_1 - \varepsilon_2} - G\right]H$$

Thermal Mechanism of Breakdown

Another mechanism proposed to explain breakdown under pulse conditions is thermal breakdown. This mechanism is based on the experimental observations of extremely large currents just before breakdown. These high current pulses are believed to originate from the tips of the microscopic projections on the cathode surface with densities of the order of 1 A/cm3. These high density current pulses give rise to localized heating of the oil which may lead to the formation of vapor bubbles.

The vapor bubbles are formed when the energy exceeds 10 W/cm. When a bubble is formed, breakdown follows, either because of its elongation to a critical size or when it completely bridges the gap between the electrodes.

In either case, it will result in the formation of a spark. According to this mechanism, the breakdown strength depends on the pressure and the molecular structure of the liquid. For example, in alkanes the breakdown strength was observed to depend on the chain length of the molecule.

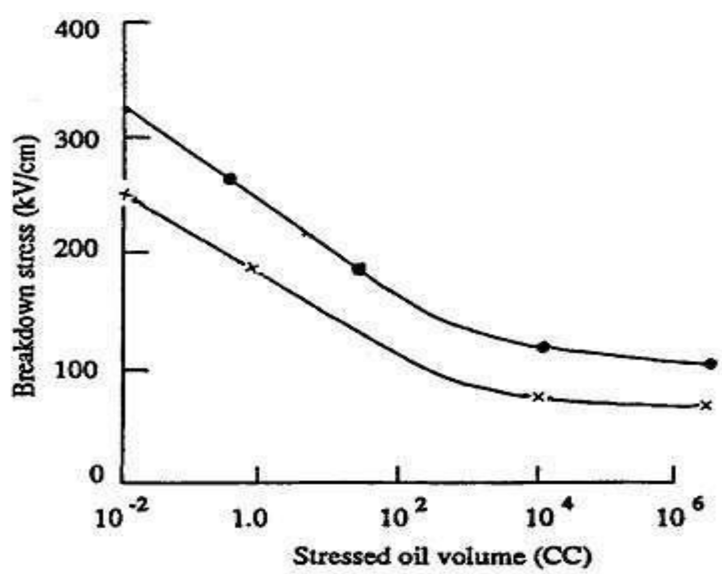
This theory is only applicable at very small lengths (< 100 \JL m) and does not explain the reduction in breakdown strength with increased gap lengths

Stressed Oil Volume Theory

In commercial liquids where minute traces of impurities are present, the breakdown strength is determined by the "largest possible impurity" or "weak link1'. On a statistical basis it was proposed that the electrical breakdown strength of the oil is defined by the weakest region in the oil, namely, the region which is stressed to the maximum and by the volume of oil included in that region.

In non-uniform fields, the stressed oil volume is taken as the volume which is contained between the maximum stress (max) contour and 0.9 max contours. According to this theory the breakdown strength is inversely proportional to the stressed oil volume.

The breakdown voltage is highly influenced by the gas content in the oil, the viscosity of the oil, and the presence of other impurities. These being uniformly distributed, increase in the stressed oil volume consequently results in a reduction in the breakdown voltage. The variation of the breakdown voltage stress with the stressed oil volume is shown in Fig.



7.Explain the various breakdown mechanism in composite dielectric.

Solid dielectric materials are used in all kinds of electrical circuits and devices to insulate one current carrying part from another when they operate at different voltages. A good dielectric should have low dielectric loss, high mechanical strength, should be free from gaseous inclusions, and moisture, and be resistant to thermal and chemical deterioration. Solid dielectrics have higher breakdown strength compared to liquids and gases. The mechanism of breakdown is a complex phenomenon in the case of solids, and varies depending on the time of application of voltage as shown in Fig. 4.1. The various breakdown mechanisms can be classified as follows:

(a) intrinsic or ionic breakdown,

(b) electromechanical breakdown,

(c) failure due to treeing and tracking,

(d) thermal breakdown,

(e) electrochemical breakdown, and

(J) Breakdown due to internal discharges.

INTRINSICBREAKDOWN

When voltages are applied only for short durations of the order of 10""8S the dielectric strength of a solid dielectric increases very rapidly to an upper limit called the intrinsic electric strength. Experimentally, this highest dielectric strength can be obtained only under the best experimental conditions when all extraneous influences have been isolated and the value depends only on the structure of the material and the temperature.

The maximum electrical strength recorded is 15 MV/cm for poly vinyl-alcoholat - 1960C. The maximum strength usually obtainable ranges from 5 MV/cm to 10MV/cm. intrinsic breakdown depend upon the presence of free electrons which are capable of migration through the lattice of the dielectric.

Usually, a small number of conduction elections are present in solid dielectrics, along with some structural imperfections and small amounts of impurities. The impurity atoms, or molecules or both act as traps for the conduction electrons up to certain ranges of electric fields and temperatures.

When these ranges are exceeded, additional electrons in addition to trapped electrons are released, and these electrons participate in the conduction process. Based on this principle, two types of intrinsic breakdown mechanisms have been proposed.

Electronic Breakdown

Intrinsic breakdown occurs in time of the order of 10~8s and therefore is assumed to be electronic in nature. The initial density of conduction (free) electrons is also assumed to be large, and electron-electron collisions occur.

When an electric field is applied, electrons gain energy from the electric field and cross the forbidden energy gap from the valency to the conduction band. When this process is repeated, more and more electrons become available in the conduction band, eventually leading to breakdown.

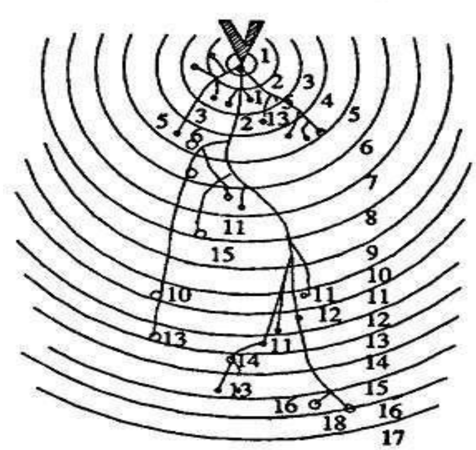
Avalanche or Streamer Breakdown

This is similar to breakdown in gases due to cumulative ionization. Conduction electrons gain sufficient energy above a certain critical electric field and cause liberation of electrons from the lattice atoms by collisions.

Under uniform field conditions, if the electrodes are embedded in the specimen, breakdown will occur when an electron avalanche bridges the electrode gap. An electron within the dielectric, starting from the cathode will drift towards the anode and during this motion gains energy from the field and loses it during collisions.

When the energy gained by an electron exceeds the lattice ionization potential, and additional electron will be liberated due to collision of the first electron. This process repeats itself resulting in the formation of an electron avalanche. Breakdown will occur, when the avalanche exceeds a certain critical size.

In practice, breakdown does not occur by the formation of a single avalanche itself, but occurs as a result of many avalanches formed within the dielectric and extending step by step through the entire thickness of the material as shown in Fig.



Electromechanical Breakdown

When a dielectric material is subjected to an electric field, charges of opposite nature are induced on the two opposite surfaces of the material and hence a force of attraction is developed and the specimen is subjected to electrostatic compressive forces and when these forces exceed the mechanical withstands strength of the material, the material collapses. If the initial thickness of the material is d0 and is compressed to a thickness d under the applied voltage V then the compressive stress developed due to electric field is

$$F = \frac{1}{2}\varepsilon_0\varepsilon_r \frac{V^2}{d^2}$$

where ε_r is the relative permittivity of the specimen. If γ is the Young's modulus, the mechanical compressive strength is

$$\gamma \ln \frac{d_0}{d}$$

Equating the two under equilibrium condition, we have

$$\frac{1}{2}\varepsilon_0\varepsilon_r \frac{V^2}{d^2} = \gamma \ln \frac{d_0}{d}$$

or $$V^2 = d^2 \cdot \frac{2\gamma}{\varepsilon_0\varepsilon_r} \ln \frac{d_0}{d} = Kd^2 \ln \frac{d_0}{d}$$

Differentiating with respect to d, we have

$$2V\frac{dV}{dd} = K\left[2d \ln \frac{d_0}{d} - d^2 \cdot \frac{d}{d_0} \cdot \frac{d_0}{d^2}\right] = 0$$

or $$2d \ln \frac{d_0}{d} = d$$

or $$\ln \frac{d_0}{d} = \frac{1}{2}$$

or $$\frac{d}{d_0} = 0.6$$

UNIT III

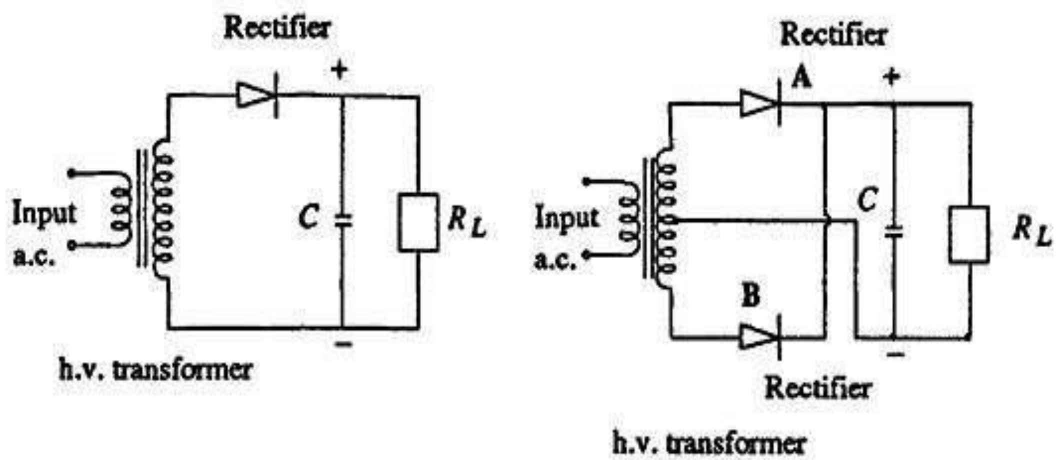
GENERATION AND MEASUREMENTS OF HIGH VOLTAGES AND HIGH CURRENTS

Explain various types of high DC voltage generation with neat diagrams.

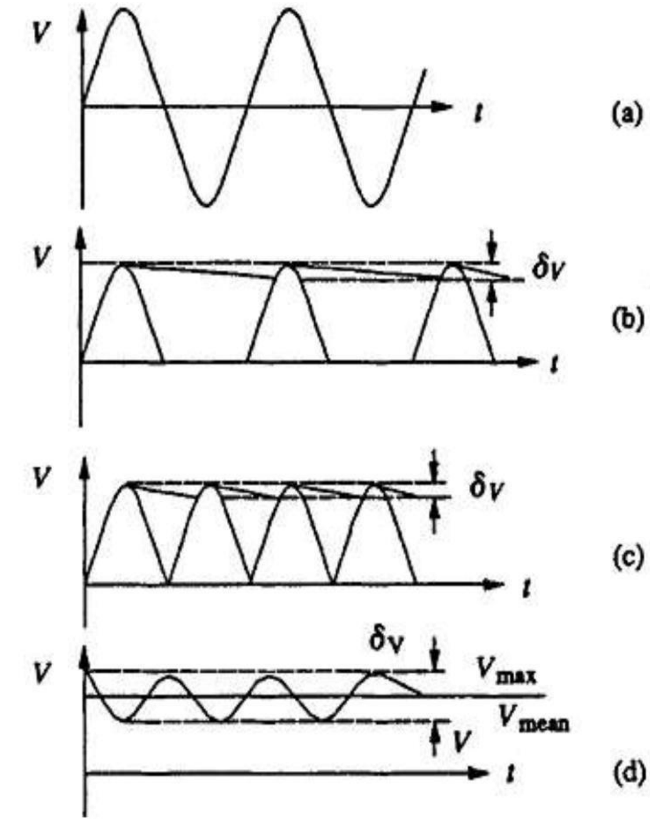
GENERATION OF HIGH D.C. VOLTAGES

Half and Full Wave Rectifier Circuits

- ✓ Rectifier circuits for producing high D.C. voltages from A.C. sources may be (a) half wave, (b) full wave, or (c) voltage doubler type rectifiers. The rectifier may be an electron tube or a solid state device.
- ✓ Now-a-days single electron tubes are available for peak inverse voltages up to 250 kV, and semiconductor or solid state diodes up to 20 kV.
- ✓ For higher voltages, several units are to be used in series. When a number of units are used in series, transient voltage distribution along each unit becomes non-uniform and special care should be taken to make the distribution uniform.



(a) Half wave rectifier (b) Full wave rectifier



(a) Input sine wave
(b) Output with half wave rectifier and condenser filter
(c) Output with full wave rectifier and condenser filter
(d) V_{max}, V_{mean} and ripple voltage and δV with condenser filter of a full wave rectifier

- ✓ In the half wave rectifier the capacitor is charged to Vmax, the maximum a.c.voltage of the secondary of the high voltage transformer in the conducting half cycle. In the otherhalf cycle, the capacitor is discharged into the load.
- ✓ The value of the capacitor C is chosen such that the time constant CR_L is at least 10 times that of the period of the a.c. supply. The rectifier valve must have a peak inverse rating of at least 2Vmax- To limit the charging current, an additional resistance R is provided in series with the secondary of the transformer
- ✓ .A full wave rectifier circuit is shown in Fig b. In the positive half cycle, the rectifier A conducts and charges the capacitor C, while in the negative half cycle the rectifier B conducts and charges the capacitor.
- ✓ The source transformer requires a center tapped secondary with a rating of 2V.For applications at high voltages of 50 kV and above, the rectifier valves used are of special construction.

- ✓ Apart from the filament, the cathode and the anode, they contain a protective shield or grid around the filament and the cathode. The anode will be usually a circular plate. Since the electrostatic field gradients are quite large, the heater and the cathode experience large electrostatic forces during the non-conduction periods.
- ✓ To protect the various elements from these forces, the anode is firmly fixed to the valve cover on one side. On the other side, where the cathode and filament are located, a steel mesh structure or a protective grid kept at the cathode potential surrounds them so that the mechanical forces between the anode and the cathode £re reflected on the grid structure only.
- ✓ In modern high voltage laboratories and testing installations, semiconductor rectifier stacks are commonly used for producing D.C. voltages. Semiconductor diodes are not true valves since they have finite but very small conduction in the backward direction.
- ✓ The more commonly preferred diodes for high voltage rectifiers are silicon diodes with peak inverse voltage (P.I.V.) of 1 kV to 2 kV. However, for laboratory applications the current requirement is small (a few milliamperes, and less than one ampere) and as such a selenium element stack with PJ.V. of up to 500 kV may be employed without the use of any voltage grading capacitors.
- ✓ Both full wave and half wave rectifiers produce D.C. voltages less than the A.C.maximum voltage. Also, ripple or the voltage fluctuation will be present, and this has to be kept within a reasonable limit by means of filters.

Ripple Voltage with Half Wave and Full Wave Rectifiers

When a full wave or a half wave rectifier is used along with the smoothing condenser C, the voltage on no load will be the maximum A.C. voltage. But when on load, the condenser gets charged from the supply voltage and discharges into load resistance RI whenever the supply voltage waveform varies from peak value to zero value.

When loaded, a fluctuation in the output D.C.voltage 6V appears, and is called a ripple. The ripple voltage SV is larger for a halfwave rectifier than that for a full wave rectifier, since the discharge period in the case of half wave rectifier is larger as shown in Fig..

The ripple δV depends on (a) the supply voltage frequency/, (b) the time constant $CR_L$and (c) the reactance of the supply transformer X_L. For half wave rectifiers, the ripple frequency is equal to the supply frequency and for full wave rectifiers, it is twice that value.

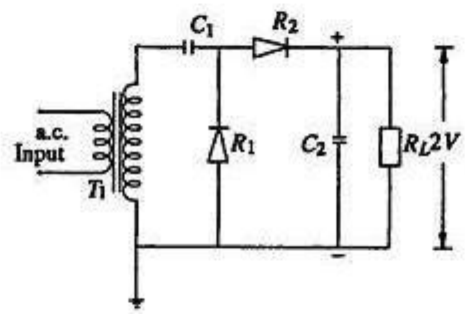
The ripple voltage is to be kept as low as possible with the proper choice of the filter condenser and the transformer reactance for a given load R_L.

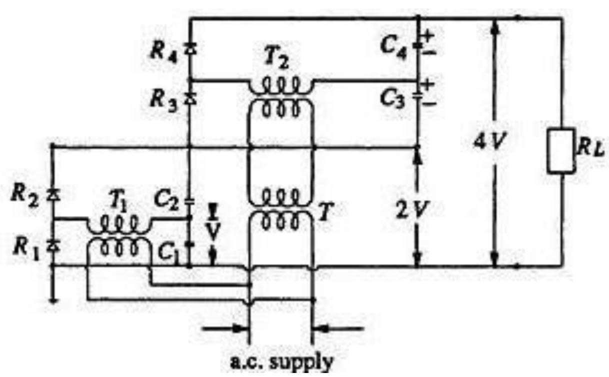
Explain the working of voltage doubler circuit with diagrams.

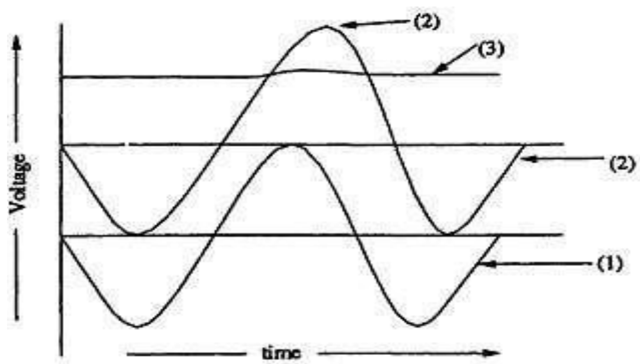
Voltage Doubler Circuits:

Both full wave and half wave rectifier circuits produce a d.c. voltage less than the a.c.maximum voltage. When higher d.c. voltages are needed, a voltage doubler or cascaded rectifier doubler circuits are used.

The schematic diagram of voltage doublers are given in Figs.In voltage doubler circuit shown in Fig. 6.3a, the condenser C1 is charged through rectifier R to a voltage of +Vmax with polarity as shown in the figure during the negative half cycle. As the voltage of the transformer rises to positive Vmax during the next half cycle, the potential of the other terminal of C\ rises to a voltage of +2Vmax.







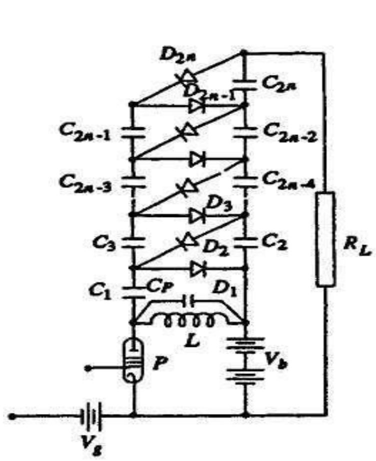
- ✓ Thus, the condenser C_2 in turn is charged through R2 to 2Vmax. Normally the d.c.output voltage on load will be less than 2Vmax, depending on the time constant $C_2$and the forward charging time constants. The ripple voltage of these circuits will be about 2% for R_L< 10 and XLr< 0.25, where X and r are the reactance and resistance of the input transformer.

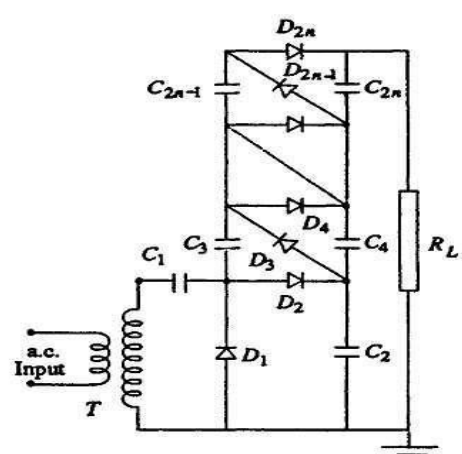
- ✓ The rectifiers are rated to a peak inverse voltage of 2Vmax,and the condensers C1and C1 must also have the same rating. If the load current is large, the ripple also is more.Cascaded voltage doublers are used when larger output voltages are needed without changing the input transformer voltage level.
- ✓ A typical voltage doubler is shown in Fig and its input and output waveforms are shown in Fig. The rectifiersR1 and R2 with transformer T1 and condensers C1 and C2 produce an outputvoltage of 2V in the same way as described above. This circuit is duplicated and connected in series or cascade to obtain a further voltage doubling to 4V.
- ✓ T is an isolating transformer to give an insulation for 2Kmax since the transformer T is at a potential of 2Vm above the ground. The voltage distribution along the rectifier string R1, R2,R3 and R4 is made uniform by having condensers C1, C2, C3 and C4 of equal values.
- ✓ The arrangement may be extended to give 6V, 8V, and so on by repeating further stages with suitable isolating transformers. In all the voltage doubler circuits,if valves are used, the filament transformers have to be suitably designed and insulated, as all the cathodes will not be at the same potential from ground. The arrangement becomes cumbersome if more than 4V is needed with cascaded steps.

With a neat circuit explain the working principle of a Cockcroft Walton voltage multiplier circuit.

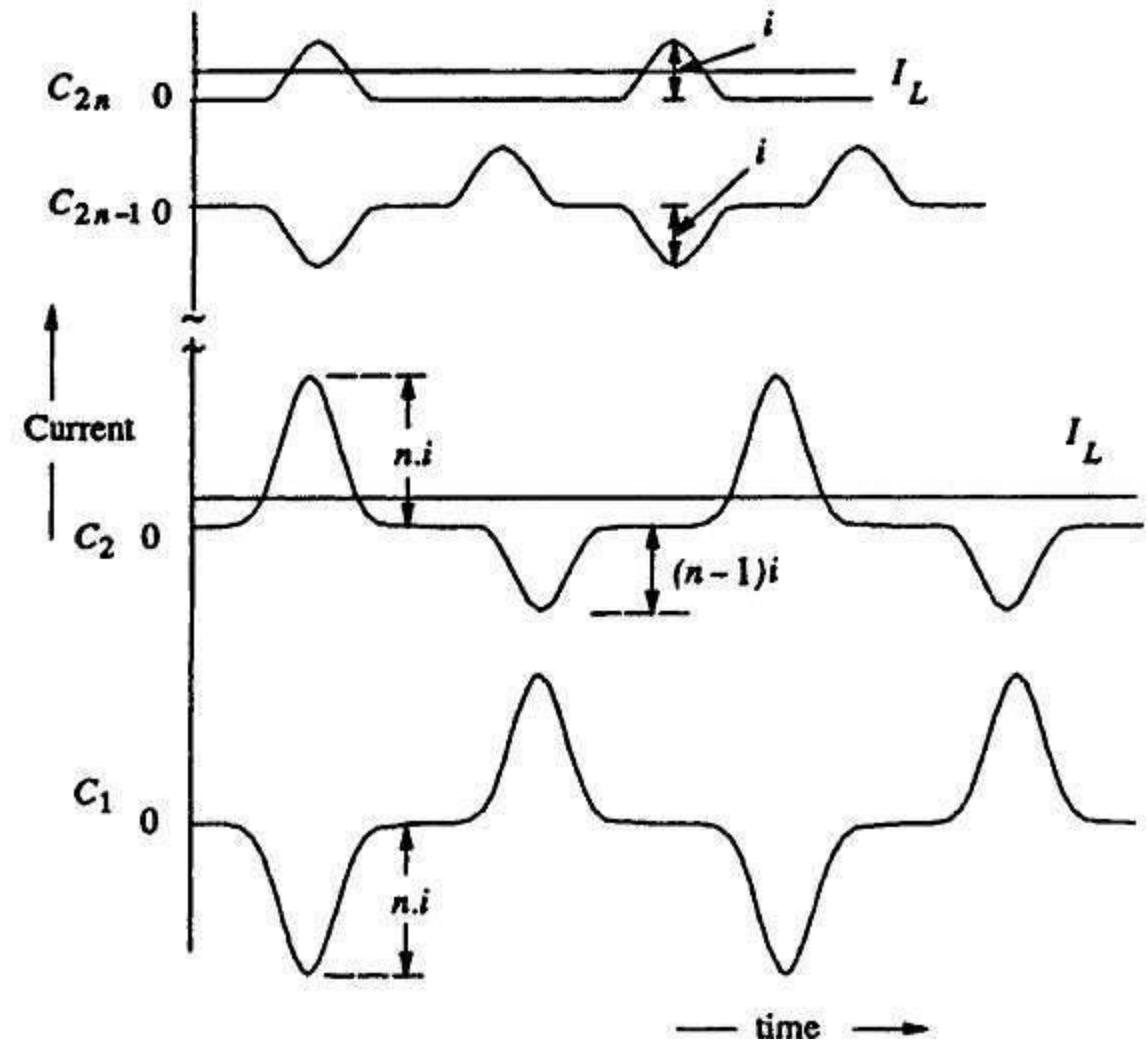
Cockcroft Walton Voltage Multiplier Circuits

Cascaded voltage multiplier circuits for higher voltages are cumbersome and require too many supply and isolating transformers. It is possible to generate very high d.c.voltages from single supply transformers by extending the simple voltage doublercircuits. This is simple and compact when the load current requirement is less than one milliampere, such as for cathode ray tubes, etc. Valve type pulse generators maybe used instead of conventional a.c. supply and the circuit becomes compact A typical circuit of this form is shown in fig.





The pulses generated in the anode circuit of the valve P are rectified and the voltage is cascaded to give an output of 2nVmax across the load R_L. A trigger voltage pulse of triangular waveform (ramp) is given to make the valve switched on and off. Thus, a voltage across the coil L is produced and is equal to Vmax = $I\sqrt{L}/Cp$where Cp isthe stray capacitance across the coil of inductance L. A d.c. power supply of about 500V applied to the pulse generator, is sufficient to generate a high voltage d.c. of 50 to100 kV with suitable number of stages. The pulse frequency is high (about 500 to 1000Hz) and the ripple is quite low (<1%). The voltage drop on load is about 5% for load currents of about 150 p, A. The voltage drops rapidly at high load currents.



Voltage multiplier circuit using the Cockcroft-Walton principle is shown in Fig..The first stage, i.e. DI, D2, D3, D4, and the transformer T are identical as in the voltage doublet shown in Fig.. For higher output voltage of 4.6,... 2n of the input voltageV,the circuit is repeated with cascade or series connection.

Thus, the condenser C4 is charged to 4Vmax and C2n to 2nVmax above the earth potential. But the volt across any individual condenser or rectifier is only 2Vmax.The rectifiers D1, D3, ... D2n-1 shown in Fig. operate and conduct during the positive half cycles while the rectifiers D2, D4... D2n conduct during the negative half cycles.

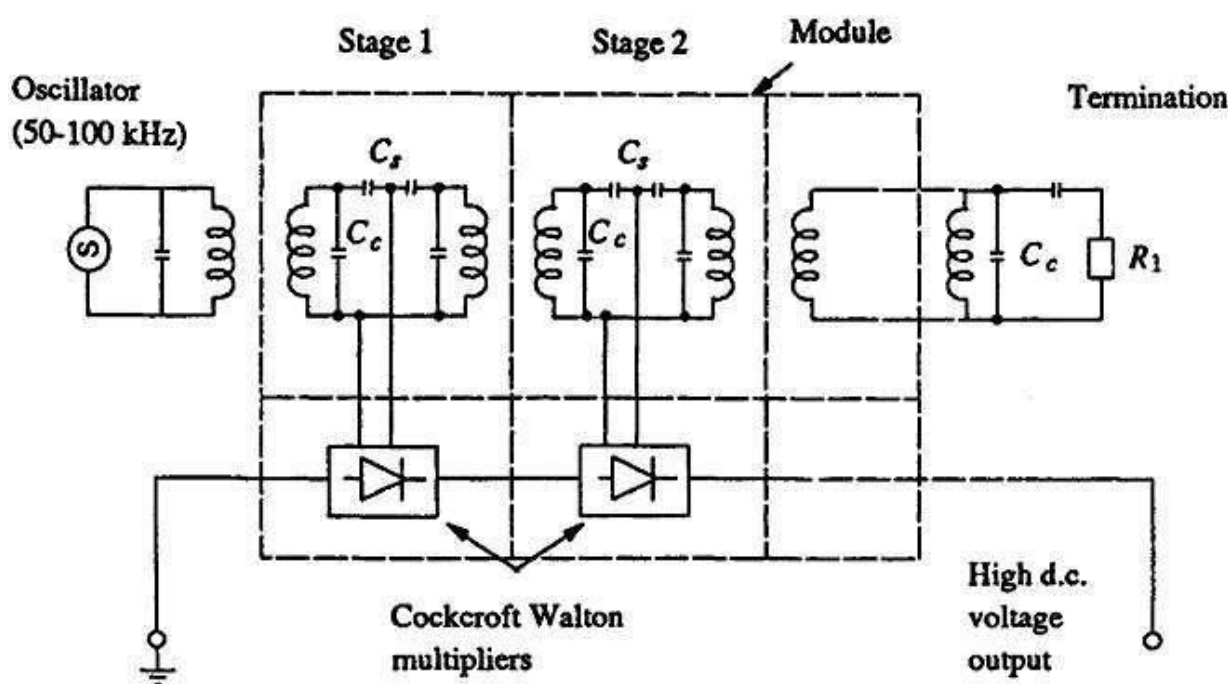
Typical current and voltage waveforms of such a circuit are shown in Figs. and respectively. The voltage on C2 is the sum of the input a.c. voltage,Vac and the voltage across condenser C1,V1) as shown in Fig . The mean voltage on C2 is less than the positive peak charging voltage (Vac + Vc1).

The voltages across other condensers C2 to C2n can be derived in the same manner, (i.e.) from the difference between voltage across the previous condenser and the charging voltage. Finally the voltage after 2n stages will be Vac (n1 + n2 + ...), where n1, n2,... are factors when ripple and regulation are considered in the next rectifier. The ripple voltage 5V and the voltage drop δV in a cascaded voltage multiplier unit are shown in Fig.

With a neat circuit explain the working principle of a Deltatron circuit.

Cascaded Modular Voltage Multipliers or "Deltatron" Circuits for Very High Voltages

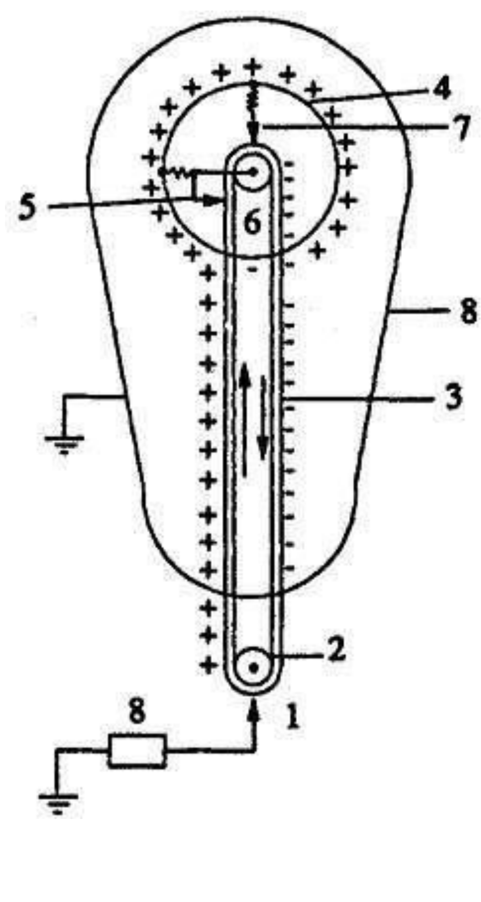
A combination of Cockcroft-Walton type voltage multiplier with cascaded transformer d.c. rectifier is developed recently for very high voltages but limited output currents having high stability, small ripple factor and fast regulation. One such unit is recently patented by "ENGE" in U.S.A., called "ENGETRON" or "DELTATRON". The schematic diagram of a typical Deltatron unit is shown inFig.



Basically this circuit consists of Cockcroft-Walton multiplier units fed from a supply transformer unit (stage 1). These supply transformers are air-cored to have low inductance and are connected in series through capacitors C. In addition, the windings of the transformers are shunted by a capacitor C to compensate for the magnetizing current. The entire unit is terminated by a load resistorR_1. All the Cockcroft-Walton multipliers are connected in series and the entire unit is enclosed in a cylindrical vessel insulated by SF_6 gas. Each stage of the unit is typically rated for 10 to 50 W, and about 20 to 25 stages are used in a unit The whole assembly is usually of smaller size and weight than a cascaded rectifier unit The supply frequency to the transformers is from a high frequency oscillator (50 to 100 kHz) and as such the capacitors used are of smaller value. The voltage regulation system is controlled by a parallel R-C divider which in turn controls the supply oscillator. Regulation due to I6ad variations orpower source voltage variations is very fast (response time < 1 ms). The disadvantage of this circuit is that the polarity of the unit cannot be reversed easily. Typical units of this type may have a rating of 1 MV, 2 mA with each module or stage rated for 50 kV with ripple content less than 1%.

Discuss with diagram the operation of Van de Graaff Generators

Van de Graff Generators



The schematic diagram of a Van deGraaff generator is shown in Fig.The generator is usually enclosed in an earthed metallic cylindrical vessel and is operated under pressure or in vacuum.

Charge is sprayed on to an insulating moving belt from corona points at a potential of 10 to 100 kV above earth and is removed and collected from the belt connected to the inside of an insulated metal electrode through which the belt moves.

The belt is driven by an electric motor ata speed of 1000 to 2000 metres per minute.A steady potential will be attained by the high voltage electrode when the leakage currents and the load current are equal to the charging current.

The shape of the high voltage electrode is so made with re-entrant edges as to avoid high surface field gradients, corona and other local discharges. The shape of the electrode is nearly spherical.

The charging of the belt is done by the lower spray points which are sharp needles and connected to a d.c. source of about 10 to 100 kV, so that the corona is maintained between the moving belt and the needles. The charge from the corona points is collected by the collecting needles from the belt and is transferred on to the high voltage electrode as the belt enters into the high voltage electrode.

The belt returns with the charge dropped, and fresh charge is sprayed on to it as it passes through the lower corona point. Usually in order to make the charging more effective and to utilize the return path of the belt for charging purposes, a self-inducing arrangement or a second corona point system excited by a rectifier inside the high voltage terminal is employed.

To obtain a self-charging system, the upper pulley is connected to the collector needle and is therefore maintained at a potential higher than that of the highvoltage terminal.

Thus a second row of corona points connected to the inside of the high voltage terminal and directed towards the pulley above its point of entry into the terminal gives a corona discharge to the belt.

This neutralizes any charge on the belt and leaves an excess of opposite polarity to the terminal to travel down with the belt to the bottom charging point. Thus, for a given belt speed the rate of charging is doubled.

The charging current for unit surface area of the belt is given by $I = bv\delta$, where bis the breadth of the belt in metres, v is the velocity of the belt in m/sec, and 5 is thesurface charge density in coulombs/m2. It is found that is $\delta \leq 1.4 \times 10^{-5}$ C/m2 to have a safe electric field intensity normal to the surface.

With b = 3 m and v = 3 m/sec, the charging current will be approximately 125 JμA. The generator is normally worked ina high pressure gaseous medium, the pressure ranging from S to IS atm. The gas maybe nitrogen, air, air-freon (CCL_2F_2 mixture, or sulphur hexafluoride (SF_6).

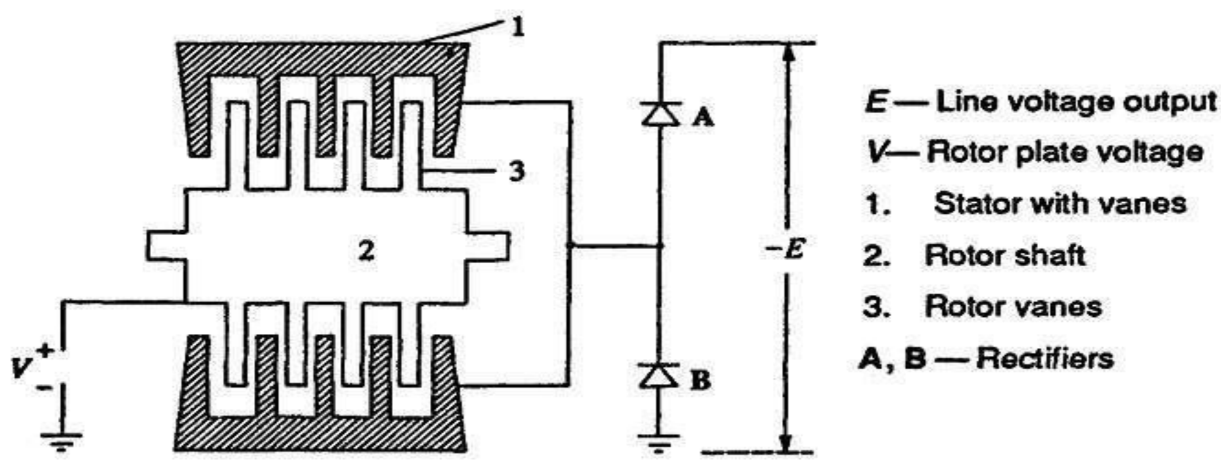
Van de Graaff generators are useful for very high voltage and low current applications. The output voltage is easily controlled by controlling the corona source voltage and the rate of charging.

The voltage can be stabilized to 0.01 %. These are extremely flexible and precise machines for voltage control.

Explain the working of Electrostatic Generators

Van de Graff generators are essentially high voltage but low power devices, and their power rating seldom exceeds few tens of kilowatts. As such electrostatic machines which effectively convert mechanical energy into electrical energy using variable capacitor principle were developed.

Electrostatic Generators



Van de Graff generators are essentially high voltage but low power devices, and their power rating seldom exceeds few tens of kilowatts. As such electrostatic machines which effectively convert mechanical energy into electrical energy using variable capacitor principle were developed. These are essentially duals of electromagnetic machines and are constant voltage variable capacitance machines. An electrostatic generator consists of a stator with interleaved rotor vanes forming a variable capacitor and operates in vacuum applied across the rectifier A and V is applied across Cm. As the rotor rotates, the capacitance C decreases and the voltage across C increases.

Thus, the stator becomes more negative with respect to ground. When the stator reaches the line potential -E the rectifier A conducts, and further movement of the rotor causes the current to flow from the generator. Rectifier B will now have E across it and the charge left in the generator will be

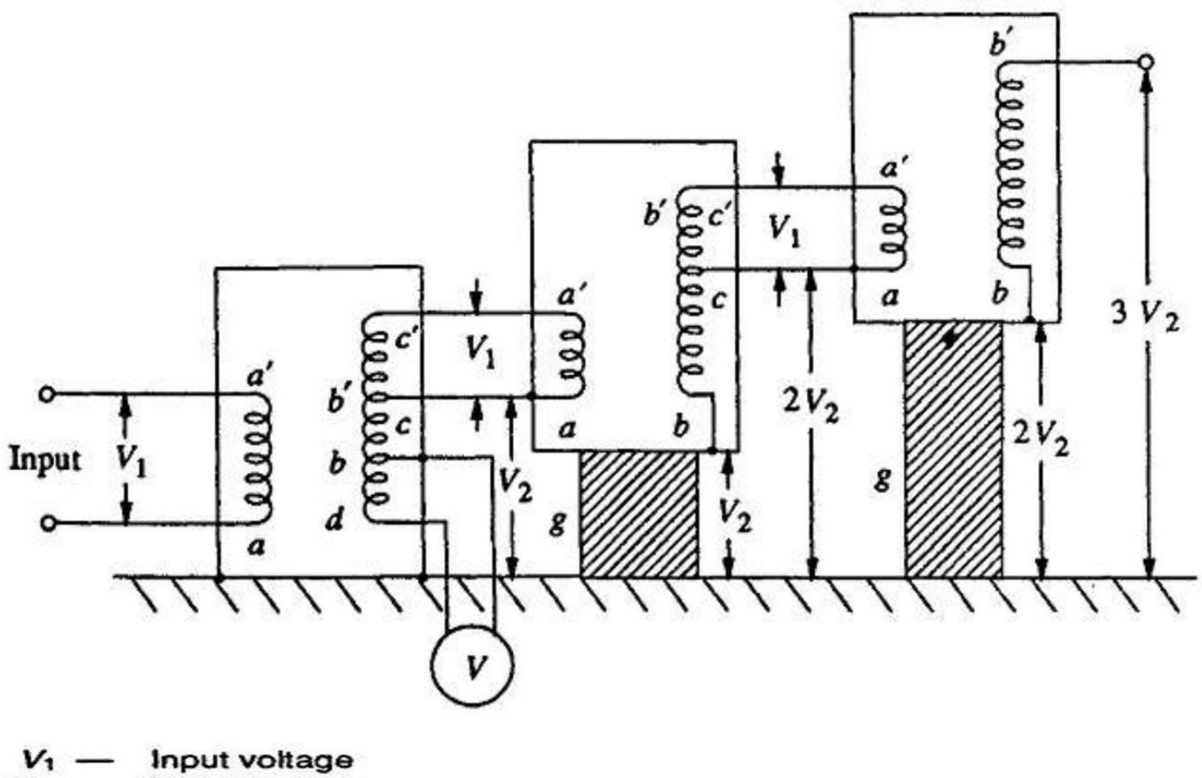
$$Q_0 = C_0 (V+E) + E(Cs + C_r),$$

where C5 is the stator capacitance to earth, Cr is the capacitance of rectifier B to earth, and CQ is the minimum capacitance value of C (stator to rotor capacitance). A generator of this type with an output voltage of one MV and a field gradient of 1 MV/cm in high vacuum and having 16 rotor poles, 50 rotor plates of 4 feet maximum and 2 feet minimum diameter, and a speed of 4000 rpm would develop 7 MW of power.

With a neat circuit explain the working generation of High AC.voltages, impulse voltages.

GENERATION OF HIGH ALTERNATING VOLTAGES

Cascade transformer connection



V_1 — Input voltage
V_2 — Output voltage
aa′ — L.V. primary winding
bb′ — H.V. secondary winding
cc′ — Excitation winding
bd — Meter winding (200 to 500 V)

When test voltage requirements are less than about 300 kV, a single transformer can be used for test purposes. The impedance of the transformer should be generally less than 5% and must be capable of giving the short circuit current for one minute or more depending on the design.

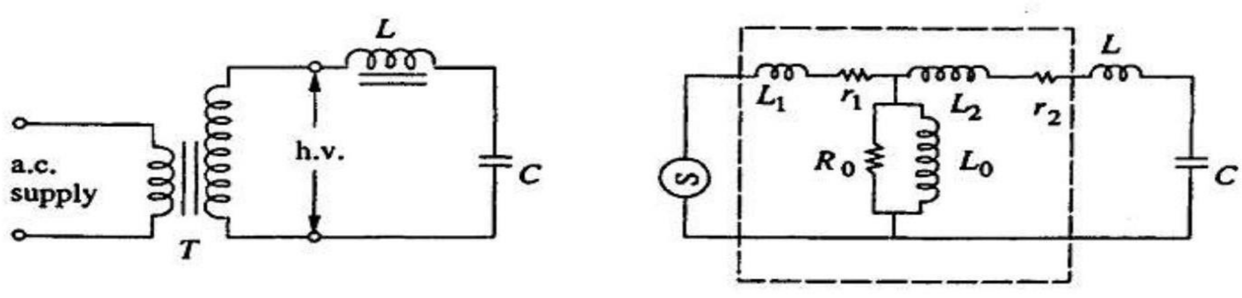
In addition to the normal windings, namely, the low and high voltage windings, a third winding known as meter winding is provided to measure the output voltage. For higher voltage requirements, a single unit construction becomes difficult and costly due to insulation problems

These drawbacks are overcome by series connection or cascading of the several identical units of transformers, wherein the high voltage windings of all the units effectively come in series.

Resonant Transformers

The equivalent circuit of a high voltage testing transformer consists of the leakage reactances of the windings, the winding resistances, the magnetizing reactance, and the shunt capacitance across the output terminal due to the bushing of the high voltage terminal and also that of the test object. This is shown in Fig. with its equivalent circuit in Fig. . It may be seen that it is possible to have series resonance at power frequency O), if (L1 +L2)=1µf. With this condition, the current in the test object is very large and is limited only by the resistance of the circuit. The waveform of the voltage across the test object will be purely sinusoidal. The magnitude of the voltage across the capacitance C of the test object will be

$$V_C = \left|\frac{-jVX_C}{R+j(X_L-X_C)}\right| = \frac{V}{R}X_C = \frac{V}{\omega CR}$$



(a) (b)

T — Testing transformer
L — Choke
C — Capacitance of h.v. terminal and test object
L_0 — Magnetizing inductance

L_1, L_2 — Leakage inductances of the transformer
r_1, r_2 — Resistances of the windings
R_0 — Resistance due to core loss

The factor Xc/R = 1/ (ωCR is the Q factor of the circuit and gives the magnitude of thevoltage multiplication across the test object under resonance conditions. Therefore, The input voltage required for excitation is reduced by a factor 1/Q, and the output kVA required is also reduced by a factor 1/Q. The secondary power factor of the circuit is unity.

This principle is utilized in testing at very high voltages and on occasions requiring large current outputs such as cable testing, dielectric loss measurements, partial discharge measurements, etc.

A transformer with 50 to 100 kV voltage rating and a relatively large current rating is connected together with an additional choke, if Excitation transformer Regulator Load capacitance Reactor Series resonant a.c. test system Excitation transformer Regulator Load capacitance Reactor necessary.

The test condition is set such that G)(Le+ L) = 1/ωC where Le is the total equivalent leakage inductance of the transformer including its regulating transformer. The chief advantages of this principle are:

(a) it gives an output of pure sine wave,

(b) power requirements are less (5 to 10% of total kVA required),

(c) no high-power arcing and heavy current surges occur if the test object

fails, as resonance ceases at the failure of the test object,

(d) cascading is also possible for very high voltages,

(e) simple and compact test arrangement, and

(f) No repeated flashovers occur in case of partial failures of the test object and insulation recovery. It can be shown that the supply source takes Q number of cycles at least to charge the test specimen to the full voltage.

Generation of High Frequency a.c. High Voltages

High frequency high voltages are required for rectifier d.c. power supplies as discussed in Sec. 6.1. Also, for testing electrical apparatus for switching surges, high frequency high voltage damped oscillations are needed which need high voltage high frequency transformers. The advantages of these high frequency transformers are:

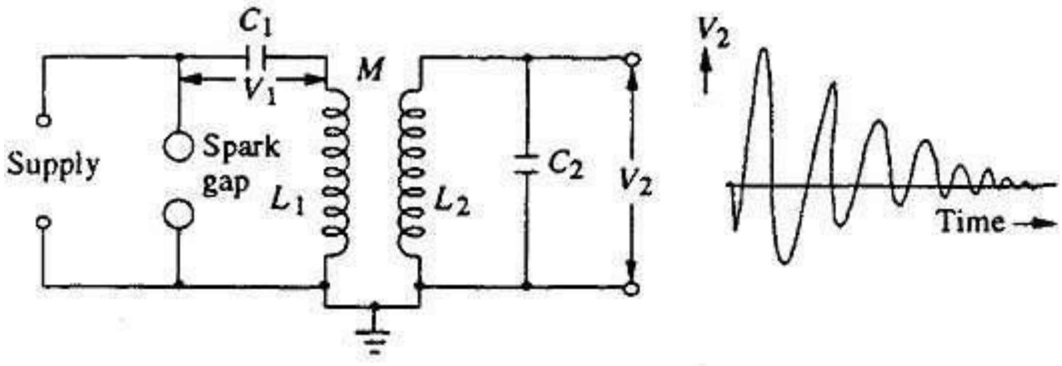
(i) the absence of iron core in transformers and hence saving in cost and size,

(ii) pure sine wave output,

(iii) slow build-up of voltage over a few cycles and hence no damage due to switching surges,

(iv) uniform distribution of voltage across the winding coils due to sub division of coil stack into a number of units.

The commonly used high frequency resonant transformer is the Tesla coil, which is a doubly tuned resonant circuit shown schematically in Fig. 6.13a. The primary voltage rating is 10 kV and the secondary may be rated to as high as 500 to 1000 kV.The primary is fed from a d.c. or a.c. supply through the condenser C1.



(a) Equivalent circuit (b) Output waveform

A spark gap G connected across the primary is triggered at the desired voltage V2which induces a high self-excitation in the secondary. The primary and the secondary windings (L1 and L2) are wound on an insulated former with no core (air-cored) and are immersed in oil. The windings are tuned to a frequency of 10 to 100 kHz by means of the condensers C1 and C2. The output voltage V2 is a function of the parameters LI, L2, C1, C2 and the mutual inductance M. Usually, the winding resistances will be small and contribute only for damping of the oscillations.

The analysis of the output waveform can be done in a simple manner neglecting the winding resistances. Let the condenser C1 be charged to a voltage V1 when the spark gap is triggered. Let a current $i_1$flow through the primary winding L1andproduce a current i_2 through L_2 and C_2

Then,

$$V_1 = \frac{1}{C_1}\int_0^t i_1\,dt + L_1\frac{di_1}{dt} + M\frac{di_2}{dt}$$

and,

$$0 = \frac{1}{C_2}\int_0^t i_2\,dt + L_2\frac{di_2}{dt} + M\frac{di_1}{dt}$$

The Laplace transformed equations for the above are,

$$\frac{V_1}{s} = \left[L_1 s + \frac{1}{C_1 s}\right] I_1 + MsI_2$$

and,

$$0 = [Ms]I_1 + \left[L_2 s + \frac{1}{[C_2 s]}\right] I_2$$

where I_1 and I_2 are the Laplace transformed values, of i_1 and i_2.

The output voltage V_2 across the condenser C_2 is

$$V_2 = \frac{1}{C_2}\int_0^t i_2 dt;$$ or its transformed equation is

$$V_2(s) = \frac{I_2}{C_2 s}$$

where $V_2(s)$ is the Laplace transform of V_2.

The solution for V_2 from the above equations will be

$$V_2 = \frac{MV_1}{\sigma L_1 L_2 C_1}\,\frac{1}{\gamma_2^2 - \gamma_1^2}\,[\cos\gamma_1 t - \cos\gamma_2 t]$$

where,

$$\sigma^2 = 1 - \frac{M^2}{L_1 L_2} = 1 - K^2$$

K = coefficient of coupling between the windings L_1 and L_2

$$\gamma_{1,2} = \frac{\omega_1^2 + \omega_2^2}{2} \pm \sqrt{\left(\frac{\omega_1^2 + \omega_2^2}{2}\right)^2 - \omega_1^2\omega_2^2(1 - K^2)}$$

$$\omega_1 = \frac{1}{\sqrt{L_1 C_1}} \text{ and } \omega_2 = \frac{1}{\sqrt{L_2 C_2}}$$

The peak amplitude of the secondary voltage V_2 can be expressed as,

$$V_{2\max} = V_1 e\sqrt{\frac{L_2}{L_1}}$$

where,

$$e = \frac{2\sqrt{(1-\sigma)}}{\sqrt{(1+a)^2 - 4\sigma a}}$$

$$a = \frac{L_2 C_2}{L_1 c_1} = \frac{W_1^2}{W_2^2}$$

A more simplified analysis for the Tesla coil may be presented by considering that the energy stored in the primary circuit in the capacitance C1 is transferred to C2 via the magnetic coupling. If W1 is the energy stored in C1 and W2 is the energy transferred to C2 and if the efficiency of the transformer is η, then

$$W_1 = \frac{1}{2}\eta C_1 V_1^2 = (\tfrac{1}{2}C_2 V_2^2)$$

$$V_2 = V_1\sqrt{\eta \frac{C_1}{C_2}}$$

It can be shown that if the coefficient of coupling K is large the oscillation frequency is less, and for large values of the winding resistances and K, the waveform may become a unidirectional impulse. This is shown in the next sections while dealing with the generation of switching surges

GENERATION OF IMPULSE VOLTAGES

Standard Impulse Wave shapes

Transient over voltages due to lightning and switching surges cause steep build-up of voltage on transmission lines and other electrical apparatus. Experimental investigations showed that these waves have a rise time of 0.5 to. 10 Ji s and decay time to 50%of the peak value of the order of 30 to 200 \i s. The waveshapes are arbitrary, but mostly unidirectional. It is shown that lightning overvoltage wave can be representedas double exponential waves defined by the equation

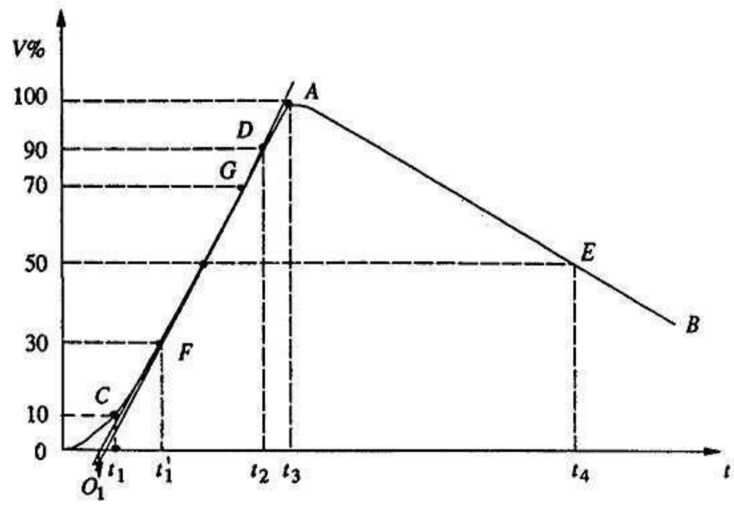
$$V = V_0 [\exp(-\alpha t) - \exp(-\beta t)]$$

whereα and β are constants of microsecond values.

The above equation represents a unidirectional wave which usually has a rapid rise to the peak value and slowly falls to zero value. The general wave shape is given in Fig. Impulse waves are specified by defining their rise or front time, fall or tail time to 50% peak value, and the value of the peak voltage.

Thus 1.2/50 μs, 1000 kV wave represents an impulse voltage wave with a front time of 1.2 (is, fall time to 50% peak value of 50μs, and a peak value of 1000 kV. When impulse wave shapes are recorded, the initial portion of the wave will not be clearly defined or sometimes will be missing. Moreover, due to disturbances it may contain superimposed oscillations in the rising portion. Hence, the front and tail times have to be defined.

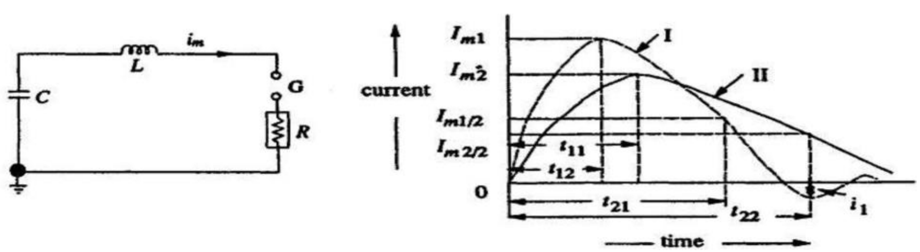
Referring to the wave shape in the peak value A is fixed and referred to as 100% value. The points corresponding to 10% and 90% of the peak values are located in the front portion (points C and D). The line joining these points is extended to cut the time axis at 0_1. 0_1 is taken as the virtual origin. 1.25 times the interval between times t\ and ti corresponding to points C and D (projections on the time axis)

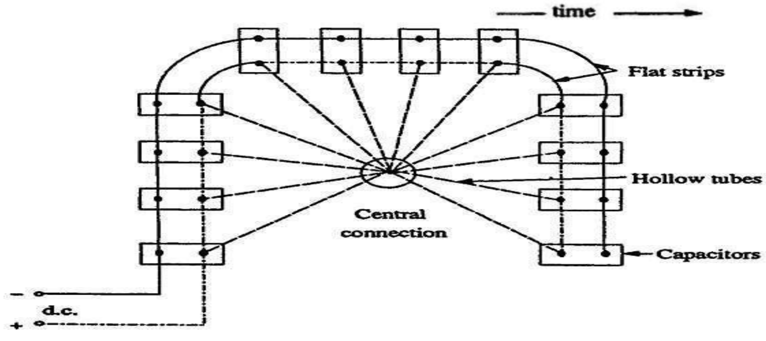


With neat diagram explain the working of generation of Impulse Currents.

GENERATION OF IMPULSE CURRENTS

Lightening discharges involve both high voltage impulses and high current impulses on transmission lines. Protective gear like surge diverters have to discharge the lightning currents without damage. Therefore, generation of impulse current waveforms of high magnitude («100 kA peak) find application in testing work as well as in basic research on non-linear resistors, electric arc studies, and studies relating to electric plasmas in high current discharges.





For producing impulse currents of large value, a bank of capacitors connected in parallel are charged to a specified value and are discharged through a series R-L circuit as shown in Fig. represents a bank of capacitors connected in parallel which are charged from a d.c. source to a voltage up to 200 kV. R represents the dynamic resistance of the test object and the resistance of the circuit and the shunt L is an air cored high current inductor, usually a spiral tube of a few turns.If the capacitor is charged to a voltage V and discharged when the spark gap is triggered, the current it will be given by the equation

$$V = R\, i_m + L\frac{di_m}{dt} + \frac{1}{C}\int_0^t i_m\, dt$$

The circuit is usually underdamped, so that

$$\frac{R}{2} < \sqrt{L/C}$$

Hence, i_m is given by

$$i_m = \frac{V}{\omega L}[\exp(-\alpha t)]\sin(\omega t)$$

where $$\alpha = \frac{R}{2L} \text{ and } \omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

The time taken for the current i_m to rise from zero to the first peak value is

$$t_1 = t_f = \frac{1}{\omega}\sin^{-1}\frac{\omega}{\sqrt{LC}} = \frac{1}{\omega}\tan^{-1}\frac{\omega}{\alpha}$$

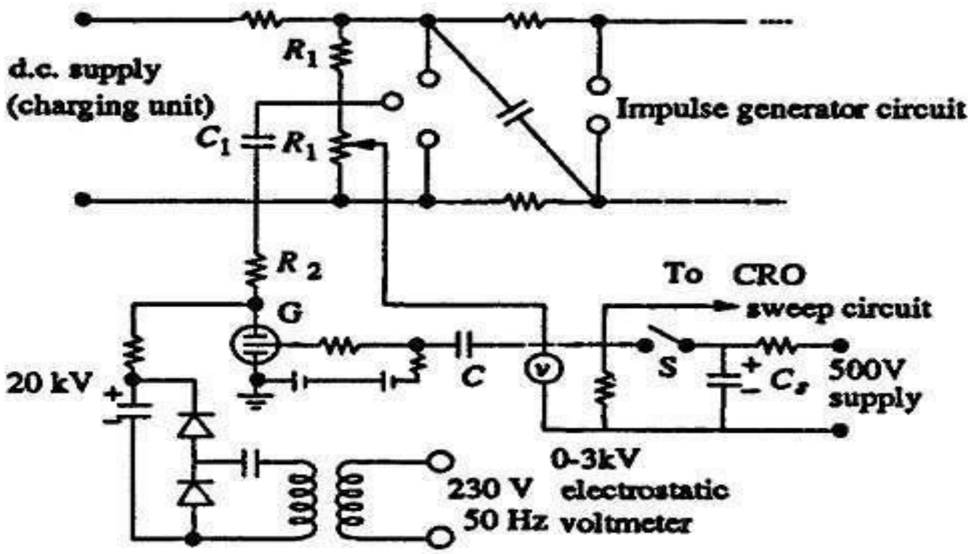
The duration for one half cycle of the damped oscillatory wave t_2 is,

$$t_2 = \frac{\pi}{\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}}$$

TRIPPING AND CONTROL OF IMPULSE GENERATORS

In large impulse generators, the spark gaps are generally sphere gaps or gaps formed by hemispherical electrodes.

The gaps are arranged such that sparking of one gap results in automatic sparking of other gaps as overvoltage is impressed on the other. In order to have consistency in sparking, irradiation from an ultra-violet lamp is provided from the bottom to all the gaps.



To trip the generator at a predetermined time, the spark gaps may be mounted on a movable frame, and the gap distance is reduced by moving the movable electrodes closer. This method is difficult and does not assure consistent and controlled tripping.

A simple method of controlled tripping consists of making the first gap a three electrode gap and firing it from a controlled source. Figure gives the schematic arrangement of a three electrode gap. The first stage of the impulse generator is fitted with a three electrode gap, and the central electrode is maintained at a potential in between that of the top and the bottom electrodes with the resistors R\ and RL.

The tripping is initiated by applying a pulse to the thyratron G by closing the switch S. The capacitor C produces an exponentially decaying pulse of positive polarity. The pulse goes and initiates the oscillograph time base. The thyrister conducts on receiving the pulse from the switch S and produces a negative pulse through the capacitance C1 at the central electrode of the three electrode gap. Hence, the voltage between the central electrode and the top electrode of the three electrode gap goes above its sparking potential and thus the gap conducts. The time lag required for the thyratron firing and breakdown of the three electrode gap ensures that the sweep circuit of the oscillograph coupling of voltage oscillations produced at the spark gap entering the oscilloscope through the common trip circuit

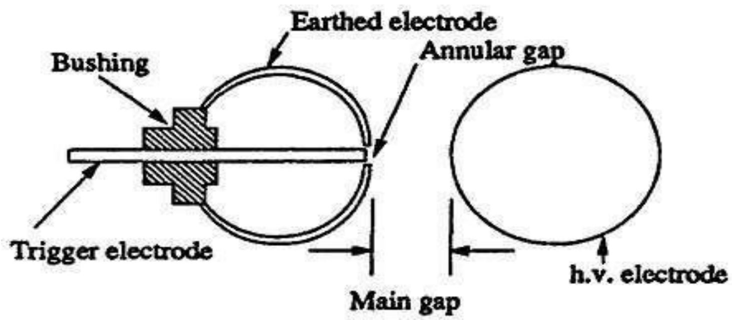
.The three electrode gap requires larger space and an elaborate construction. Now-a-days a trigatron gap shown in Fig. is used, and this requires much smaller voltage for operation compared to the three electrode gap.

A trigatron gap consists of a high voltage spherical electrode of suitable size, an earthed main electrode of spherical shape, and a trigger electrode through the main electrode. The trigger electrode is a metal rod with an annular clearance of about 1 mm fitted into the main electrode through a bushing.

The trigatron is connected to a pulse circuit as shown in figure. Tripping of the impulse generator is effected by a trip pulse which produces a spark between the trigger electrode and the earthed sphere. Due to space charge effects and distortion of the field in the main gap, spark over of the main gap Three Electrode Gap for Impulse Current Generator

In the case of impulse current generators using three electrode gaps for tripping and control, a certain special design is needed. The electrodes have to carry high current from the capacitor bank. Secondly, the electrode has to switch large currents in a small duration of time (in about a microsecond).

Therefore, the switch should have very low inductance. The erosion rate of the electrodes should be low. For high current capacitor banks, a number of spark gap switches connected in parallel as shown in Fig. are often used to meet the requirement.



Recently,trigatron gaps are being replaced by triggered vacuum gaps, the advantage of the latter being fast switching at high currents (> 100 kA) in a few nanoseconds. Triggering of the spark gaps by focused laser beams is also adopted since the performance is better than the conventional triggering methods.

UNIT IV

HIGH VOLTAGE TESTING &INSULATION COORDINATION

Explain the various methods involved in DC measurement with neat diagrams

High Ohmic Series Resistance with Micro ammeter

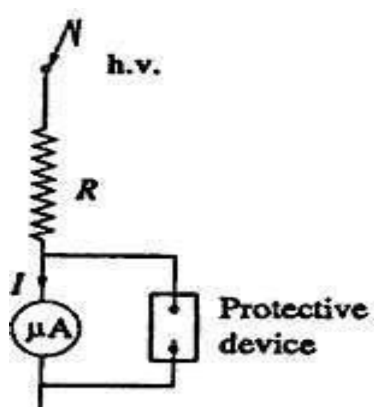
- ✓ High d.c. voltages are usually measured by connecting a very high resistance (few hundreds of mega ohms) in series with a micro ammeter as shown in Fig. Only the current I flowing through the large calibrated resistance R is measured by the moving coil micro ammeter. The voltage of the source is given by the voltage drop in the meter is negligible, as the impedance of the meter is only few ohms compared to few hundred mega-ohms of the series resistance R.
- ✓ A protective device like a paper gap, a neon glow tube, or a zener diode with a suitable series resistance is connected across the meter as a protection against high voltages in case the series resistance R fails or flashes over.
- ✓ The ohmic value of the series resistance R is chosen such that a current of one to ten microamperes is allowed for full-scale deflection. The resistance is constructed from a large number of wire wound resistors in series. The voltage drop in each resistor element is chosen to avoid surface flashovers and discharges.kV/cm in good oil is permissible.
- ✓ The resistor chain is provided with corona free terminations. The material for resistive elements is usually a carbon-alloy with temperature coefficient less than $10^{-4}/^{0}C$. Carbon and other metallic film resistors are also used.
- ✓ A resistance chain built with ±1% carbon resistors located in an airtight transformer oil filled P.V.C. tube, for 100 kV operations had very good temperature stability. The limitations in the series resistance design are:

(i) power dissipation and source loading,

(ii) temperature effects and longtime stability,

(iii) voltage dependence of resistive elements, and

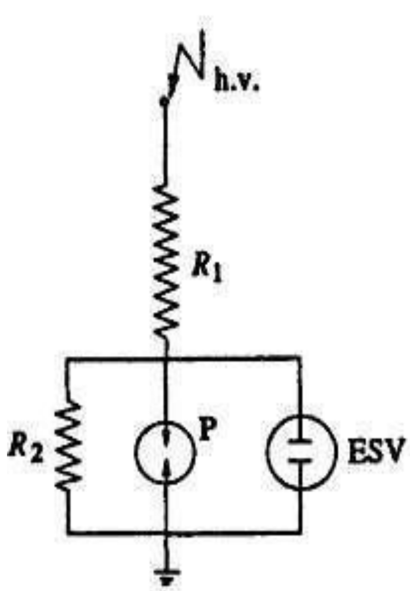
(iv) sensitivity to mechanical stresses.

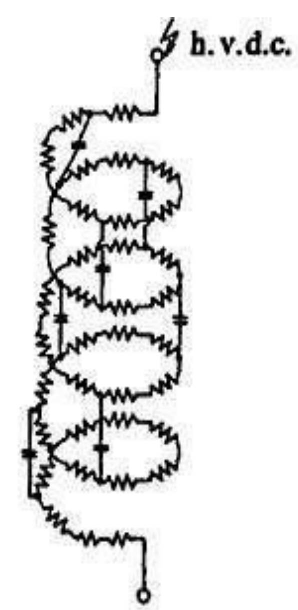


Series resistance meters are built for 500 kV d.c. with an accuracy better than 0.2%.

Resistance Potential Dividers for D.C. Voltages

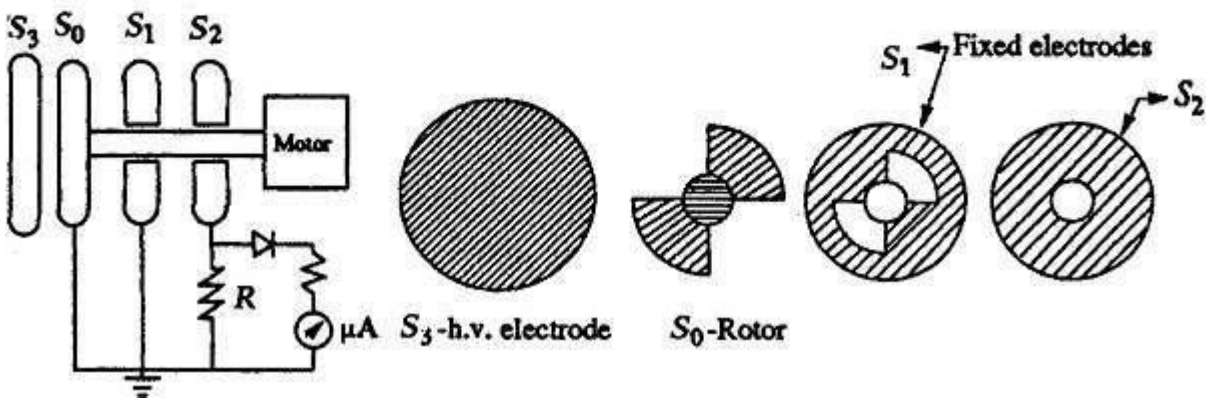
- A resistance potential divider with an electrostatic or high impedance voltmeter is shown in Fig The influence of temperature and voltage on the elements is eliminated in the voltage divider arrangement. The high voltage magnitude is given by [(R1 + R2)/R2]V2, where V2 is the d.c. voltage across the low voltage arm R2.
- With sudden changes in voltage, such as switching operations, flashover of the test objects, or source short circuits, flashover or damage may occur to the divider elements due to the stray capacitance across the elements and due to ground capacitances.
- To avoid these transient voltages, voltage controlling capacitors are connected across the elements. A corona free termination is also necessary to avoid unnecessary discharges at high voltage ends.
- A series resistor with a parallel capacitor connection for linearization of transient potential distribution is shown in Fig. Potential dividers are made with 0.05% accuracy up to 100 kV, with 0.1% accuracy up to 300 kV, and with better than 0.5% accuracy for 500 kV.





Explain with neat diagram Generating voltmeter.

Generating Voltmeters



- ✓ High voltage measuring devices employ generating principle when source loading is prohibited (as with Van de Graff generators, etc.) or when direct connection to the high voltage source is to be avoided.
- ✓ A generating voltmeter is a variable capacitor electrostatic voltage generator which generates current proportional to the applied external voltage. The device is driven by an external synchronous or constant speed motor and does not absorb power or energy from the voltage measuring source
- ✓ A generating voltmeter with a rotating cylinder consists of two exciting field electrodes and a rotating two pole armature driven by a synchronous motor at a constant speed n. The a.c. current flowing between the two halves of the armature is rectified by a commutator.
- ✓ This device can be used for measuring a.c. voltages provided the speed of the drive-motor is half the frequency of the voltage to be measured. Thus a four-pole synchronous motor with 1500 rpm is suitable for 50 Hz.
- ✓ For peak value measurements, the phase angle of the motor must also be so adjusted that Cmax and the crest value occur at the same instant. Generating voltmeters employ rotating sectors or vanes for variation of capacitance.
- ✓ Figure gives a schematic diagram of a generating voltmeter. The high voltage source is connected to a disc electrode S_3 which is kept at a fixed distance on the axis of the other low voltage electrodes S0, S1 and S2 The rotor S0 driven at a constant speed by a synchronous motor at a suitable speed (1500,1800,3000, or 3600 rpm).

- ✓ The rotor vanes of S0 cause periodic change in capacitance between the insulated disc S_2 and the h.v. electrode S_3. The shape and number of the vanes of S_0 and S_1 are so designed that they produce sinusoidal variation in the capacitance.
- ✓ The generated a.c. current through the resistance R is rectified and read by a moving coil instrument an amplifier is needed, if the shunt capacitance is large or longer leads are used for connection to rectifier and meter. The instrument is calibrated using a potential divider or sphere gap. The meter scale is linear and its range can be extended

Advantages of Generating Voltmeters

(i) No source loading by the meter,

(ii) no direct connection to high voltage electrode,

(iii) scale is linear and extension of range is easy, and

(iv) A very convenient instrument for electrostatic devices such as Van de Graff generator and particle accelerators.

Limitations of Generating Voltmeters

(i) They require calibration,

(ii) careful construction is needed and is a cumbersome instrument requiring an auxiliary drive,

(iii) Disturbance in position and mounting of the electrodes make the calibration invalid.

Explain the various methods involved in High AC measurement with neat diagrams

Series Impedance Voltmeters

- ✓ For power frequency a.c. measurements the series impedance may be a pure resistance or a reactance. Since resistances involve power losses, often a capacitor is preferred as a series reactance.
- ✓ Moreover, for high resistances, the variation of resistance with temperature is a problem, and the residual inductance of the resistance gives rise to impedance different from its ohmic resistance.
- ✓ High resistance units for high voltages have stray capacitances and hence a unit resistance will have an equivalent circuit as shown in Fig. At any frequency ω of the a.c. voltage, the impedance of the resistance R is For power frequency a.c. measurements the series impedance may be a pure resistance or a reactance.

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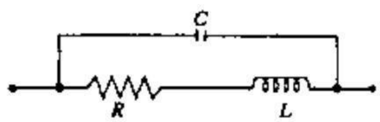
- ✓ High resistance units for high voltages have stray capacitances and hence a unit resistance will have an equivalent circuit as shown in Fig. At any frequency ω of the a.c. voltage, the impedance of the resistance R is

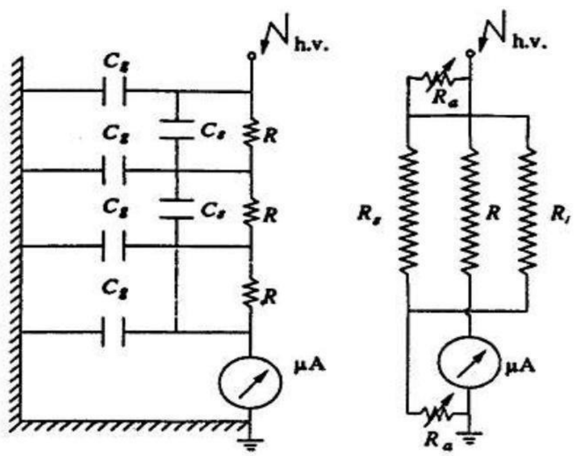
$$Z = \frac{R + j\omega L}{(1 - \omega^2 LC) + j\omega CR}$$



Simplified lumped parameter equivalent circuit of a high ohmic resistance R

L — Residual inductance

C —Residual capacitance



- ✓ For extended and large dimensioned resistors, this equivalent circuit is not valid and each elemental resistor has to be approximated with this equivalent circuit.
- ✓ The entire resistor unit then has to be taken as a transmission line equivalent, for calculating the effective resistance. Also, the ground or stray capacitance of each element influences the current flowing in the unit, and the indication of the meter results in an error.

- ✓ The equivalent circuit of a high voltage resistor neglecting inductance and the circuit of compensated series resistor using guard and timing resistors is shown in fig respectively.
- ✓ Stray ground capacitance effects can be removed by shielding the resistor by a second surrounding spiral Rs, which shunts the actual resistor but does not contribute to the current through the instrument.
- ✓ By tuning the resistors Ra the shielding resistor end potentials may be adjusted with respect to the actual measuring resistor so that the resulting compensation currents between the shield and the measuring resistors provide a minimum phase angle.

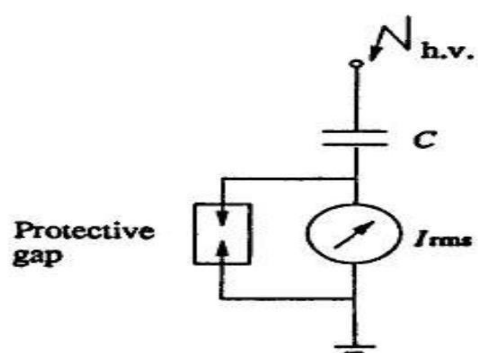
Series Capacitance Voltmeter

To avoid the drawbacks pointed out earlier, a series capacitor is used instead of a resistor for a.c. high voltage measurements. The schematic diagram is shown in Fig.. The current Ic through the meter is:

$$I_c = j\omega CV$$

Hence, the resultant rms current is:

$$I = \omega C (V_1^2 + 4V_2^2 + \ldots + n^2 V_n^2)^{1/2}$$



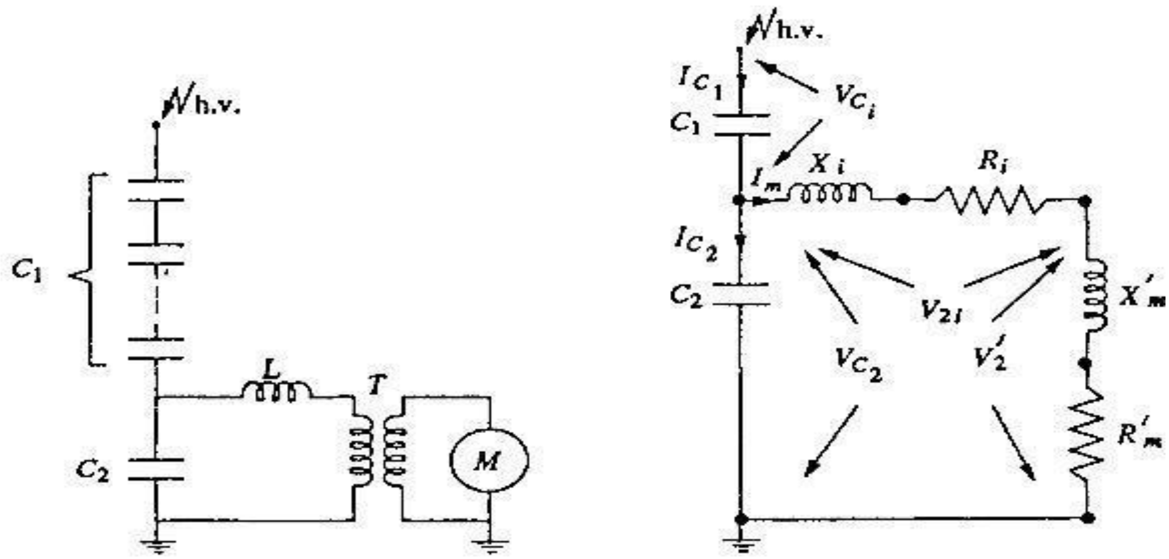
- ✓ Series capacitance voltmeters were used with cascade transformers for measuring rms values up to 1000 kV. The series capacitance was formed as a parallel plate capacitor between the high voltage terminal of the transformer and a ground plate suspended above it.
- ✓ A rectifier ammeter was used as an indicating instrument and was directly calibrated in high voltage RMS value. The meter was usually a 0-100 μAmoving coil meter and the overall error was about 2%.

Explain the working of CVT with diagrams.

CAPACITANCE VOLTAGE TRANSFORMER—CVT

- ✓ Capacitance divider with a suitable matching or isolating potential transformer tuned for resonance condition is often used in power systems for voltage measurements. This is often referred to as CVT.
- ✓ In contrast to simple capacitance divider which requires a high impedance meter like or an electrostatic condenser voltmeter, a CVT can be connected to a low impedance device like a condenser wattmeter pressure coil or a relay coil CVT can supply load of a few VA.
- ✓ The schematic diagram of a CVT with its equivalent circuit is given in Fig. C1 is made of a few units of high voltage condensers, and the total capacitance will be around a few thousand picofarads as against a gas filled standard condenser of about 100 pF.
- ✓ A matching transformer is connected between the load or meter M and C2. The transformer ratio is chosen on economic grounds, and the h.v. winding rating may be 10 to 30 kV with the Lv. winding rated from 100 to 500 V.
- ✓ The value of the tuning choke L is chosen to make the equivalent circuit of the CVT purely resistive or to bring resonance condition. This condition is satisfied when

$$\omega(L + L_T) = \frac{1}{\omega(C_1 + C_2)}$$



(a) Schematic representation

(b) Equivalent circuit

The advantages of a CVT are:

(i) simple design and easy installation,

(ii) Can be used both as a voltage measuring device for meter and relaying purposes and also as a coupling condenser for power line carrier communication and relaying.

(iii) frequency independent voltage distribution along elements as against conventional magnetic potential transformers which require additional insulation design against surges, and

(iv) Provides isolation between the high voltage terminal and low voltage metering.

The disadvantages of a CVT are:

(i) the voltage ratio is susceptible to temperature variations, and

(ii) The problem of inducing Ferro-resonance in power systems.

Explain the working of Electrostatic Voltmeters with diagrams.

Electrostatic Voltmeters

Construction

Electrostatic voltmeters are made with parallel plate configuration using guard rings to avoid corona and field fringing at the edges. An absolute voltmeter is made by balancing the plate with a counter weight and is calibrated in terms of a small weight.

Usually the electrostatic voltmeters have a small capacitance (5 to 50 pF) and high insulation resistance ($R > 10^{13}$ Q). Hence they are considered as devices with high input impedance. The upper frequency limit for a.c. applications is determined from the following considerations:

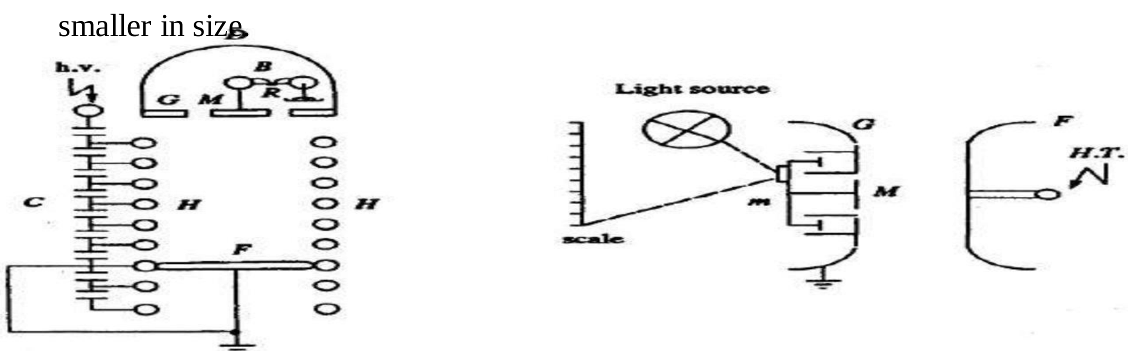
(i) natural frequency of the moving system,

(ii) resonant frequency of the lead and stray inductances with meter capacitance,

(iii) The R-C behavior of the retaining or control spring

- ✓ An upper frequency limit of about one MHz is achieved in careful designs. The accuracy for a.c. voltage measurements is better than ±0.25%, and for d.c. voltage measurements it may be ±0.1% or less.
- ✓ The schematic diagram of an absolute electrostatic voltmeter or electrometer is given in Fig. It consists of parallel plane disc type electrodes separated by a small distance. The moving electrode is surrounded by a fixed guard ring to make the field uniform in the central region.
- ✓ In order to measure the given voltage with precision, the disc diameter is to be increased, and the gap distance is to be made less. The limitation on the gap distance is the safe working stress (V/s) allowed in air which is normally 5 kV/cm or less.

- ✓ The main difference between several forms of voltmeters lies in the manner in which the restoring force is obtained. For conventional versions of meters, a simple spring control is used, which actuates a pointer to move on the scale of the instruments.
- ✓ In more versatile instruments, only small movements of the moving electrodes are allowed, and the movement is amplified through optical means (lamp and scale arrangement as used with moving coil galvanometers).
- ✓ Two air vane dampers are used to reduce vibrational tendencies in the moving system, and the elongation of the spring is kept minimum to avoid field disturbances. The range of the instrument is easily changed by changing the gap separation so that V/s or electric stress is the same for the maximum value in any range.
- ✓ Multi-range instruments are constructed for 600 W rms and above. The constructional details of an absolute electrostatic voltmeter are given in Fig. The control torque is provided by a balancing weight the moving disc M forms the central core of the guard ring G which is of the same diameter as the fixed plate F.
- ✓ The cap D encloses a sensitive balance B, one arm of which carries the suspension of the moving disc. The balance beam carries a mirror which reflects abeam of light. The movement of the disc is thereby magnified.
- ✓ As the spacing between the two electrodes is large, the uniformity of the electric field is maintained by the guard rings H which surround the space between the discs F and M. The guard rings H are maintained at a constant potential in space by a capacitance divider ensuring a uniform special potential distribution.
- ✓ Some instruments are constructed in an enclosed structure containing compressed air, carbon dioxide, or nitrogen. The gas pressure may be of the order of IS atm. working stresses as high as 100 kV/cm may be used in an electrostatic meter in Light sources vacuum. With compressed gas or vacuum as medium, the meter is compact and much smaller in size.



(a) Absolute electrostatic voltmeter

m — mirror

(b) Light beam arrangement

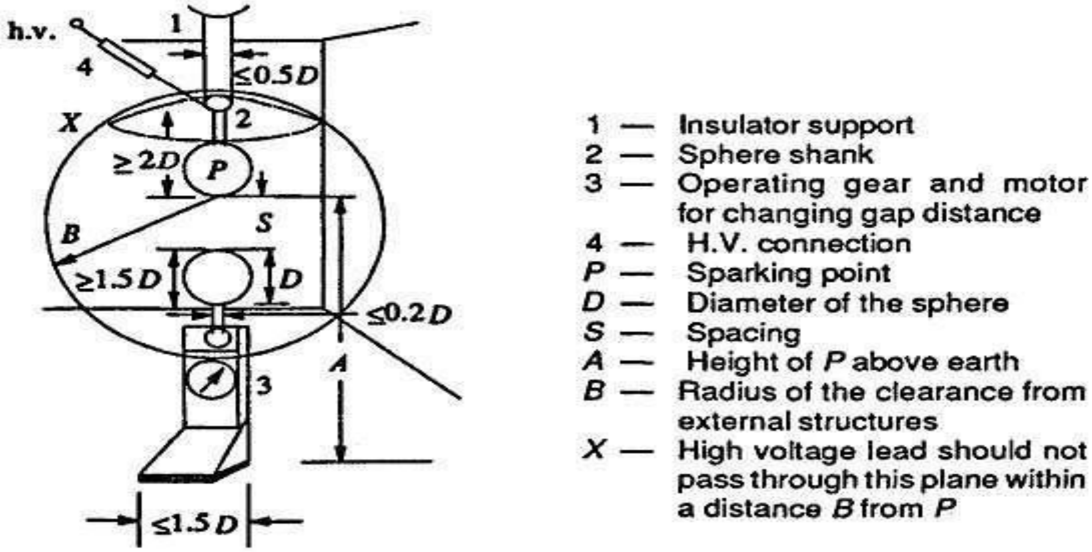
M — Mounting plate
G — Guard plate
F — Fixed plate
H — Guard hoops or rings

B — Balance
C — Capacitance divider
D — Dome
R — Balancing weight

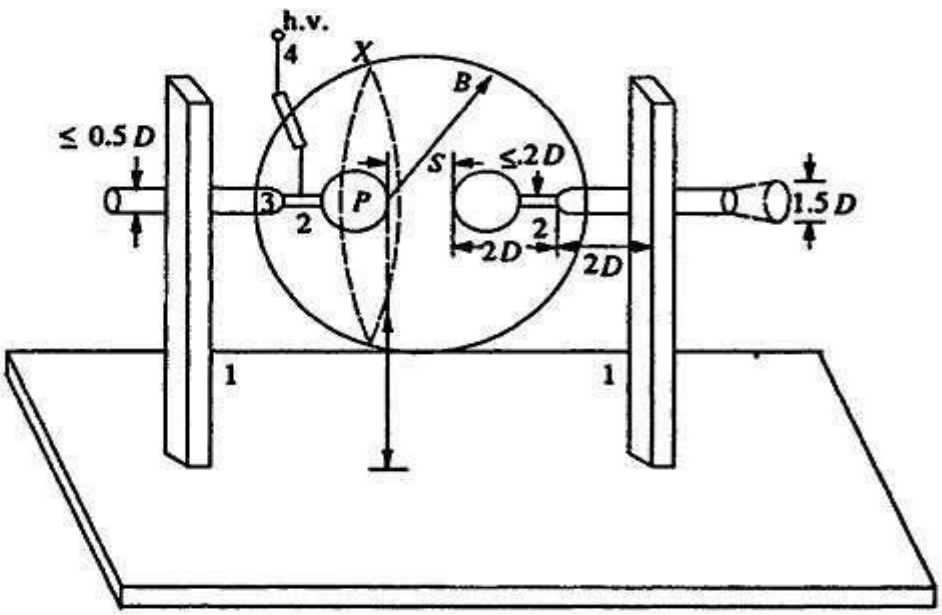
Explain the working of Spark Gaps for Measurement of High D.C., A.C. and Impulse Voltages

Spark Gaps for Measurement of High D.C., A.C. and Impulse Voltages (Peak Values)

- ✓ A uniform field spark gap will always have a spark over voltage within a known tolerance under constant atmospheric conditions. Hence a spark gap can be used for measurement of the peak value of the voltage, if the gap distance is known.
- ✓ A spark over voltage of 30 kV (peak) at 1 cm spacing in air at $2O^{0}$ C and 760 torr pressure occurs for a sphere gap or any uniform field gap. But experience has shown that these measurements are reliable only for certain gap configurations.
- ✓ Normally, only sphere gaps are used for voltage measurements. In certain cases uniform field gaps and rod gaps are also used, but their accuracy is less. The spark gap breakdown, especially the sphere gap breakdown, is independent of the voltage waveform and hence is highly suitable for all types of waveforms from d.c. to impulse voltages of short rise times(rise time > 0.5 M. s).
- ✓ As such, sphere gaps can be used for radio frequency a.c. voltage peak measurements also (up to 1 MHz).Sphere Gap Measurements Sphere gaps can be arranged either (i) vertically with lower sphere grounded, or (ii)horizontally with both spheres connected to the source voltage or one sphere grounded.
- ✓ In horizontal configurations, it is generally arranged such that both spheres are symmetrically at high voltage above the ground. The two spheres used are identical in size and shape. The schematic arrangement is shown in Figs..
- ✓ The voltage to be measured is applied between the two spheres and the distance or spacing 5 between them gives a measure of the spark over voltage. A series resistance is usually connected between the source and the sphere gap to (i) limit the breakdown current, and (ii) to suppress unwanted oscillations in the source voltage when breakdown occurs (in case of impulse voltages).
- ✓ The value of the series resistance may vary from 100 to 1000 kilo ohms for a.c. or d.c. voltages and not more In the case of a.c. peak value and d.c. voltage measurements, the applied voltage is uniformly increased until spark over occurs in the gap.
- ✓ Generally, a mean of about five breakdown values is taken when they agree to within ±3%. In the case of impulse voltages, to obtain 50% flashover voltage, two voltage limits, differing by not more than 2% are set such that on application of lower limit value either 2 or 4 flashovers take place or on application of upper limit value 8 or 6 flashovers take place respectively.
- ✓ The mean of these two limits is taken as 50% flashover voltage. In any case, a preliminary spark over voltage measurement is to be made before actual measurements are made.



(a) Vertical arrangement of sphere gap



Factors Influencing the Spark over Voltage of Sphere Gaps

Various factors that affect the spark over voltage of a sphere gap are:

(i) nearby earthed objects,

(ii) atmospheric conditions and humidity,

(iii) irradiation, and

(iv) Polarity and rise time of voltage waveforms.

Effect of nearby earthed objects

The effect of nearby earthed objects was investigated by enclosing the earthed sphere inside an earthed cylinder. It was observed that the spark overvoltage is reduced. The reduction was observed to be

$$\Delta V = m \log (B/D) + C$$

$\Delta V =$ percentage reduction,
$B =$ diameter of earthed enclosing cylinder,
$D =$ diameter of the spheres,
$S =$ spacing, and m and C are constants.

(ii) Effect of atmospheric conditions

The spark over voltage of a spark gap depends on the air density which varies with the changes in both temperature and pressure. If the spark over voltage is V under test conditions of temperature T and pressure p to rr and if the spark over voltage is VQ under standard conditionsof temperature T » 2O0C and pressure p = 760 to rr, then

$$V = kV_0$$

where k is a function of the air density factor d, given by

$$d = \frac{p}{760}\left(\frac{293}{273+T}\right)$$

(iii) Effect of Irradiation

Illumination of sphere gaps with ultra-violet or x-rays aids easy ionization in gaps. The effect of irradiation is pronounced for small gap spacings. A reduction of about 20% in spark over voltage was observed for spacings of 0.1 D to 0.3 D for a 1.3 cm sphere gap with d.c. voltages. The reduction in sparkover voltage is less than 5% for gap spacings more than 1 cm, and for gap spacings of 2 cm or more it is about 1.5%. Hence, irradiation is necessary for smaller sphere gapsof gap spacing less than 1 cm for obtaining consistent values.

(iv) Effect of polarity and waveform

It has been observed that the spark over voltages for positive and negative polarity impulses are different. Experimental investigation showed that for sphere gaps of 6.25 to 25 cm diameter, the difference between positive and negative d.c. voltages is not more than 1%. For smaller sphere gaps (2 cm diameter and less) the difference was about 8% between negative and positive impulses of 1/50μ s waveform. Similarly, the wave front and wave tail durations also influence the breakdown voltage. For wave fronts of less than 0.5 μs and wave tails less than 5 μ s the breakdown voltages are not consistent and hence the use of sphere gap is not recommended for voltage measurement in such cases.

Mention the different Electrical test on Over Head insulators

TESTING OF OVERHEAD LINE INSULATORS

High voltage testing of electrical equipment requires two types of tests:

(i) Type tests, and
(ii) Routine test.

Type tests involves quality testing of equipment at the design and development level

Routine tests are meant to check the quality of the individual test piece. This is carried out to ensure quality and reliability of individual test objects.

High voltage tests include

(i) Power frequency tests and
(ii) Impulse tests.

These tests are carried out on all insulators.

(i) 50% dry impulse flash over test.

(ii) Impulse withstand test.

(iii) Dry flash over and dry one minute test.

(iv) Wet flash over and one minute rain test.

(v) Temperature cycle test.

(vi) Electro-mechanical test.

(vii) Mechanical test.

(viii) Porosity test.

(ix) Puncture test.

(x) Mechanical routine test.

The tests mentioned above are briefly described here.

(i) The test is carried out on a clean insulator mounted as in a normal working condition. An impulse voltage of 1/50 μ sec. wave shape and of an amplitude which can cause 50% flash over of the insulator, is applied, i.e. of the impulses applied 50% of the impulses should cause flash over. The polarity of the impulse is then reversed and procedure repeated. There must be at least 20 applications of the impulse in each case and the insulator must not be damaged. The magnitude of the impulse voltage should not be less than that specified in standard specifications.

(ii) The insulator is subjected to standard impulse of 1/50 μ sec. wave of specified value under dry conditions with both positive and negative polarities. If five consecutive applications do not cause any flash over or puncture, the insulator is deemed to have passed the impulse withstand test. If out of five, two applications cause flash over, the insulator is deemed to have filed the test.

(iii) Power frequency voltage is applied to the insulator and the voltage increased to the specified value and maintained for one minute. The voltage is then increased gradually until flash over occurs. The insulator is then flashed over at least four more times, the voltage is raised gradually to reach flash over in about 10 seconds. The mean of at least five consecutive flash over voltages must not be less than the value specified in specifications.

(iv) If the test is carried out under artificial rain, it is called wet flash over test. The insulator is subjected to spray of water of following characteristics:

The insulator with 50% of the one-min. rain test voltage applied to it, is then sprayed for two minutes, the voltage raised to the one minute test voltage in approximately 10 sec. and maintained there for one minute. The voltage is then increased gradually till flash over occurs and the insulator is then lashed at least four more times, the time taken to reach flash over voltage being in each case about10 sec. The flash over voltage must not be less than the value specified in specifications.

(v) The insulator is immersed in a hot water bath whose temperature is 70° higher than normal water bath for T minutes. It is then taken out and immediately immersed in normal water bath for T minutes. After T minutes the insulator is again immersed in hot water bath for T minutes. The cycle is repeated three times and it is expected that the insulator should withstand the test without damage to the insulator or glaze. Here T = (15 + W/1.36) where W is the weight of the insulator in kgs.

(vi) The test is carried out only on suspension or tension type of insulator. The insulator is subjected to a 2½ times the specified maximum working tension maintained for one minute. Also, simultaneously 75% of the dry flash over voltage is applied. The insulator should withstandthis test without any damage.

(vii) This is a bending test applicable to pin type and line-post insulators. The insulator is subjected to a load three times the specified maximum breaking load for one minute. There should be no damage to the insulator and in case of post insulator the permanent set must be less than 1%. However, in case of post insulator, the load is then raised to three times and there shouldnot be any damage to the insulator and its pin.

(viii) The insulator is broken and immersed in a 0.5% alcohol solution of fuchsin under a pressure of 13800 kN/m2 for 24 hours. The broken insulator is taken out and further broken. It should not show any sign of impregnation.

(ix) An impulse over voltage is applied between the pin and the lead foil bound over the top and side grooves in case of pin type and post insulator and between the metal fittings in case of suspension type insulators. The voltage is 1/50 μ sec. wave with amplitude twice the 50% impulse flash overvoltage and negative polarity. Twenty such applications are applied. The procedure is repeated for 2.5,3, 3.5 times the 50% impulse flash over voltage and continued till the insulator is punctured. The insulator must not puncture if the voltage applied is equal to the one specified in the specification.

(x) The string in insulator is suspended vertically or horizontally and a tensile load 20% in excess of the maximum specified working load is applied for one minute and no damage to the string should occur.

What are the different tests conducted on cables? Explain any one of them.
TESTING OF CABLES

High voltage power cables have proved quite useful especially in case of HV d.c. transmission. Underground distribution using cables not only adds to the aesthetic looks of a metropolitan city but it provides better environments and more reliable supply to the consumers.

Preparation of Cable Sample

The cable sample has to be carefully prepared for performing various tests especially electrical tests. This is essential to avoid any excessive leakage or end flash overs which otherwise may occur during testing and hence may give wrong information regarding the quality of cables. The length of the sample cable varies between 50 cms to 10 m. The terminations are usually made by shielding the ends of the cable with stress shields so as to relieve the ends from excessive high electrical stresses.

A cable is subjected to following tests:

(i) Bending tests.

(ii) Loading cycle test.

(iii) Thermal stability test.

(iv) Dielectric thermal resistance test.

(v) Life expectancy test.

(vi) Dielectric power factor test.

(vii) Power frequency withstand voltage test.

(viii) Impulse withstand voltage test.

(ix) Partial discharge test.

(i) It is to be noted that a voltage test should be made before and after a bending test. The cable is bent round a cylinder of specified diameter to make one complete turn. It is then unwound and rewound in the opposite direction. The cycle is to be repeated three times.

(ii) A test loop, consisting of cable and its accessories is subjected to 20 load cycles with a minimum conductor temperature 5°C in excess of the design value and the cable is energized to1.5 times the working voltage. The cable should not show any sign of damage.

(iii) After test as at (ii), the cable is energized with a voltage 1.5 times the working voltage for a cable of 132 kV rating (the multiplying factor decreases with increases in operating voltage) and the loading current is so adjusted that the temperature of the core of the cable is 5°C higher than its specified permissible temperature. The current should be maintained at this value for six hours.

(iv) The ratio of the temperature difference between the core and sheath of the cable and the heat low from the cable gives the thermal resistance of the sample of the cable. It should be within the limits specified in the specifications.

(v) In order to estimate life of a cable, an accelerated life test is carried out by subjecting the cable to a voltage stress higher than the normal working stress. It has been observed that the relation between the expected life of the cable in hours and the voltage stress is given by

$$g = \frac{K}{n\sqrt{t}}$$

where K is a constant which depends on material and n is the life index depending again on the material.

(vi) High Voltage Schering Bridge is used to perform dielectric power factor test on the cable sample. The power factor is measured for different values of voltages e.g. 0.5, 1.0, 1.5 and 2.0 Times the rated operating voltages. The maximum value of power factor at normal working voltage does not exceed a specified value (usually 0.01) at a series of temperatures ranging from 15°C to 65°C. The difference in the power factor between rated voltage and 1.5 times the rated voltage and the rated voltage and twice the rated voltage does not exceed a specified value.

Sometimes the source is not able to supply charging current required by the test cable, a suitable choke in series with the test cable helps in tiding over the situation.

(vii) Cables are tested for power frequency a.c. and d.c. voltages. During manufacture theentire cable is passed through a higher voltage test and the rated voltage to check the continuity ofthe cable. As a routine test the cable is subjected to a voltage 2.5 times the working voltage for 10 min without damaging the insulation of the cable. HV d.c. of 1.8 times the rated d.c. voltage of negative polarity for30 min. is applied and the cable is said to have withstood the test if no insulation failure takes place.

(viii) The test cable is subjected to 10 positive and 10 negative impulse voltage of magnitude as specified in specification, the cable should withstand 5 applications without any damage. Usually, after the impulse test, the power frequency dielectric power factor test is carried out to ensure that no failure occurred during the impulse test.

(ix) Partial discharge measurement of cables is very important as it gives an indication of expected life of the cable and it gives location of fault, if any, in the cable. When a cable is subjected to high voltage and if there is a void in the cable, the void breaks down and a discharge takes place. As a result, there is a sudden dip in voltage in the form of an impulse. This impulse travels along the cable as explained in detail in Chapter VI. The duration between the normal pulse and the discharge pulse is measured on the oscilloscope and this distance gives the location of the void from the test end of the cable. However, the shape of the pulse gives the nature and intensity of the discharge. In order to scan the entire length of the cable against voids or other imperfections, it is passed through a tube of insulating material filled with distilled water. Four electrodes, two at the end and two in the middle of the tube are arranged. The middle electrodes are located at a stipulated distance and these are energized with high voltage. The two end electrodes and cable conductor are grounded. As the cable is passed between the middle electrode, if a discharge is seen on the oscilloscope, a defect in this part of the cable is stipulated and hence this part of the cable is removed from the rest of the cable.

What are the different tests conducted on Bushings? Explain in detail

TESTING OF BUSHINGS

Bushings are an integral component of high voltage machines. A bushing is used to bring high voltage conductors through the grounded tank or body of the electrical equipment without excessive potential gradients between the conductor and the edge of the hole in the body. The bushing extends into the surface of the oil at one end and the other end is carried above the tank to a height sufficient to prevent breakdown due to surface leakage.

Following tests are carried out on bushings:

(i) Power Factor Test

The bushing is installed as in service or immersed in oil. The high voltage terminal of the bushing is connected to high voltage terminal of the Schering Bridge and the tank or earth portion of the bushing is connected to the detector of the bridge. The capacitance and p.f. of the bushing is measured at different voltages as specified in the relevant specification and the capacitance and p.f. should be within the range specified.

(ii) Impulse Withstand Test

The bushing is subjected to impulse waves of either polarity or magnitude as specified in the standard specification. Five consecutive full waves of standard wave form (1/50 μ sec.) are applied and if two of them cause flash over, the bushing is said to be defective. If only one flash over occurs, ten additional applications are made. If no flash over occurs, bushing is said to have passed the test.

(iii) Chopped Wave and Switching Surge Test

Chopped wave and switching surge of appropriate duration tests are carried out on high voltage bushings. The procedure is identical to the one given in (ii) above.

(iv) Partial Discharge Test

In order to determine whether there is deterioration or not of the insulation used in the bushing, this testis carried out. The procedure is explained in detail in Chapter-VI. The shape of the discharge is an indication of nature and severity of the defect in the bushing. This is considered to be a routine test for high voltage bushings.

(v) Visible Discharge Test at Power Frequency

The test is carried out to ascertain whether the given bushing will give rise to ratio interference or not during operation. The test is carried out in a dark room. The voltage as specified is applied to the bushing (IS 2099). No discharge other than that from the grading rings or arcing horns should be visible.

(vi) Power Frequency Flash Over or Puncture Test

(Under Oil): The bushing is either immersed fully in oil or is installed as in service condition. This testis carried out to ascertain that the internal breakdown strength of the bushing is 15% more than the power frequency momentary dry withstand test value.

TESTING OF POWER TRANSFORMERS

Transformer is one of the most expensive and important equipment in power system. If it is not suitably designed its failure may cause a lengthy and costly outage. Therefore, it is very important to be cautious while designing its insulation, so that it can withstand transient over voltage both due to switching and lightning. The high voltage testing of transformers is, therefore, very important and would be discussed here. Other tests like temperature rise, short circuit, open circuit etc. are not considered here. However, these can be found in the relevant standard specification.

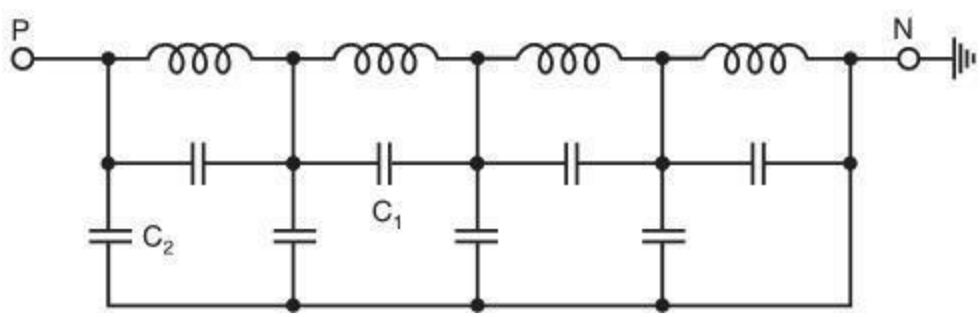
Partial Discharge Test

The test is carried out on the windings of the transformer to assess the magnitude of discharges. The transformer is connected as a test specimen similar to any other equipment as discussed in Chapter-VI and the discharge measurements are made. The location and severity of fault is ascertained using the travelling wave theory technique as explained in Chapter VI. The measurements are to be made at all the terminals of the transformer and it is estimated that if the apparent measured charge exceeds 104picocoulombs, the discharge magnitude is considered to be severe and the transformer insulation should be so designed that the discharge measurement should be much below the value of 104 pico-coulombs.

Impulse Testing of Transformer

The impulse level of a transformer is determined by the breakdown voltage of its minor insulation(Insulation between turn and between windings), breakdown voltage of its major insulation (insulation between windings and tank) and the flash over voltage of its bushings or a combination of these. The impulse characteristic of internal insulation in a transformer differs from flash over in air in two main respects. Firstly the impulse ratio of the transformer insulation is higher (varies from 2.1 to 2.2) than that of bushing (1.5 for bushings, insulators etc.).bSecondly, the impulse breakdown of transformer insulation in practically constant and is independent of time of application of impulse voltage. Fig. shows that after three micro seconds the flash over voltage is substantially constant. The voltage stress between the turns of the same winding and between different windings of the transformer depends upon the steepness of the surge wave front.

The voltage stress may further get aggravated by the piling up action of the wave if the length of the surge wave is large. In fact, due to high steepness of the surge waves, the first few turns of the winding are overstressed and that is why the modern practice is to provide extra insulation to the first few turns of the winding. Fig. shows the equivalent circuit of a transformer winding for impulse voltage.

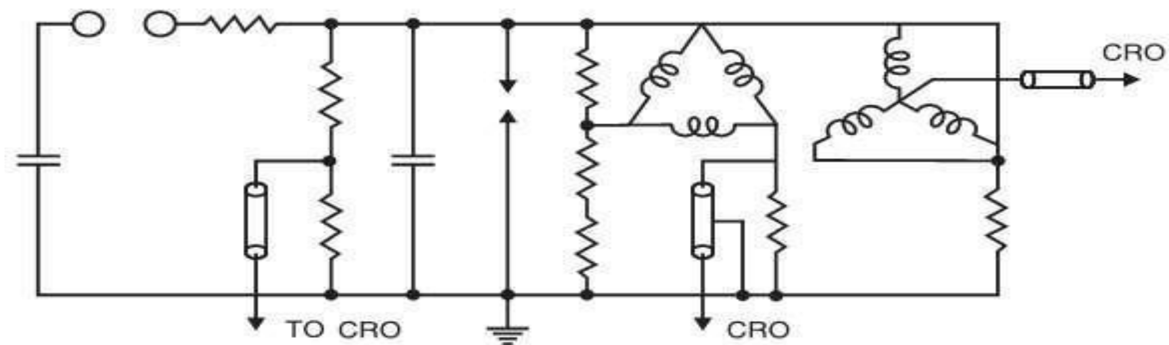


Here C1 represents inter-turn capacitance and C2 capacitance between winding and the ground(tank). In order that the minor insulation will be able to withstand the impulse voltage, the winding is subjected to chopped impulse wave of higher peak voltage than the full wave. This chopped wave is produced by flash over of a rod gap or bushing in parallel with the transformer insulation. The chopping time is usually 3 to 6 micro seconds. While impulse voltage is applied between one phase and ground, high voltages would be induced in the secondary of the transformer. To avoid this, the secondary windings are short-circuited and finally connected to ground. The short circuiting, however, decreases the impedance of the transformer and hence poses problem in adjusting the wave front and wave tail timings of wave. Also, the minimum value of the impulse capacitance required is given by

$$C_0 = \frac{P \times 10^8}{Z \times V^2}\ \mu F$$

where P = rated MVA of the transformer Z = per cent impedance of transformer. V = rated voltage of transformer.

Fig. shows the arrangement of the transformer for impulse testing. CRO forms an integralpart of the transformer impulse testing circuit. It is required to record to wave forms of the applied voltage and current through the winding under test.



Impulse testing consists of the following steps:

(i) Application of impulse of magnitude 75% of the Basic Impulse Level (BIL) of the Transformer under test.

(ii) One full wave of 100% of BIL.

(iii) Two chopped wave of 115% of BIL.

(iv) One full wave of 100% BIL and

(v) One full wave of 75% of BIL.

During impulse testing the fault can be located by general observation like noise in the tank or smoke or bubble in the breather. If there is a fault, it appears on the Oscilloscope as a partial of complete collapse of the applied voltage. Study of the wave form of the neutral current also indicated the type of fault. If an arc occurs between the turns or form turn to the ground, a train of high frequency pulses are seen on the oscilloscope and wave shape of impulse changes. If it is a partial discharge only, high frequency oscillations are observed but no change in wave shape occurs.The bushing forms an important and integral part of transformer insulation. Therefore, its impulse flash over must be carefully investigated. The impulse strength of the transformer winding is same for either polarity of wave whereas the flash over voltage for bushing is different for different polarity. The manufacturer, however, while specifying the impulse strength of the transformer takes into consideration the overall impulse characteristic of the transformer.

TESTING OF CIRCUIT BREAKERS

Equipment when designed to certain specification and is fabricated, needs testing for its performance. The general design is tried and the results of such tests conducted on one selected breaker and are thus applicable to all others of identical construction. These tests are called the type tests. These tests are classified as follows:

1. Short circuit tests:

(i) Making capacity test.

(ii) Breaking capacity test.

(iii) Short time current test.

(iv)Operating duty test

2. Dielectric tests:

(i) Power frequency test:

(a) One minute dry withstand test.

(b) One minute wet withstand test.

(ii) Impulse voltage dry withstand test.

3. Thermal test.

4. Mechanical test

Once a particular design is found satisfactory, a large number of similar C.Bs. are manufactured for marketing. Every piece of C.B. is then tested before putting into service. These tests are known as routine tests. With these tests it is possible to find out if incorrect assembly or inferior quality materialh as been used for a proven design equipment. These tests are classified as

(i) operation tests,

(ii) millivolt drop tests,

(iii)power frequency voltage tests at manufacturer's premises, and

(iv) power frequency voltage tests after erection on site.

We will discuss first the type tests. In that also we will discuss the short circuit tests after the other three tests.

Dielectric Tests

The general dielectric characteristics of any circuit breaker or switchgear unit depend upon the basic design i.e. clearances, bushing materials, etc. upon correctness and accuracy in assembly and upon the quality of materials used. For a C.B. these factors are checked from the viewpoint of their ability to withstand over voltages at the normal service voltage and abnormal voltages during lightning or other phenomenon.

The test voltage is applied for a period of one minute between

phases with the breaker closed,(ii) phases and earth with C.B. open, and across the terminals with breaker open. With this the breaker must not flash over or puncture. These tests are normally made on indoor switchgear. For such C.Bs the impulse tests generally are unnecessary because it is not exposed to impulse voltage of a very high order. The high frequency switching surges do occur but the effect of these in cable systems used for indoor switchgear are found to be safely withstood by the switchgear if it has withstood the normal frequency test. Since the outdoor switchgear is electrically exposed, they will be subjected to over voltages caused by lightning. The effect of these voltages is much more serious than the power frequency voltages in service. Therefore, this class of switchgear is subjected in addition to power frequency tests, the impulse

Voltage tests.

The test voltage should be a standard 1/50 μ sec wave, the peak value of which is specified according to the rated voltage of the breaker. A higher impulse voltage is specified for non-effectively grounded system than those for solidly grounded system. The test voltages are applied between (i) each pole and earth in turn with the breaker closed and remaining phases earthed, and (ii) between all terminals on one side of the breaker and all the other terminals earthed, with the breaker open. The specified voltages are with stand values i.e. the breaker should not flash over for 10 applications of the wave. Normally this test is carried out with waves of both the polarities. The wet dielectric test is used for outdoor switchgear. In this, the external insulation is sprayed for two minutes while the rated service voltage is applied; the test overvoltage is then maintained for30 seconds during which no flash over should occur. The effect of rain on external insulation is partly beneficial, insofar as the surface is thereby cleaned, but is also harmful if the rain contains impurities.

Thermal Tests

These tests are made to check the thermal behaviour of the breakers. In this test the rated current through all three phases of the switchgear is passed continuously for a period long enough to achieve steady state conditions. Temperature readings are obtained by means of thermocouples whose hot junctions are placed in appropriate positions. The temperature rise above ambient, of conductors, must normally not exceed 40°C when the rated normal current is less than 800 amps and 50°C if it is 800amps and above.An additional requirement in the type test is the measurement of the contact resistances between the isolating contacts and between the moving and fixed contacts. These points are generally the main sources of excessive heat generation. The voltage drop across the breaker pole is measured for different values of d.c. current which is a measure of the resistance of current carrying parts and hence that of contacts.

Mechanical Tests

A C.B. must open and close at the correct speed and perform such operations without mechanical failure. The breaker mechanism is, therefore, subjected to a mechanical endurance type test involving repeated opening and closing of the breaker. B.S. 116: 1952 requires 500 such operations without failure and with no adjustment of the mechanism. Some manufacture feel that as many as 20,000operations may be reached before any useful information regarding the possible causes of failure maybe obtained. A resulting change in the material or dimensions of a particular component may considerably improve the life and efficiency of the mechanism.

Short Circuit Tests

These tests are carried out in short circuit testing stations to prove the ratings of the C.Bs. Before discussing the tests it is proper to discuss about the short circuit testing stations.There are two types of testing stations; (i) field type, and (ii) laboratory type.In case of field type stations the power required for testing is directly taken from a large powersystem. The breaker to be tested is connected to the system. Whereas this method of testing is economical for high voltage C.Bs. it suffers from the following drawbacks:

1. The tests cannot be repeatedly carried out for research and development as it disturbs the whole network.

2. The power available depends upon the location of the testing stations, loading conditions,installed capacity, etc.

3. Test conditions like the desired recovery voltage, the RRRV etc. cannot be achieved conveniently.In case of laboratory testing the power required for testing is provided by specially designed generators. This method has the following advantages:

1. Test conditions such as current, voltage, power factor, restriking voltages can be controlled

accurately.

2. Several indirect testing methods can be used.

3. Tests can be repeated and hence research and development over the design is possible.The limitations of this method are the cost and the limited power availability for testing the breakers.